INTERNAL REPORT

LEAP project at SRT: Hardware, software and implementation

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Abstract

We report on the participation of SRT in the Large European Array for Pulsars (LEAP) project, which performs simultaneous observations of millisecond pulsars at 5 large European telescopes. We describe the hardware and software that were installed at SRT to allow the participation of SRT in LEAP. We then present results from the May 21-22, 2014 session, which was the first time SRT joined for the entire 25-hour long session and for the entire LEAP bandwidth (128 MHz). 20 out of 22 millisecond pulsars were successfully observed during this session, despite the presence of significant RFI at L-band.

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Contents

1 Introduction

The Large European Array for Pulsars (LEAP) [1] project performs simultaneous observations of millisecond pulsars at 5 large European radio telescopes: the Lovell telescope at Jodrell Bank Observatory (UK), the Westerbork Synthesis Radio Telescope (Netherlands), the Effelsberg Telescope (Germany), the Nançay Radio Telescope (France) and the Sardinia Radio Telescope (Italy). This project is part of the European Pulsar Timing Array [2] (EPTA)'s effort to directly detect gravitational waves from supermassive black hole binaries using an array of millisecond pulsars. By observing pulsars simultaneously, baseband data from each telescope can be added coherently in phase, which leads to a greater increase in the signal-to-noise of the observed pulsars. Observing pulsars with LEAP is equivalent to observing with a single dish of 196 meters in diameter, which is similar to the illuminated area of the Arecibo dish, but with a larger range of observable declinations.

The Sardinia Radio Telescope [3] (SRT) is the latest telescope to join the LEAP effort. LEAP observations started in early 2012 with the Effelsberg and Westerbork telescopes, and were joined later that year by the Lovell and Nançay telescopes. Observations are performed monthly and are 25 hours long. The participation of SRT in LEAP was made possible once the dual-band L/P receiver was installed at the primary focus of the telescope (June 2013) and the ROACH (Reconfigurable Open Architecture Computing Hardware) [4] backend was installed on-site (July 2013). The first ever LEAP session was conducted on July 27, 2013 for one pulsar (PSR J1022+1001), which was observed simultaneously at all 5 telescopes. The observation at SRT was limited to one 16 MHz band (we chose the band centered at 1436 MHz) due to hardware limitations. Indeed, the ROACH backend was controlled by a computer ("Dorian") that only allowed data acquisition in one 16 MHz sub-band. In subsequent months, SRT participated in LEAP in the 1436 MHz sub-band (September, November, December, January). The August 2013 and February 2014 sessions were skipped because of the antenna's unavailability.

In February 2014, a computer cluster with eight nodes was installed at SRT. Data acquisition and pulsar analysis software were installed on the cluster, and first tests were performed to record baseband data in 8 x 16-MHz sub-bands, covering the full 128 MHz LEAP bandwidth (1332-1460 MHz). We were successful in observing the bright pulsar B0329+54 and the bright millisecond pulsar B1937+21 in all eight bands. This paved the way for the participation of SRT in the full LEAP bandwidth. On March 23, SRT participated in LEAP for the first time using the full 128 MHz bandwidth, joining for part of the 25-hour run. SRT joined for the April 12-13 LEAP run as well.

Because of the high volume of data (64 MB/sec for each 16 MHz sub-band), one 25-hour run needs about 40 TB of space for the full bandwidth at each telescope. The SRT cluster can accommodate 7 TB per node, or 56 TB in total. The routine performing of 25-hour runs and the recording of many TB of data at SRT was however not possible until a storage system was installed on-site (April 2014). In April 2014, a storage system with a capacity of 96 TB was shipped alongside 32 x 3 TB disks by the LEAP project in Manchester. Previous data were copied onto disk and the cluster was made ready for the first-ever 25-hour LEAP run at SRT on May 21-22, 2014.

2 LEAP hardware

LEAP observations are made in L-band. The L-band receiver [5] is located at the primary focus of the telescope and requires the use of a “parabolic” shape for SRT's active surface. The L-band receiver detects the two linear polarizations of the incoming electromagnetic waves in the 1,300-1,800 MHz frequency range, which are then transferred to the apparatus box (“Box AP”), where they are mixed with a monochromatic signal (set at a frequency of 2,316 MHz) generated by a synthesizer, and are thus down-converted to the adequate backend frequency range. The signal is then sent to the Digital Base Band Converter [6] (DBBC) backend (used for VLBI) and, exploiting a few power splitters contained in the DBBC, to the ROACH backend as well. This enables the RFI monitoring [7] of the L-band while recording data with the ROACH. The 10 MHz clock and 1 PPS provided by a maser allow synchronization of the synthesizer contained in the DBBC; it provides the 1,024 MHz sampling clock necessary for the analog-to-digital converters (ADCs) of both the DBBC and the ROACH. The clock used for VLBI (with the DBBC) and LEAP (with the ROACH) is therefore identical.

The ROACH backend consists of an FPGA-based board developed by the CASPER [8] group in Berkeley (California) and is identical to the backends used at Effelsberg and Jodrell Bank for LEAP [9]. The analog-to-digital converters work at a sampling frequency of 1,024 MS/s with an 8-bit representation, providing 512 MHz of bandwidth for each polarization. At SRT, the ADCs operate in the second Nyquist zone (512 – 1024 MHz).
The ROACH produces 32 complex channels of 16 MHz each; the desired sub-bands can be chosen by modifying an IP table.

The observable frequencies are determined as follows:

First observable band	1,292 – 1,300 MHz and 1,796 – 1,804 MHz
Second observable band	1,300 – 1,316 MHz
3rd observable band	1,316 – 1,332 MHz
4th observable band	1,332 – 1,348 MHz: first LEAP band
...	
...	
11th observable band	1,444 – 1,460 MHz: last LEAP band
...	
...	
32nd observable band	1,780 – 1,796 MHz

The 128 MHz bandwidth (1,332 – 1,460 MHz) used for LEAP is thus covered by bands 4-11. To process them, an 8-node cluster, where each node processes one 16 MHz sub-band, is therefore sufficient (note that at Jodrell Bank, they have a 32-node cluster which processes all 32 x 16 MHz bands for general EPTA pulsar timing). We plan to test the acquisition of multiple bands on a single cluster node for EPTA timing. This is however not needed for LEAP observations.

The acquired cluster is composed of 8 servers/nodes + 1 management server (frontend or head node), with a dual-socket motherboard (G34).
Each node is equipped with:

1) 2 x 8 core 2.5 GHz CPUs (16 cores in total for each node)
2) 64 GB of RAM (DDR3-1600)
3) RAID: Adaptec 6805 SAS/SATA
4) HDD: 4 x 2 TB
5) LAN: 4 x 1 Gbe ports + 1 port dedicated to IPMI

In order to send the data from the ROACH to the cluster, a 10 Gbe switch equipped with four CX4 connectors (paid for and shipped by the LEAP team at Manchester) was installed.

Finally, the system is complemented by a storage unit with a capacity of 32 disks of 3 TB = 96 TB. Each node is directly linked to 4 disks, where baseband data is copied to after a LEAP run. Once completely full, the disks are shipped to Manchester.

The general setup of the observing system (astronomical signal from antenna to ROACH and cluster) is illustrated in Figure 1, while the ROACH/cluster/storage system is illustrated in more detail in Figure 2.

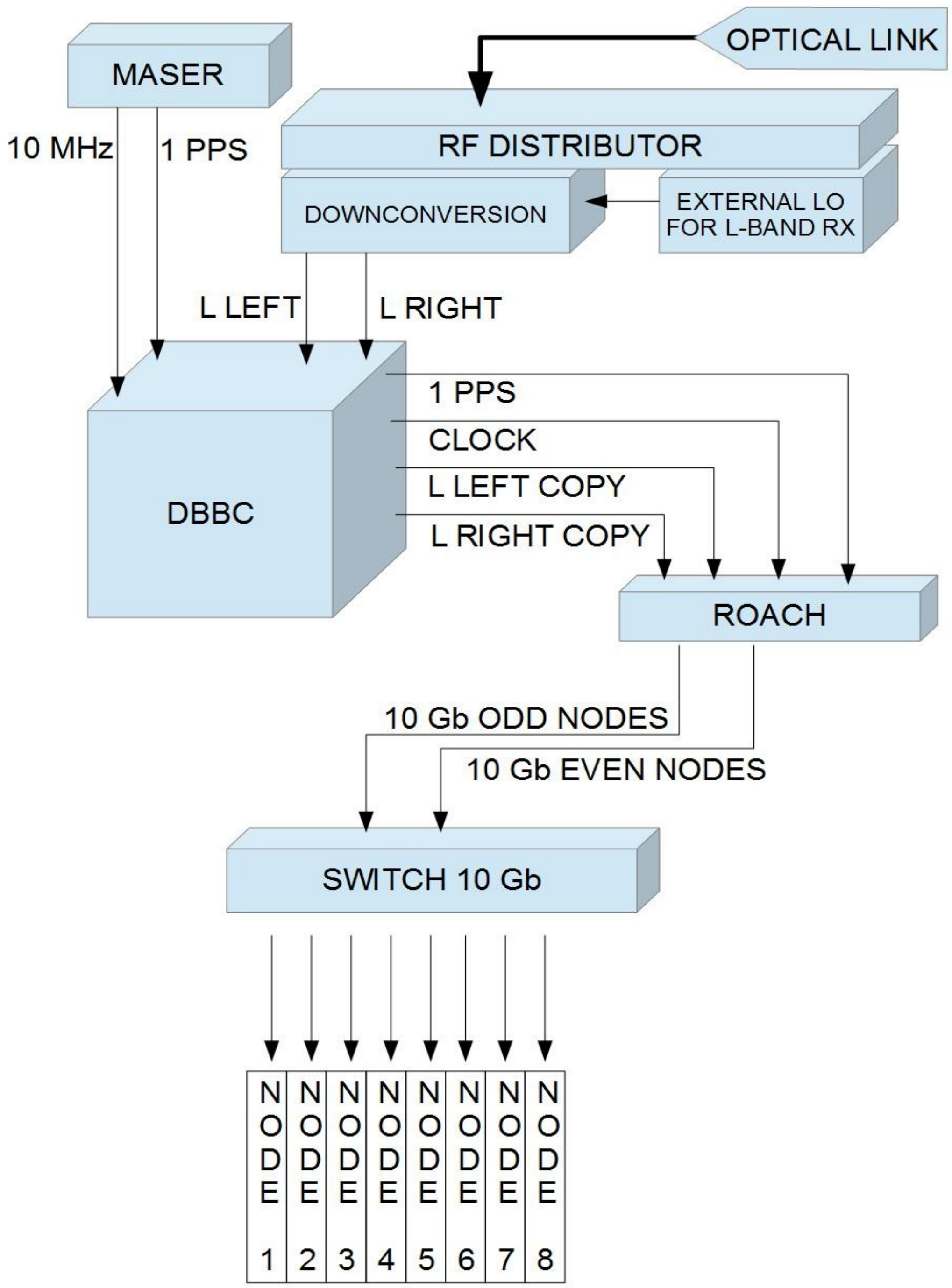

Figure 1: General setup (radioastronomical signal from antenna to computer cluster)

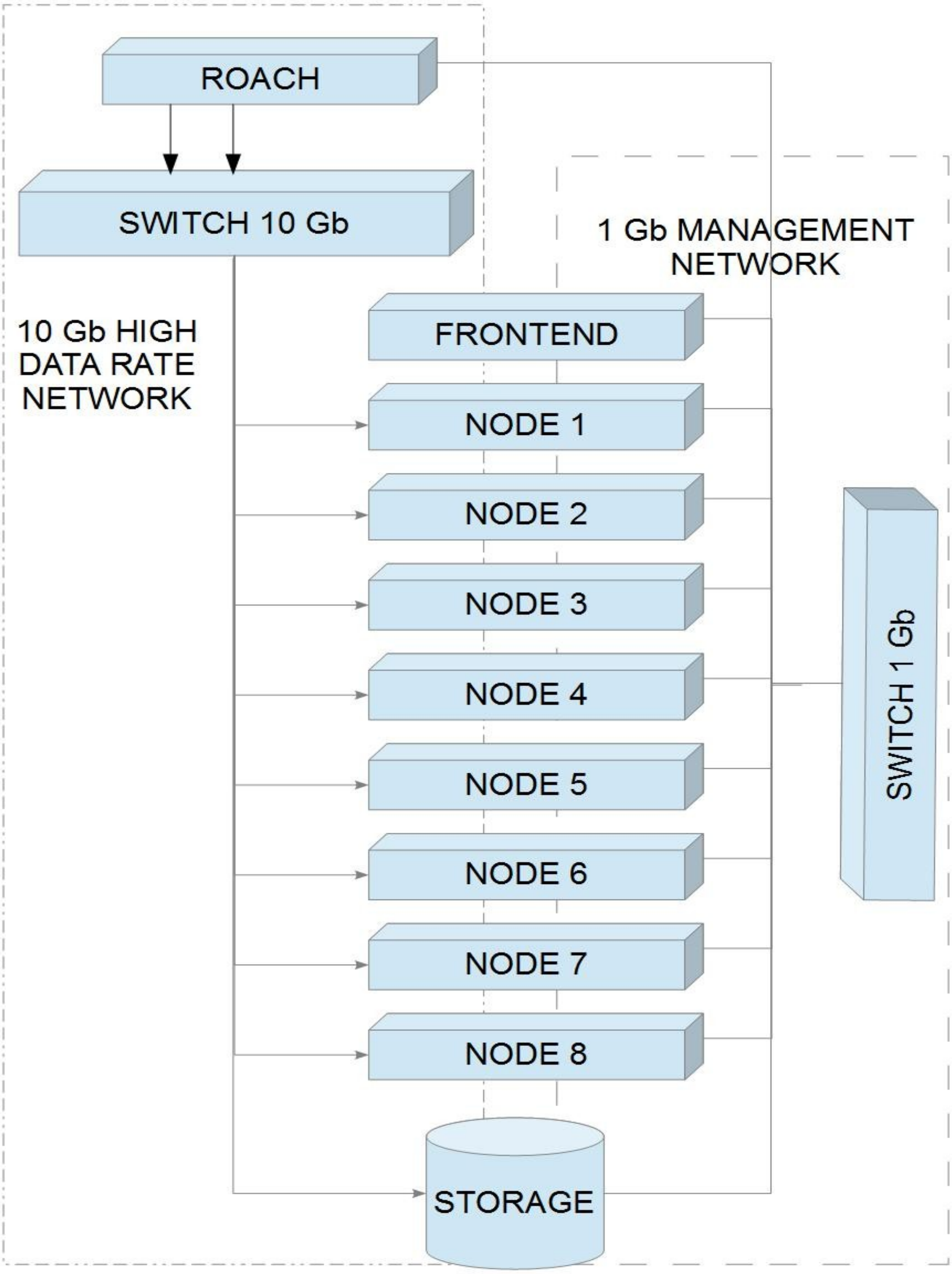

Figure 2: ROACH/cluster/storage system

3 LEAP software

The computer cluster is equipped with the CentOS [10] operating system. In the /home/user/linux directory, we have installed data acquisition and pulsar analysis software. This consists of:

1) pgplot 5.2.2
2) cfitsio 3.360
3) fftw 3.3.3
4) gsl 1.16
5) tempo (old stable version)
6) tempo2
7) psrchive (development branch)
8) psrcat
9) psrdada
10) dspsr
11) udp2db (Cees Bassa)
12) control software (Cees Bassa)
13) dadatest (Cees Bassa)

Software 1-10 is freely available online. Software 1-4 consists of prerequisites for the installation of the pulsar timing software "tempo2" [11] and "psrchive" [12]. "psrdada" [13] enables the creation of ring buffers, reading from ring buffers and writing data to disk (with the command *"dada_dbdisk"*). The baseband data is written in "dada" format (for "Distributed Acquisition and Data Analysis"). In order for the cluster to receive data packets from the ROACH backend, another piece of software was installed: *"udp2db"* (courtesy of Cees Bassa/Jodrell Bank; this code is not freely available). We note that the *"udp2db"* version installed on the "Dorian" machine was a different version, provided courtesy of Ramesh Karuppusamy (Max Planck). Additionally, control software (courtesy of Cees Bassa) was installed to automate the acquisition of baseband data on all 8 nodes simultaneously. The *"dspsr"* commands enable the folding and coherent de-dispersion of the baseband data, producing folded archives, which can then be analyzed with the "psrchive" software.

4 LEAP observations

A LEAP session consists of a 25-hour run divided into a short session of 5 hours, and a long session of 20 hours. LEAP sessions are normally run once per month. The exact dates and times are decided a couple of months in advance after consultation of scientists at all 5 telescopes. 22 pulsars and associated calibrators are observed simultaneously at all 5 telescopes. The observing of each pulsar (typically 40-60 minutes) is preceded and followed by the observing of a calibrator (typically 5-10 minutes), which could be a quasar or some other bright source. This is done because with the observations of bright calibrators, we can easily find the fringes between the different telescopes. The fringe solution is then applied to the pulsar which is fainter. We show a sample LEAP schedule:

```
640 J0606-0024   236 07:16:40 236 07:19:40  06001  415  1398  20
641 J0613-0200   236 07:23:00 236 08:21:00  06001  415  1398  20
642 J0616-0306   236 08:24:00 236 08:30:00  06001  415  1398  20

643 J0619+0736   236 08:33:20 236 08:37:20  06001  415  1398  20
644 J0621+1002   236 08:39:50 236 09:24:50  06001  415  1398  20
645 J0619+0736   236 09:27:10 236 09:30:10  06001  415  1398  20

646 J0743+1714   236 09:33:10 236 09:38:10  06001  415  1398  20
647 J0751+1807   236 09:40:40 236 10:21:40  06001  415  1398  20
648 J0743+1714   236 10:24:40 236 10:27:40  06001  415  1398  20
```

where the first column is the observation number, the second column the source name, the fourth column the start time in UTC, the sixth column the stop time in UTC, and the ninth column is the center frequency of the observation. Other listed columns are only useful at other telescopes. We note that the second source in each group of three sources is always a pulsar (e.g. J0613-0200, J0621+1002 and J0751+1807), while the first and third sources are calibrators. This is the original LEAP schedule distributed by the LEAP collaboration, and it is in UTC format. Nuraghe does not yet accommodate UTC for schedules. In the meantime, to meet Nuraghe's requirements, we are converting the LEAP schedule to a format involving durations. The Nuraghe-compatible LEAP schedule is placed in the Nuraghe schedule directory in LEAP/LEAP.scd. One can launch the LEAP schedule and the antenna will track each source for the required duration, then move on to the next source.

For data acquisition, we do not at all use the Total Power backend. Instead, we use the ROACH backend, which is not integrated with the *"Nuraghe"* [14] antenna control system. We proceed separately (but with coordination) with Nuraghe and the ROACH.

1) Nuraghe: once Nuraghe is launched and the L-band receiver is set up, we choose a parabolic shape for the active surface. We then launch the Nuraghe LEAP schedule: *LEAP/LEAP.scd*.

2) ROACH backend: we start and stop data acquisition using control software that uses the *"dada_dbdisk"* and *"udp2db"* software for data acquisition. "start" is done once the antenna is tracking the source, while "stop" is done once the antenna starts slewing to the next source.

3) Data quality is checked using: *"dadatest"* to check for missing packets in each cluster node; *"digistat"* for dynamic range (see example Figure 3); *"passband"* to examine the bandpass in each 16 MHz sub-band, and in particular check that the HI line is visible between 1420 and 1421 MHz (see example Figure 4)

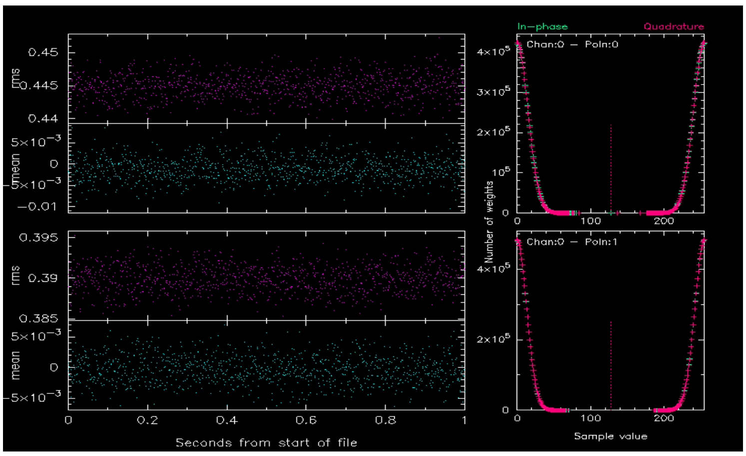

Figure 3: "digistat" test showing nice Gaussian shape for dynamic range

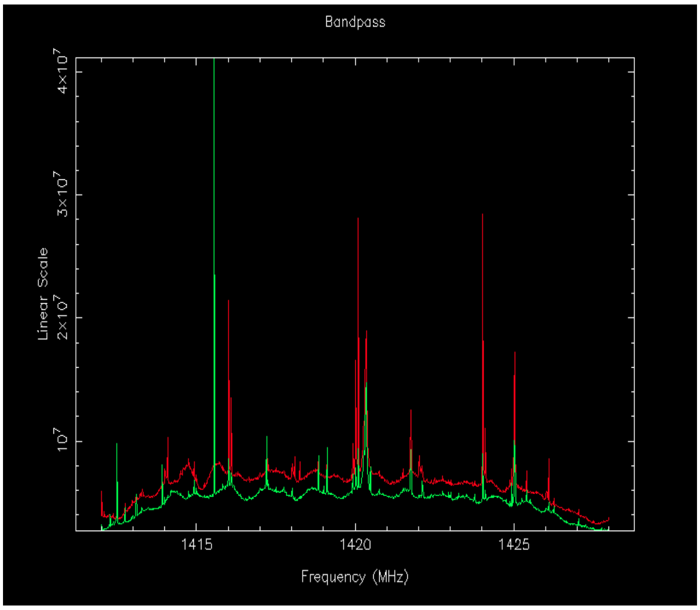

Figure 4: bandpass for sub-band centered at 1420 MHz, with HI line visible

4) Analysis: after the observations are finished, *"dspsr"* is run to obtain a pulsar profile and check that the observation went as planned. One can then obtain plots of power vs. phase (*pav -dDFTp*); frequency vs. phase (*pav -dGTp*); time vs. phase (*pav -dFYp*).

5) Baseband data are copied onto disk (on storage unit) and shipped to Manchester to be combined with the data from the other 4 telescopes, i. e. it will be correlated and coherently added with the LEAP correlation software in order to increase the S/N for each pulsar.

5. May 21-22 LEAP run

In the May 21-22 LEAP run, the antenna and all 8 nodes of the cluster worked well.

The "dadatest" test revealed no major packet loss during data acquisition, but a few packets were missed as is normal. We will write software to remediate occasional packet loss so it doesn't negatively influence the data analysis.

The “digistat” test revealed a nice Gaussian for the dynamic range, as in Figure 3. This shows that setting the attenuation of each polarization to zero in the Nuraghe commands is adequate.

The “passband” test showed the bandpass for each sub-band. This revealed a number of RFI sources, some of them most likely generated at the SRT site, others by radars. A particularly problematic radar for LEAP is the one emitting at 1,359 MHz and malfunctioning in one polarization up to 1,460 MHz, thus covering the entire LEAP band, including the protected astronomical band from 1,400 to 1,427 MHz.

After running “dspsr”, we saw 20 out of 22 pulsars despite the presence of RFI, which was deemed a great success. In the figures below, we show the plots of power vs. phase, time vs. phase and frequency vs. phase for the millisecond pulsar J1643-1224. The baseband data were copied to disk and will be analyzed with the LEAP correlation software for 5-telescope coherent addition.

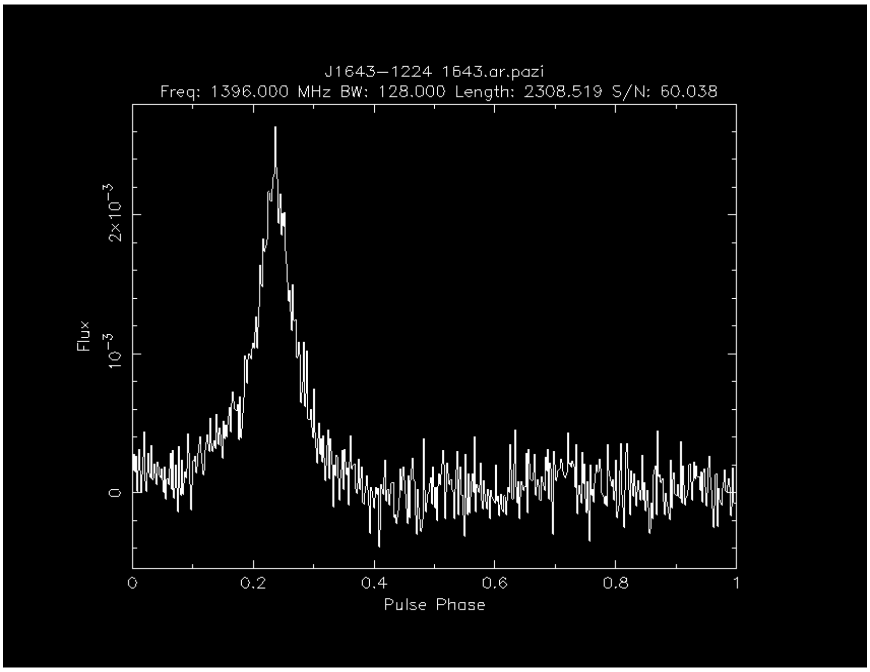

Figure 5: Plot of power vs. phase

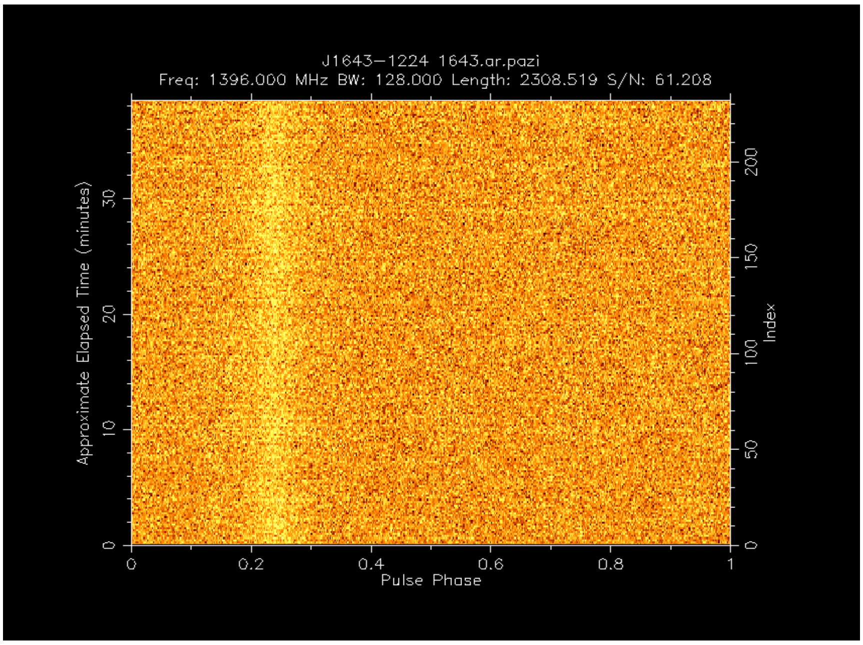

Figure 6: plot of time vs. phase

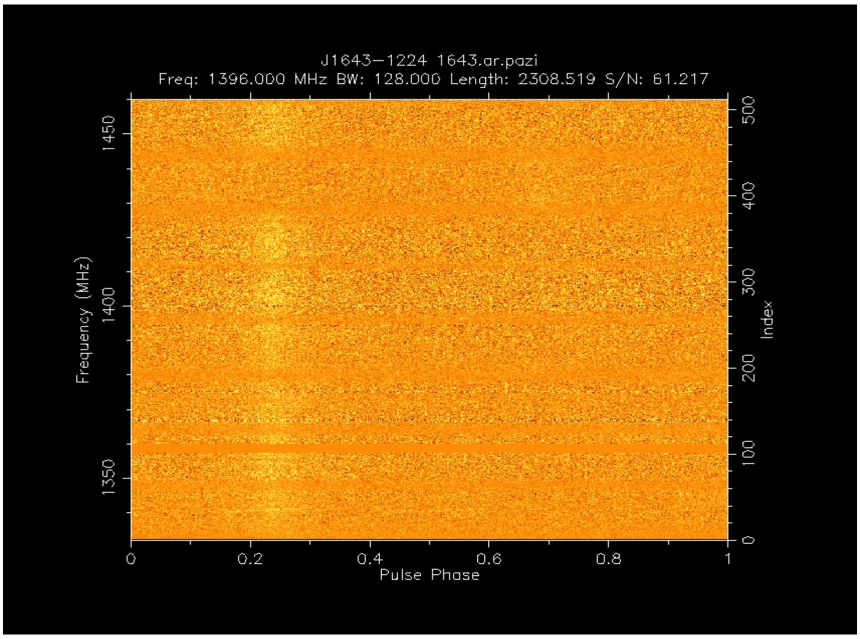

Figure 7: plot of frequency vs. phase

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