Master's Thesis - Planning Report

"Monitoring repeating fast radio bursts"

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1 Background and aim

Fast Radio Bursts (FRBs) are bright *ms*-duration radio transients which are extragalactic in origin. The first detection of an FRB was presented in a paper 2007 by Lorimer et al. during a search for pulsars. This burst, called the 'Lorimer burst', was initially estimated to have a spectral flux density >30 Jy and a pulse width of 5 ms. The dispersion measure (DM) of the burst was greater than the DM contribution of the Milky Way indicating the burst was extragalactic in origin.

FRB pulses have similarities to the pulses that we detect from pulsars but there are a few key differences. Firstly, Pulsar pulses repeat with a specific repetition rate whereas FRB pulses are mostly one off events. Until early 2019 only two FRBs, FRB 121102 & FRB 180814.J0422+73, had been observed to repeat [1]. Secondly, FRB pulses are intrinsically much brighter than pulsars. The Lorimer burst was so bright is saturated the receiver of the primary beam of the Parkes telescope [1]. So far FRBs have been detected as narrowband signals in the frequency range 150 MHz – 8 GHz.

The physical process behind the FRBs is not yet known, however we can say a lot about the medium in which the pulse propagates towards us. One of the main factors to look at is the dispersion measure (DM) of the pulse. As the pulse travels through a medium with a frequency dependent refractive index higher frequency components of the pulse will travel at different velocities to lower frequency components, resulting in a time delay Δt between the arrival time of the two components at the observer. If the medium is a plasma the dispersion will be quadratic in nature resulting in a time delay [2]

$$\Delta t = 4.148808(f_{lo}^{-2} - f_{hi}^{-2})\mathrm{DM}\ [\mathrm{ms}] \tag{1}$$

where $f_{lo/hi}$ are the two frequency components in GHz and the DM is given as

$$\mathrm{DM} = \int_0^d n_e(l)dl\ [\mathrm{cm}^{-3}\mathrm{pc}] \tag{2}$$

where n_e is the electron number density along the path of propagation l. The observed DM can be divided into several contributions i.e. DM = DM_{ISM}+ DM_{IGM}+ $\frac{\mathrm{DM}_{host}}{1+z}$. There exists models for the electron density in our own galaxy (i.e. the ISM) and by assuming that the IGM contributes most of the remaining DM (i.e. $DM_{IGM} >> DM_{host}$) we can calculate an approximate distance to the origin. Conversely, measuring the distance by other means, e.g. by redshift, the host galaxy contribution can be estimated telling us more about the local environment. FRB DMs have been measured in a wide range from about 100 to 2000 $cm^{-3}pc$.

After de-dispersion the fluence of the pulse can be measured, usually in [Jy ms]. Combined with the distance to the origin of the pulse we can calculate the energy release of the event. FRBs can have equivalent isotropic energy releases on the order of 10^{32} J which is within a few orders of magnitude from the energy release of giant radio bursts and supernovae explosions [1].

While we do not know the physical process behind FRBs there exists many models for what it might be. Some speculate that due to the massive amounts of energy released FRBs should be generated in a cataclysmic event, however the detection of repeating FRBs clearly shows that not all FRBs are caused by cataclysmic events. Furthermore while it's rather "simple" to detect a repeating FRB, it's more difficult to say if FRBs are non-repeaters as their repetition rate might just be very low. Perhaps the repeating FRBs are the same as the non-repeaters so far detected, or there might exist sub-groups of FRBs. More observations are necessary to answer these questions.

In addition to detecting more FRBs it's also important to accurately determine the environment in which they occur in order to understand the underlying physical mechanism. The different sub-groups of FRBs might just be of the same origin but located in different environments. In order to determine their surrounding environment however their host galaxy must first be determined through precise localisation. Recently the CHIME/FRB-collaboration published 18 new repeating FRBs. Localising these FRBs and identifying their host galaxies is an important step to understanding FRBs.

Up until early 2020 it was believed that FRBs were only an extragalactic phenomenon, however on April 28 an FRB was detected from the galactic magnetar SGR 1935+2154 [3]. The fluence of this burst was 1.5 ± 0.3 MJy ms which corresponds to an equivalent isotropic energy release of $2.2(4) \cdot 10^{28}$ J, over 1000 times brighter than the brightest Galactic event and only about 30 times weaker than the weakest extragalactic FRB. This detection indicate that magnetars might be the progenitor of FRBs, as have been previously hypothesised [1]. However then the question arises why we haven't detected any previous FRBs from the ~ 30 known magnetars in the Milky Way. One possible reason is that the Galactic FRBs are so bright (on the order of MJy) that they saturate receivers or are flagged as Radio Frequency Interference (RFI).

With the background of FRBs outlined above the aim of this master's thesis will be two-fold:

1. Perform observations and possibly localisation of repeating FRBs
2. Analyse FRB detection pipeline to determine if FRBs from galactic sources saturate the receivers to the point of not being detected as possible FRBs

NB: I use the terms "receiver system" and "FRB detection pipeline" interchangeably. They include both the analog and digital parts of the system.

2 Objectives and methods

The objectives for the master's thesis are divided into two sets, one which will focus on observations and the other which will focus on testing and analysing the receiver systems.

2.1 Observations of FRBs

The observations will be performed using the 25-m radiotelescope at Onsala Space Observatory. The observations will be performed at L-band, with a centre frequency of 1.4 GHz, which is why the 25-m telescope is used over the 20-m telescope which is sensitive in other frequency bands.

Since it is unlikely that an FRB will actually be detected during the thesis work some time will be spent learning the system by performing observations of the Crab pulsar and analysing the data using FETCH. FETCH contains 11 different models for analysing pulsar data. The 11 models will be used on the data and compared to manual detection in order to quantify the models' performances and determine which model is most suitable for the OSO 25-m telescope.

After this is done time will be spent planning and running observations of FRB sources, mainly those presented in references [4] & [5]. Observation of Galactic magnetars, e.g. SGR 1935+2154, will also be performed. The data will be analysed using the FETCH-model which proved the most suitable.

Finally if time allows it a more dynamic RFI-mitigation strategy will be implemented in the FRB detection pipeline. Currently only frequencies with known continuous RFI are removed from the measurements prior to analysis of the data.

2.2 Receiver system testing

The detection pipeline will be tested by injecting a fake-FRB signal and analysing the results. One of the main questions is how much fluence the system handles before it saturates and what a saturated signal will look like in the recorder.

In order to generate a fake-FRB signal a signal generator will be used. The generator will need to be able to generate a quadratic sweep in frequency to simulate the dispersion of the pulse, as well as the various pulse widths and fluences. The pulse characteristics are shown in table 1. First however, a linear sweep will be injected into the system at the recorder. Then a quadratic sweep will be injected successively into the pipeline beginning directly at the recorder, then injecting before the ADC, and finally testing the entire system by injecting the signal directly at the feed.

Table 1: Different values which will be tested when creating and injecting fake-FRB pulses into the receiver system

Frequency	1200 – 1700 MHz
DM	10 – 1500 cm^{-3}pc
W	100 μs–1 ms

If time allows it the physical fake-FRB tests may also be complemented by simple simulations and analytical analysis of the receiver response. This would be done mainly by creating a simplified receiver block diagram and/or simulating the signal propagation through the receiver in MATLAB. This might also make it possible to quantify metrics for determining overall performance of the FRB detection pipeline used at OSO. However, as of writing this planning report, it's unclear exactly how these metrics would be defined.

3 Societal, ethical and ecological aspects

There exists no societal, ethical or ecological aspects which need to be taken into consideration during the production of the thesis work and writing of the master's thesis. The thesis work will focus on radioastronomy and passive observations of astronomical sources thus there is no risk of creating radio frequency interference for other users. There are also no third parties directly involved, e.g. consumers, whom would be affected.

There is of course the possibility that this master's thesis will result in a world changing scientific discovery. In that case I will be sure to thoroughly analyse the effects in the final thesis.

4 Timetable

An initial **approximate** timeline for the thesis is shown in table below. Many elements are dependant on outside factors, for example it's unclear exactly when the signal generator will be accessible and when exactly observations can be performed.

<table>
<tr><th>Month</th><th>Week</th><th>Writing tasks</th><th>Observational tasks</th><th>Pipeline tasks</th></tr>
<tr><td>January</td><td>3.</td><td></td><td rowspan="2"></td><td rowspan="2"></td></tr>
<tr><td></td><td>4.</td><td>Finish planning report</td></tr>
<tr><td>February</td><td>1.</td><td rowspan="3"></td><td rowspan="3">Observe Crab pulsar</td><td rowspan="2">Create simple fake FRB models</td></tr>
<tr><td></td><td>2.</td></tr>
<tr><td></td><td>3.</td><td rowspan="2">Begin using signal generator (if available)</td></tr>
<tr><td></td><td>4.</td><td>Thesis structure complete</td><td rowspan="3">Analyse Crab data (continuous)</td></tr>
<tr><td>March</td><td>1.</td><td rowspan="2"></td><td></td></tr>
<tr><td></td><td>2.</td><td rowspan="2">More advanced (realistic) FRB models</td></tr>
<tr><td></td><td>3.</td><td rowspan="2">Write theory section</td><td rowspan="8">Test FETCH models

Observations and data analysis (continuous)</td></tr>
<tr><td></td><td>4.</td><td rowspan="7">Analyse receiver system with fake FRB-signals</td></tr>
<tr><td>April</td><td>1.</td><td rowspan="2"></td></tr>
<tr><td></td><td>2.</td></tr>
<tr><td></td><td>3.</td><td rowspan="2">Write methods/discussion</td></tr>
<tr><td></td><td>4.</td></tr>
<tr><td>May</td><td>1.</td><td>Write introduction</td></tr>
<tr><td></td><td>2.</td><td rowspan="3">Re-writing and finalizing thesis</td></tr>
<tr><td></td><td>3.</td><td rowspan="2"></td><td rowspan="2"></td></tr>
<tr><td></td><td>4.</td></tr>
<tr><td>June</td><td>1.</td><td colspan="3">Finished!</td></tr>
</table>

References

[1] E. Petroff, J. W. T. Hessels, and D. R. Lorimer. "Fast radio bursts". In: 27.1, 4 (May 2019), p. 4. DOI: `10.1007/s00159-019-0116-6`. arXiv: `1904.07947 [astro-ph.HE]`.

[2] D. R. Lorimer and M. Kramer. *Handbook of Pulsar Astronomy*. Vol. 4. 2004.

[3] C. D. Bochenek et al. "A fast radio burst associated with a Galactic magnetar". In: 587.7832 (Nov. 2020), pp. 59–62. DOI: `10.1038/s41586-020-2872-x`. arXiv: `2005.10828 [astro-ph.HE]`.

[4] E. Fonseca et al. "Nine New Repeating Fast Radio Burst Sources from CHIME/FRB". In: 891.1, L6 (Mar. 2020), p. L6. DOI: `10.3847/2041-8213/ab7208`. arXiv: `2001.03595 [astro-ph.HE]`.

[5] CHIME/FRB Collaboration et al. "CHIME/FRB Discovery of Eight New Repeating Fast Radio Burst Sources". In: 885.1, L24 (Nov. 2019), p. L24. DOI: `10.3847/2041-8213/ab4a80`. arXiv: `1908.03507 [astro-ph.HE]`.