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The most important questions in pulsar- and fast transient research (and limitations through RFI)

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Abstract. Coherent emission from the magnetospheres of compact objects, such as radio pulsars and likely fast radio burst and long period transients, varies on short ("fast") time scales. Observations of these sources occur primarily between 100 MHz and 10 GHz. Furthermore, particle showers from cosmic rays impacting Earth's atmosphere generate radio pulses on nanosecond-scales, which are detectable below 1 GHz. Radio frequency interference negatively impacts the science of fast transients. It can overwhelm the desired astrophysical signal, leaving the latter undetected, and introduce orders of magnitude more false positives than true positives. But most importantly, developing RFI mitigation techniques diverts person-hours away from scientific investigations of these interesting events.

Keywords. radio frequency interference, fast transients

1. Introduction

The radio sky is highly dynamic with signals varying over a wide range of time scales. The shortest timescale emission is often emitted through coherent emission processes in the magnetospheres of stars. In some cases, the astrophysical origin of the signals is well-established, while for other cases, it is still an astrophysical mystery. Moreover, these sources are often useful tools for fundamental physics. Additionally, cosmic ray showers interact with the Earth's atmosphere and produce short-duration radio pulses.

Pulsars Pulsars are rotating neutrons stars that emit beamed emission from their magnetic poles (D. R. Lorimer & M. Kramer 2004). If this beamed emission crosses our line of sight, we see a pulsed radio signal. Due to their large density, they are extremely stable rotators and valuable astronomical clocks. Binary pulsars are used to conduct the most stringent tests of General Relativity in the strong field regime (e.g. M. Kramer et al. 2021).

Fast radio bursts Fast radio bursts (FRBs) are extragalactic radio transients with characteristic durations of μs to ms (J. M. Cordes & S. Chatterjee 2019; E. Petroff et al. 2022). Their astrophysical origin is still a matter of debate but most studies suggest a neutron star origin (E. Platts et al. 2019) with magnetars being the current favoured model (C. D. Bochenek et al. 2020; CHIME/FRB Collaboration et al. 2020). FRBs are also promising probes for a wide range of astrophysical and cosmological applications. For example, a large sample can be used to measure the spatial distribution of matter in the IGM (Macquart et al. 2020) or the Hubble constant (e.g. C. W. James et al. 2022).

Long Period Transients Long Period Transients are a new class of Galactic transients with spin periods ranging from minutes to hours (e.g. N. Hurley-Walker et al. 2022; M. Caleb et al. 2024). Their radio emission is highly linearly polarized with pulsations during individual rotations lasting seconds to minutes. Their astrophysical nature is unknown but proposed models include long period magnetars and white dwarfs. Their discovery was made possible due to wide-field surveys that generate images on high time resolutions.

Cosmic rays and neutrinos For cosmic rays the atmosphere of the Earth is not transparent and they can only be observed from space, or at the highest energies by their interaction remnants in the atmosphere and on ground. There, so called particle showers emit nanosecond-scale radio signals that allow the triangulation of the incoming particle and the high resolution information about its mass (e.g. F. G. Schröder 2017). This also works for high-energy neutrinos that interact in the surface of the Earth, which uniquely point to astrophysical sources of particle acceleration.

2. Ideal observing frequencies

Choosing the optimal observing frequency for fast transients is a balance between astrophysical considerations, such as the intrinsic spectrum of the sources' radio emission and frequency dependent propagation effects, and practical considerations, such as the field of view and sensitivity of available receivers and telescopes. Pulsars are generally steep spectrum sources with the median spectral index around -1.6 but with significant variation from source to source (e.g. F. Jankowski et al. 2018). The emission spectra for FRBs and LPTs are not well-constrained given the limited frequency range of detections. Pulses induced by cosmic ray showers are extremely broad-band, with most of the signal being below 200 MHz, but reaching as high as 1 GHz. Table 1 shows an overview of the established frequency ranges (E) where observations are routine, special frequency ranges (S) that are only used in certain circumstances, and so-far unexplored frequency bands (U) often due to technical limitations.

Pulsars, FRBs, and LPTs are all subject to propagation effects through the ionized interstellar medium in our Milky Way galaxy, and for the case of FRBs, the extragalactic ionized media as well. Dispersion is the frequency-dependent arrival time of the signal, and the delay between two frequencies is proportional to the integrated column density of electrons (S. R. Kulkarni 2020). In pulsar and FRB searches, the dispersion delay within a frequency channel increases the effective time resolution of the data and may broaden short-duration pulses, while for follow-up observations of known sources, this

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Table 1. Observing frequency ranges for fast transients.

	10-100 MHz	100 MHz - 1 GHz	1-10 GHz	>10 GHz
Pulsars	S	E	E	S
Fast radio bursts	U	E	E	U
Long period transients	E	E	U	U
Cosmic rays	E	E	-	-

Notes: E = established observing range, S = special observing range, U = unexplored observing range, - = no signal expected

intra-channel dispersion can be removed (so-called "coherent dedispersion"). An increase in the observing bandwidth can correct for the interstellar medium noise, effectively reducing long-term dispersion noise in pulsar timing observations. Additionally, a burst or pulse may also be scattered by structures in the ionized media, thereby following multiple paths that are slightly longer than the direct path. This temporal broadening reduces a pulse's signal-to-noise and can not be mitigated (J. M. Cordes & M. A. McLaughlin 2003). Furthermore, it is highly frequency and line-of-sight dependent and a main consideration when choosing an observing frequency.

Practical considerations of telescope sensitives and fields of view have the final word. Radio telescopes are diffraction limited, so there is a trade off between sensitivity and field of view. Historically, pulsar (and later FRB) searches have benefited from multi-beam receivers developed for 21-cm mapping (e.g. R. N. Manchester et al. 2001), and therefore, the "classic" observing frequency is around 1.4 GHz.

3. Impact of RFI

RFI impacts on our ability to extract science from our data in several ways. First, an RFI signal is often stronger than the astronomical signal, and if not mitigated, renders the desired astrophysical signal undetectable. For example, if RFI is folded into an observation of a known pulsar, it can distort the baseline so much that the pulsar signal is not recognisable. An RFI signal occurring simultaneously with an FRB can lead us to completely miss the discovery. A heavily RFI-contaminated observation can impact our ability to associate an FRB with its host galaxy, which is essential for many aspects of FRB science, by reducing the localization precession.

Second, the candidate events generated by our detection pipelines are dominated by false positives from RFI. For example, satellites are seen as streaks as they move through a radio images. When a difference imaging technique is applied to identify variable sources, these satellite streaks can produce a large number of false positives. Additional algorithms must be developed to automatically identify these false positives, which are never perfect. For cosmic rays and neutrinos, these false positives may even prohibit the detection altogether as for broad-band signals, data recording relies on a trigger. If no efficient triggering algorithm can be found, the system will be flooded with false triggers and no science data is recorded.

Finally, developing techniques to remove RFI from our data and accurately sift through the large number of false positives generated uses a large number of person-hours than could otherwise be used for doing science.

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