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MEERTRAP: Finding fast radio transients on the fly

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Abstract

In the era of multi-messenger astrophysics with new types of transients (fast radio transients or gravitational wave events), real-time detection of transients and rapid multi-wavelength follow-up is crucial. MeerTRAP is one such instrument that has been deployed on the MeerKAT radio telescope in South Africa to search for fast radio bursts (FRBs) [1]. The commensal nature of the project means that MeerTRAP will keep looking for transients even if the telescope is not being used specifically for that purpose. Using a compute cluster with state-of-the-art CPUs and GPUs, MeerTRAP constantly searches the entire Field of View of MeerKAT for fast radio bursts and single pulses from new pulsars or Rotating Radio Transients (RRATs) across different radio frequencies, ultimately from 500 MHz all the way to 3.5 GHz. This gives MeerTRAP a unique combination of sensitivity and field-of-view to discover new FRBs and RRATs. The ability of MeerTRAP to rapidly localize the transient and optical co-pointing with the MeerLICHT telescope gives the instrument an edge in finding and identifying the nature of potential transients on short timescales. Moreover, MeerTRAP is part of large collaborations whose primary goal is to discover and follow-up any transient event with a slew of telescopes spanning the whole electro-magnetic spectrum.

Figure 1. A photograph of the MeerTRAP compute cluster in the Karoo Processing Building on site. Figure taken from [4]

1 Hardware

For any transient survey, there is always a trade-off between the field of view (FoV) of the telescope, the sensitivity of the survey and the angular resolution. This is the primary limitation for radio surveys with single dish radio telescopes that provide high sensitivity at the expense of angular resolution and FoV. An interferometer can overcome this limitation by combining signals from multiple small single dishes. This enables one to sample the entire FoV of a small single dish with a much higher angular resolution and higher sensitivity. To sample even 50% of the total FoV of a radio interferometer like MeerKAT with highly sensitive beams, requires a large pool of computational resources. In order to achieve that, heterogeneous compute servers, combining the computational power of multi-core processors and Graphical Processor Units (GPUs) are required. The MeerTRAP compute cluster consists of 66 servers with one head node and 65 compute nodes. Each compute node comprises two Intel Xeon 8C/16T CPUs that possess a total of 32 logical threads. Each node is also equipped with two Nvidia GTX 1080 Ti GPUs. Each compute node has a total of 256 GB of RAM and 500 GB solid state drive to save interesting candidates. All nodes communicate with the head node via 1-GbE links. The cluster was procured in early 2018 and then assembled on site in the summer of the same year. Figure 1 shows a completely installed cluster on site (also known as Trasient User Supplied Equipment (TUSE)).

2 MeerTRAP pipeline

The science goals of MeerTRAP requires immense computational resources in order perform a real-time search for FRBs. This required development of highly efficient software in PYTHON and C++ that makes use of heterogeneous compute resources for real-time data processing. The data processing and the real-time search pipelines are built using the C++11 highly templated and highly typed software suite called CHEETAH [1]. CHEETAH is an open source

[1] https://gitlab.com/SKA-TDT/cheetah

C++11 software aimed at providing real-time transient processing. The design goal is to provide a way to prototype algorithms in such a way that enables continuous integration and deployment on heterogeneous systems. Thus a cheetah pipeline adopts a generic modular framework that allows it to be implemented as part of a real time telescope backend, as well as on a local machine for data analysis without any modifications to the source code. A pipeline in CHEETAH is made up of multiple modules that can interface with each other for seamless transfer and processing of data. Each module may have any number of algorithms that may use the compute resources available on the machine efficiently. The CHEETAH scheduler and higher level manager will then use the most suitable algorithm for the compute resources that are available at the time, acting as an effective load balancer. The CHEETAH pipeline is also currently being developed as a prototype for the Square Kilometre Array. The MeerTRAP transient search pipeline works mainly in three observing modes:

- **Incoherent Search Mode**
  In the incoherent search mode, the entire FoV of MeerKAT is sampled and searched for FRBs. The signal of all 64 antennas are detected and added to create a single beam with an effective FoV of 1.27 sq.deg at 1.4 GHz over a bandwidth of 856 MHz. The incoherent search mode has the advantage of a larger instantaneous sky coverage with a loss of sensitivity due to the incoherent addition of signals. The entire beamforming pipeline was developed and deployed at MeerKAT as a separate compute cluster called Filterbank BeamFormer User Supplied Equipment (FBFUSE) by the Max-Planck-Institut für Radioastronomie in Bonn, Germany.
- **Coherent Search Mode**
  In this mode, a fraction of the primary FoV of MeerKAT is tessalated by highly sensitive coherent beams that are formed by adding signals coherently from the inner most 40 antennas. Multiple coherent beams are created by multiplying the phased signal by appropriate beam weights. FBFUSE can produce upto 1000 coherent beams in real-time. More details about the beamforming cluster and its deployment will be presented in a future publication. The coherent beams are received by the TUSE cluster over a 10GbE link and are searched for radio transients in real-time. Currently, TUSE can process up to 768 coherent beams in real-time. Because of this limitation, MeerTRAP can only cover up to 0.2–0.5 sq.deg of FoV (depending on the elevation and beam spacing) in the coherent mode although the sensitivity of the search is higher than the incoherent mode by a factor of 5.
- **Transient Capture Mode**
  Lastly, we have recently developed a transient buffer capture mode whereby in the event of a real-time detection of an FRB by TUSE, a portion of complex voltage data around the time of the FRB are captured on the FBFUSE nodes in order to study the burst at higher time resolution and to image and localize it to arc-second precision. This mode does depend on the MeerTRAP cluster sending an event trigger to FBFUSE to perform voltage capture in real-time. The voltage extraction algorithm takes care of the dispersion delay due to the large dispersion measure of the FRB and only saves data around the time of the FRB at every frequency. The details of these pipelines will published in a separate paper (Stappers et al. in prep).

The hardware was procured and installed on site in the summer of 2018. The initial commissioning of the instrument was performed in the summer of 2019 where we were able to test various functionalities of the system. We observed known pulsars in the Galaxy, detected single pulse from them in real-time, observed multiple pulsars within the FoV of MeerKAT by putting separate tiles of coherent beams at their positions and also managed to trigger and image a single pulse from a bright pulsar PSR B0835-45. The results of commissioning are shown in Figure 2

There are additional functionalities that makes MeerTRAP a versatile instrument. For example, MeerTRAP can request for multiple coherent beam tiles from FBFUSE across the total FoV of MeerKAT (see Figure 2). This is crucial in order to perform radio follow-up of any interesting radio transients and know repeating FRBs that may happen to be in FoV. Morevoer, MeerTRAP also has opportunities to obtain simultaneous optical coverage with the 0.65 m MeerLICHT telescope [2] in Sutherland, South Africa. MeerLICHT can provide a 2.7 sq.deg of simultaneous optical sky coverage that covers the entire the FoV of MeerKAT. This holds exciting prospects for MeerTRAP to find prompt optical flash in the direction of an FRB detected by MeerTRAP or an optical afterglow, providing tight constraints on the progenitors of FRBs. Robotic operations of synchronized MeerLICHT and MeerKAT observations have recently begun.

3 Results

The first science observations with the real-time system started in August of 2019 where most of the commensal observations were dominated by the pulsar timing project at MeerKAT (MeerTIME, [5]). As a result, the majority of our observing time has been spent in the Galactic plane. That gave us the opportunity to thoroughly test our pipeline as MeerTRAP detected several know radio pulsars (see Figure 3) as they traversed the FoV. More recently, MeerTRAP has started observing commensally on all the large survey projects (LSPs) that have been allocated time at MeerKAT which has resulted in a significant increase in the on-sky time. Over the last year since MeerTRAP became operational, it has discovered new FRBs (Rajwade et al. in prep), new radio transients in the Galaxy (Bezuidenhout et al. in prep). Along with the commensal observing success, MeerTRAP has been involved in multiple targeted ob-

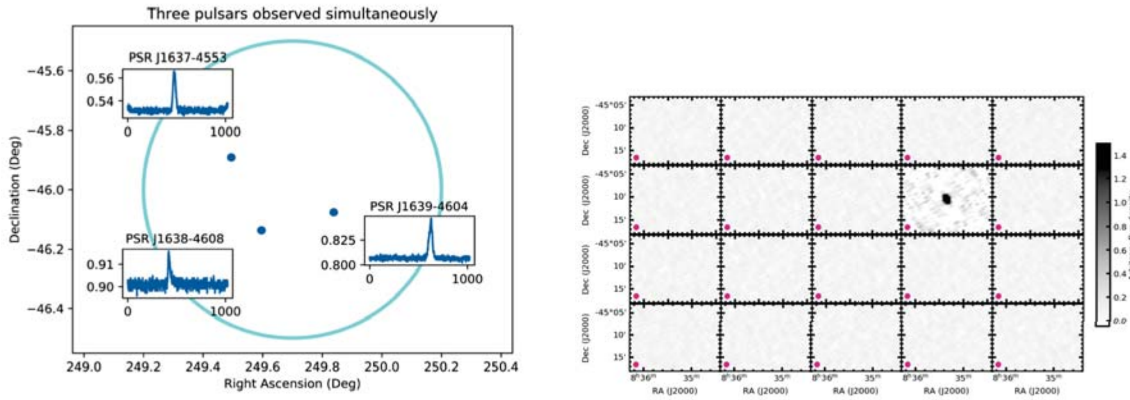

Figure 2. Left Panel: Three pulsars detected by observing them simultaneously with MeerTRAP using three separate beam tilings formed by FBFUSE (blue dots) within the primary Field of View (cyan circle). The inset shows the folded profile of the pulse from the data taken by the MeerTRAP cluster. **Right Panel:**Plot showing 20 panels of a radio image made from 100 ms of raw complex voltage data from MeerKAT. Each panel represents 5 ms of integrated data. The Vela single pulse is clearly detected in one panel as the pulse width is less than 5 ms. The pink dot represents the size of the synthesized beam in this image. Both Figures taken from [4].

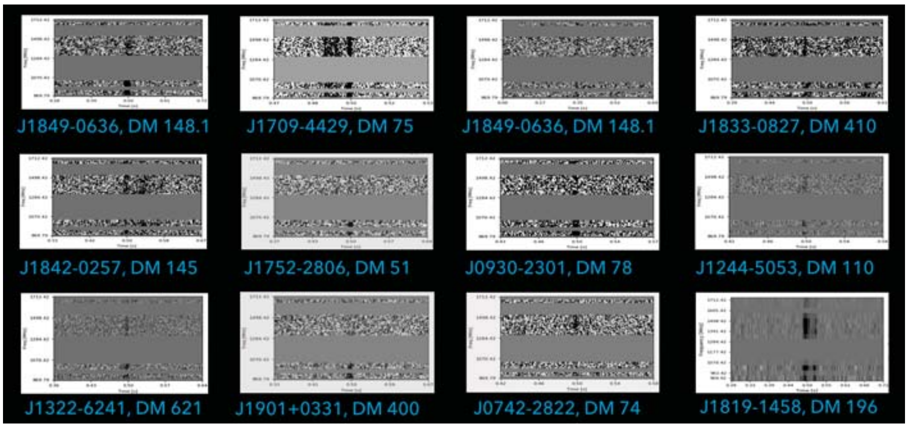

Figure 3. Dynamic spectrum of detections of single pulses from known Galactic sources during the commissioning phase of MeerTRAP.

serving campaigns of known FRBs and Galactic magnetars (highly magnetized neutron stars) and MeerTRAP has been crucial contributor to the scientific results from these campaigns [3] (Bailes et al. submitted).

4 Summary

Here, we have presented a detailed overview of the MeerTRAP instrument. MeerTRAP can search for FRBs in real-time in an instantaneous FoV of 1.3 sq.deg and has the ability to localize detected FRBs by imaging raw voltage data captured during the event. The potential of simultaneous optical observations with the MeerLICHT telescope holds great prospect for detecting optical afterglows in the direction of an FRB or detecting contemporaneous optical bursts. Such a synergy between multi-wavelength facilities has a lot of promise to put significant constraints on the progenitors of FRBs. Over the last year, MeerTRAP was successfully commissioned and is fully operational at MeerKAT and has started to significantly contribute to the field of FRB astrophysics.

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References

[1] Lorimer D. R., Bailes M., McLaughlin M. A., Narkevic D. J., Crawford F., 2007,"Millisecond burst of Extragalactic origin", *Science*, **318**, p.777, doi:10.1126/science.1147532.

[2] Bloemen S., et al., 2016, "MeerLICHT and BlackGEM: custom-built telescopes to detect faint optical transients", *SPIE*, 990664, SPIE.9906, doi: 10.1117/12.2232522

[3] Caleb M., et al., 2020, "Simultaneous multi-telescope observations of repeating FRB 121102", *MNRAS*, **496**, p.4565, doi:10.1093/mnras/staa1791

[4] Rajwade K. M., et al., 2020, "MeerTRAP in the era of multi-messenger astrophysics", Proceedings of SPIE, **11447**, doi:10.1117/12.2559937

[5] Bailes, M., et al., 2020, "The MeerKAT telescope as a pulsar facility: System verification and early science results from MeerTime". *PASA*, **37**, e028, doi: 10.1017/pasa.2020.19