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1. **Introduction**

2. **Telescope and Instrumentation**

3. **Pulse detection: detection thresholds and dedispersion**

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5. **RFI mitigation**

Radio frequency interference (RFI) from terrestrial sources must be eliminated from the data in order to select for signals from astrophysical sources. RFI detections overwhelm detections from pulsars, black holes, or other astrophysical sources.

The dominant RFI sources at Arecibo Observatory are nearby radars, which emit one of (at least) 6 repeating patterns. Several of these radars produce chirped pulses that are detectable by Astropulse: (as usual, a sample is 0.4 \( \mu s \))

1. The FAA radar: a 5-period signal: 6581, 7052, 6864, 6487, and 8274 samples. The signal is outside our band, at 1330 MHz and 1350 MHz. However, we can still detect the FAA radar when it saturates our electronics. According to Phil Perillat, “the transmitter is located east of San Juan. The radar is used for traffic control around Puerto Rico (it is not the radar used for landing the planes.)”  

2. This radar is detectable every 12 seconds (between 11.88 s and 12.01 s, with an average of 11.95 s.) The signature of the radar, which is wideband relative to our 2.5 MHz band, would be found throughout almost all parts of our data if we did not correct for it.

2. The aerostat radar: a 7-period signal: 8759, 7688, 7021, 7260, 8224, 9189, and 9428 samples. This is “a tethered balloon radar that flies above Lajas Puerto, and is used for drug interdiction.”  

2 This radar transmits 10% to 50% of the time.

3. Four single period signals: 6998, 6900, 6782, and 7044 samples. These radars are usually not detectable in our data.

5.1. **RFI mitigation methods**

I rejected RFI using several methods:

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1\[http://www.naic.edu/~phil/rfi/rdr/faa/faardr.html\]

2\[http://www.naic.edu/~phil/rfi/rdr/aerostat/aerostat.html\]
5.1.1. Arecibo’s high pass filter

Arecibo can turn on a high pass filter that will remove the FAA radar’s signature from the data. The filter removes signals at the FAA radar’s frequencies and below, but permits signals in our 1420 MHz band. However, SETI@home / Astropulse is a commensal (piggyback) survey, and not all users of the ALFA receiver want the high pass filter to be turned on. (Some of them wish to observe sources at the radar’s frequencies.) Currently, the filter is usually turned off. So I must rely on other methods.

5.1.2. Hardware blanker

Arecibo Observatory provides us with a blanking signal (which we will call the “hardware” blanking signal), a single bit which is turned on when the FAA radar is transmitting a pulse. Since ALFA has 7 beams and 2 polarizations, each with a real and complex bit, we store our data in 4 bytes per 0.4 µs sample. That’s 28 bits for the data, and 4 are left over. This means we have some extra space to record the hardware blanking signal. When the Astropulse splitter turns a tape file into a workunit, it detects this signal and blanks the surrounding data as it creates the workunit. So the “hardware” blanker has two components:

1. The hardware component at Arecibo, which adds a blanking bit to our tape files.
2. The software component in our splitter, which detects the bit and blanks the appropriate data.

It is critical that I blank the data with noise that has the same frequency profile as the clean data. If I instead blank the data with white noise (bits set randomly to 1 and 0), I’ll get a plot like Figure 1.

This is a “waterfall plot” of frequency versus time, obtained by performing 64-point Fourier transform across a block of data from a workunit, dated 1/8/09.

You can see two effects here. First, there’s a series of pulses that weren’t caught by the hardware blanker. (The black horizontal bars, centered vertically.) This first problem is unavoidable at this stage, if the hardware blanker fails to notice the radar. But the second problem could have been avoided: notice that the blanker has altered the frequency envelope. The highest and lowest frequency has much lower power – this is the natural envelope of our filter. But at regular intervals, the envelope becomes flat. This part of the data has been blanked, and the inserted noise had a flat spectrum. If I were to use this method, the blanked regions would be detected by the client as chirped pulses, because the client would see a high (and low) frequency, followed by a region with no high or low frequency, followed by a low (and high) frequency. The sequence of high - middle - low is a chirped pulse.

Instead, I need to blank the data using noise whose envelope matches our filter. To do this, I sample the unblanked data, take its Fourier transform, and construct an appropriate stream of shaped noise.

Unfortunately, the hardware blanker is imperfect. First, we believe it doesn’t mark every FAA radar pulse. Sometimes the radar’s phase changes, and it takes some time for
the hardware blanker to catch up. At other times, a single radar pulse may arrive that is out of sync with the other pulses. Second, the hardware blanker only searches for the FAA radar, not for other radar. So we have written our own software blanker, which processes the data downstream from the hardware blanker. The software blanker handles both the FAA radar and the aerostat radar.

5.1.3. Software blanker

The software blanker runs in our splitter, examining the data for the repeating patterns that signify radar. It looks specifically for the FAA and aerostat radar. The software blanker was programmed by Luke Kelley and Matt Lebofsky.

Like the hardware blanker, the software blanker has two components:

1. A software component at our lab in Berkeley, which adds a blanking bit to our tape files. This function is performed by a suite of programs. One program identifies the radar and generates a “blanking instruction file.” Another program takes the raw data and the instruction file, and sets the new software blanking bit accordingly.

2. The software component in our splitter, which detects the bit and blanks the appropriate data.

To find the aerostat radar, component 1 looks at samples in groups of 10. We would like to know whether the bits are predominantly 1 or 0. (That’s 280 bits, counting all
28 bits for each sample – 2 polarizations, 7 beams, and both real and imaginary bits.) At maximum strength, the radar will produce long strings of bits that are all set to 1, regardless of whether they represent real or imaginary data. At lesser strengths, the radar produces less skewed sets of samples, with a “ring down” oscillation between 1 and 0 bits. Nevertheless, these samples at lesser strengths can provide an important indication of radar. We fold the data over 25 seconds at the known radar period, and threshold the resulting amplitudes at 25% above the mean. Actually, we fold at around 200 trial periods, each varying slightly from the average radar period. This is necessary because the radar’s period can drift slightly.

Once a radar signal has been detected, we blank the peaks, and some number of samples before and after the peaks.

5.1.4. Software blanker: previous attempts

We made several attempts at creating a software blanker before settling on our current program. Our first software blanker looked for all types of radar, but assumed that only one radar was hitting us at any time. This turned out to be an erroneous assumption. We looked for regions of samples set to 1’s, and determined the number of samples between such regions. We then attempted to find the implied sequence of interpulse period(s), and deduce the radar pattern. However, this computation can be somewhat complicated, and becomes unmanageable when several radar signatures overlap in a given data set.

Our next attempt was to cross correlate the data stream with a simulated FAA and aerostat radar sequence. (But not both simultaneously.) This involves using some FFT’s to determine how well the data is matched by a sequence of pulses that simulate the radar. Effectively, we were taking the dot product of our data with the radar-like sequence, viewing the sample times as elements of a vector. By displacing the sequences by a varying amount, one finds that the dot product is largest when the phases align. We tried radar sequences in the shape of square waves, gaussians, and sawtooths, and found little difference between them.

However, it turned out that the folding method was even faster than the cross correlation method. The cross correlation takes time $O(N^2)$ when it’s done the “obvious” way, and time $O(N \log N)$ when done the “fast” way, where $N$ is the length of the data stream. But the folding algorithm takes time $O(N)$.

5.1.5. Client blanker

As discussed above, one characteristic of the radar noise is that it’s strong enough to saturate our electronics, producing a long string of identical samples. While this signal is not always detected by the Astropulse client (as it is not dispersed), it tells us that the radar is active at that time. Therefore, I blank all data within 400,000 samples (0.16 s) of the detected event. This method differs from the software blanker in that I consider individual RFI events, rather than folding several events together. This enables detection of RFI with unknown periods. The client blanker is located in the Astropulse client, and proceeds by performing a Fourier transform of the data, and examining the power in the central bin (the DC component.)
5.1.6. Fraction blanked restriction

For each workunit, we record the fraction of the data that we blanked, using the client blanker. This allows us to remove workunits entirely if too much RFI was present. That is, the presence of too much RFI in one region of the workunit may indicate a smaller amount of RFI in other regions.

5.1.7. DM repetition

If I see a signal at the same DM repeatedly at different parts of the sky, I conclude that it came from a terrestrial source. There’s no reason that the same DM should have been observed from several different directions in quick succession.

5.1.8. Multiple simultaneous beams

Since our beams are separated by several arcminutes, an astrophysical source (or any relatively weak source) should not appear in multiple beams simultaneously. However, a very strong source, for instance a terrestrial source, might appear in the beams’ sidelobes. The source’s radio waves might arrive at the telescope by scattering from the ionosphere or nearby terrain, or by propagating through the telescope structure. In this case, the waves might appear in multiple beams. Since the telescope never points at or below the horizon, such sources would appear only in the sidelobes and never in the main lobe.

Therefore, we could rule out some RFI by ignoring pulses that appear in multiple beams simultaneously. Unfortunately, experiments show that a few real, astrophysical signals appear in multiple beams simultaneously. This may happen because the main lobes intersect slightly, albeit at greatly diminished sensitivity, or because strong astrophysical signals could be detected in sidelobes. So such a method is imperfect at best.

5.1.9. Two simultaneous polarizations

A signal from an unpolarized astrophysical source will appear in both polarizations simultaneously (unless it is only marginally detectable.) RFI might also behave this way, but noise will not. Therefore, we can reject a great deal of interference by requiring two simultaneous polarizations.

5.1.10. Frequency profile

We are looking for broadband pulses with a short intrinsic timescale. Thus, the pulse should have the same mean power at all frequencies. We perform a chi square test to determine whether the mean power is the same everywhere. However, the chi square distribution is not a perfect description of the power vs. frequency distribution unless the power has a Gaussian distribution at each frequency. In fact, it has an exponential distribution.
The frequency profile test calculates a “log prob” statistic, which is the natural log of the estimated probability that this frequency profile would occur by chance. However, if the chi square is inaccurate, so is the log prob. Nevertheless, the log prob should decrease (and is negative) as the power becomes concentrated at particular frequencies. Although the log prob has uncertain meaning in the absolute sense, its relative value is meaningful.

5.2. Figure of Merit

We can assign a figure of merit to each RFI rejection algorithm, or to all algorithms together. The figure of merit is defined as:

\[
\frac{\text{(% of astrophysical pulses passing)}}{\text{(% of all pulses passing)}}.
\]

Another way of writing this is:

\[
\frac{\text{(% of pulses that are astrophysical after the algorithm is applied)}}{\text{(% of pulses that are astrophysical before the algorithm is applied)}}.
\]

If the figure of merit is equal to 1, the algorithm does not change the % of pulses that are astrophysical. In other words, we could have achieved the same result by throwing out a random collection of our pulses. Therefore, an algorithm cannot be useful unless its figure or merit is greater than 1.

This definition of the figure of merit is not the only one imaginable. For example, suppose we have 1000 pulses, of which 100 are astrophysical, and two algorithms. The first algorithm cuts the list down to 10 pulses, of which 9 are astrophysical. It has a figure of merit equal to 9. The second algorithm instead cuts the list down to 100 pulses, of which 80 are astrophysical. It has a figure of merit equal to 8. Then one might prefer the latter algorithm, on the grounds that it yields more data to work with. (Even though a smaller % of that data is good.)

Nevertheless, this figure of merit is reasonable, and we will find its value for each of our RFI rejection algorithms.

5.2.1. Fraction blanked restriction: figure of merit

It turns out that we can obtain the best figure of merit by passing only those workunits for which the fraction blanked (by the client blanker) is < 20%. Note that the client blanker has already removed a portion of each workunit. Here, we do not consider the figure of merit resulting from the client blanker itself. That is not possible, since we don’t know how many pulses would have been detected in the removed portions. Rather, we are throwing out workunits for which a large portion has already been removed. As of December 2009:

Space, in workunit-lengths, available for astrophysical pulses:

\[
x = \text{total space for pulses} = \text{total of (1 - fraction_blanked)} = 2457187
\]

\[
y = \text{total space for pulses with fraction_blanked} < 0.2 = 1368632
\]

\[
z = \text{% of astrophysical pulses passing} = y / x = 0.556991
\]
Pulses in workunits analyzed so far for rfi:

\[ x_2 = \text{total number of pulses} = 256085 \]

\[ y_2 = \text{total number of pulses in workunits with fraction blanked} < 0.2 = 122627 \]

\[ z_2 = \% \text{ of all pulses passing} = \frac{y_2}{x_2} = 0.478852 \]

figure of merit \[ = \frac{z}{z_2} = 1.16318 \]

5.2.2. DM repetition: figure of merit

To simulate the fraction of astrophysical pulses that would be accepted by the DM repetition algorithm, I performed a Monte Carlo study, generating a list of 37,572 pulses at random times. The times were determined by considering the start times of actual workunits, then determining a random time within that workunit. The random-time test pulses were also given a random dispersion measure, beam, polarization and scale (co-add). These values were distributed uniformly over the range of allowed values. I compared the random-time test pulses with the list of all detected pulses stored in our database. Using the random dispersion measures, I counted the number of detected pulses with the same dispersion measure preceding and following the test pulses. The test pulses were accepted or rejected using the same criteria as the DM repetition RFI rejection method.

Monte Carlo for simulated astrophysical pulses, after 3 passes through 12,524 workunits, generating 37,572 test pulses:

\[ \text{total pulses} = 37572 \]
\[ \text{passing DM repetition test} = 35994 \]
\[ \text{fraction passing} = 0.958001 \]

Pulses in workunits analyzed so far for rfi:

\[ \text{total pulses} = 204994 \]
\[ \text{passing DM repetition test} = 114795 \]
\[ \text{fraction passing} = 0.559992 \]

figure of merit \[ = \frac{0.958001}{0.559992} = 1.71074 \]

5.2.3. Multiple simultaneous beams: figure of merit

To simulate the fraction of astrophysical pulses that would be accepted by the “simultaneous beams” algorithm, I used the same Monte Carlo study that I performed for DM repetition. The test pulses were accepted or rejected using the criteria from the “simultaneous beams” RFI rejection method.

Monte Carlo for simulated astrophysical pulses, after 3 passes through 12,524 workunits, generating 37,572 test pulses:
total pulses = 37572
pulses passing the multi beams test = 37420
fraction passing multi beams = 0.995954
Pulses in workunits analyzed so far for rfi:
total pulses = 256085
pulses passing the multi beams test = 220573
fraction passing = 0.861327
figure of merit = 0.995954 / 0.861327 = 1.1563

5.2.4. Two simultaneous polarizations: figure of merit

If all detected astrophysical pulses were completely unpolarized, or were above threshold in both polarizations, then all of them would pass the “simultaneous polarizations” test. However, even if the astrophysical component of the pulse is unpolarized, the noise component may not be. Thus, pulses near threshold may be detectable in only one polarization.

To simulate the fraction of astrophysical pulses that would be accepted by this test, I generated peak power values with a cumulative distribution \( c(s) \propto s^{-3/2} \), or a probability density function \( h(s) \propto s^{-5/2} \), where the random variable \( S \) is the peak power. To generate this distribution, we take the \(-2/3\) power of a uniform distribution. That is, if \( X \) is uniform with distribution \( f(x) \), and \( S = s(X) \) is the peak power, then:

\[
\begin{align*}
h(s) & \propto s^{-5/2} \\
h(s(x)) ds/dx & = f(x) = \text{constant} \\
ds/dx & \propto s^{5/2} \\
s^{-5/2} ds & \propto dx \\
s^{-3/2} & \propto x \\
s & \propto x^{-2/3}
\end{align*}
\]

The reason for the \( s^{-3/2} \) cumulative distribution is that if we assume a standard candle source (same luminosity vs. time for all sources), then the sources at distance \( r \) have flux at Earth proportional to \( \frac{1}{r^2} \). The number of sources within distance \( r \) (hence with flux greater than \( S \propto \frac{1}{r^2} \)), goes like \( r^3 \propto S^{-3/2} \).

After determining the test pulse’s peak power, I generate two mini workunit files that contain the pulse. Each file combines the pulse with noise randomly, so that different noise is generated in the two mini workunits. Then, I dedisperse the two files and find the noise-modified peak powers. The pulse passes the “simultaneous polarization” test if it is above the detection threshold in both polarizations. If it is only above threshold in one polarization, it fails the test. And if it is below threshold in both polarizations, it would not
be detected at all, so it does not pass or fail.

Note that for a given power threshold at a particular pulse scale (co-add), there is a unique probability density function (pdf) with \( h(S) \propto S^{-5/2} \), so there is no ambiguity about normalization. If more astrophysical sources are present, the total number of sources detected will increase, but the pdf will not change.

After 1,000 pairs of test pulses:

- total pulses inserted = 2000
- pulses detected in both pols = 522 \cdot 2
- detected in both, after removing 50% (redundant pulses) = 522
- pulses detected in only one pol = 42
- total pulses detected (counting redundant) = 522 \cdot 2 + 42 = 1086
- fraction of detected test pulses passing multi pols = 522 / 1086 = 0.4807
- fraction of pulses in database passing multi pols (after removing 50%) = 0.03862
- figure of merit = 0.4807 / 0.03862 = 12.45

5.2.5. Frequency profile: figure of merit

Using the same mini workunits generated for the polarization test, I determine whether the pulse would pass the frequency profile test. Again, the pdf of the pulse power is unique, given the thresholds for each scale, therefore there is no ambiguity as to the pulse powers we should use.

Monte Carlo using threshold log_prob > -1; after 1000 pairs of test pulses:

- total pulses inserted = 2000
- pulses detected = 1075
- passing the chi square test = 1075 - 218 = 857
- fraction passing the chi square test = 0.7972

Pulses in workunits analyzed so far for rfi:

- total pulses = 246870
- passing the chi square test = 149277
- fraction passing the chi square test = 0.6047
- figure of merit = 0.7972 / 0.6047 = 1.318
5.2.6. Overall: figure of merit

There seems to be no reason that the astrophysical pulses' passing fractions, as described above, should be correlated. (Especially if we exclude the multi-beams test, which is probably unreliable.) An astrophysical pulse that passes the DM repetition test is no likelier than any other to pass the multi-pols test, the fraction blanked test, or the frequency profile test.

To see this, one has to consider the tests in pairs, and think about the nature of the tests. In each case, the property measured by one test is entirely unrelated to the property measured by the other. A pulse passes the multi-pols test if it is strong and/or unpolarized, and it fails the DM repetition test if nearby (noise or RFI) pulses have the same DM as the signal. It passes the fraction blanked test if its workunit has a lot of RFI that overwhelms our electronics, and it passes the frequency profile test if it spectrum is flat.

So we expect the fraction of astrophysical pulses passing all tests to be: $0.557 \cdot 0.958 \cdot 0.481 \cdot 0.797 = 0.205$, where we have just multiplied the fraction passing from each test above.

On the other hand, the fraction of database pulses passing all tests is: $47/412001 = 0.000114$, as of February 2001. This makes for a figure of merit equal to 1797, substantially larger than the product of the individual figures of merit. This makes sense, because the multi-pols test is designed to catch noise, whereas the other tests are designed to catch RFI. So we might expect each test to be less effective on its own, but more effective in combination with other tests. (For instance, imagine a fictitious data set in which 49% of all signals are noise, 49% are RFI, and 2% are real. If algorithm A removes all noise, and algorithm B removes all RFI, then the two together have a figure of merit of $1/0.02 = 50$, whereas separately they have $1/0.51 \approx 2$.)

6. Testing and Verification

7. Results and interpretation

8. Stardust@home

9. Suggestions for further research