One Year of Observing the Vela Pulsar

Steve Olney (HawkRAO : 33° 34.0' S, 150° 44.7' E)

Introduction
The milestone of one year of observation of the Vela pulsar is the culmination of 4 years of research and experimentation - a combination of self-education, guidance from fellow citizen scientists and professional astronomers. The basic aims of the observation program are five-fold.

1. Research the characteristics of the Vela pulsar to determine the issues to addressed
2. Build a hardware system capable of detecting the Vela pulsar
3. Write software to automatically take daily observations of the pulsar
4. Generate scientific data from the observations
5. Observe a 'glitch' in the observational data

Of the 5 above aims, 4 have been achieved – as will be described below.

Over the course of the year improvements have been made to the software to curate the data to eliminate poor data (corrupted by radio frequency interference - RFI, poor intrinsic flux density, environmental effects) to achieve a level of data quality to allow scientific results to be obtained.

Background Research
The choice of the Vela pulsar as the target pulsar had two main drivers – it is the strongest pulsar over a wide range of frequencies and passes almost directly overhead at this location (Vela pulsar – declination -45°; HawkRAO – latitude 34° S).

The Vela pulsar has the following characteristics...

<table>
<thead>
<tr>
<th>Name</th>
<th>RA</th>
<th>DEC</th>
<th>P0 (ms)</th>
<th>W50/W10 (ms)</th>
<th>DM</th>
<th>S400 (mJy)</th>
</tr>
</thead>
<tbody>
<tr>
<td>B0833-45</td>
<td>08:35:20.61</td>
<td>-45:10:34.87</td>
<td>89.328385024</td>
<td>2.1/4.5</td>
<td>67.99</td>
<td>5000</td>
</tr>
</tbody>
</table>

...where...
RA: Right ascension (hours minutes seconds)
Dec: Declination (degrees minutes seconds)
P0: Barycentric period of the pulsar (s)
DM: Dispersion measure (cm-3 pc)
W50: Width of pulse at 50% of peak (ms)
W10: Width of pulse at 10% of peak (ms)
S400: Mean flux density at 400 MHz (mJy)

**Observational Frequency**
The fact that the Vela pulsar has a flux density of 5 Jy at 400 MHz compared with 1.1 Jy at 1400 MHz (a 6.6 dB difference) meant a strong preference for a lower observation frequency. Given the availability of ready-made components for the 70 cm amateur radio band, a choice of an observation frequency within that band was made. The selection of 436 MHz as the centre observation frequency was made after a spectrum analyser survey of the 70 cm amateur radio band to find a relatively clear space in between interfering terrestrial signals. Due to the prevalence of other users in this frequency range, an observational bandwidth of about 2 MHz was determined to be a reasonable compromise between radiometer sensitivity and the ability to avoid interference.

**Receiver**
Given the success of the project was not certain at the start, a cheap option for the receiver chain was chosen. The ready availability of a very cheap ~$25 USB dongle that can be used as a computer based radio astronomy receiver determined the selection of this device. The RTL-SDR is a re-purposed DVB-T TV tuner dongle that is based on the RTL2832U chipset. The driver software for the RTL-SDR is also readily available as well as various utilities. Access to the source code for these utilities makes the customisation for radio astronomy purposes possible. Preceded by suitable low noise amplifiers (LNA) and filters, the RTL-SDR becomes a very useful radio astronomy receiver. Depending on the particular model it can receive frequencies up to 1.5 GHz and bandwidths up to 2.4 MHz.

**Antenna**
The Vela pulsar radiation is almost 100% linearly-polarised with a small amount of circular polarisation. By contrast another strong pulsar (B0329+54) is almost completely unpolarised – meaning that radiation is received equally on all polarisation angles during the pulse on-time. As a result, a linearly-polarised receiving antenna will receive the same signal level from B0329+54 irrespective of its polarisation alignment. In the case of the Vela pulsar, it might be thought that a linearly-polarised antenna aligned to the received linearly-polarised radiation angle would be suitable. However, this is not the case for a number of reasons. Firstly, the polarisation angle of the Vela pulsar's radiation swings by nearly 90° during the on-pulse phase duration of ~2 ms, therefore, for a significant proportion of the pulse on-time the polarisations of the antenna and the signal will not be aligned – even if they are aligned at the peak of the pulse. Secondly, the polarisation angle of the radiation is altered by Faraday rotation along its path through the interstellar medium (ISM) and the Earth's ionosphere. While the rotation angle caused by the ISM is relatively stable, that part of the rotation caused by the ionosphere is not – changing markedly in a random fashion over time. For the Vela pulsar the solution to these factors has been to adopt the use of a circularly-polarised antenna. In this fashion the combined effects of intrinsic polarisation swing and Faraday rotation are mitigated.
Calculations using the radiometer equation returned an antenna aperture requirement of the order of 6 m$^2$ – which corresponds to approximately 19 dBi at a frequency of 436 MHz. A commercially available 42-element circularly-polarised antenna for the 70 cm amateur radio band was chosen (M2 Incorporated 436CP42UG) to fulfil these requirements.

Software

While the software drivers and utility software is freely available from third parties (without which this project couldn't be attempted using the RTL-SDR device), the output data produced by that software needs to be further processed to extract the pulsar signal. Two basic processing strategies were considered – either use software packages already used by professional astronomers, or develop custom software in-house. Using software used by professionals has the distinct advantage of producing output results familiar to that cohort and so increases the ease of any discussion about results. On the other hand, the author has some specific ideas about methods employed to extract the pulsar data, for which custom software would need to be written. Also, it was hoped to upload daily observation results automatically to a website and so it was decided to combine all tasks into one software package. However, it was decided that the processing chain should produce intermediate data file formats that could be processed by professional software packages. The two file formats addressed for this purpose are the filterbank format (*.fil) and the time series format (*.tim).

The filterbank format creation process takes the raw observation data derived from the whole observation bandwidth and breaks it into separate frequency channels. The reason for this channelisation is that an effect of the ISM called dispersion – where higher frequency signals from the pulsar arrive before lower frequency signals. Without further processing (called 'de-dispersion') the pulse energy across the observation bandwidth would not line up – causing smearing of the pulse shape and a loss in signal-to-noise ratio of the pulse profile. De-dispersion is the process of shifting the data in each channel in time such that the pulses line-up again. Splitting the signal into separate channels also allows the exclusion of interference residing in individual channels. Note that hardware used by professional radio astronomers (and some advanced radio astronomy citizen scientists) can output this format natively. The RTL-SDR device outputs raw IQ binary data only, so further software processing is required to get this output format.

The time series format is produced by de-dispersing the filterbank data into single time samples of the pulsar data.

The Velar pulsar signal has a dispersion measure (DM) of 68. For an observation bandwidth of 2 MHz at 436 MHz this corresponds to a dispersion delay of 16 ms. The dispersion delay is the time difference between signals arriving at the high frequency end of the observation bandwidth and signals at the low frequency end. As the pulse width of the Vela pulsar is 2.1 ms a dispersion compensation resolution of 0.5 ms (25% of the pulse width) was considered to be sufficient. The number of frequency channels across the observation bandwidth is therefore equal to 16 ms / 0.5 ms = 32 channels. The HawkRAO Vela pulsar filterbank data file, therefore, contains 32 channels.
Processing Protocol

The processing chain differs slightly from professional and other known citizen scientist projects. Professional astronomers use a software package called 'TEMPO' which basically gives information about the timing of pulses. The sophisticated hardware available to professional astronomers allows them to predict the arrival time of pulses even between observations separated by days or longer. Notification of 'glitches' (sudden increases in spin frequency) is given by graphing 'residuals' – the deviation from expected pulse arrival times. All known citizen scientist pulsar observations use 'ephemerides' to extract pulsar data by processing at the period predicted by the pulsar's ephemeris. Processing at different periods around the predicted period is used in result verification tasks, but this processing is not used to extract a period measurement as the main function.

The processing used at HawkRAO also uses an ephemeris to predict the pulse period, but this predicted period is only used as the centre of a search range for a processing algorithm which attempts to measure the actual observed period. The output result of the HawkRAO processing is the pulse period which returns the best pulse signal-to-noise ratio during the period search.

Epoch Folding

The fundamental principle behind the period search algorithm is a process called 'epoch-folding'. For amateur small aperture antenna observations the collected signal energy is not usually strong enough to detect individual pulses. To extract the pulsar signal out of the noise, successive pulses are added in a synchronous fashion. While the relative timing of the pulses in the received data is usually unknown in amateur observations, the extremely regular spacing of the pulses allows pulses to be aligned with each other by 'folding' the data record at the period of the pulses. More detail can be found here…

http://neutronstar.joataman.net/technical/epoch_folding.html

Science Outcome

Aside from the author's fascination with pulsars and the challenge of developing a system which can reliably and consistently produce scientifically verified detection results of a pulsar, the prospect of measuring some physical property of such a fantastic object provided strong motivation to persevere with the project over a long period of time.

The Vela pulsar is a particularly active pulsar with regards to 'glitching' behaviour. Glitches are sudden spin-ups of a rotating neutron star which interrupt the normal gradual spin-down due to radiation energy loss. The spin down for the Vela pulsar is ~ -45 ppm/year. A large Vela glitch is about 1 to 3 ppm and to observe such a Vela glitch in the data is a primary aim of these observations. In addition, because of Vela's frequent glitches (20 glitches in the space of 48 years – an average of a glitch every 2.4 years), a published ephemeris for Vela can become inaccurate after a few years. After sufficient observation time it is possible to self-generate an ephemeris from HawkRAO data. First order ephemerides are generated from 28-day blocks of data, while a second-order ephemeris is generated by the whole data set (more than a year of observation activity).

Science outcomes are uploaded after each daily observation to a dedicated HawkRAO web subsite.
Hardware Block Diagram

The block diagram below describes the hardware system used for the detection of the Vela pulsar.

![Hardware Block Diagram](image)

**Figure 1: Hardware Block Diagram**

The individual components in the block diagram are described below.

**Antenna**


Manufacturer: M2 Antenna Systems

Model ......................... 436CP42UG
Frequency Range ............... 430 To 438 MHz
Gain ............................. 18.9 dBiC
Front to back .................... 25 dB Typical
Ellipticity ........................ 1.5 db Typical
Beamwidth ........................ 21° circular
Feed type ........................ Folded Dipole
Feed Impedance ............... 50 Ohms Unbal.

![Circularly-Polarised Antenna](image)
Maximum VSWR .................. 1.5:1
Input Connector .................... “N” Female
Boom Length / Diameter........... 18’ 10” / 1-1/2” To 1”

The aperture is theoretically roughly equivalent to a 2.8 metre diameter dish antenna @ 50% efficiency - but be warned: expert opinion and experience holds that the theoretical gain of small dishes (say < 5 metre diameter) is not achieved in practice @ 400 MHz.

**First Low Noise Amplifier**

A short 2 m length of LMR400 coaxial cable connects the antenna to the first low noise amplifier (LNA). The LNA is a commercial design purchased from VHF DESIGN.

Model..................... LNA 70cm - EME
Noise Figure............ 0.3 dB
Gain....................... 16 dB
OIP3..................... 33 dBm
3 dB Bandwidth....... 20 MHz

To stabilise impedances, the output of the LNA is connected to the following LNA via an inline 3 dB attenuator.

**Second LNA**

A second LNA purchased from RF Bay Inc (model: LNA-1800) further raises the signal level before driving 25 m of RG213/U coaxial cable run into the observatory desk.

Frequency Range..... 1KHz-1800MHz
Gain...................... 30dB @ 1000MHz
P1dB..................... +8dBm
IP3....................... +20dBm
Noise Figure.......... 2.2dB
Reverse Voltage Protected
SMA Connector

Both LNAs are powered by a 15 Vdc feed line from a power supply housed in the observatory building reduced to 12 Vdc via a linear regulator.

**Third LNA**

The third LNA is located inside the observatory and is a 0.8 dB NF 20dB gain unit bought on eBay from 'Kitmanlaw'. This LNA is primarily used to amplify the signal to a level where gain settings of around 30 dB can be used on the following RTLSDR dongle to ensure enough bits of digitisation occur.
To stabilise impedances another 3 dB pad is added to the output path.

At this point in the RF chain an LNA is not needed (as a higher noise figure general purpose amplifier will not degrade the noise figure significantly), but it was available and so was used. The LNA could be replaced by an MMIC amplifier (ERA-5) without significant NF penalty.

**RTLSDR Dongle**

The ubiquitous RTLSDR dongle is actually a DVBT USB-based receiver re-purposed. A range of software has been made available which allows access to the 8-bit IQ RF data stream. This system uses a modified (by the author) version of the provided 'rtl_sdr.exe' console application.

The dongle itself has been modified to accept an external TCXO 28.8 MHz input - improving the stability of the sampling rate.

A heatsink has been soldered to the pad below the RTL2832U chip onto which a small 5V fan blows air. The provision of this heatsink has been shown to improve the stability of the data stream - especially at the higher sampling rates.

An unmodified unit is shown in the foreground.

**Data Acquisition Computer**

For data acquisition (and also for data analysis) a Windows 10 PC is used with the following specifications...

```
Windows edition
Windows 10 Pro
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System
Processor: Intel(R) Core(TM) i5-6600 CPU @ 3.30GHz  3.30 GHz
Installed memory (RAM): 8.00 GB (7.88 GB usable)
System type: 64-bit Operating System, x64-based processor
```

*Figure 7: Data Acquisition PC Specifications*
Software Architecture

The PC runs a GUI multi-threaded application written in C# implementing a 'Virtual Control Panel' (VCP) which performs various tasks - observation scheduling, data acquisition, data format conversion, de-dispersion, impulse RFI excision (3σ clipping), filtering, scaling of data to 8-bit, epoch folding, data quality assessment and results display.

Data Processing Chain

Radio frequency data is acquired and stored in a file in IQ 8-bit unsigned format. After the observation run, this data file is analysed by being converted to FILTERBANK format, de-dispersed, re-combined into a Time Series (TIM) format file, impulse RFI excised, scaled and converted to 8-bit data format and then epoch-folded. A search is performed for a range of periods (±5 ppm) to find the best S/N period and a final fold is performed at that period. Offsets between the predicted and the observed period are calculated and plotted. Over time it is hoped that a glitch in the Vela data will be detected.
Data Stream Hardware Interface

The RF IQ data is acquired via a USB interface connected to the RTLSDR dongle. General wisdom says that the dongle should not be plugged in directly into the PC USB port, but connected by a good-quality cable of a few metres in length. This is to reduce the level of RFI induced from the PC. The dongle is a USB 2.0 device, so any port capable of supporting that speed should suffice. If an external USB hub is used it is strongly recommended that it be a self-powered hub. Ideally a dedicated internal USB card would be used, with only the dongle plugged in to ensure unfettered access to bandwidth and power.

RTLSDR Dongle Software

The data acquisition consists of a special version of the standard console application 'rtl_sdr.exe'. The author has modified the source code and recompiled to produce a version of 'rtl_sdr.exe' which uses 64-bit variables - necessary to handle files > 4 GB in size. At a nominal sampling rate of 2.4 Msps the data size produced is about 17 Gbytes/hour.

The modified 'rtl_sdr.exe' console application is called from within the VCP application with parameters set via the VCP. The IQ data is saved in a binary unsigned 8-bit file identified by a number of parameters in the filename.

These filename parameters are used by the following data analysis software to identify the conditions under which the data was acquired - e.g., centre frequency, sampling rate, time of acquisition, hardware configuration, target object - and is used to identify the correct external observation parameters file which is used to generate header information for the FILTERBANK and Time Series (TIM) data files.
Such parameters as the number of channels, the highest channel frequency and spacing between
channels, the reference dispersion measure and sampling clock error correction, time of acquisition,
hardware configuration, target object are used to identify the correct analysis settings throughout the
following processing chain.

**Supervisory and Processing GUI Program: Virtual Control Panel**

The Virtual Control Panel GUI program (VCP) has been written to eliminate external calls to
applications (except for the RTLSDR dongle drivers, the modified 'rtl_sdr.exe' data acquisition console
program and the 'AstroPy' calculation of doppler) and includes all steps in the data processing chain
forming a virtual control panel.

The GUI main VCP is divided into sub-panels with the processing sequence going from left to right (See
Figure 9).

**Typical Daily Observation Result**

Each day as the Vela pulsar passes through the fixed antenna beam data is automatically acquired and
then processed.

The purpose of the observation is to measure the spin frequency of the pulsar. A calculation is done to
predict what the spin frequency should be (using an ephemeris) and then individual test epoch-fold
operations (typically 100) in a range around the predicted spin period in small increments in period
(typically 0.1 ppm). The range tested is ±5 ppm around the predicted spin period. From the published
literature the maximum glitch jump observed so far with Vela is +3 ppm – so the ±5 ppm range should
cover any future glitch. The epoch-fold period which returns the best pulse profile signal-to-noise is
chosen to be the measured period.

A typical result is shown in Figure 11.

A scan quality evaluation is done to exclude poor signal-to-
noise results – caused, for example, by poor signal strength or
RFI corruption. About 20% of the observations are excluded
on the basis of failing the scan quality test.

Results which pass the scan quality test are added to the 'Glitch
Monitor' graphic (Figure 10) which plots the difference
between the measured spin frequency and the predicted period
(light blue plot). Statistics are calculated for the standard
deviation of the differences. A 6 sigma level (six times the
standard deviation) is chosen as the criterion for a valid glitch event detection (purple horizontal line).
The signal-to-noise ratio is also plotted (yellow) overlaid with an averaged value (green trace).

Various VCP panels are uploaded to a dedicated website
(http://hawkrao.joataman.net/pulsar/daily_obs/index.html).

Figure 10: Glitch Monitor Panel
A daily summary file as well as a science result file are also uploaded.

Although not generated daily, production of results in a format more familiar to the professional radio astronomy community is possible via the intermediate format files produced as part of the VCP processing. This is useful to provide a verification of results more acceptable to that cohort. Figure 12 shows an example PREPFOLD result generated from a filterbank file produced by the VCP program.

**Science Results**

Although being able to verify detection of a signal from a pulsar is a satisfying result in itself, being able to measure a change in some intrinsic physical parameter of a pulsar is an order more satisfying to the
author. Examples of long-term observations of individual pulsars by amateurs are rare – in fact the author is only aware of one other example: observations by Andrea Dell’Immagine (IW5BHY) of B0329+54. Andrea has observed that pulsar almost daily since September 2016 where the variation in received signal is collected along with averaged pulse profiles.

HawkRAO Science Results

Producing some scientific results is a major aim of the project.

Vela Pulsar Spindown

Along with plotting daily variations in signal-to-noise ratio (which is not actually totally intrinsic to the pulsar as it is affected by local RFI levels as well as the passage of the pulsar signal through the ISM), the measured spin frequency is recorded (which IS totally intrinsic to the pulsar).

The daily measured spin frequency can be plotted against observation modified Julian day (MJD) to show the intrinsic spin-down of the pulsar over time (See Figure 13). The spin frequency values have been corrected to remove the doppler shift resulting from Earth's orbit around the Sun as well diurnal rotation.

It should be noted that the 'bumps' on the plot in Figure 13 are not intrinsic to the Vela pulsar, but are noise on the observation spin frequency measurements made at HawkRAO.

It can be seen from Figure 13 that the Vela pulsar has slowed down over the course of ~1 year by about 500 uHz (approximately -45 ppm).
As mentioned previously, Vela's frequent glitches (20 glitches in the space of 48 years – an average of a glitch every 2.4 years), can cause a published ephemeris for Vela to become inaccurate after a few years. The long-term observation of the Vela pulsar at HawkRAO makes it possible to self-generate ephemerides. First order ephemerides are generated every 28 days, while a second-order ephemeris is generated by the whole data set.

These ephemerides are uploaded every observation day to the website (See Figure 14 for an example). After over a year's observation (without intervening glitches) the accuracy of the HawkRAO second-order ephemeris is sufficient to replace externally-sourced ephemerides for period prediction use.

**Future Activities**

As of August 2018 no glitch has been detected in the HawkRAO data. The detection of a Vela pulsar glitch is a primary aim of the project. Therefore, observations and measurement of the spin frequency of the pulsar will continue.

Refinements to the VCP program will contain to improve the quality of the results. In addition, the antenna used will be increased in aperture by a factor of 4. This is expected to result in better measurement accuracy, and therefore should result in the 6 sigma glitch threshold to be reduced.
Conclusion

Over a year of daily observations (> 98 % of days) has been completed. Of the observed days ~80 % have resulted in data of sufficient quality to make a measurement of the Vela pulsar's spin frequency. From the observations a plot of the spin frequency of the pulsar has been produced. In addition, ephemerides (1st & 2nd order) have been generated from the HawkRAO data, allowing prediction of spin frequency for current and future dates to within ±0.1 ppm (until the next 'glitch').

With the benefit of a year's worth of real data it is clear that there are many man-made signals which can imitate a pulsar signal. Over that time there have been many convincing 'pulsar' signals which hover at the 4 sigma and below significance level which are, in fact, false positives. This is well known to professional astronomers and should be taken into account by amateurs to preserve the validity of their results. This is especially important to amateur observations as the characterisation of the local RFI environment is well below that of professional observatories and therefore the 'significance bar' needs to be set higher to avoid false positives.
The author will continue to observe the Vela pulsar in the hope of detecting a glitch in the HawkRAO data.

For further information visit these websites…

http://hawkrao.joataman.net/pulsar/index.html

and…

http://neutronstar.joataman.net/

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Now retired, his technical experience is in the field of electronic engineering (mostly in medical electronics) and holds a Degree in Electrical Engineering, Diploma in Electronic Engineering and a Diploma in Technical Teaching from the NSW Institute of Technology (NSWIT). Steve holds an Advanced Grade Amateur Radio Licence (VK2XV/VK2ZTO). He is also a qualified Six-Sigma Green Belt. He has lived in many places in the State of New South Wales, Australia, but has lived in the Hawkesbury River District (60 km N-W of Sydney, NSW) for the last 40-odd years.

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