3rd URSI AT-AP-RASC, Gran Canaria, 29 May – 3 June 2022

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

Marcin Sokolowski*(1), Danny C. Price(1) and Randall B. Wayth(1)
(1) ICRAR/Curtin University, Perth 6102, Australia, e-mail:marcin.sokolowski@curtin.edu.au

Abstract

Despite hundreds of Fast Radio Burst (FRB) detections at frequencies above 400 MHz, only a handful of FRBs have been observed at lower frequencies, hence the FRB rates at frequencies below 350 MHz remain highly uncertain. This paper describes our efforts to increase the observing bandwidth (to ∼40 MHz) and imaging time resolution (to ∼10 ms) of the Engineering Development Array 2 (EDA2), a prototype station of the low-frequency Square Kilometre Array (SKA-Low), which will increase its sensitivity to short, FRB-like, radio pulses by two orders of magnitude and convert it into a high-time resolution all-sky monitor for FRBs and signals from extraterrestrial intelligence (technosignatures). Based on highly uncertain FRB rates at these frequencies and sensitivity of SKA-Low stations, we expect to detect up to hundreds of FRBs per year and firmly establish the FRB rates in this relatively under-explored parameter space.

1 Introduction

Fast Radio Bursts (FRB) are one of the most intriguing astrophysical phenomena discovered less than 15 years ago. Their origin and nature is arguably one of the biggest open question in high-energy astrophysics. FRBs are energetic events that last a few milliseconds, and are bright enough to detect across cosmological distances. FRBs were originally discovered at 1.4 GHz by the Australian Murriyang (also known as Parkes) radio telescope in 2007 in archival (2001) data [1]. Later, more FRBs at GHz frequencies were detected by Parkes [2] and the Australian Square Kilometre Array Pathfinder (ASKAP) during the Commensal Real-Time ASKAP Fast-Transients Survey (CRAFT) [3]. In the following years FRBs were detected at sub-GHz frequencies, initially at 843 MHz [4] by the upgraded Molonglo Observatory Synthesis Telescope (UTMOST). Since 2018, a similar telescope in the Northern Hemisphere, the Canadian Hydrogen Intensity Mapping Experiment (CHIME) [8], has detected many repeating and non-repeating FRBs in the 400 – 800 MHz band [11, 12]. However, up until very recently, FRBs were not detected below 350 MHz. Historical, non-targeted ("blind") FRB searches with archival data from the SKA-Low precursor, the Murchison Widefield Array (MWA) [9], were unsuccessful [5, 6, 7]. These non-detections can be explained by a combination of observing strategy and signal processing constraints that limited sensitivity to $\gtrsim$500 Jy ms. The MWA was not optimised for high-speed imaging. hence the relatively poor time resolution ($\geq$0.5 s) and frequency resolution (at best 1.28 MHz) used in these surveys limited sensitivity to FRBs. Searches for low-frequency counterparts to ASKAP FRBs using simultaneously recorded MWA visibilities with 0.5 s integrations were unsuccessful too [13]. However, FRBs often appear over narrow bandwidths (e.g. [19]). Moreover, commensal observations of FRB 20180916B with LOFAR and Apertif [20] at 1.4 GHz, revealed that low and high frequency signals were anti-correlated, i.e. low frequency emission is not detected when high frequency emission is and vice-versa. This anti-correlation and band-limited emission can explain the MWA non-detections of ASKAP FRBs by [13]. Similarly, non-detections resulted from the efforts by low-frequency telescopes in the Northern Hemisphere [14, 15, 16, 17, 18]. More recently, FRBs were finally detected at frequencies $\leq$350 MHz. The repeating FRB 20180916B was detected at 328 MHz by the Sardinia Radio Telescope (SRT) [10] and also at 110 – 188 MHz by LOFAR [21, 22]. Further, FRB 20200125A was discovered by the Green Bank Telescope (GBT) at 350 MHz [23]. Due to a very small number of detections, estimates of the FRB event rates are highly uncertain and need to be refined by detecting more FRBs below 350 MHz. We aim to address this by using the relatively unique all-sky imaging capability of prototype stations of SKA-Low [31]. The sensitivity to FRB-like radio pulses will be improved by about two orders of magnitude by increasing the observing bandwidth to about 40 MHz and high-time resolution imaging to approximately 10 ms.

2 SKA-Low prototype stations

The upcoming SKA-Low telescope will provide an unprecedented view of the radio sky with unmatched sensitivity at frequencies 50 – 350 MHz. Although, the SKA-Low construction will be completed around the end of the current decade, two second-generation SKA-Low prototype stations, the Engineering Development Array (EDA2) [24] and Aperture Array Verification System 2 (AAVS2) [25, 26], have already been constructed at the Murchison Radio-astronomy Observatory (MRO) and operated since 2019. Both stations are composed of 256 dual-polarised antennas. However, EDA2 consists of MWA bowtie dipoles, whilst the AAVS2 station is composed of SKALA4.1AL antennas [27]. Besides the antenna design the stations are virtually identical, including the digital back-ends as described in [26, 28]. In the last few years, these stations have been regularly collecting data to compare their performance against each other, the SKA-Low specifications [34] and predictions of simulations. The measured sensitivity of the stations agrees with the predictions of electromagnetic simulations and results of these verifications for AAVS2 station can be found in [25, 29] and for the EDA2 in [24].

3 All-sky transient monitoring

The individual antennas in the stations are sensitive to almost the entire hemisphere, so by using the stations as imaging interferometers (rather than beamformers as they will be used in the full SKA-Low), they are ideal instruments for all-sky transient monitoring. Therefore, the data recorded by both stations (usually observing in parallel) during the commissioning and verification period were also converted to all-sky images with 2 s time resolution. These images were used to perform a pilot search for radio transients in 2-s all-sky images using difference imaging. Despite the bandwidth limited to a single coarse channel ($\approx$0.93 MHz) and time resolution to 2 s, early science results could be generated, for instance, upper limits on fluence of low-frequency counterparts of FRBs detected at GHz frequencies [30], upper limits on surface density of radio-transients at 2 s timescale, and detection of extreme activity of pulsar PSR B0950+08 [31]. An example of an astrophysical radio transient (repeating at the same position with respect to other radio sources for several hours) is shown in Figure 1.

4 High-time resolution all-sky monitor

The sensitivity of the current system to FRBs is limited by its small observing bandwidth of (a single coarse channel $\approx$0.93 MHz) and imaging time resolution of 2 s. However, the existing back-end can digitise even 60 coarse channels worth of bandwidth, and the main limitations are due to limited throughput of the existing networking infrastructure (hence an additional 100 GBit 32 port network switch is required) and data acquisition computers, which we are planning to upgrade with off-the-shelf components. Using additional computing hardware and fast imaging GPU-based software, we will upgrade the digital back-end of at least one of the stations (primarily EDA2) and increase its observing bandwidth to at least 40 MHz and imaging time resolution to about 10 ms. The upgrade will convert EDA2 into a high-time resolution all-sky monitor for FRBs and technosignatures called CHASM (pronounced "chase 'em"). The resulting high time resolution images will be searched for highly dispersed FRB-like signals in real-time, which is computationally very challenging task (especially at low frequencies) and will be performed in real-time on GPUs in the data acquisition computers. Similar systems exist only in the Northern Hemisphere and operate at lower frequencies ($\leq$100 MHz) [32, 33]. Therefore, the upgraded system will be unique in terms of the parameter space (i.e. southern sky coverage and frequency range).

4.1 Prognosis for FRB detections

We estimate the expected number of FRB detections per year with CHASM using the recent LOFAR measurement of 3 – 450 FRBs $\text{sky}^{-1}\text{day}^{-1}$ above fluence limit of 50 Jy ms [22]. This rate is consistent (within the large uncertainties) with the GBT rate [23] and the rates determined by the earlier low-frequency FRB surveys. We adopt the SKA-Low station sensitivity (System Equivalent Flux Density of $\approx$2500 Jy) as defined in the SKA specifications [34], and confirmed by our sensitivity simulations and measurements [29, 24]. Assuming a Euclidean source count distribution and continuous monitoring of nearly the entire hemisphere (elevations $<20^\circ$ are currently excluded due to radio-frequency interference (RFI) at the horizon), the upgrade will result in standard deviation of the noise (σ) in 10 ms images $\sim$2 Jy (i.e. fluence threshold $10\sigma \sim$ 200 Jy ms). This will enable autonomous 10σ detection of between 40 and up to 6000 FRBs per year at frequencies below 350 MHz. These high detection rates are also in agreement with the simulation predictions performed with the FRBPOPPY population synthesis package [35]. Even in the most pessimistic scenario (3 $\text{day}^{-1}\,\text{sky}^{-1}$ above 50 Jy ms) the number of 8 and 5-σ detections per year will be approximately 60 and 110 respectively, which in the relatively clean RFI environment of the MRO can be sufficient to distinguish genuine FRBs. In any case CHASM will enable us to firmly establish the FRB rates at frequencies below 350 MHz.

4.2 An all-sky technosignature search

Furthermore, the same data and shared software pipelines will be used for searches of technosignatures over the entire hemisphere. While several technosignature searches have been conducted with the MWA [40, 39, 38], the low-frequency radio sky remains under-explored. All-sky technosignature surveys have been proposed as an effective search strategy [36, 37]; by covering the entire hemisphere, stronger statistical arguments about the prevalence of intelligent life beyond Earth can be made.

We will create an all-sky dataset at high frequency resolution, and will perform a narrow-band technosignature search. The survey will be the first all-sky technosignature survey in the Southern Hemisphere, and the most sensitive all-sky technosignature survey ever undertaken. In addition, we will also search our 10 ms images for putative pulsed signals that appear engineered, such as those exhibiting artificial dispersion sweeps, for example negative dispersion measure (DM) [41]. This search can be performed at the same time as FRB searches and is synergistic, as it will will help us build a strong understanding of the RFI environment.

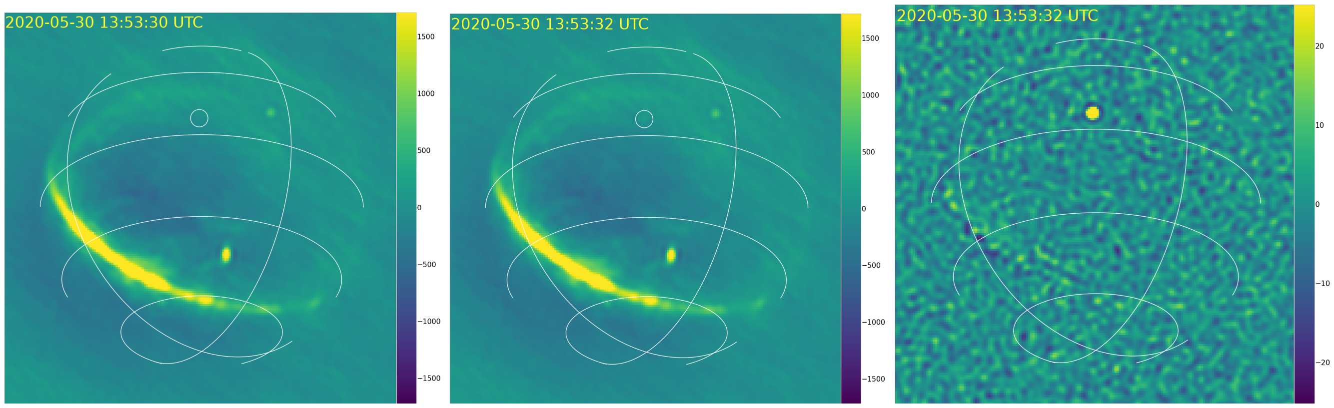

Figure 1. Example all-sky images from the EDA2 station at 160 MHz recorded on 2020-05-30, showing an example of a bright radio transient detected multiple times at the same position with respect to other radio sources. It was considered as a potential pulsar candidate and followed up the MWA but so far has not been confirmed. Left: Image from 13:53:30 UTC. Center: Image from 13:53:32 UTC. Right: difference of the two images showing a very bright (∼160 Jy/beam) transient. The white circles in the left and centre images indicate the position of this object, which is prominent in the difference image (right) but very difficult to see in the original image (centre).

5 Conclusions

Although FRBs have recently been detected at frequencies below 350 MHz, their event rates at these frequencies are very uncertain due to the small number of detections thus far. The SKA-Low prototype stations are ideally suited to detect many low-frequency FRBs provided that the sensitivity to short radio pulses can be increased. We will achieve this with a relatively small upgrade of the digital back-end of one the SKA-Low prototype stations (primarily EDA2), which only requires additional off-the-shelf networking infrastructure and data acquisition computers equipped with GPU cards. Such an upgrade will increase the observing bandwidth to about 40 MHz and imaging time resolution to 10 ms, which will enable two order of magnitudes improvement in sensitivity to FRBs (to $\sim$ 200 Jy ms). Based on the current estimates of FRB rates at these frequencies, we expect to detect between tens to hundreds of low-frequency FRBs and firmly establish the rates and properties of these events at low frequencies. Finally, this project will also pave the way towards similar FRB searches with more SKA-Low stations (currently 512 planned) soon to be built at the MRO.

6 Acknowledgements

AAVS2 and EDA2 are hosted by the MWA under an agreement via the MWA External Instruments Policy. This scientific work makes use of the Murchison Radio-astronomy Observatory, operated by CSIRO. We acknowledge the Wajarri Yamatji people as the traditional owners of the Observatory site. This work was further supported by resources provided by the Pawsey Supercomputing Centre with funding from the Australian Government and the Government of Western Australia. The acquisition system was designed and purchased by INAF/Oxford University and the RX chain was design by INAF, as part of the SKA design and prototyping program.

References

[1] Lorimer, D. R., Bailes, M., McLaughlin, M. A., Narkevic, D. J., & Crawford, F. 2007, Science, 318, 777

[2] Thornton, D., Stappers, B., Bailes, M., et al. 2013, Science, 341, 53

[3] Macquart, J.-P., Bailes, M., Bhat, N. D. R., et al. 2010, PASA, 27, 272

[4] Caleb, M., Flynn, C., Bailes, M., et al. 2017, MNRAS, 468, 3746

[5] Rowlinson, A., Bell, M. E., Murphy, T., et al. 2016, MNRAS, 458, 3506

[6] Keane, E. F., Johnston, S., Bhandari, S., et al. 2016, Nature, 530, 453

[7] Tingay, S. J., Trott, C. M., Wayth, R. B., et al. 2015, AJ, 150, 199

[8] CHIME/FRB Collaboration, Amiri, M., Bandura, K., et al. 2018, ApJ, 863, 48

[9] Tingay, S. J., Goeke, R., Bowman, J. D., et al. 2013, PASA, 30, e007

[10] Pilia, M., Burgay, M., Possenti, A., et al. 2020, ApJL, 896, L40

[11] CHIME/FRB Collaboration, Amiri, M., Andersen, B. C., et al. 2020, Nature, 582, 351

[12] CHIME/FRB Collaboration, Amiri, M., Bandura, K., & Bhardwaj, M. 2019, Nature, 566, 230

[13] Sokolowski, M., Bhat, N. D. R., Macquart, J. P., et al. 2018, ApJL, 867, L12

[14] Coenen, T., van Leeuwen, J., Hessels, J. W. T., et al. 2014, A&A, 570, A60

[15] Karastergiou, A., Chennamangalam, J., Armour, W., et al. 2015, MNRAS, 452, 1254

[16] Amiri, M., Bandura, K., Berger, P., et al. 2017, ApJ, 844, 161

[17] Chawla, P., Kaspi, V. M., Josephy, A., et al. 2017, ApJ, 844, 140

[18] Burke-Spolaor, S., Trott, C. M., Brisken, W. F., et al. 2016, ApJ, 826, 223

[19] Kumar, P., Shannon, R. M., Flynn, C., et al. 2021, MNRAS, 500, 2525

[20] Maan, Y., & van Leeuwen, J. 2017, in 2017 XXXIInd URSI GASS, 2

[21] Pleunis, Z., Michilli, D., Bassa, C. G., et al. 2021, ApJL, 911, L3

[22] Pastor-Marazuela, I., Connor, L., van Leeuwen, J., et al. 2021, Nature, 596, 505

[23] Parent, E., Chawla, P., Kaspi, V. M., et al. 2020, ApJ, 904, 92

[24] Wayth, R., Sokolowski, M., Broderick, J., et al. 2021, Journal of Astronomical Telescopes, Instruments, and Systems, 8, 1

[25] Macario, G., Pupillo, G., Bernardi, G., et al. 2022, Journal of Astronomical Telescopes, Instruments, and Systems, 8, 1

[26] van Es, A. J. J., Labate, M. G., Waterson, M. F., et al. 2020, in Ground-based and Airborne Telescopes VIII, Vol. 11445

[27] Bolli P., et al., 2020, IEEE Open Journal of Antennas and Propagation, DOI: 10.1109/OJAP.2020.2999109, 1, 253

[28] G. Naldi, A. Mattana *et al.*, "The Digital Signal Processing Platform for the Low Frequency Aperture Array: Preliminary Results on the Data Acquisition Unit," *Journal of Astronomical Instrumentation*, vol. 6, no. 1, p. 1641014, Mar. 2017.

[29] Sokolowski M., et al., 2021, in 2021 15th European Conference on Antennas and Propagation (EuCAP). pp 1–5, DOI: 10.23919/EuCAP51087.2021.9410962

[30] Sokolowski et al., M. 2020, The Astronomer's Telegram, 14044

[31] Sokolowski, M., Wayth, R. B., Bhat, N. D. R., et al. 2021b, PASA, 38, e023

[32] Prasad, P., Huizinga, F., Kooistra, E., et al. 2016, Journal of Astronomical Instrumentation, 5, 1641008

[33] Ellingson, S. W., Taylor, G. B., Craig, J., et al. 2013, IEEE Transactions on Antennas and Propagation, 61, 2540

[34] Caiazzo, M. 2017, SKA Phase 1 System Requirements V11, Tech. Rep. SKA-TEL-SKO-0000008, SKA Organisation

[35] Gardenier, D. W., Connor, L., van Leeuwen, J., Oostrum, L. C., & Petroff, E. 2021, A&A, 647, A30

[36] Garrett, M., Siemion, A. & Van Cappellen, W. *ArXiv E-prints*. pp. arXiv:1709.01338 (2017,9)

[37] Houston, K., Siemion, A. & Croft, S. 2021, AJ, 162, 151

[38] Tremblay, C. & Tingay, S. 2020, PASA, 37, 035

[39] Tingay, S., Tremblay, C. & Croft, S. 2018, ApJ 856, 31

[40] Tingay, S., Tremblay, C., Walsh, A. & Urquhart, R. 2016, ApJL 827, 22

[41] Gajjar, V., Perez, K., Siemion, A., et al. 2021, AJ, 162, 33