Subject: Detecting Pulsars with Horns.
Memo: 25, Revision 5
From: Glen Langston, Kevin Bandura
Date: 2019 April 10

Summary: Detecting Radio Pulsars is difficult, but possible with a 32inch diameter horn. Bigger horns or more horns with signals averaged eases detection of Pulsars.

This note summarizes an approach to detecting radio pulsars with Science Aficionado horns. We summarize the properties of pulsars and the sensitivity of the horns, to estimate the observations required to detect pulsars. Note that detection is always possible with with any telescope, if the data are averaged long enough.

The two main questions we answer are: First: ***How long of an observation is required to detect a normal brightness, say 1 Jansky, pulsar?*** Second: ***Can individual Crab Giant Pulses (> 40,000 Jy), be detected with a small horn?***

Background

Radio Pulsars have been known to exist for decades. However until recently detecting pulsars has been only possible using custom and expensive radio telescopes and receivers. The radio pulsars are brighter at low frequencies (< 300 MHz) but detection is difficult due to the dispersion of the pulses in frequency and time. The net effect of dispersion is that pulses arrive earlier at higher frequencies than at lower frequencies, making detection more difficult, due to pulse smearing. Through some signal processing this effect can be compensated for in software.

There are many papers and books describing pulsar observations. Notable books are ***Handbook of Pulsar Astronomy*** by Duncan Lorimer and **Essential Radio Astronomy** by James Condon & Scott Ransom. A good paper on Crab Pulsar Giant Pulses describes the signal to noise ratio calculations (by Karuppusamy, Stappers and van Straten, 2012, https://arxiv.org/pdf/1004.2803.pdf). We've also written a few papers on Crab Giant Pulses including *A Giant Sample of Giant Pulses from the Crab Pulsar* (Mickaliger et al 2012, https://arxiv.org/abs/1210.0452) Memos showing how to build Horn Telescopes are at: http://opensourceradiotelescopes.org/wk and http://github.com/WVURAIL

Crab Giant Pulses; Estimated brightness in Kelvins

We hope to test event detection software by observations of Giant Pulses from the Crab Pulsar. References suggest that pulses are as bright as 45,000 Jy at 1400 MHz (see references above).

We first calculate the sensitivity of a 32-inch diameter horn for detection of pulses, then compute effect of dispersion reducing the peak brightness in a band.

Our 32-inch diameter horn has an effective area, A_e, of 0.5 m^2. The combination of amplifiers and feed probe we use has an effective system temperature, T_{sys}, of 110 K. We use Boltzmann's constant, k, to convert the system temperature-times-area into a System Equivalent Flux Density (SEFD) value for our telescope, in Jansky units. Jansky units are used

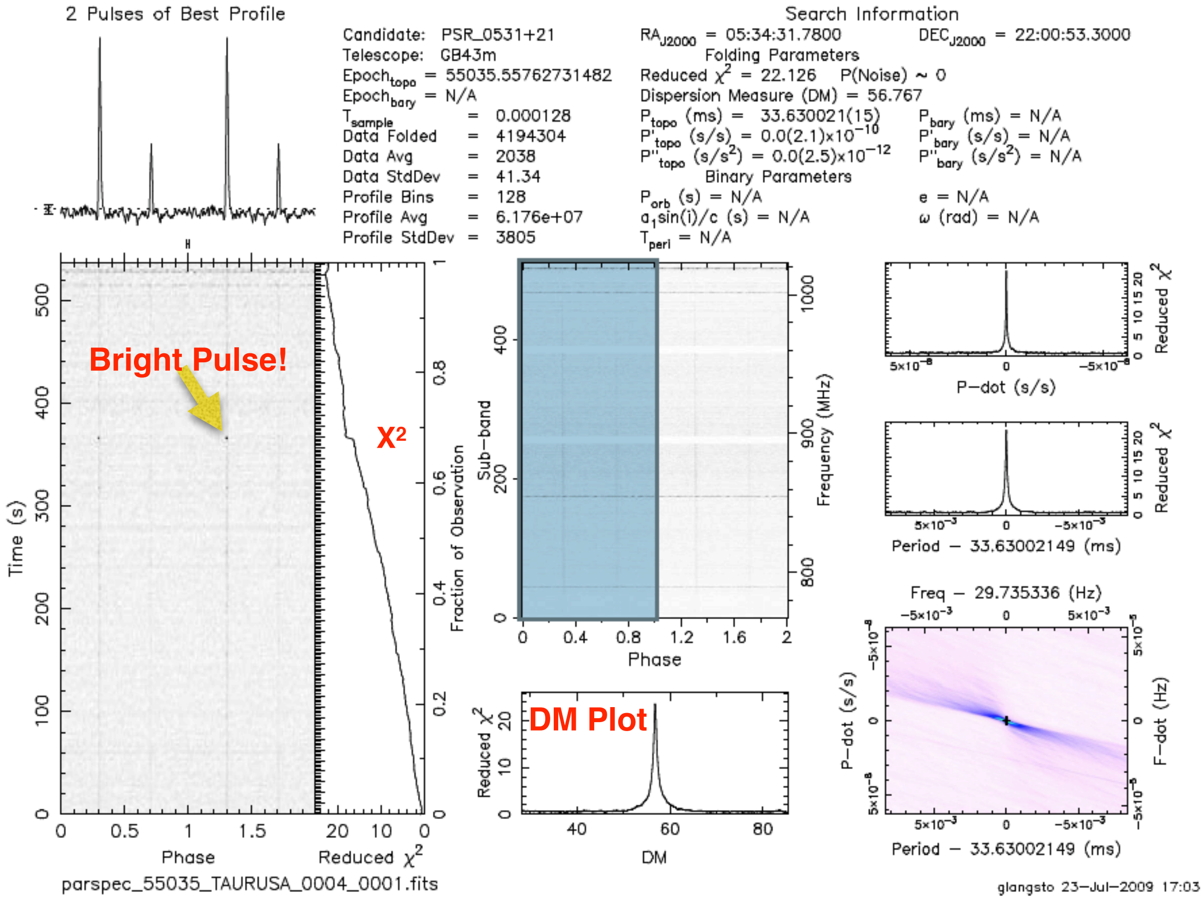


***Figure 1**: Observations of the Crab Pulsar with the GBO 140ft telescope. The figure is complex, showing many aspects of the computer search for pulsed signals in the data samples. The intensity versus time plot, in the upper left, shows the average profile measured in this 10 minute observation. The pulsar period is shown twice, so the total time in the plot is twice the pulsar period, twice 0.03363 seconds. The arrow marks the time of the giant pulse.The image shows time increasing from the bottom. The Chi-squared plot, **X²**, is related to the signal-to-noise ratio of the detection. The **X²** value has a jump increase because the signal is stronger at the time of the giant pulse. The **DM** plot, bottom middle, shows that the pulsar is only detected if the correct DM is applied in the software.*

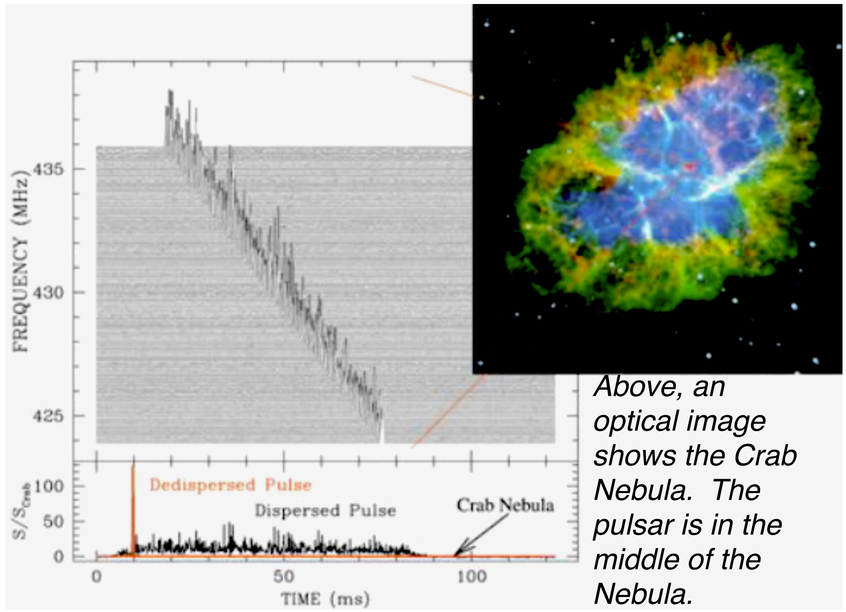
by Astronomers. Jansky are units of power, in watt-seconds per meter squared. 1 Jy = 10^{-26} Watts/m^2/Hz. Next we calculate the Gain, G, the Kelvins-per-Jansky-factor for our small horn. Boltzmann's constant, k, is 1380 Jy m^2 / K.

$G = A_e / 2k$ = 0.5 m^2 / 2. k = 0.25 m^2 / 1380 = 0.00018 K/Jy.

Therefore a 1 Jy source increases the system temperature by 0.00018K, a very small amount. A 1000 Jy source raises the system temperature by 0.18 K. The SEFD is the ratio of system temperature to K/Jy-factor, which is 110K/0.00018 K/Jy = 611,000 Jy for our horn. (See https://www.haystack.mit.edu/edu/undergrad/materials/NotRA4.pdf)

Astronomers observe at different frequencies, ν, to match their astronomical targets and capabilities for constructing sensitive telescopes. Because signals are so weak, astronomers use as large a bandwidth, $\Delta\nu$, as possible. There are a wide variety of radio sources. We

Figure 2: Crab Pulsar effect of dispersion on pulsar signal. *The top plot shows a series of intensity versus frequency versus time plots. The X axis is time. They Y axis is frequency of the observation. The Z axis is pulsar intensity. The pulse signal occurs at different times for different frequency channels. Bottom plot shows the strength of the average signal with, and without, de-dispersion.*



Above, an optical image shows the Crab Nebula. The pulsar is in the middle of the Nebula.

http://www.atnf.csiro.au/research/radio-school/2011/talks/pulsar_observations.pdf

define the brightness of a source as S_{src}. Brighter sources are, of course, much easier to detect.

Extremely bright sources, such as one of the most extreme Crab giant pulses (45,000 Jy), would increase the system temperature by about 8 K. **Figure 1** shows a bright (not giant) pulse Langston detected with the Green Bank Observatory (GBO) from observations with the 140ft telescope. The giant pulse was present for about 0.0001 seconds. Note that the giant pulse is only detectable in de-dispersed processed pulsar signals. Dispersion Measure is discussed in the next section.

Dispersion Measure

The observations of pulsars are interesting, and more difficult, because of subtle effects on the signals as they travel through our Milky Way Galaxy. The Milky Way's interstellar medium contains an ionized plasma. This plasma has the effect of slowing down radio waves as they pass from distant objects to our telescopes. The delay in the signal is not constant, but instead depends on the frequency of observations, with lower frequency signals arriving later. **Figure 2** shows this effect for observations of the Crab Pulsar.

The amount of plasma along the line of sight is related to a measurement we make with our radio telescopes. The bigger delay, the bigger the amount of Dispersion Measure (DM). For the Crab Pulsar the measured DM is 56.767. (See pulsar books for details.) The delay, ΔT, across a $\Delta\nu$= 6 MHz bandwidth, with frequency ν = 1.42 GHz, is given by the formula below:

ΔT = 8.3 x 6. x 56.767 /1.42^3 = 983 micro-seconds = 0.000983 seconds.

The Crab pulsar has a period of 0.0336 seconds. So, the pulsar signal is detectable in the samples about 3% of the time when observing at ν=1.420 GHz, with $\Delta\nu$= 6 MHz bandwidth.

At 6 MHz bandwidth (12 MHz samples), the total time a giant pulse is present in 12 * 10^6 * 0.000983 = about 12,000 samples. If the band was divided into 128 channels, a pulse would be seen in 92 spectra. To collect a whole pulse, at least 12,000 samples should be recorded. For reference, an entire pulse period is 0.0336*12*10^6 = about 400,000 samples.

Question 1: Averaging time needed to detect a "Normal" Pulsar?

Assuming that a very long observations of a pulsar could be recorded with our software defined radio (which is difficult), and the de-dispersion calculation can be implemented, then detecting the pulsar with a small horn is only a matter of averaging for long enough. ***But how long?***

After all processing, you can think of the detection as a matter of reducing the noise in the observations compared to the fixed signal strength of the pulsar. Assuming a system temperature of T_{sys} = 110 K, the reduction of noise, σ, goes as the square root of (Bandwidth * time). The formula for noise in a observation is:

$$\sigma = \frac{T_{sys}}{\sqrt{\Delta\nu\ time}}$$

In our case the bandwidth, $\Delta\nu$, is 6 x 10^6 Hz and we need to calculate the time needed to get a significant Signal-to-Noise ratio, 5 σ, detection. Since 1 Jy increases the system temperature by 0.00018 K, a 5-sigma detection means the noise, σ, must be less than 0.00004 K.
We want to make a certain detection, so require:

$$\sigma = 0.00004K > \frac{T_{sys}}{\sqrt{\Delta\nu\ time}}$$

and, substituting in our values for T_{sys} and solving for time yields:

$$\Delta\nu\ time > (110/0.00004)^2 \sim 367{,}000^2$$

Finally dividing both sides by bandwidth yields:

$$time > 367{,}000^2/6 \times 10^6 = 2{,}240{,}000\ s\ \ \sim 26\ days.$$

So, a 1 Jy pulsar could be detected with a horn, if we could average for 26 days. This is a very long time! We'd have to keep moving the horn to track the pulsar across the sky. We'd also have to stop averaging after the pulsar went below the horizon. We don't yet have enough space to store all this data, so practically the answer is ***no we can not detect a normal pulsar***.

If the pulsar were 10 times brighter, a 10 Jy pulsar, we'd only have to observe 1/100th as long, because of the square root in the formula. Then a detection could be made in 22,400 seconds, or about 6 hours. That would be doable, but would still be a lot of data. Since these samples are taken at a 12 MHz rate, the 22,400 seconds would be recorded in 22,400*12x10^6 * 2 bytes, about 600 Giga-bytes, assuming each sample is recorded in 2 bytes. So possibly a ***10 Jy pulsar be detected with a horn, maybe, but with great difficulty.*** Unfortunately there are no known 10 Jy pulsars.

Question 2: Can an individual Giant Pulse be detected?

As we noted above, very bright pulses are much easier to detect than many, many fainter ones averaged. We change the previous question around a bit and ask: ***How bright a pulse is needed to make a 5 sigma detection of a single pulse?*** The calculation is similar to that above, but the integration time is now very short, only the duration of a single pulse, about 0.0001 seconds. So in this case the product of bandwidth x time is small.

$\Delta\nu$ x time = 6×10^6 * 0.0001 = 600.

So the noise in this observation is reduced compared to the system temperature by the square root of 600.

$$\sigma \ = 110K/\sqrt{600} \sim 110\ K/24.5 \sim 4.5\ K.$$

So we'd believe the detection of a pulse 5 times this noise level, or 23 K. As we noted above we'd still have to do all the de-dispersion processing on the signals. Since we think that Crab pulsar giant pulses might be as bright as 8 K, then the answer is ***no, we could not detect the very brightest individual Crab pulsar pulses with a single small horn.***

So, to detect pulsars or giant pulses, we'd need a bigger telescope. Assuming our targets were Crab giant pulses and we'd believe a detection if the signal was 5 times the noise, then we calculate the size of the telescope needed. The signal is increased linearly by increasing the telescope collecting area. We'd calculated that for a 0.5 m^2 horn, the peak signal is 8K. We'd need 3 times the telescope area to increase the signal to greater than 23 K. That means we'd need a horn about twice the diameter, to 64 inches (5.5 feet or 1.6m), or average the signal from 3 small horns.

The next question is: ***How often do these brightest pulses occur?*** There are many papers on studies of Crab Giant Pulses. The paper by Karuppusamy, Stappers and van Straten (2010) suggests that 1 in about 500,000 pulses is as strong at 40,000 Jy. So how long will it take to observe 500,000 pulses? The pulse period is 0.0336 seconds, so 500,000 pulses are seen in 16,800 seconds, a little less than 5 hours. So a such giant pulse would be expected about once a night of observation, if we moved the telescope to track the source. Or once every 5 nights, if we left the telescope pointed at the same elevation for several nights and let the pulsar drift through the telescope beam.

Observing Time formula

We combine all these formulas into a single formula for estimating observing time. The Signal-to-Noise Ratio Parameter (SNR) sets how certain you are about potential discoveries. Generally SNR must be greater than 5 for any other astronomers to believe your results.

Decreasing your system temperature, increasing the telescope gain (i.e. size), increasing the bandwidth and source brightness all reduce the observing time required.

$$\text{time} = \frac{T_{sys}^2 \ (SNR)^2}{\Delta\nu \ G^2 \ S_{src}^2}$$

Quicker (shorter) is better!

Conclusion

Detecting pulsars is possible, but very difficult, with a horn telescope. By constructing bigger horns and using more sensitive electronics, the observing project is made easier. Also by using wider bandwidths and averaging signals from multiple horns can we can reduce the time required to detect pulsars.

The rare, but very bright events, due to special types of astronomical *creatures*, could be detectable with a horn telescopes!

Thanks to my family and friends for their support for this project.