A High-Speed All-Sky Monitor for Fast Radio Bursts and Technosignatures

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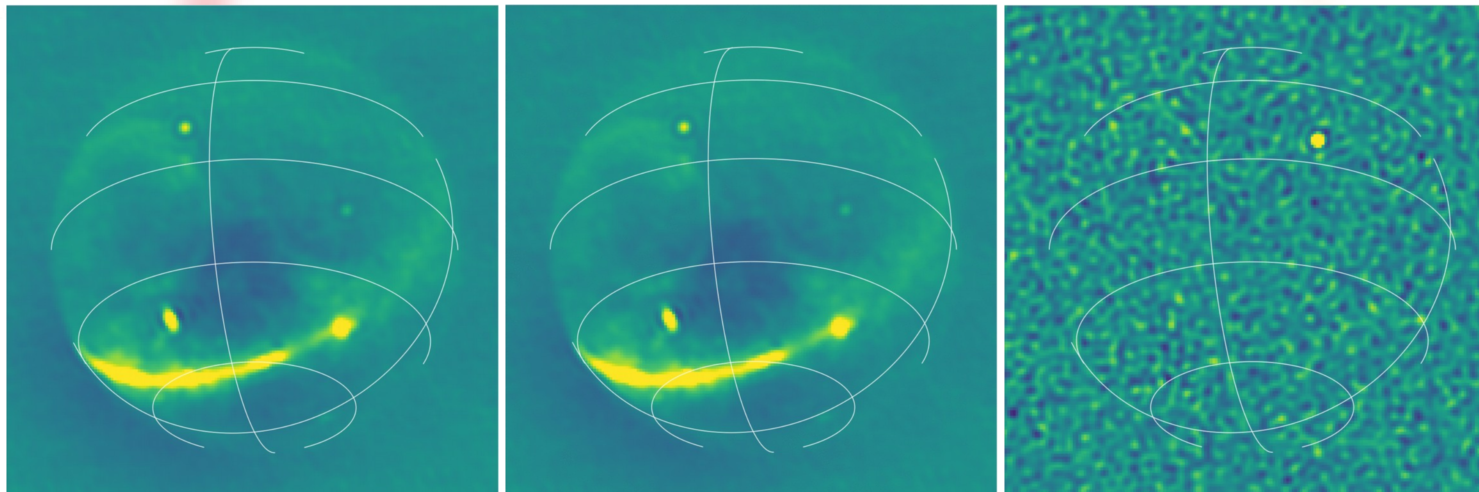
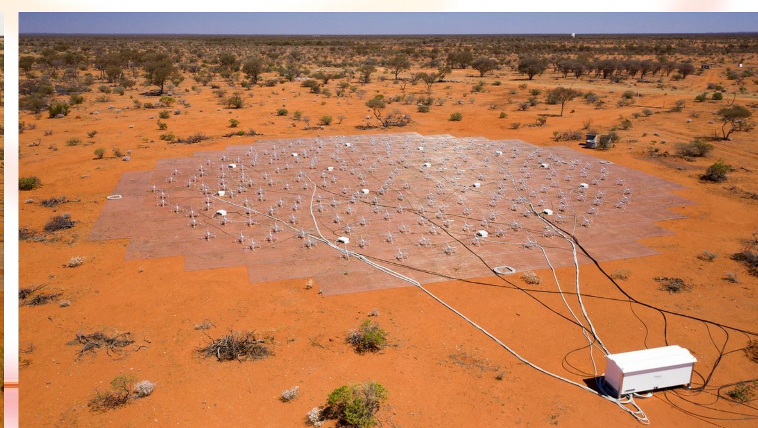
(ICRAR / Curtin University)

ICRAR

International Centre for Radio Astronomy Research





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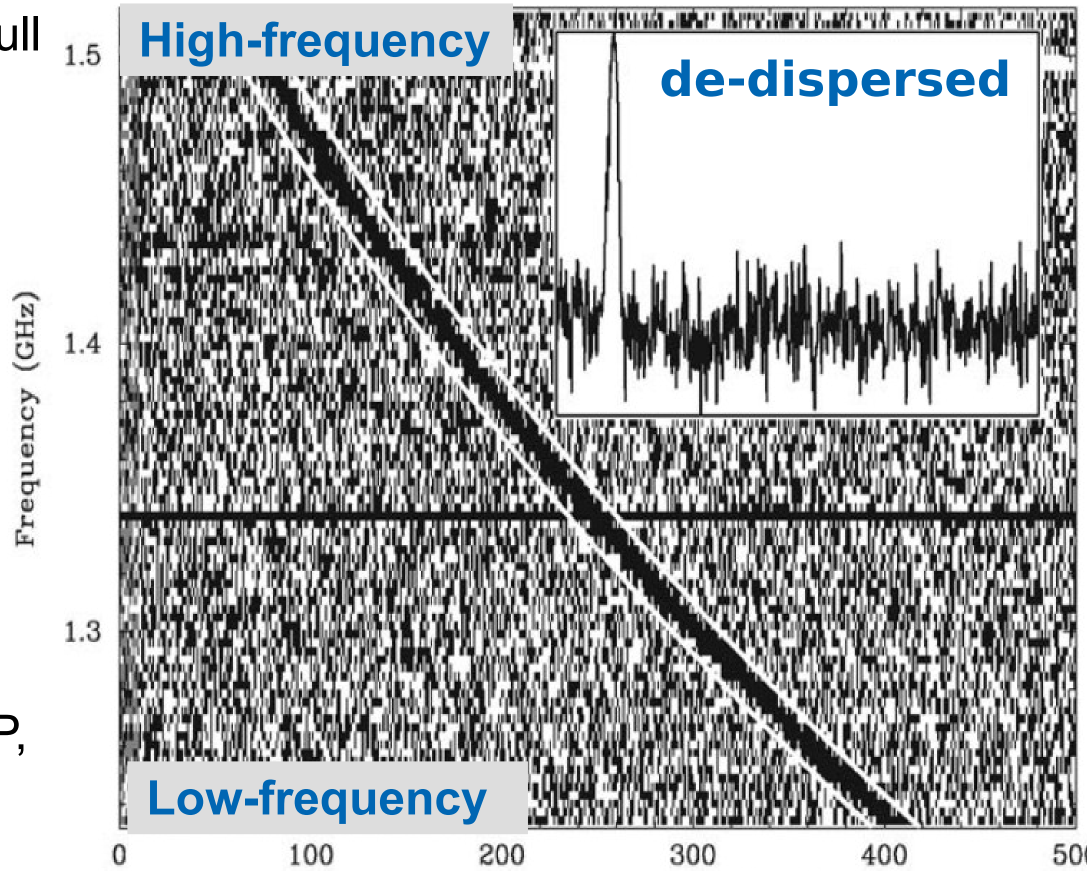
Fast Radio Bursts (FRBs)

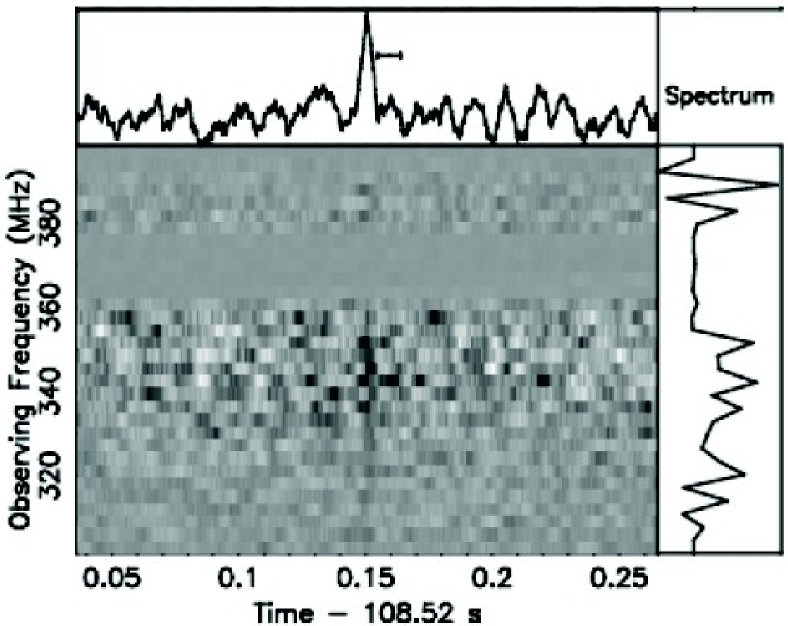
- **FRBs** are short (~millisecond) dispersed radio pulses
- Discovered 15 years ago and still awaiting full physical explanation
- Dispersed pulses at higher frequencies arrive earlier than at low frequencies
- Extragalactic origin confirmed by redshifts measurements of several host galaxies
- Extreme energies of the order of 10^{39} erg
- Require coherent emission mechanism
- By several radio-telescopes: Parkes, ASKAP, Areceibo, UTMOST, CHIME, GBT etc.
- ~5% FRBs repeat
- At 100 MHz ≤ ν ≤ 8 GHz , but only very few were detected ≤ 350 MHz)

The first FRB detected in archive data from Murriyang (Parkes) radio telescope by Lorimer et al (2007)

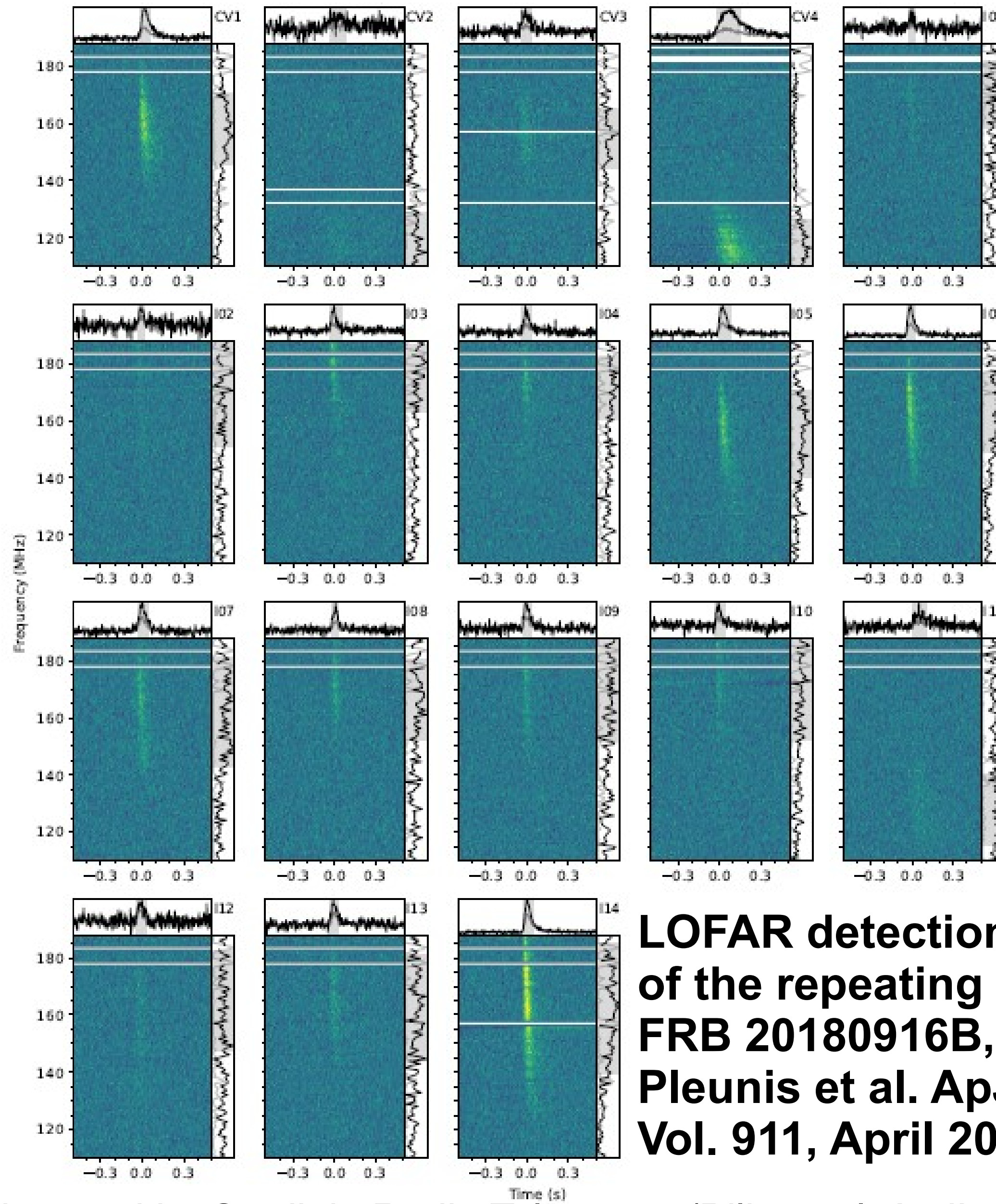


$$t_2 - t_1 = \frac{e^2}{2\pi m_e c}\left(\frac{1}{\nu_1^2} - \frac{1}{\nu_2^2}\right) DM$$, where $$DM = \int_0^d n_e \, dl$$

Detections of FRBs at low radio-frequencies (≤ 350 MHz)



FRB 200125A detected by GBT at 350 MHz (Parent et al., ApJ, Dec 2020)



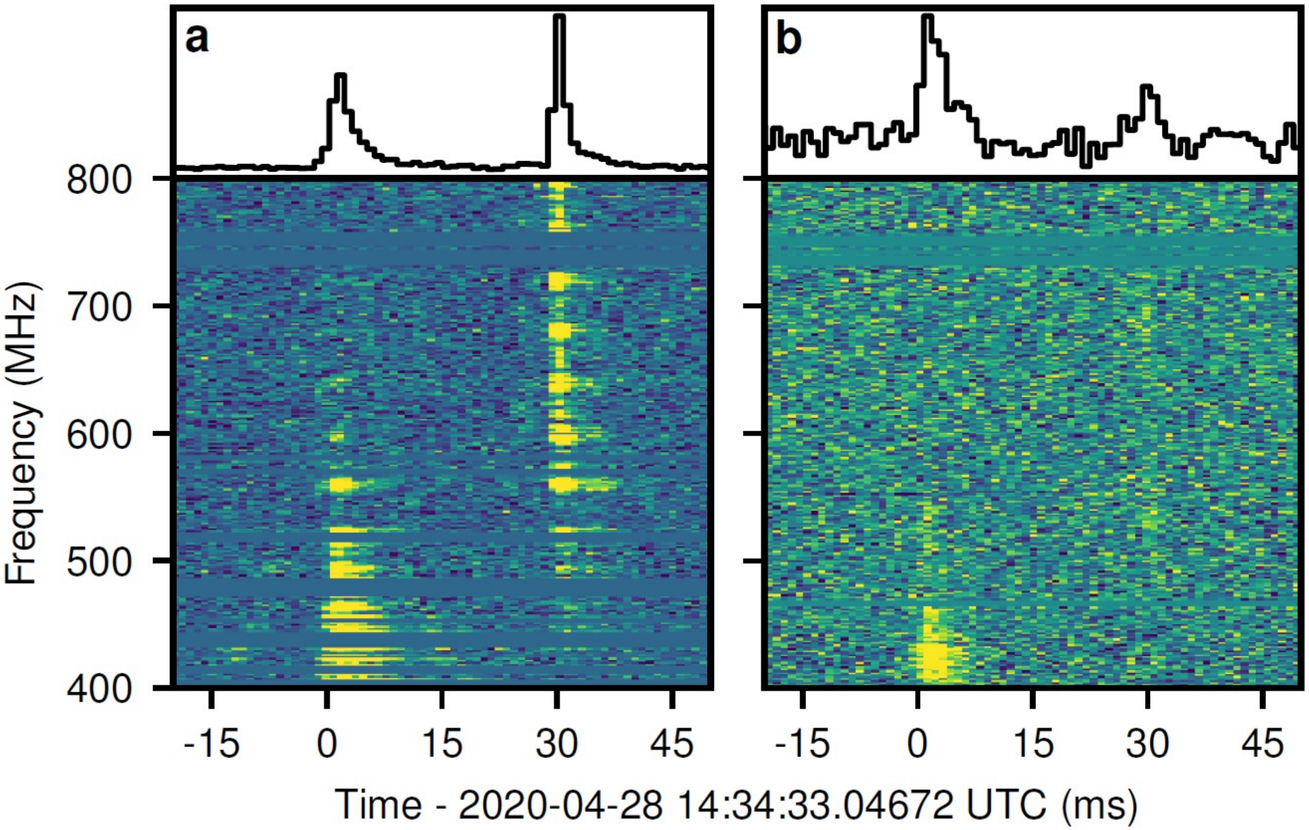
LOFAR detections of the repeating FRB 20180916B, Pleunis et al. ApJL, Vol. 911, April 2021

Also detected by Sardinia Radio Telescope (Pilia et al. ApJL, 2020)

Detections of Galactic Magnetar SGR 1935+2154 at DM ~ 332.7 pc/cm^3

CHIME detection in 400 - 800 MHz band

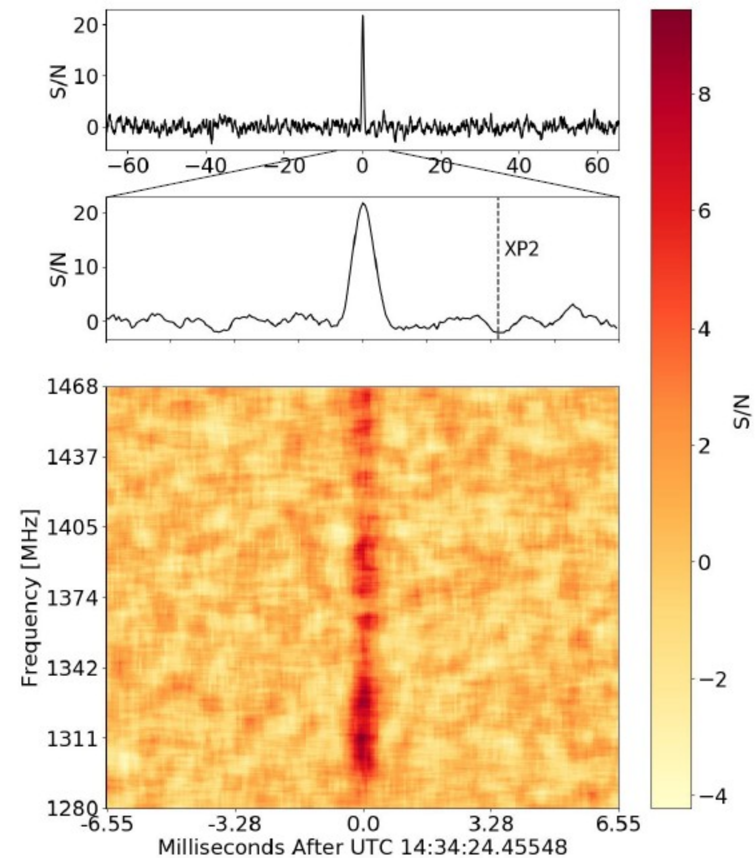
- Peak flux density 110 - 150 kJy (fluence 220 - 480 kJy ms)
- Burst energy ~3 x 10^{34} erg
- Magnetars have extreme magnetic fields ~ 10^{15} G



CHIME/FRB Collaboration, Nature, Vol. 587, Nov 2020

STARE2 radio array at 1281 - 1468 MHz

- Peak fluence ~1.5 mega-Jy ms
- Burst energy ~2.2 x 10^{35} erg (~ 40 fainter than the weakest extragalactic FRB)



Bochenek et al., Nature, Vol. 587, Nov, 2020

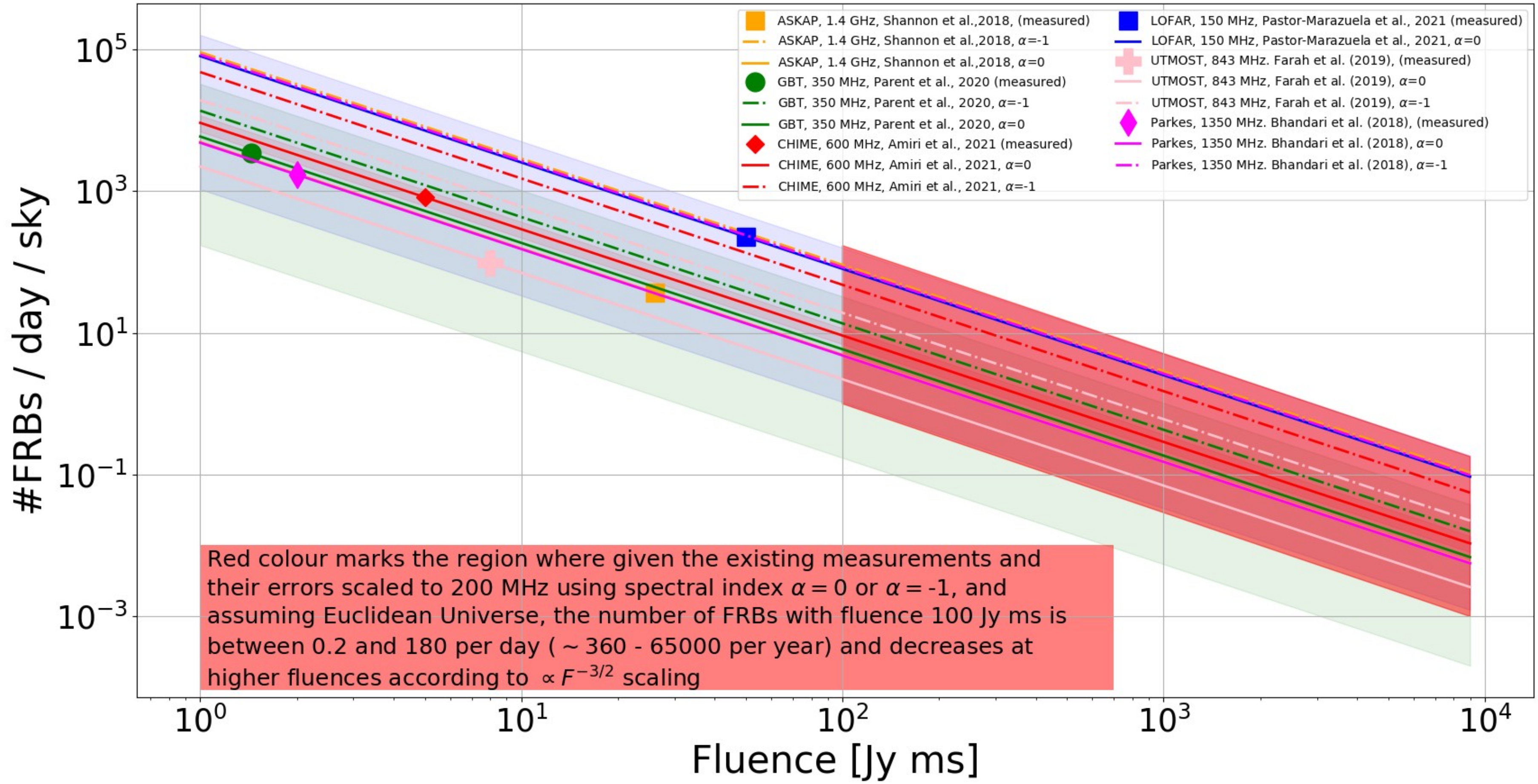
The case for all-sky FRB detectors

Survey	FoV [deg²]	Observing Time (T) in [days]	Sensitivity (S) in [Jy ms]	Figure of merit (M) N_{FRB} / year
Parent et al. (2020) - reference survey with GBT, detected one FRB at 350 MHz	$FoV_0 = 0.27$	$T_0 = 173.6$	$S_0 = 1.26$	$M_0 = 2.1$
Coenen et al. (2014)	75	9.7	71	1.09
Karastergiou et al. (2015)	24	60.25	310	1.6
Rajwade et al. (2020)	0.61	58	46	0.62
Rowlinson et al. (2016)	452	3.3	223 500	2.4×10^{-7}
Tingay et al. (2015)	610	0.44	700	3.6
An all-sky FRB detector	**12000**	**At least ~180 per year (planned)**	**200**	**142**

$$N_{FRB}/year = \frac{FoV}{FoV_0}\left(\frac{S}{S_0}\right)^{-3/2}\frac{365}{T_0[days]}\frac{\delta t_0}{\delta t}$$

where FoV is Field-of-View, S sensitivity (fluence threshold), T total observing time and δt_0 is time resolution of the survey in the table above. Subscript "0" stands for the parameters of the reference survey at 350 MHz Parent et al. (1st row in the table), which detected 1 FRB in 173.6 days of data.

FRB rates at 200 MHz derived from higher frequency measurements assuming flat rate or rate ~ ν^{-1}

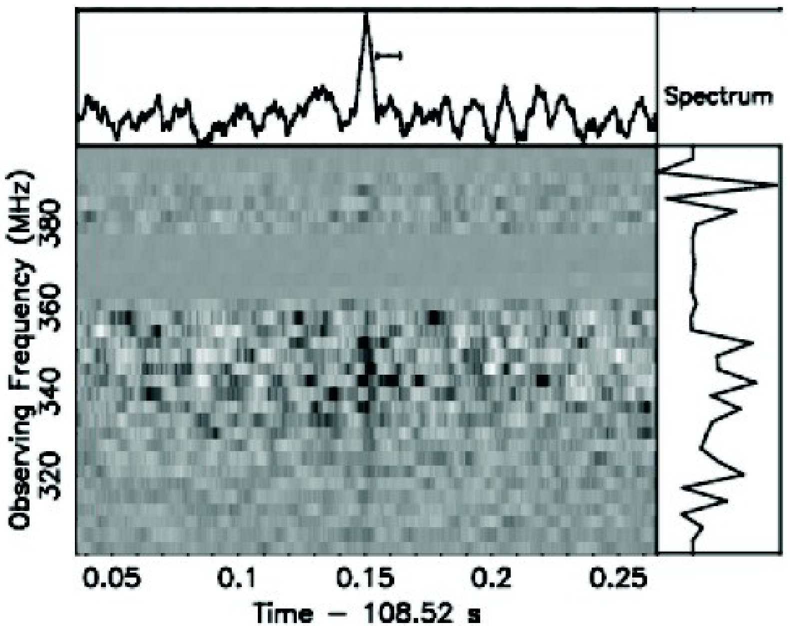


Expected number of 10σ (≥ 200 Jy ms) detections ~ 10s - 100s / year of FRBs mainly in the local Universe (redshift < 1)

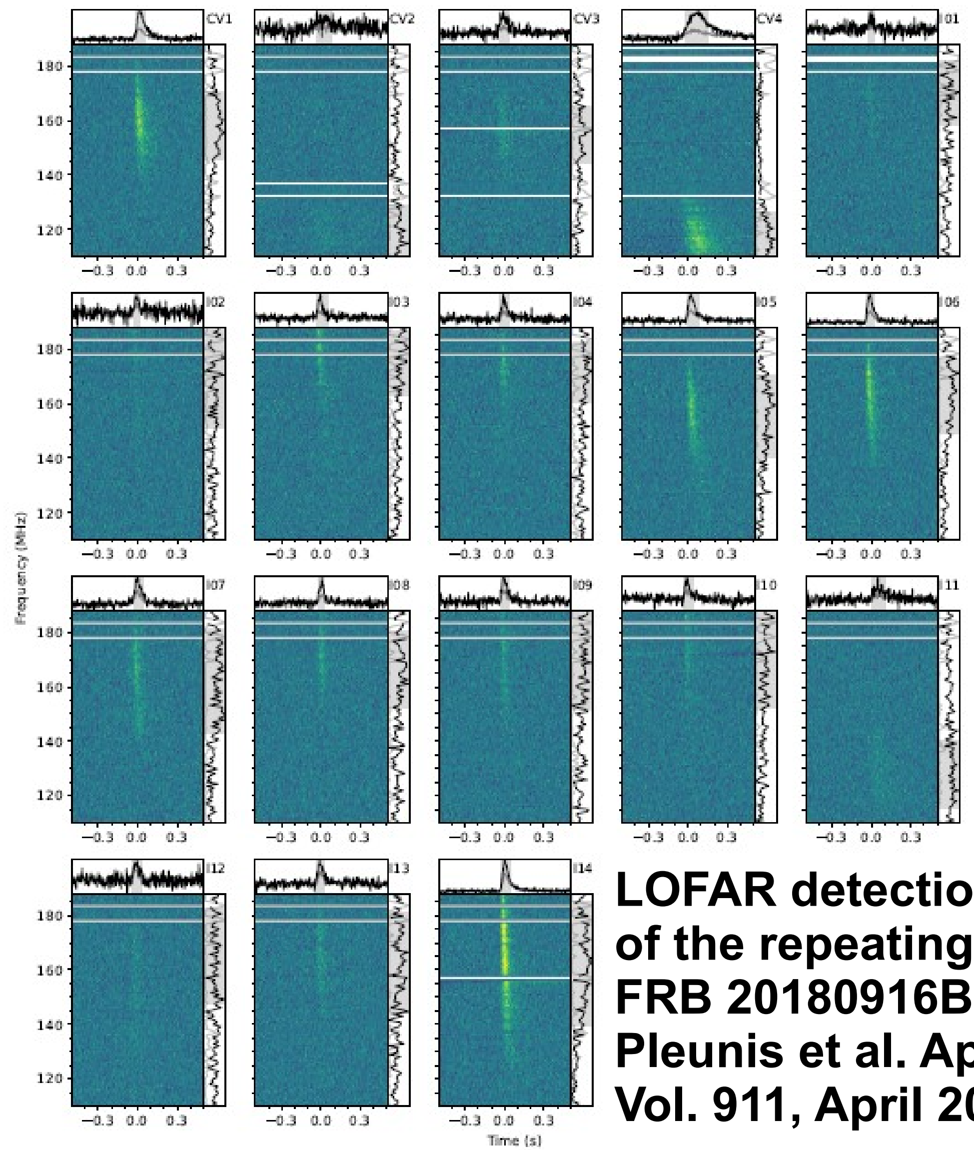
Scattering considerations

Low frequency FRBs are unscattered (probably selection effect), for example :

- FRB 20180916B (Lofar FRB)
- FRB 20200125A (GBT FRB)



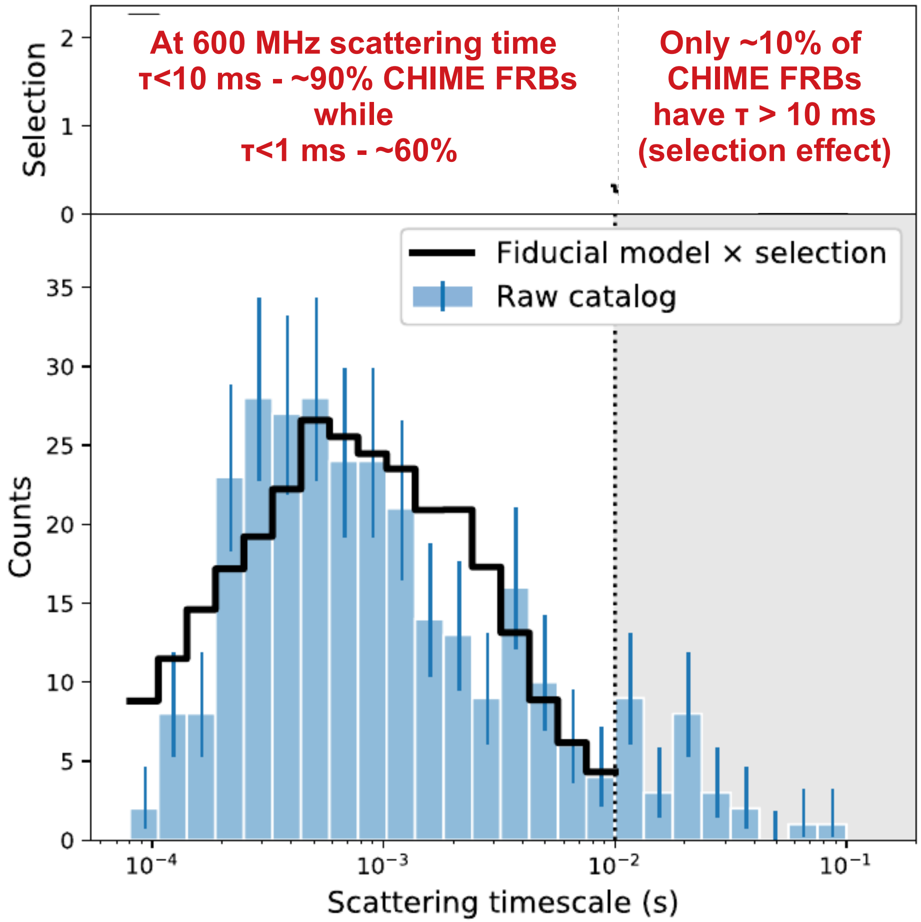
FRB 200125A detected by GBT at 350 MHz (Parent et al., ApJ, Dec 2020)



LOFAR detections of the repeating FRB 20180916B, Pleunis et al. ApJL, Vol. 911, April 2021

Scattering considerations

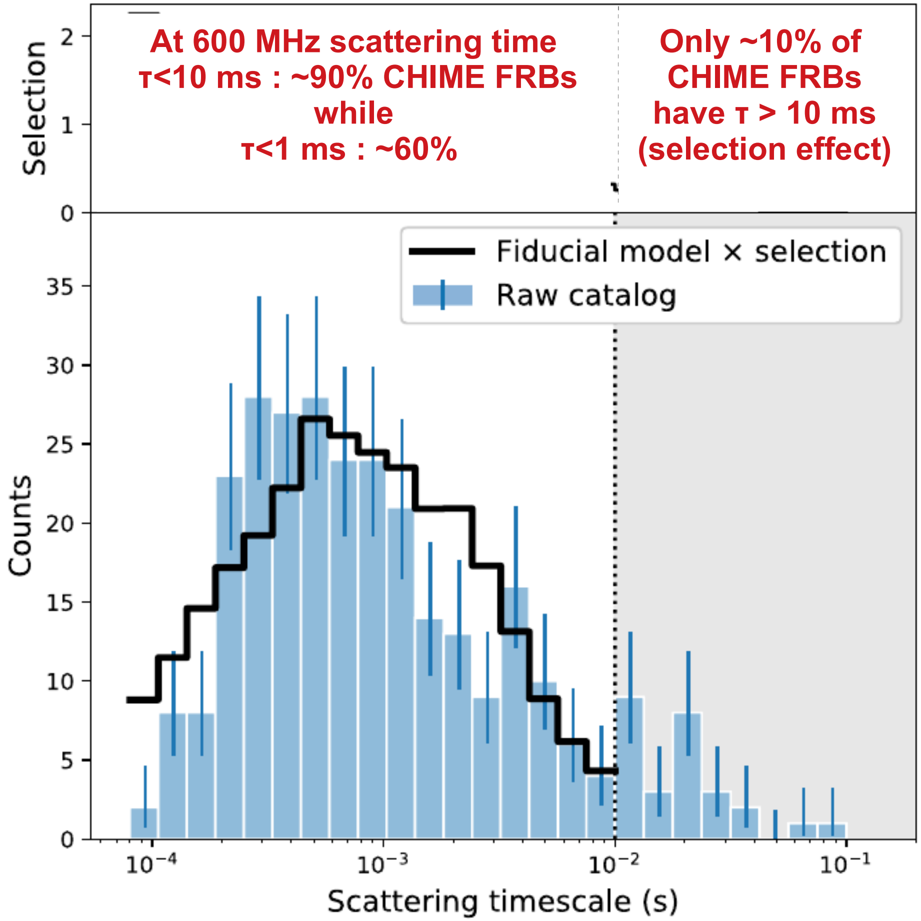
BASED ON CHIME FRB CATALOGUE (*Amiri et al. (2021)*) :



Scattering time [ms]	Fraction of FRBs (out of ~293) [%]
<10ms	89.4
<1ms	**58.7**
>10ms	9.2

Scattering considerations

BASED ON CHIME FRB CATALOGUE at 600 MHz (*Amiri et al. (2021)*) :



Scattering time [ms]	Fraction of FRBs (out of ~293) [%]
<10ms	89.4
<1ms	**58.7**
>10ms	9.2

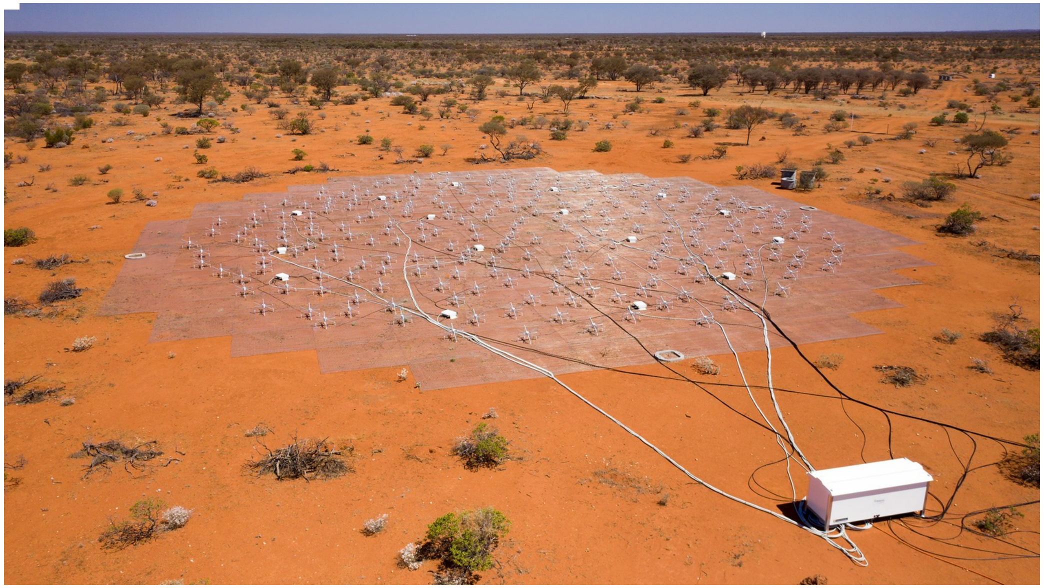
Scattering power law index	Scattering time at 100 MHz [ms]	Scattering time at 200 MHz [ms]	Scattering time at 300 MHz [ms]	Scattering time at 350 MHz [ms]
-4	1296.0	81.0	16	8.63
-4.4	2653.8	125.7	21.1	10.7
Optimal imaging time resolution	a few seconds	~100 - 200 ms	~20 ms	~10 ms

- ~60% of CHIME FRBs with measured scattering (~293 of out 536 have scattering time <1ms
- This translates to scattering times between 10 - 130 ms at 350 and 200 MHz respectively
- Hence ~10 - 100ms time resolution is reasonable

SKA-Low (50 - 350 MHz) prototype stations

Aperture Array Verification System 2 (AAVS2)
256 SKALA-4.1 antennas
(van Es et al, Proc. of SPIE, 2020, Macario et al, SPIE JATIS ,2022)

Engineering Development Array 2 (EDA2)
256 MWA Dipoles
(Wayth et al., SPIE JATIS, 2022)

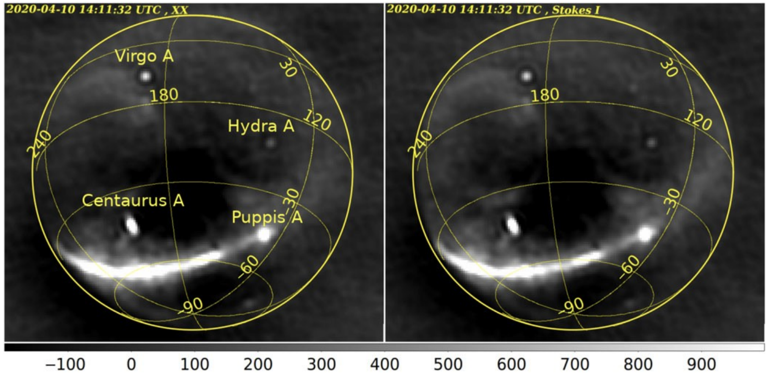


- Antennas individually digitised → 16 SmartBoxes → 5 km fibre → Tile Processing Units (TPMs)
- 16 TPMs per station (32 inputs per TPM) output data in 1.08 usec resolution :
  - Complex voltages from all antennas in 1 coarse channel (~0.93 MHz)
  - Station beam (~3.3° at 150 MHz) : complex voltages coherently added in the TPMs
- Observing in 50 - 350 MHz band with the following modes available :
  - **Standalone interferometer: station antennas cross-correlated with xGPU correlator (all-sky images in 2s , 1 coarse channel ~0.93 MHz resolutions)**
  - Station beam : tested on drift scan observations and detections of multiple pulsars
  - High-time resolution voltages : 0.28s dumps and starting to get more

Commissioning and test observations in 2019 and 2020 used to demonstrate transients monitoring capabilities

Start Date (UTC)	Frequencies[a] (MHz)	Observing interval (hours)
2020-04-10	159.4 / 159.4	22.80
2020-04-11	229.7 / 229.7	33.16
2020-04-16	320.3 / 320.3	23.00
2020-04-29	159.4 / 159.4	10.21
2020-05-30	159.4 / 229.7	10.9
2020-06-26	159.4 / 159.4	131.47
2020-07-07	159.4 / 229.7	23.91
2020-07-09	159.4 / 229.7	1.00
2020-09-11[f]	159.4 / 229.7	2.84
2020-09-14	159.4 / 229.7	32.25
2020-09-18	159.4 / 229.7	25.69
2020-09-25	159.4 / 229.7	32.66
2020-09-27	159.4 / 312.5	15.59
2020-10-01	159.4 / 312.5	0.78

[Sokolowski, Wayth, Bhat, Price et al. 2021, PASA]



Publications of the Astronomical Society of Australia (2021), **38**, e023, 18 pages
doi:10.1017/pasa.2021.16

Research Paper

A Southern-Hemisphere all-sky radio transient monitor for SKA-Low prototype stations

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Abstract

We present the first Southern-Hemisphere all-sky imager and radio-transient monitoring system implemented on two prototype stations of the low-frequency component of the Square Kilometre Array (SKA-Low). Since its deployment, the system has been used for real-time monitoring of the recorded commissioning data. Additionally, a transient searching algorithm has been executed on the resulting all-sky images. It uses a difference imaging technique to enable identification of a wide variety of transient classes, ranging from human-made radio-frequency interference to genuine astrophysical events. Observations at the frequency 159.375 MHz and higher in a single coarse channel (≈0.926 MHz) were made with 2 s time resolution, and multiple nights were analysed generating thousands of images. Despite having modest sensitivity (∼ few Jy beam^{-1}), using a single coarse channel and 2-s imaging, the system was able to detect multiple bright transients from PSR B0950+08, proving that it can be used to detect bright transients of an astrophysical origin. The unusual, extreme activity of the pulsar PSR B0950+08 (maximum flux density ∼155 Jy beam^{-1}) was initially detected in a 'blind' search in the 2020 April 10/11 data and later assigned to this specific pulsar. The limitations of our data, however, prevent us from making firm conclusions of the effect being due to a combination of refractive and diffractive scintillation or intrinsic emission mechanisms. The system can routinely collect data over many days without interruptions; the large amount of recorded data at 159.375 and 229.6875 MHz allowed us to determine a preliminary transient surface density upper limit of 1.32×10^{-9}deg^{-2} for a timescale and limiting flux density of 2 s and 42 Jy, respectively. In the future, we plan to extend the observing bandwidth to tens of MHz and improve time resolution to tens of milliseconds in order to increase the sensitivity and enable detections of fast radio bursts below 300 MHz.

Keywords: instrumentation: interferometers – telescopes – methods: observational – pulsars: individual(PSR B0950+08) – radio continuum:transients

(Received 6 February 2021; revised 13 March 2021; accepted 29 March 2021)

Some things do not need sophisticated algorithms to be detected (ISS pass at FM 98.4 MHz)

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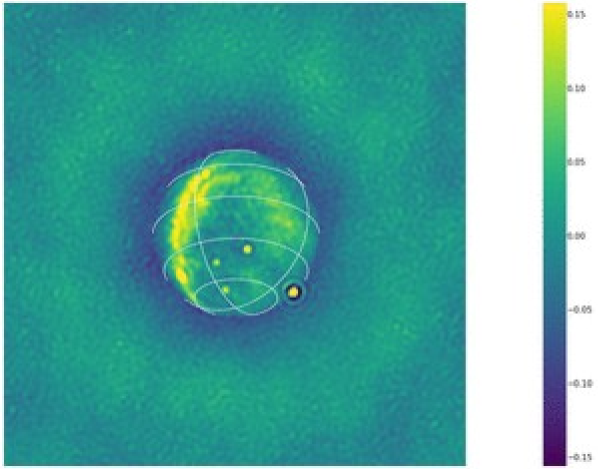
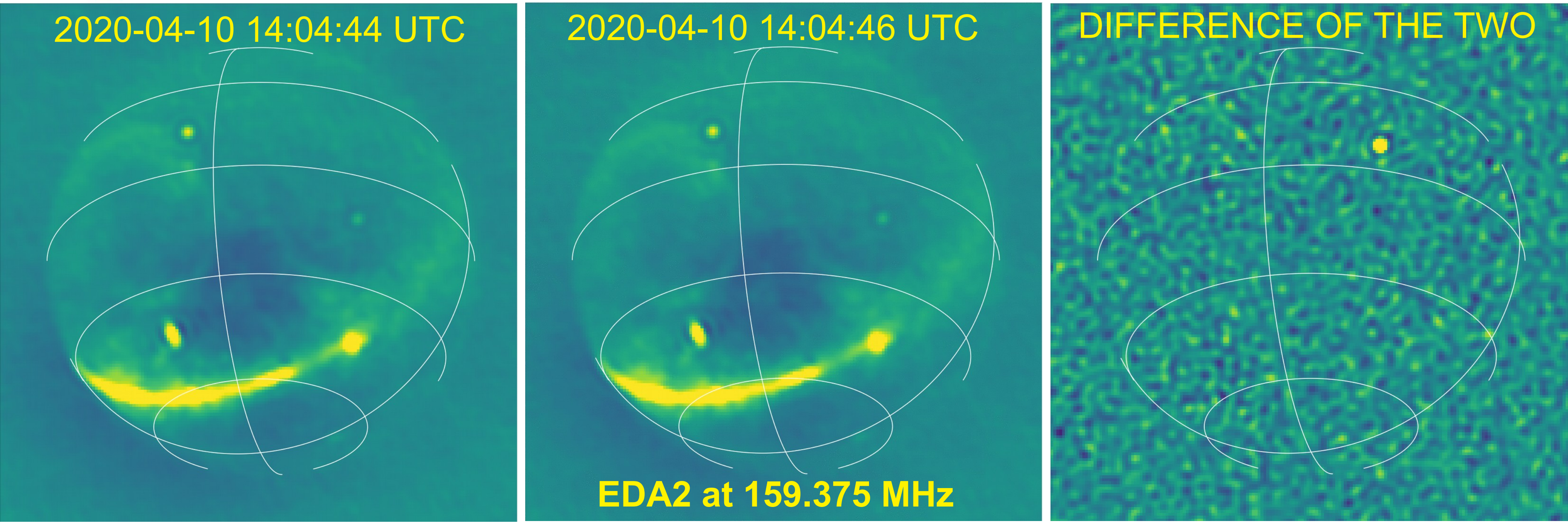
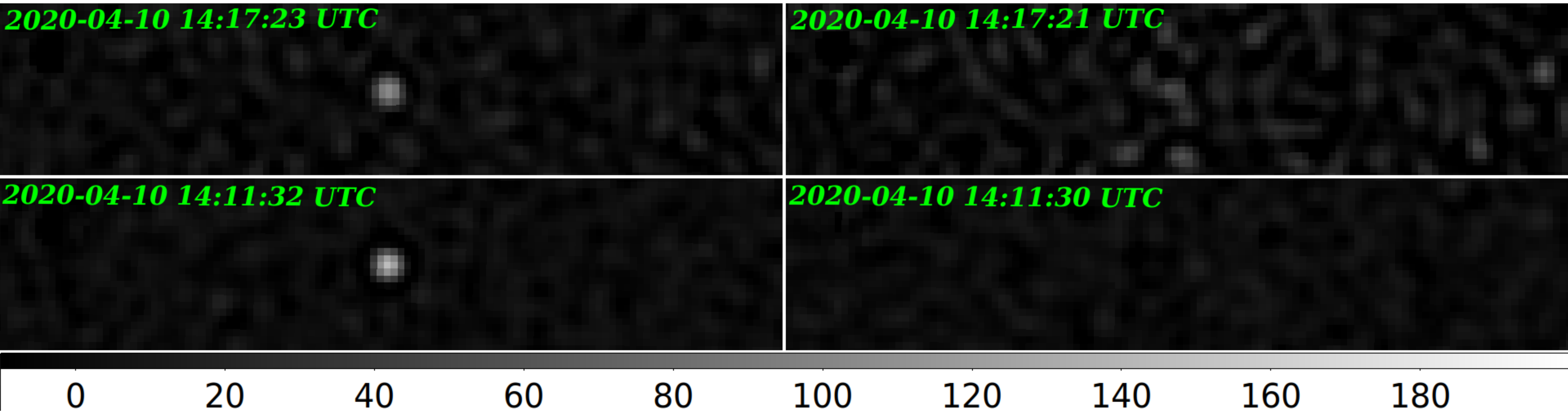


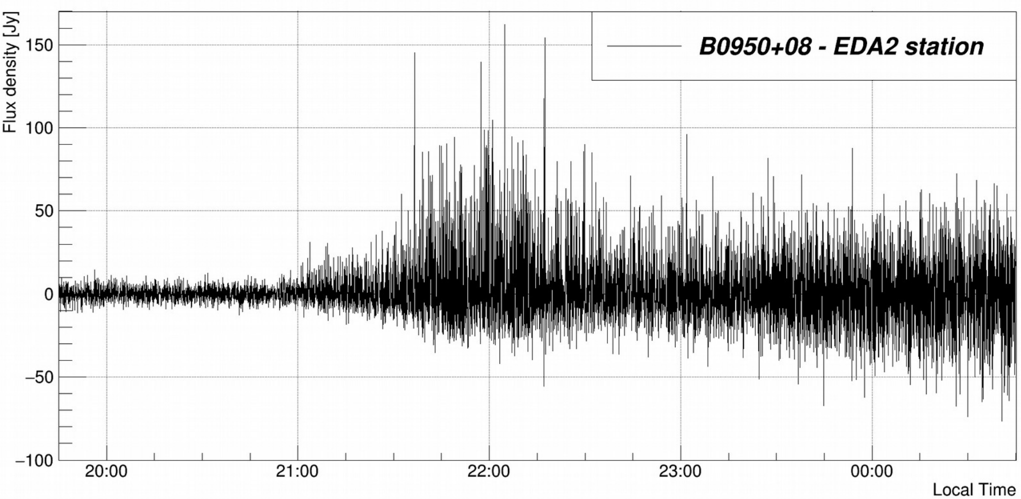
Difference imaging technique was used to identify transient candidates in the 2 second all-sky images from both stations

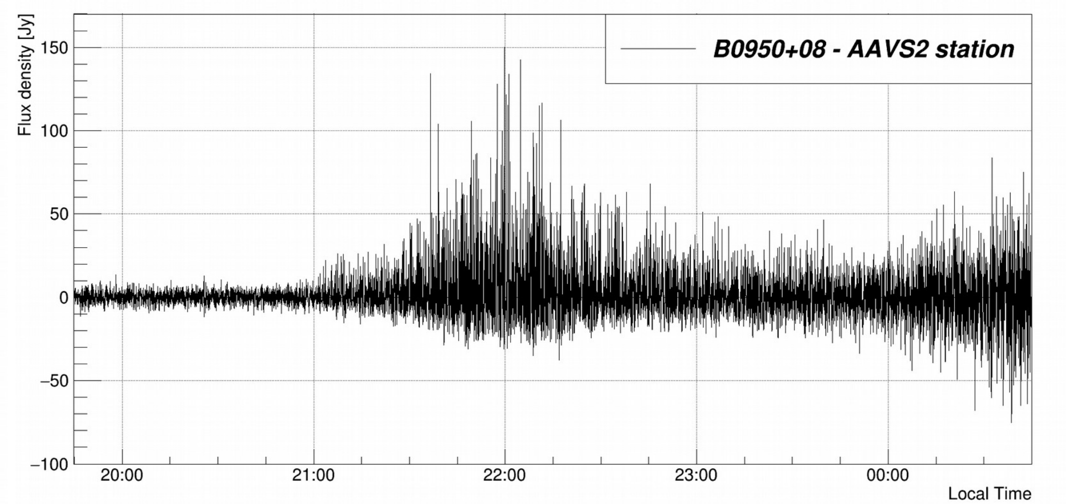


- Transient candidates identified in difference images from both stations
- Excluding regions around bright radio-sources to remove subtraction artefacts
- Time and spatial coincidence of the candidates from both stations required
- Filtering out candidates at positions known objects in the Earth orbit, airplanes, radio frequency-interference (RFI) from ground based FM and DTV transmitters

Detection of extreme activity of a nearby pulsar B0950+08 during the night 2020-04-10/11







Radio transients up to 160 Jy in 2 seconds images due to a combination of diffractive and refractive scintillation

Fast Radio Bursts (FRBs) : upper limits on low-frequency counterparts of one ASKAP and two DWF FRBs

- No detections of low-frequency FRBs
- Observed when three FRBs were detected by ASKAP and Deeper Wider Faster (DWF)
- FRB 20191228 (ASKAP) ~40 Jy ms FRB, EDA2 and AAVS2 upper limit, but no ATEL for that one
- DWF FRBs 200914 and 200919 both stations observed → upper limits
- Using 0.93 MHz bandwidth and 2s images upper limits on fluence ~30 Jy s (**30 kJy ms**)
- Demonstrates that if transient, like gamma-ray burst or gravitational wave is detected by other instruments will have images before, during and after the event !
- **Larger bandwidth and better time resolution are needed to start detecting FRBs ...**

Upper limits on low-frequency emission from FRBs 200914 and 200919 from SKA-Low prototype stations

ATel #14044; *M. Sokolowski, N. D. R. Bhat, R. B. Wayth, J. Broderick, D. Minchin, A. McPhail, D. Ung, B. Crosse, D. Davidson, T. Booler, S. Tingay, D. Price, B. Juswardy, A. Sutinjo (ICRAR/Curtin University) on behalf of the EDA2 Team. G. Bernardi, P. Bolli, J. Monari, A. Mattana, F. Perini, G. Comoretto, G. Macario, G. Pupillo, M. Schiaffino (INAF) on behalf of the AAVS2 Team. A. Magro (University of Malta), R. Chiello (University of Oxford), P. Benthem (ASTRON) and M. Waterson (SKA Organisation, Manchester)*
on ***27 Sep 2020; 12:17 UT***
Credential Certification: Marcin Sokolowski (marcin.sokolowski@curtin.edu.au)

Subjects: Radio, Fast Radio Burst

Tweet

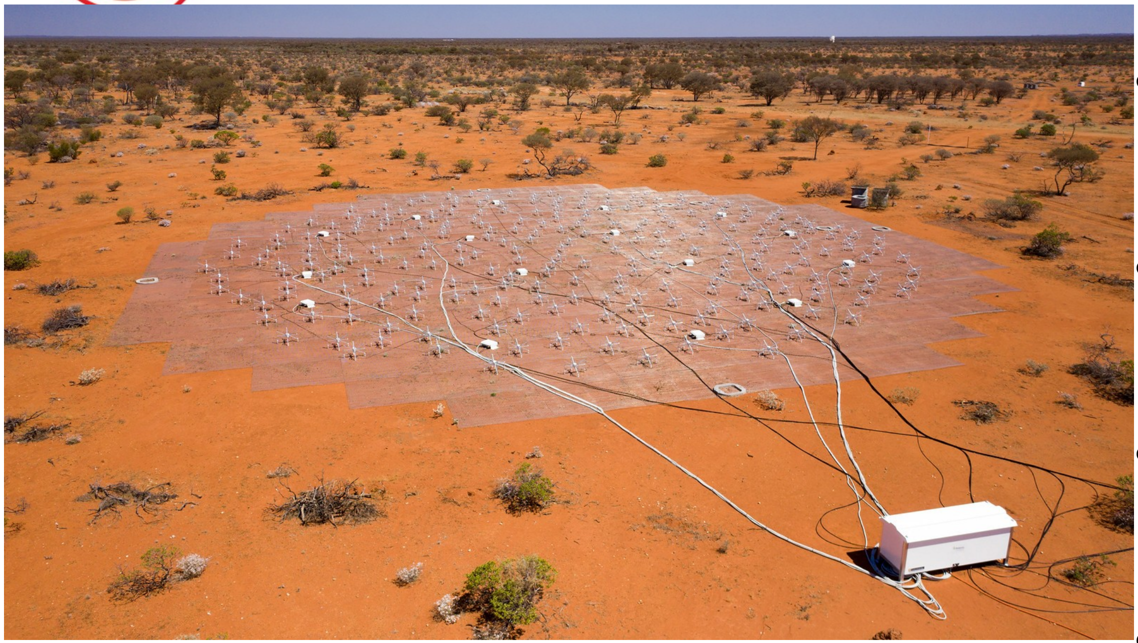
The Engineering Development Array 2 (EDA2; Wayth et al., in prep.) and the Aperture Array Verification System 2 (AAVS2; Bolli et al., in prep.) are two prototype stations of the low-frequency component of the Square Kilometre Array (SKA-Low). During the times of FRBs 200914 and 200919 (Gupta et al. ATEL #14040), both EDA2 and AAVS2 were performing test commissioning observations, and thus fortuitously, effectively co-observed the FRBs at low frequencies. The data were collected in a correlated mode using a single coarse (narrow-band) channel (approximately 0.926 MHz bandwidth), at central frequencies 159.4 (EDA2) and 229.7 MHz (AAVS2), which can be used to produce all-sky images in near real-time. The correlated data were analysed using an automatic transient detection algorithm (Sokolowski et al., in prep.), and the data around the vicinity of FRB locations and the times were also visually inspected.
Neither of these have revealed any low-frequency counterparts, resulting in the following (1 sigma) upper limits:

EDA2 at 159.4 MHz :
FRB200919 : ~25 kJy ms, implied spectral index limit > -4.0 (between 159.4 MHz and 1400 MHz)
FRB200914 : ~26 kJy ms, implied spectral index limit > -4.7 (between 159.4 MHz and 1400 MHz)

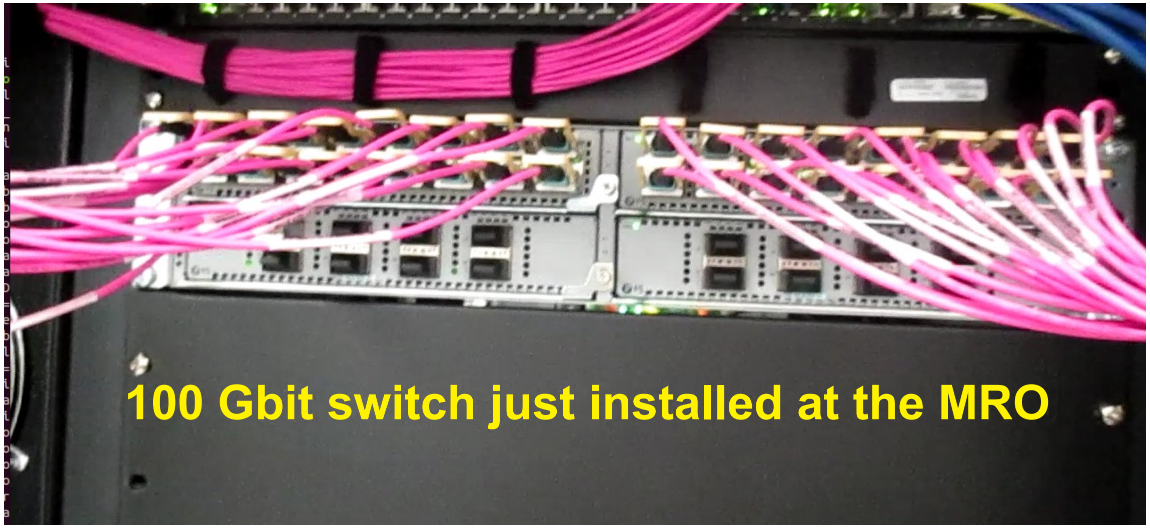
AAVS2 at 229.7 MHz :
FRB200919 : ~33 kJy ms, implied spectral index limit > -4.9 (between 229.7 MHz and 1400 MHz)
FRB200914 : ~32 kJy ms, implied spectral index limit > -5.8 (between 229.7 MHz and 1400 MHz)

Both the systems are currently in their early stages of development, and we note that both FRBs were observed at fairly low elevations. As a result, the sensitivities achieved are at ~10% level of the near-zenith (maximum). Improved sensitivities (and hence better constraints) will be possible in the future when more instantaneous bandwidth becomes available and for observations at more optimal elevations.

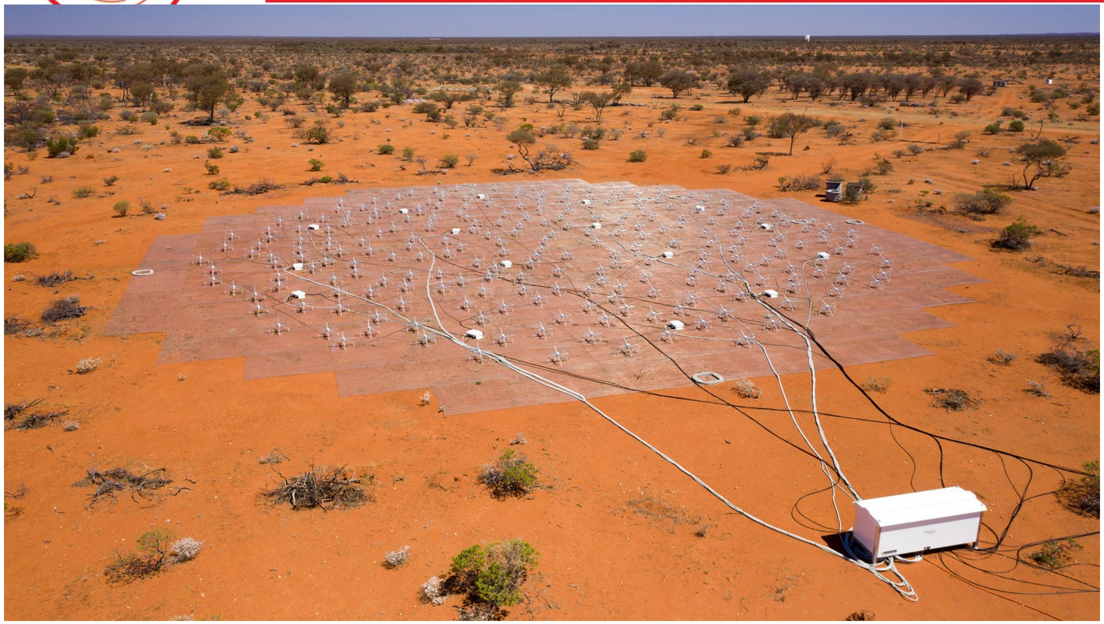
For a start network upgrade

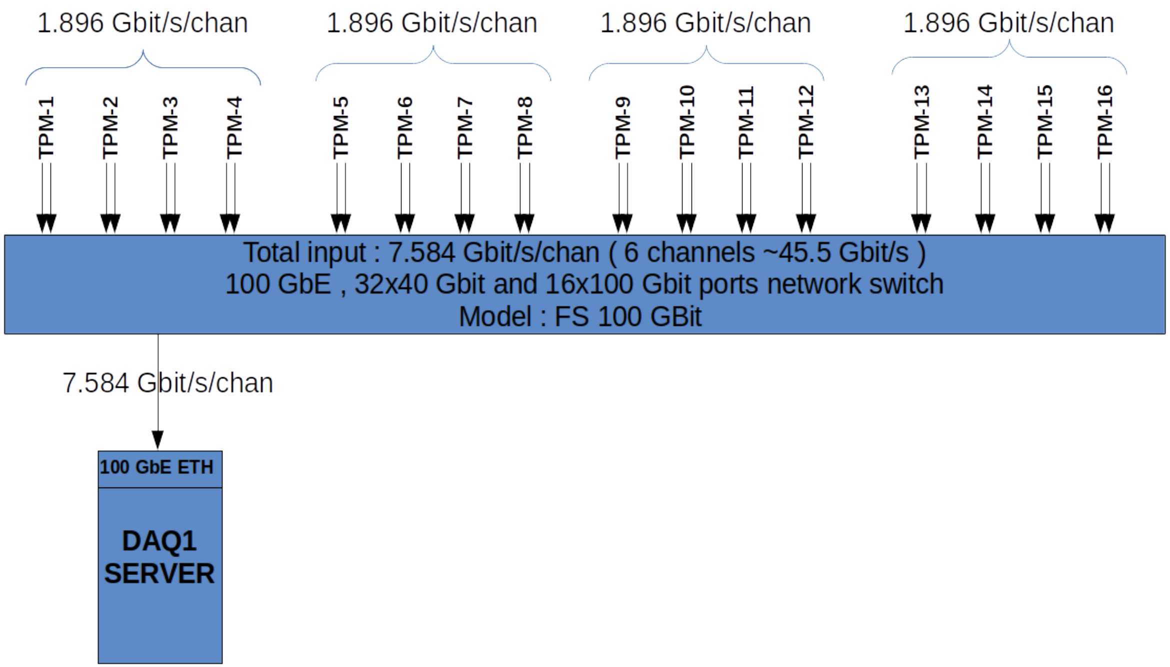


- High-throughput switch
  32 x 40 Gbit + 8 x 100 Gbit
- 1 data acquisition computer to capture a few MHz bandwidth
- Test capturing >1 coarse channel from all antennas
- Test real-time imaging



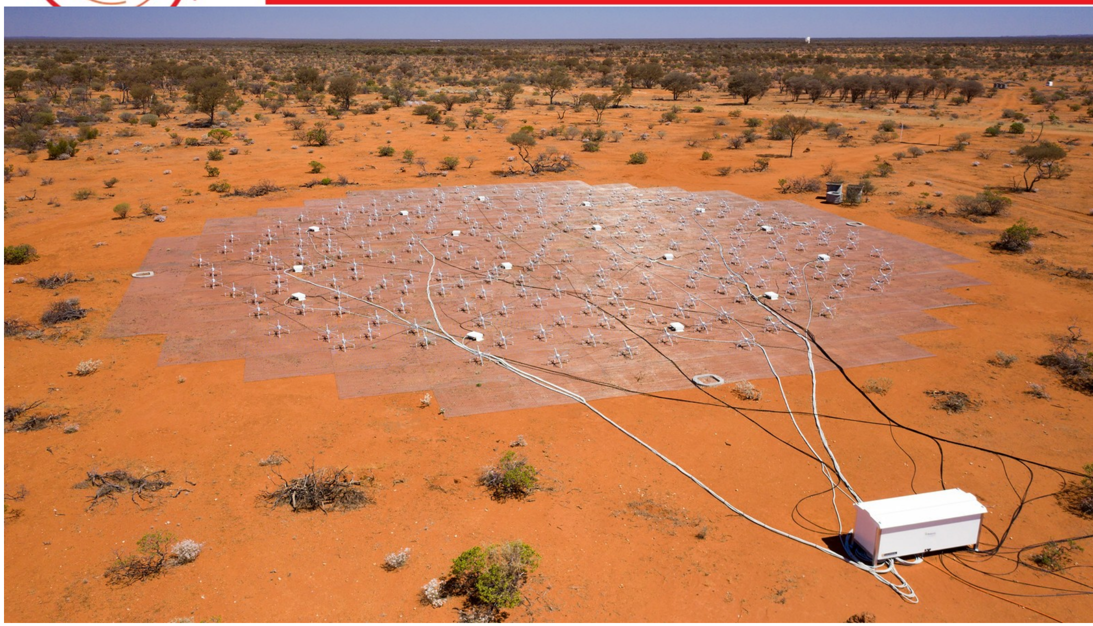
Upgrade of EDA2 bandwidth and high-time resolution imaging capability

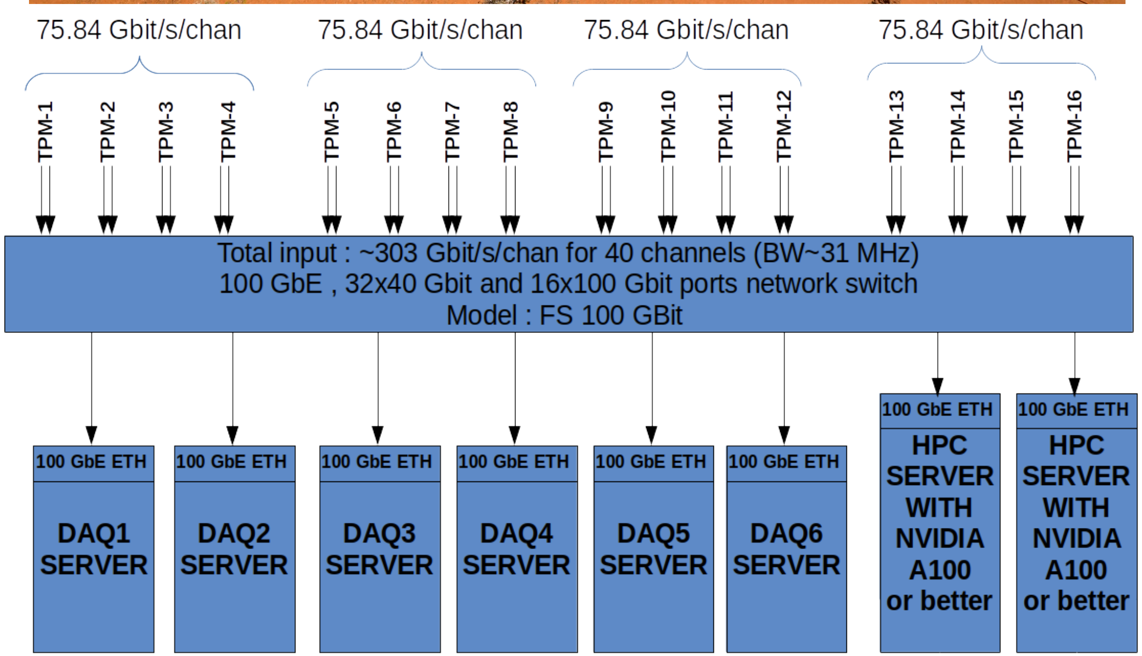




- High-throughput (100 Gbit) :
  - 32x40 Gbit TPM inputs
  - 1x100 Gbit output
- 1 data acquisition computers to capture ~50 Gbit/s per computer
- Data rate ~7.6 Gbit / s
- Enables capturing of up to 6 coarse (BW~5 MHz) channels from all antennas

Upgrade of EDA2 bandwidth and high-time resolution imaging capability





- High-throughput (100 Gbit) 64 port network switch
- 6 data acquisition computers to capture ~50 Gbit/s per computer, form 10-ms images and copy to FRB search servers (~10 GBit/s)
- FRB search servers with state of art GPUs (A100 or better) to perform de-dispersion and search for FRBs
- Software for 10ms all-sky imaging and FRB searches being developed under the PaCER project with PAWSEY (funding a PhD position)
- **Sensitivity to FRBs ~200 Jy ms at frequencies ≤ 350 MHz**

GPU-based high-time resolution imaging software (PaCER BLINK project)

Image of the entire visible hemisphere at 160 MHz obtained with MIRIAD package

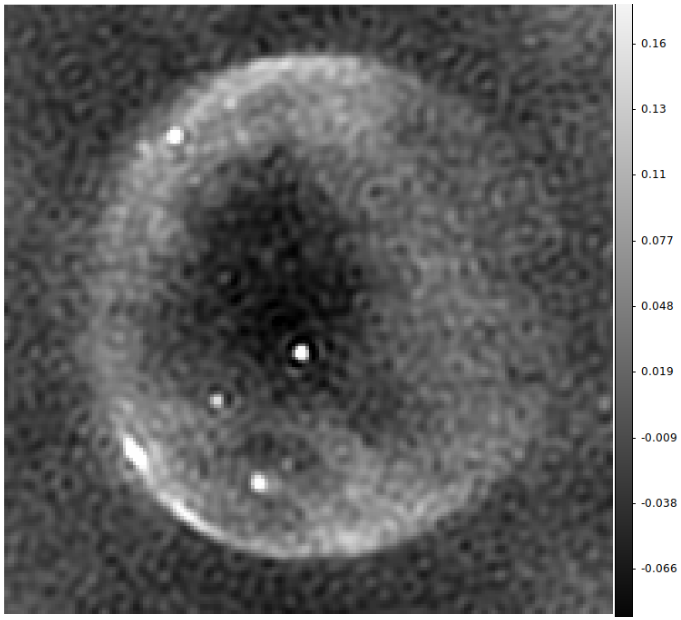


Image of the entire visible hemisphere at 160 MHz obtained with CASA package

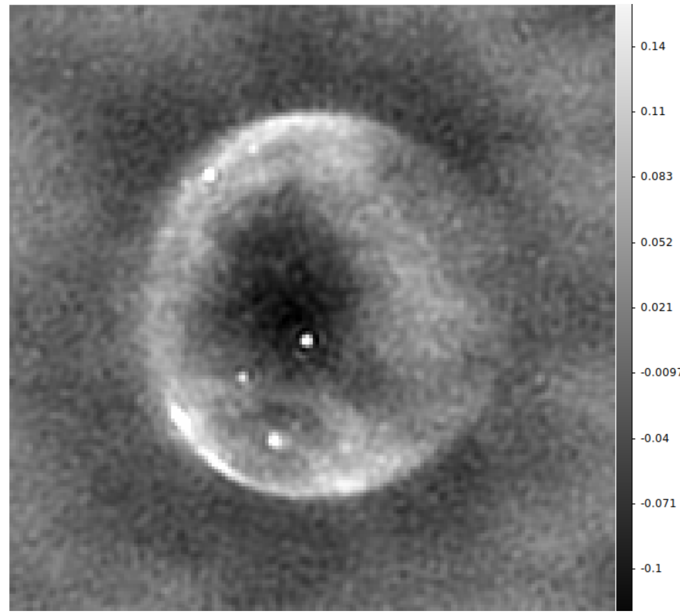
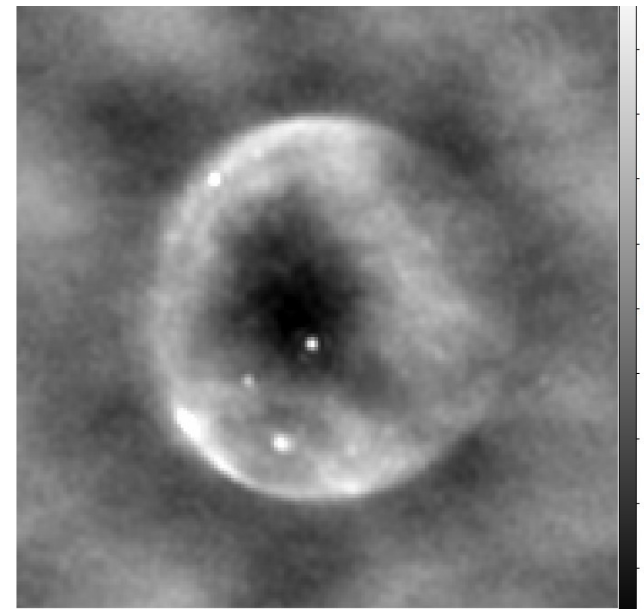


Image of the entire visible hemisphere at 160 MHz obtained with BLINK (our!) imager



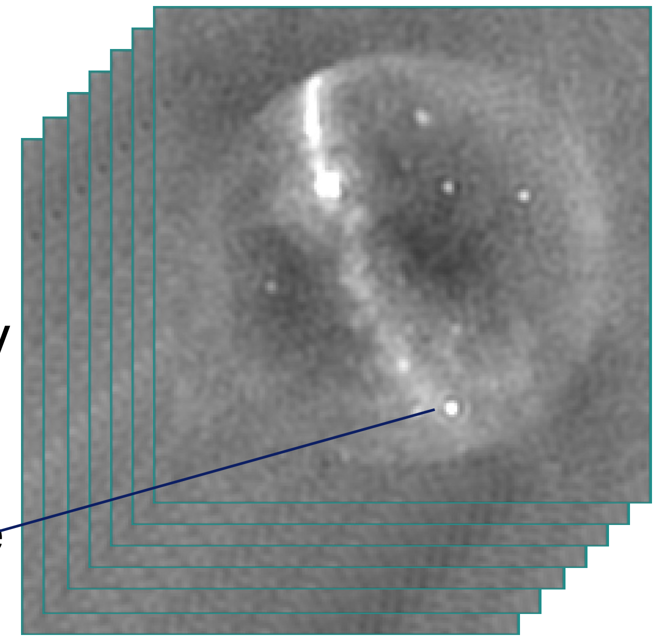
Flux scale is incorrect in this particular case

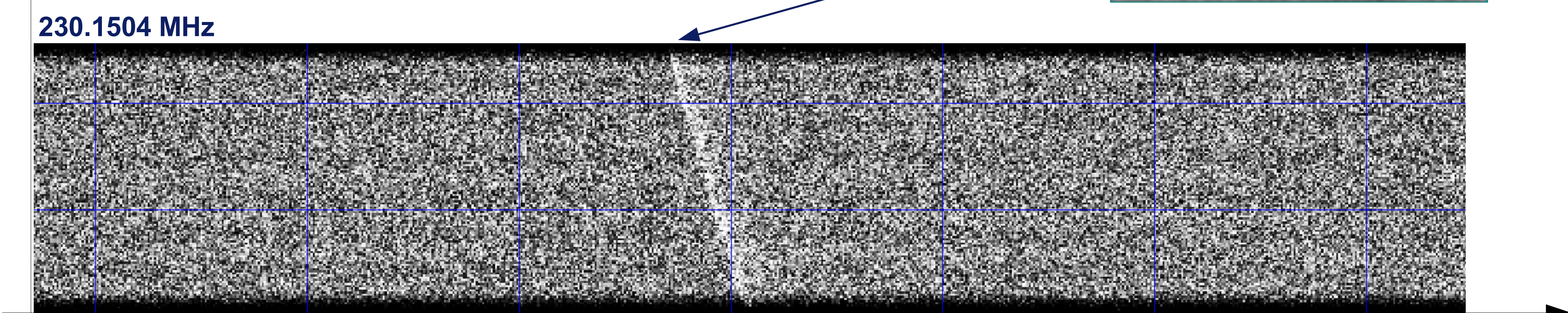
- **Validation of the code against standard radio astronomy packages on sample EDA2 data (2022_01_18_ch204_station_beam) at 160 MHz , 180x180 images**
- **Right : BLINK_pipeline program (correlation + imaging in 1-go)**
- **Validation on simulation data underway**
- **Production version of imaging pipeline under development**

A High-Speed All-Sky Monitor for Fast Radio Bursts and Technosignatures (CHASM)

- BW ~30 MHz imaging time resolution to ~10 ms
- **Sensitivity to FRBs by ~2 orders of magnitude to ~300 Jy ms (~ few Jy in 10ms images)**
- For DM=1000 pc/cm^3, 230 - 200 MHz band, e.g. dispersion delay ~ 24.7s * 0.64GB/s ~ 16 GB memory bandwidth ~1.6 TB/s for 200x200 images)
- This development will require algorithms for high-time resolution images and searches for dispersed pulses

Time / frequency data cube

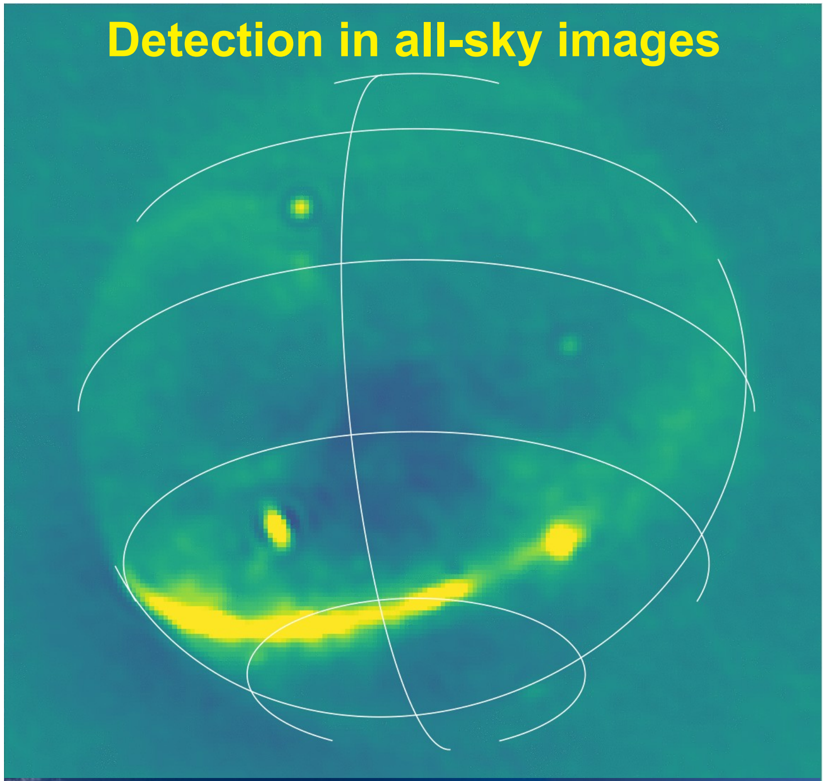


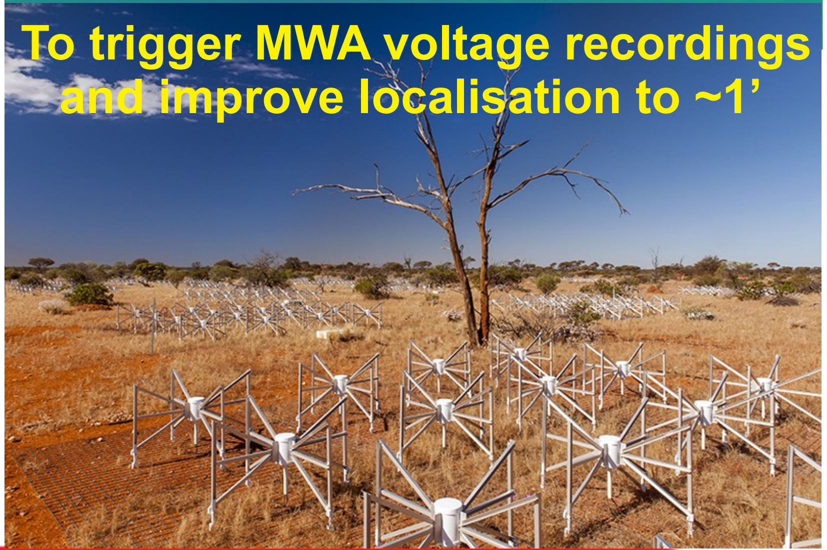


Detection of giant pulse from Crab pulsar (B0531+21) in dynamic spectrum from EDA2 station bean data

FRB localisation with CHASM and MWA

- Localisation accuracy of all-sky images from EDA2 ~1 degree
- Detection at 300 MHz can trigger MWA high-time resolution observations at 200 MHz for example, DM=350 pc/cm^3 -> ~20s dispersion delay, DM=1000 pc/cm^3 ~60sec - sufficient to trigger MWA observations and refine localisations to ~1 arcmin
- Test SKA-Low station triggering capabilities using EDA2 detections to trigger AAVS2 (~15 arcmin accuracy)
- And later first SKA-Low stations improving localisation accuracy to sub-arcmin (maximim baselines a bit longer than MWA)





Main targets for FRB science with the upgraded EDA2 (CHASM'em)

- **Robustly measure still highly uncertain FRB rates below 350 MHz**

- Detect population of bright FRBs in the local Universe, Local Group of Galaxies, Virgo Cluster, Galactic magnetars etc.
  Best candidates for possible multi-wavelengths studies, which can be used to study progenitors and emission mechanisms

- Long duration transients like ultra-long magnetar found in MWA data by Hurley-Walker et al. (2022) and similar other detections

- 24/7 observations will provide data at the positions of many FRBs, GRBs, Gravitational Wave events etc. before during and after and contribute to broadband spectral modelling transient processes

- **Technosignatures / Cradle of Life - perform all-sky search for Extraterrestial Intelligence (SETI search)**

- All-sky monitoring of radio-frequency interference (RFI) at the MRO

- Space debris and Space Situational Awareness (SSA)

- Space weather / ionosphere monitoring

Summary

- Prototype SKA-Low stations have been used to develop first southern-hemisphere all-sky transient monitor Universe at frequencies 50 - 350 MHz mostly unexplored by similar systems

- Preliminary transient survey with BW~1 MHz and 2-second images led to detections of bright transients from PSR B0950+08, derive upper limits on low-frequency counterparts of several FRBs (e.g. ATEL #14044), and upper limit on surface density (SD) of transients brighter than 42 Jy at 2s timescale

- **We have just upgraded the backend with a new 100 Gbit switch which enables multiple coarse channels (with one DAQ computer up to 6, i.e. BW ~ 5 MHz)**

- More computers will enable capturing 40 channels (BW ~ 30 MHz) MHz

- Currently developed GPU-based software will enable FRB and SETI searches in high-time (or frequency) resolution images (or UV plane)

- Based on existing data we expect that such an all-sky monitor should be able to **detect hundreds of FRBs per year**

- We will observe the sky 24/7 and have all-sky images before, during and after Gravitational Waves (GW) events, GRBs and transients detected by other instruments