Final report of a CTA399 student's work with VLBI pulsar observations

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Abstract

Pulsars, periodic radio sources, emit radiation in characteristic pulses that vary in shape and frequency. The mechanism whereby such pulses are generated is still not well understood, but with greater resolving power it might prove possible to probe the nature of the pulses in more detail. This may lead to the discovery of the intricacies of the magnetic field that produces such striking lighthouse emission. To achieve the requisite level of resolving power, this project aims to use Very Long Baseline Interferometry (VLBI) to resolve the images of the pulsar that have been scattered by interstellar medium. Such scattering provides an opportunity for interferometry with a baseline on the order of an astronomical unit, further resolving the pulsar to nanoarcsecond precision. To this end, raw voltage observations were taken at 325 MHz and 150 MHz on bright calibrator sources and fainter millisecond pulsars at the ARO, GMRT, LOFAR and Effelsberg telescopes. We have successfully spotted both bright and millisecond pulsars at ARO and GMRT. At the moment, the project is still in the early stage of interpreting observations and confirming pulsar sightings at each individual telescope. This paper details the efforts of one student involved in these first steps of the project, from understanding the computing environment to generating helper files and analyzing some of data to confirm the ARO pulsar sightings. Further observations will be taken later in the year in order to attempt the interstellar interferometry that is the primary aim.

1 Introduction

1.1 Pulsars

Pulsars, by emitting in radio at well-defined intervals, provide a useful observational source with a known timescale. This property of periodic emission is helpful because a pulsar is either 'on' or 'off', and the shifts between these two states make its presence obvious against the continuum of the background. In addition, pulsars are point sources, unaffected by the smearing that distorts larger objects. Their point source nature allows for observable scintillation.

All stellar objects visible to the naked eye can be seen to scintillate. The term refers to the 'twinkling' caused by turbulence in the Earth's atmosphere where stars seem to grow brighter and fainter with time. Pulsars exhibit the same phenomenon, though it is invisible to the unassisted human observer - as is the pulsar itself in all but a few cases. Like the earth's atmosphere, the clumps of gas and dust that make up the interstellar medium (ISM) cause scintillation in radio sources. The scintillation has a timescale anywhere from hours to days - much longer than the period of any pulsar. There is not yet an agreed upon model that explains the various properties of this pulsar signal scattering. Unlike the twinkling of stars, pulsar scintillation is not the product of turbulence[4]. Turbulence is a random process, and that random quality would be evident in observations. Instead, images of the pulsar caused by its lensing through the ISM are clearly distributed along a line. In addition, a turbulent scattering model would require overdensities in the ISM much higher than can be easily accounted for by known plasma behaviors. From this, it has been proposed that the pulsar's regular signal (the pulse) has been scattered by a thin sheet, the exact geometry of which has yet to be determined [5].

For the purposes of this project, the exact mechanism of pulsar scintillation is not as important as the property itself. A new technique, dubbed scintellometry, makes use of it in an interesting way.

1.2 Scintellometry and VLBI

VLBI is a technique used by radio astronomers to extend the baseline of their observations and thus gain greater resolving power. Any two telescopes that can see the same source in the sky at the same time can be used to perform interferometry. Since the distance between telescopes is known, it is possible to calculate the difference in signal arrival time between them. With this information, the signal can be phased up - that is, the data can be shifted so that the signal from each telescope can be added up in phase. This can be done on small scales (as with GMRT's 30 antennas), as well as very large ones. In the case of VLBI, the distances are akin the diameter of the planet: as if the entire Earth were a single huge dish. The larger the distance between the two receivers of the signal, the greater the resolving accuracy, since the diffraction limit is inversely proportional to the effective diameter of the receiving dish. Current VLBI achieves an angular resolution on the order of milliarcseconds[3].

However, scintellometry makes use of pulsar scattering to decrease the diffraction limit exponentially - down to the picoarcsecond scale[2]. This will be done by using the ISM itself as a series of antennas. To achieve this, VLBI will be done with several telescopes across the world. These telescopes will be used to resolve the images of the pulsar as scattered by the ISM[3]. By applying the principles of interferometry again on a grander scale, it will be possible to treat the scattered images as the signal reaching an array of telescopes with a baseline the size of Earth's orbital radius.

This new technique would make it possible to probe the nature of pulsars more deeply than before, perhaps even affording some understanding of the ways in which they produce pulses. Even with the greater resolution afforded by scintellometry, it would not be possible to actually discern the actual shape of even the closest pulsars. However, greater resolution would allow further development of explanations of pulsars' unusual emission.

1.3 Why Radio?

Observing in radio has a few advantages over its optical counterpart. While most Earth-bound astronomy is hampered by the fluctuations and molecular absorption in the atmosphere, this does not pose a problem for radio astronomers. They are forced to contend with emission rather than absorption. Radio astronomy also means that VLBI is possible - an essential feature of the current project. Observing in radio wavelengths ensures that pulse signals are actually scattered as desired, where a wave with a shorter wavelength might pass through scattering media unscathed. Finally, there are pulsars with well-defined pulse profiles in radio wavelengths, and the existing body of knowledge about pulsars at our observing frequencies confirms the accuracy of our work.

1.4 Goals

The overall aim of this project is to use VLBI to perform scintellometry and increase the resolution on pulsar targets of scientific interest. This summers work was a step in that direction. First, the software needed to be tested, then the VLBI itself was done at two different wavelengths. Before it is possible to contemplate scintellometry, it will be necessary to see the pulsar at each of the telescopes that will ultimately be used. Observations taken this summer will be used to that end as to well as to determine preferred observing frequency and to attempt a first trial of scintellometry.

2 Observations

The highlights of the course were the two trips made to ARO to do VLBI work, but many observations were made over the course of the summer.

2.1 Tests

The tests were conducted entirely at GMRT, and for the most part involved software adjustments. A new bandwidth option was developed for the raw voltage GMRT data correlator - 32 MHz in place of the usual 16. This required some trial runs before bringing it to bear on VLBI. Test observations were run on May 16, June 11, and June 29. The first two were conducted at 325 MHz, the third at 150 MHz. My part in the observations was limited to communicating with the GMRT operator - relaying our intended plan for our allotted time and the settings we wanted to test, as well as ensuring things stayed on track as the test progressed. It was during one of these tests that we discovered the importance of double-checking the LO frequency that would be used to mix the signal down. During the June 29 observations, we decided on the importance of a system that would name files based on a timestamp rather than relying on the name being changed manually.

We observed a variety of targets, including pulsar B1919+21, millisecond pulsar B1957+20, and the crab pulsar. The former two would be targets of the VLBI observations, and the data taken over a separation of weeks might offer some evidence of scintillation that might not be glimpsed on the shorter timescale of individual observations.

2.2 VLBI

Two weeklong trips were made to ARO, one on June 24 (observing frequency: 325 MHz) and the other on July 21 (observing frequency:150 MHz). Both instances of VLBI included ARO and GMRT, with Effelsberg providing more baselines in the former case and the aptly named LOFAR in the latter. Targets were reasonably consistent: bright pulsars with periods on the order of a second like B1919+21, B2111+46, and B0329+54, as well as fainter millisecond pulsars like B1957+20, and J1810+1744. B1957+20, being in a binary system[1], is of particular interest. At 150 MHz, the Radio Frequency Interference (RFI) was much more pronounced, but during the earlier 325 MHz trip, there were still significant bugs to be resolved (not the least of which was constructing a feed for the dish). However, during each trip, VLBI was successful on at least one of the observing days.

3 CITA Computing

At the beginning of my involvement with this project, the CITA computing environment was a complete unknown to me. As such, it was necessary to come to grips with a few essential tools to become proficient at CITA computing.

3.1 Git Repositories

For this project, git repositories were the primary location of necessary code. The general repository was mhvk/scintellometry.git. This repository contained code for gathering and analyzing pulsar data from all four telescopes used in the project. Anyone working on the project could create their copy of the scintellometry git repository and make changes to files they wanted to work with. Requests would be sent to merge these changes if they were deemed useful for everyone involved.

An additional repository, NatalieP-J/work-share.git tracked progress on my individual assignments. The repository was created to more easily share files between home and work machines, so that the working version of a particular code would always be the most up to date in either location. The repository also contains many supplementary files, including timestamp files, generated delay times, generated sequence files, and journal articles.

The commented versions of unique codes I wrote are located in this repository in the Code directory. A subdirectory called Edits contains the code I needed to change to use.

3.2 Package Set Up

Computing at CITA starts with a desktop machine, but other, faster machines are readily available, some with different software configurations. For this project, where a good Python environment was important, *chime* and *prawn* were used often. A desktop machine at CITA often raised problems when running Fortran90 code, and such issues were not present on the faster machines.

Python was the language of choice for my assignments, and so it was necessary to build a proper environment within my CITA account. In particular, installing up to date versions of numpy, matplotlib and novas for python, as well as the latest developer build of astropy, was essential. It is these four packages upon which most of the python code was based. Other modules used were generally built-in ones for Python 2.7.5. It was this version of Python that was kept as standard for Python code written this summer.

4 GMRT Computing

The GMRT setup of computers can be accessed remotely with the correct passwords to get through a gateway machine. I was given access to nodes 17-48 and nodes 111-118 to work on, as well as the root password. This gave me the ability to mount disks from each node as needed. Each node at GMRT has four disks mounted on it; each of these disks divided into multiple partitions. The raw dump voltage software backend records information to four disks on each of the sixteen nodes simultaneously. This takes up space quite quickly, and because of this, most of the work that needed to be done at GMRT was of a data crunching variety.

4.1 Python at GMRT

In order to run Python scripts at GMRT, it was necessary to install an updated version of Python. The chosen distribution was Anaconda. This initially caused some problems with library locations for other codes, but was resolved by editing the shell login file. The distribution was installed in the /mnt/code directory, which is mounted across all nodes an important factor when trying to run a script across a sequence of nodes.

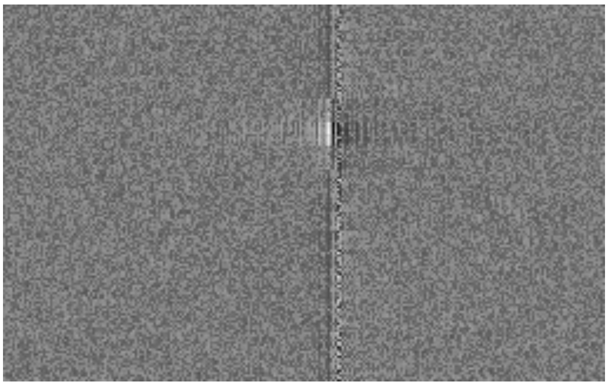
4.2 Disk Mounting

One particular assignment involved copying data from the node17-32 cluster to the node33-48 cluster (hereafter referred to as the old and new cluster respectively). The data to be moved was taken during the second VLBI run this summer, from July 21 to July 28. The copying script read from four disks on the old cluster and copied the data to four disks on the new cluster, which made the process much faster than secure copying each file individually. However, the script also required specific naming of the disks to be written to. It was necessary that disks with enough space to hold the files be mounted on a node of the new cluster and given a consistent naming scheme. This mounting work was largely done manually during overnight copying sessions, since disk space fluctuated over the course of the week and had to be recounted every night.

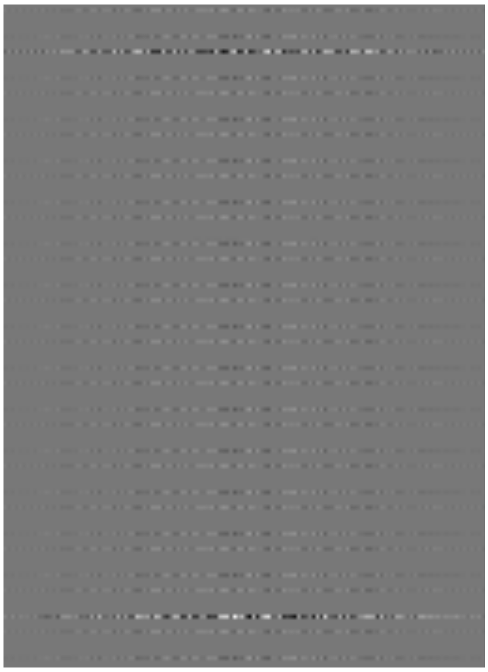
In addition to this, some of the disks were unmounted during reboots, causing us to believe there was less space available than there actually was. From time to time, even the essential disks were unmounted, and files went missing. Fortunately, existing scripts allowed us to efficiently remount the disks on both clusters (once the scripts were located).

4.3 Fringestopping

Another assignment was fringestopping, a data reduction routine that was intended to clear out some space on the node111-118 cluster. A description of the details of the process can be found on this project's wiki. This process ran smoothly for January 2013 data fringestopped for Liam Connor, but required more thought for older data belonging to Prasun Dutta. The main concern was missing files or inconvenient file locations. Duttas files had been transferred from the 33-48 cluster of nodes in a suboptimal manner, and it was necessary write a script to locate all of the files required to run the program. Dutta also required a higher number of frequency channels, and it took quite a while to confirm that the fringestop was still doing what was expected of it after this alteration (see Figure 1 for unexpected or unwanted results). This was checked by examining lag plots of the fringestopped data in search of a pulsar. In the end, the fringestop was successful for scans where enough files could be found for it to run (see Figure 2 for



(a) A successful fringestop of Dutta's data using 128 frequency channels. The bright spot is the pulsar.



(b) An example of a possible unsuccessful fringestop lag using 2048 frequency channels. The data is garbled and the pulsar is not visible.

Figure 1: Unsuccessful or undesired fringestopping results on the sixth scan taken on pulsar B0329+54 on August 22 2012 by Prasun Dutta.

the desired results). However, with over 900 of Duttas scans to process, no significant headway was made before the end of the summer.

The code used to locate and link the files for fringestopping is located within the Code directory mentioned in section 3.1

4.4 Epoch of Reionization Project

Another project worked on this summer was the monitoring of the Epoch of Reionization (EoR) correlator. This was another space juggling exercise on nodes 33-48. The data was written to the disk called EoR_correlation on each node, but space was consumed at a ferocious rate. My monitoring duties consisted mostly of ensuring that enough space remained on each such disk. This required using a few python scripts to investigate the disk situation and to mount disks with space to the appropriate locations.

5 Algonquin Radio Observatory

Work at ARO was more varied in that it was not uniformly software-based. As at GMRT, the ARO setup had a number of nodes (5, in this case, with a few backups and spares).

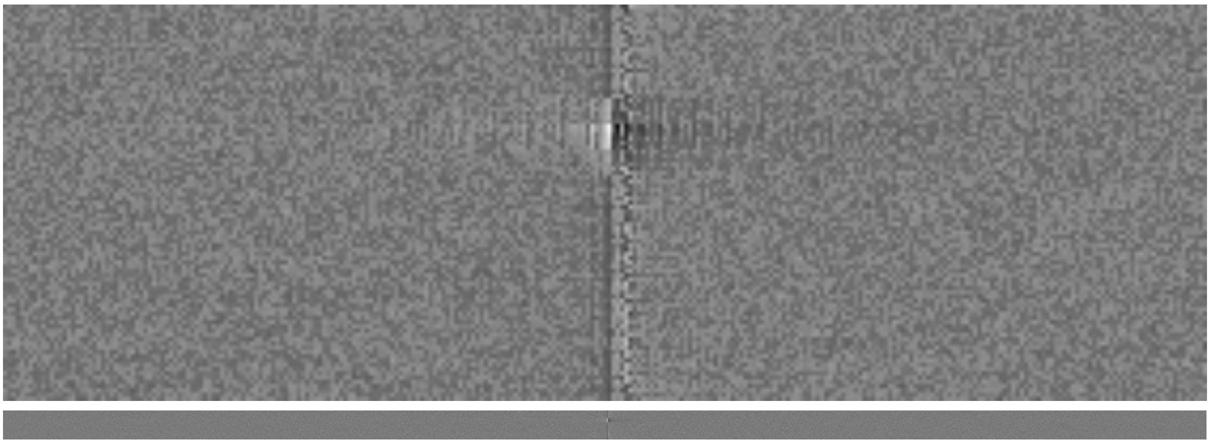


Figure 2: The results of a successful fringestop using 2048 frequency channels on the same scan used in Figure 1. The top image is a cropped section of the bottom one, zoomed to show the pulsar. In the original image, the pulsar is just visible as a white dot in the center. This original image is the exact product of the process used to generate Figure 1a and has a far higher resolution of the pulsar image.

In total, there are three versions of the ARO setup that I am aware of - two at CITA for testing, as well as the one actually in use at ARO.

5.1 Hardware and Node Set Up

For each ARO setup created, it was necessary to install the correct CentOS 6 as well as a number of libraries. In addition, two of the nodes required Analog to Digital Converter (ADC) boards. We installed these in the nodes at ARO, and moved the board when one of the nodes needed to be swapped out. We also installed large hard drives in each node to maintain the high rate of data acquisition, and removed them to transfer data back to CITA.

We also helped with feed construction by building a ground plane and the smaller fat dipole antenna modeled after GMRTs antennas during the 150 MHz run. However, both of these were eventually deconstructed in favor of the final product.

5.2 Ubuntu Node (Pen Node 10)

In addition to the four nodes used for acquisition and processing of the data, there was a fifth running a 64bit OS that gave us a real time display of the signal reaching the feed. I set up this node with some assistance from Phil Isaac with the operating system. Though it was a 64bit OS, it needed 32bit libraries to work with the other nodes. I installed Python and the primarily used modules and set up a git account for the machine that wouldnt be tied to any particular user. In addition, I copied over the 32bit openmpi and Intel libraries from the CITA network, as well as installing a newer, 64bit version of openmpi.

6 Pulsar Folding

Pulsar folding is the process of binning time and adding across a pulsars period so that signal of the pulse is increased while the surrounding noise is decreased. When folding signal from multiple antennas, it is also necessary to account for the delays between them. Adding up a signal from multiple antennas also increases the signal to noise, as well as the resolution.

6.1 Delay Times

In order to phase together the signal at each GMRT antenna (as well as the different VLBI locations), it was necessary to generate delay files. Such files consisted of the delay in metres for each location of interest at each timestamp during an observation.

At first, the files were generated with many small codes in languages including Fortran90, C, Perl, and Python. After the first VLBI run of observations, a Python script was written that incorporated all of these steps into a single, streamlined process. Key points in the process were finding the location of the antennas in the appropriate coordinate system and converting the timestamps to readable format. Only then could the baselines from a reference point be calculated.

At GMRT, the antenna coordinates are kept up-to-date in a particular file, but the VLBI coordinates proved to be more of a challenge. The easiest way to find the baselines is to convert telescope latitude, longitude, and altitude to Cartesian coordinates with a common origin and find the distance between them for each pair of telescopes. The baselines are then used to find delays in conjunction with the pulsar's location in hour angle and declination. However, even establishing a longitude, latitude, and altitude proved to be challenge.

I generated delays for each observing day at GMRT as well as VLBI coordinates for the second VLBI run. However, I have been unable to confirm that the VLBI coordinates are correct. The Python script was tailor-made for GMRT delay times, and modifying it for VLBI will take some effort. It was much easier to change a smaller code that I had already written to do the job, but I have not yet confirmed the code's functionality to my satisfaction. In addition, there is the matter of there being different timestamp intervals at GMRT and ARO (a stamp approximately every 0.251 or 0.336 seconds respectively) - I have not yet seen any timestamp files from Effelsberg or LOFAR. Since I am not entirely sure how the delay files I generate are used, I will need more information before generating a standard delay file for the VLBI.

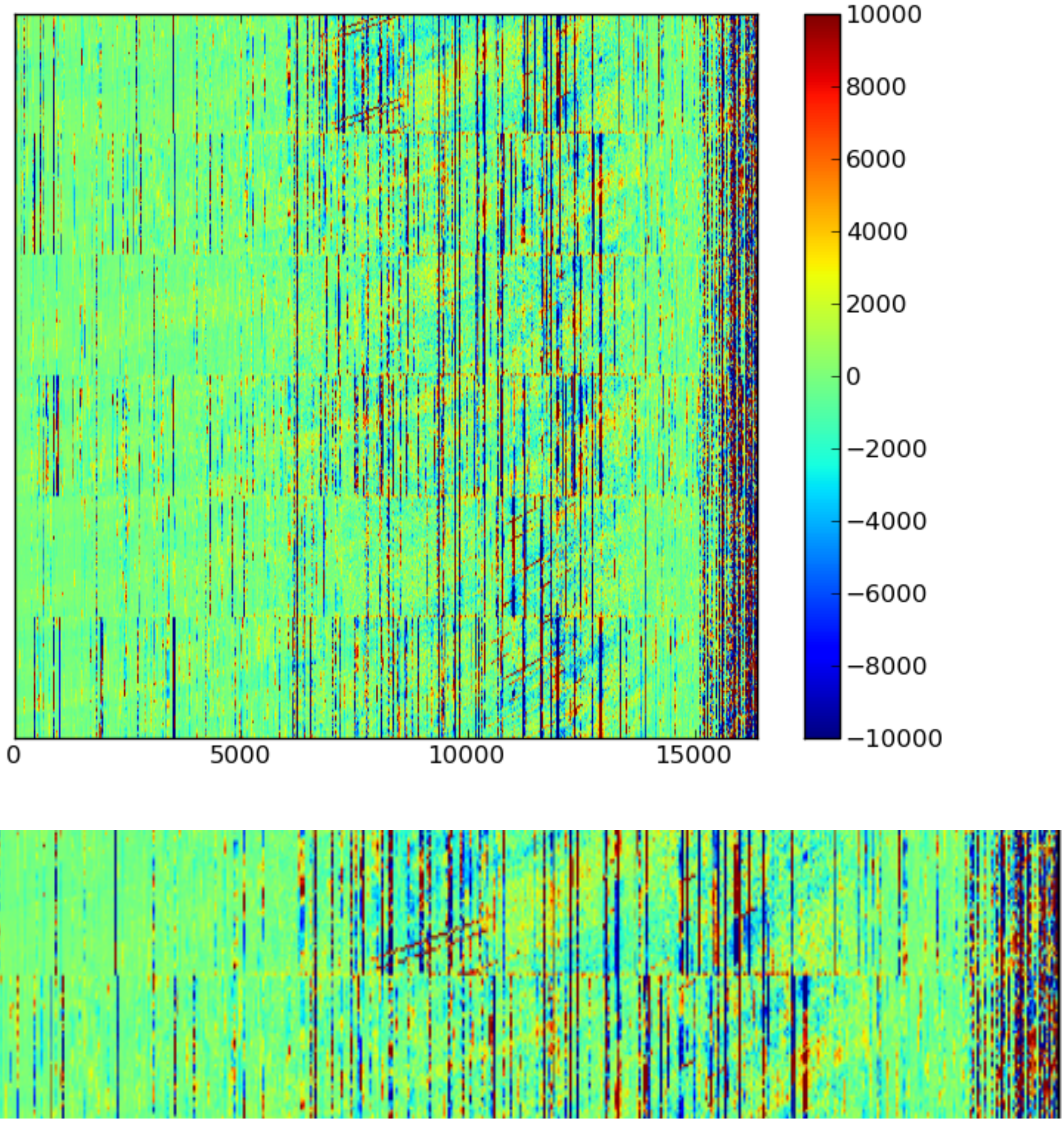


Figure 3: A plot of the signal of pulsar B1919+21 folded over 16 minutes with 16384 frequency channels and divided into 6 time bins along the y-axis. The x-axis is the number of the frequency bin, the colourbar the intensity of the signal. The plot shows the polarization recorded to node9. The pulsar is visible as a horizontal line. In this plot, it falls along the division between bins. The cropped portion below is a selection from the first two bins, the pulsar signal following the divide between them. Data was taken July 25 2013.

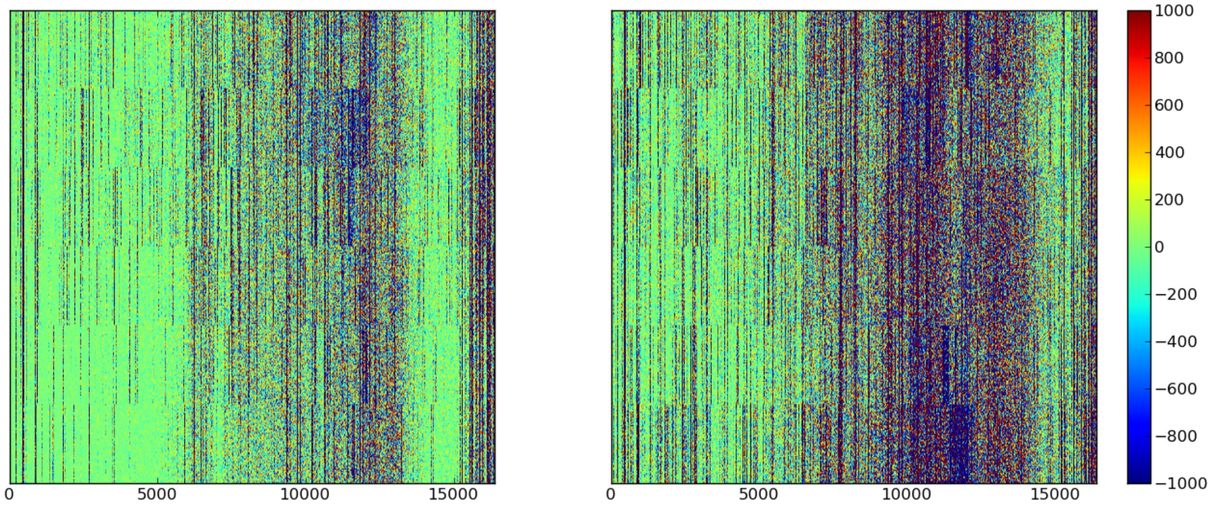


Figure 4: Plots of both polarizations of the millisecond pulsar J1810+1744 folded over an hour and a half with 16384 frequency channels and divided into 6 time bins along the y-axis. The x-axis is the number of the frequency bin, the colourbar the intensity of the signal. The left plot is the polarization recorded onto node9, the right is the polarization recorded onto node7. In neither is the pulsar visible. Data was taken on July 24 2013.

6.2 Generating Sequence Files

There are few related files generated when raw voltages are recorded in the very similar GMRT and ARO recording systems. One is the timestamp file, mentioned in Section 6.1. This file is simply a list of chronological timestamps spaced by a set interval. These timestamps are a record of the time at which information was entered into the raw voltage file on one of the disks. Another related file is the sequence file - a file with two columns. The first is the sequence number, and the second is the disk number of the raw voltage file that was written to for that particular sequence number. The sequence numbers are consecutive, beginning at two, and increasinging by one with each timestamp that passes.

However, the timestamp files and the sequence file do not always match up. If a timestamp is missing, this should be reflected in the sequence file numbering, and vice versa. Since this is not always the case, a series of functions were written in a Python script to generate a sequence file from the timestamps recorded. The functions account for missing timestamps in the sequence numbers, as well as identifying duplicate timestamps - this occurs when information was written to more than one disk at the same timestamp. The functions can also substitute a value for missing timestamps if necessary. This became helpful later on when the folding began on ARO data (Section 6.3). The sequence numbers were coordinated across all disks on all nodes to provide a comprehensive map of data locations.

Generated sequence files were then checked against the sequence files produced during observations to identify possible problems with the hardware or software used. It was during this process that it was discovered that one of the nodes had lost clock synchronization. During the 325 MHz observations, node34 was 14 minutes behind the other nodes. This skewed the timestamps (and thus, the generated sequence files) quite remarkably. A similar problem occurred during the 150 MHz recording, with node18 being the culprit. The sequence generator also alerted us to the possibility of duplicate timestamps. The functions used to generate the sequence files are included in the code directory referenced in Section 3.1.

6.3 Folding

Once the data had been gathered, it required folding to make the pulsar visible. Folding is (as explained earlier in this section), a way to increase the signal-to-noise ratio of the data. It works only because pulsars have a well-defined period. Even the millisecond pulsars, for which the change in period is a noticeable fraction of the period itself, can be reasonably well described with ephemerides and tempo files.

The raw data is first divided into time bins. In the case of the associated figures, there were six time bins. The time is then chopped into instantaneous period-length chunks. These chunks are added together so that (if the instantaneous period is correct), the brightest part of the pulse adds constructively while the noise destructively interferes with itself. In this way, pulsar signal is maximized despite high levels of Radio Frequency Interference (RFI).

The described operation was performed on data from ARO taken during the second VLBI run. The first attempt was made on a bright pulsar with a relatively unchanging period, B1919+21, and the result was quite promising (see Figure 3). However, folding on millisecond pulsar J1810+1744 was less successful (Figure 4). RFI obscures any possible evidence of the pulsar, and even at the same scaling as the B1919+21 plot no pulse is revealed. The current colourbar scale shows just how dramatic the effects of RFI can be. It was hypothesized that folding at a millisecond timescale should eliminate the RFI, which has a timescale more like a second. However, this does not seem to have had any effect on the J1810+1744 plot.

7 Conclusion

Overall, the analysis work partially finished this summer must progress to show any evidence of viable scintellometry. There was a lot left unfinished, but after a summer of managing different software and networks, future work could be done more efficiently.

In particular, one of the most frequent trials of our observations was locating space for our data to be recorded or moved. However, this is work that could be undertaken much more effectively now than at the beginning of the summer. Likewise, the fringestopping process, having finally been approved in its latest version, could also continue. Certainly, my understanding of programming languages and the perspective needed to use them well has been much improved over the course of the summer. The next steps will be to complete the VLBI phasing, and then moving onto to attempt scintellometry.

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