A Taxonomy of RFI Mitigation and Excision Algorithms in Radio Astronomy

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1 Introduction

Radio astronomy has made great progress in the last few years. Receivers are becoming more and more sensitive, allowing for more accurate and detailed observations, and creating new opportunities to learn about the universe we inhabit.

However, with this newfound sensitivity comes a price: the sky is not the only one making noise. There are many sources of radio waves, ranging from actual radio stations to electrical equipment, cars, airplanes and many more.

All these sources of interference are recorded by sensitive radio telescopes as well, polluting the data of interest. This clearly affects the obtained results, and may even make weak astronomical sources impossible to detect.

Therefore radio frequency interference (RFI) is a substantial problem in radio astronomy. Polluted data must be cleaned before analysis, or discarded if this is not possible.

A method, or more accurately, several methods of dealing with this radio frequency interference are therefore a necessity. Without an adequate way of mitigating this interference, all this new sensitivity is wasted.

RFI comes in different shapes and sizes, and manifests itself in the final data in different patterns. As these patterns differ, so do the methods used to excise or mitigate this corruption.

The purpose of this literature review is to provide an overview of different types of interference possible within radio astronomy and a selection of algorithms designed to deal with them, to inform the reader of possible problems and matching solutions.

In section 2 we discuss the methodology that we used to collect and analyze the data. We, then, introduce some radio astronomy notions and describe the used data structures, to give the reader a basic understanding of the input of the algorithms. Following are the results of the literature research, presenting all the latest methods of dealing with the types of RFI presented in section 3. The paper closes with a discussion of the findings and a conclusion derived from the results.

2 Methodology

This literature study aims to categorize the current state of RFI mitigation and excision algorithms, and classify them based on which types of interference they are able to deal with. The first step in creating this taxonomy was to identify all possible types of radio frequency interference that could occur in radio astronomy. The results of this search can be found in section 4.

The possible types of radio interference are well known. Well-cited research on this topic can be found in [6], which in turn is based on [7] and [10].

After acquiring a solid understanding of the different challenges, a survey of existing algorithms was done. The work in [13] was used as a basis.

Finally, when the different types of interference and the methods had been identified, papers were sought describing each algorithm or method. Summaries of these papers are presented in sections 5 and 6.

After studying and understanding the different methods they were classified into the different categories of RFI to which they are applicable. A summary of this classification can be found in section 7.

The selection of the papers describing the methods is based on several criteria. In most cases the original research, or the first paper describing the algorithm is used. All papers have been peer-reviewed and published, and have been cited several times in other papers. This is to assure a basic level of quality in the material.

3 Background

In this work, we assume that the data captured by a single node of a radio telescope is received in three dimensions: time, frequency and intensity. A single measurement consists of a point in time at which multiple frequencies are monitored. These frequencies are split up in sub-bands, and at each sub-band a certain power of radio waves is detected. Such a measurement is most easily visualized in a so called grey-plot (Figure 1).

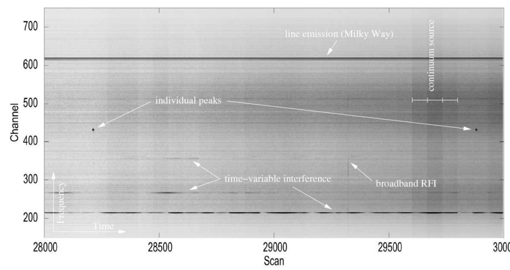


Figure 1: An example grey-plot showing radio-astronomical data as received by a radio telescope. Notice the RFI present in these measurements. This image was taken from [6]

After receiving data a node transmits it to a central processing station. This is were the correlation phase happens. In correlation, the data from all different nodes are combined into a single picture. In this stage, the difference in position of the different nodes is cancelled out by applying formulas correcting for the movement of the Earth and the relative distance from the nodes to the inspected area.

Methods for removing RFI, also referred to as algorithms, can be divided in to two categories: on-line and off-line algorithms.

On-line methods can be run during the collection of data. What this means is that they must be capable of processing the incoming data as quickly as it is generated. Especially for large modern telescopes, this is not an easy feat.

Off-line algorithms operate on complete observations, and are run only after the data has been received, processed and stored. This gives them much more time to carefully detect interference.

Apart from specifying for which type of interference the methods presented are suited, the specifications will also explain whether the algorithm is suited for on- or off-line processing.

This is interesting because large telescopes generating great amounts of data will most likely require the filtering methods to be on-line, as not to create a backlog of unprocessed data to which the algorithm can never catch up, as the rate of data production is greater than the rate of processing.

4 Types of Radio Frequency Interference

Man-made high frequency noise like the interference in radio-astronomic data can be classified into three types [7]:

1. Impulse-like bursts
2. Long narrow-band random oscillations
3. A superposition of the previous types

Figure 2 shows the first two types of interference.

Impulse-like RFI often manifests itself as broad-band interference, meaning that it occurs in multiple frequency sub-bands simultaneously. It is short in duration, resulting in vertical stripes in the grey-plot, which can be seen in figure 1, labelled as broadband RFI.

Long narrow-band interference is located in a much smaller sub-band. This type of RFI can be seen as horizontal stripes in grey-plots (not present in the example figure).

The super-position of the two types can be seen in figure 1 as well, labelled time-variable interference.

Other than these three variations, man-made RFI can be of one of two types: stationary or non-stationary. Simply put, this means that the source of the interference can be moving, or radiating from a fixed location.

Different types of interference cause different patterns in the collected data, and require different methods of removal. The rest of this paper will describe a set of algorithms and the types of RFI to which they are applicable.

5 Stationary RFI

Stationary RFI is generated by a non moving source. Examples include radio stations and electrical equipment from the telescope itself.

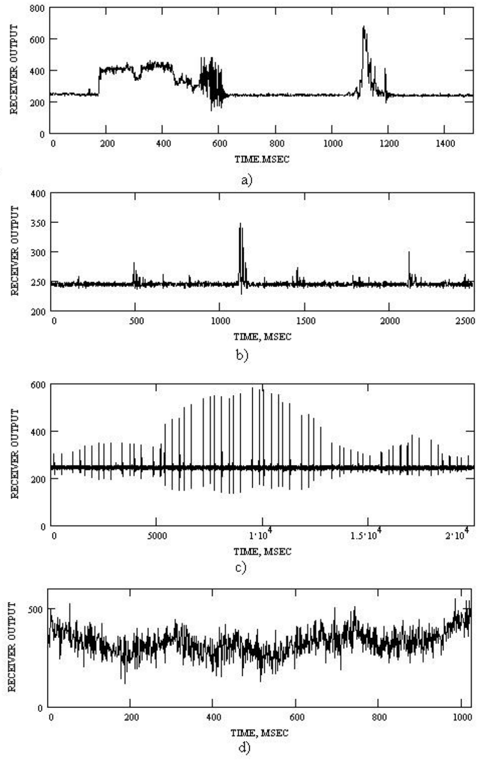


Figure 2: Examples of man made RFI: *a*) and *b*) are random impulse-like RFI, *c*) is impulse-like RFI caused by a radar and *d*) shows long narrow-band RFI.This image is taken from [7].

Stationary RFI is usually simpler to detect and remove than non-stationary. The following sections list and describe a set of algorithms designed for dealing with this type of interference.

Some algorithms are suited for removing several kinds of RFI. If this is the case, they will not be described again. Section 7 contains a table giving an overview of the applicability of the different algorithms to types of RFI.

5.1 Impulse-like RFI

5.1.1 Thresholding

This section is based on papers [2], [8], [12], [15].

Out of all known RFI filtering methods, thresholding is most likely the simplest. As the name implies, this method is based around the concept of a threshold. As mentioned in section 3 data arrives at the algorithm in three dimensions: time, frequency and power. RFI can often be recognized by simply looking at a graphical representation of this image. Interference forms unusual patterns that differ significantly from the baseline.

Any unusual peaks in power can be removed simply by implementing a threshold. If the power at [t,v], in which t indicates time and v frequency, is over a certain value, it is very likely to be interference and it can be flagged and deleted.

For the threshold to work, the actual value of the threshold needs to be set correctly. Set it too high and interference will end up in the final data. Too low, and correct data will be discarded.

Thresholds can be set manually, but this is unfeasible on large data sets. It is therefore necessary to find a way of automatically setting this value.

An effective way of setting the threshold is by using the median or most common power value in a time or frequency slice. If a value then exceeds this threshold by a certain amount, it will be flagged for removal.

Figure 3 shows the output after a simple threshold flagging.

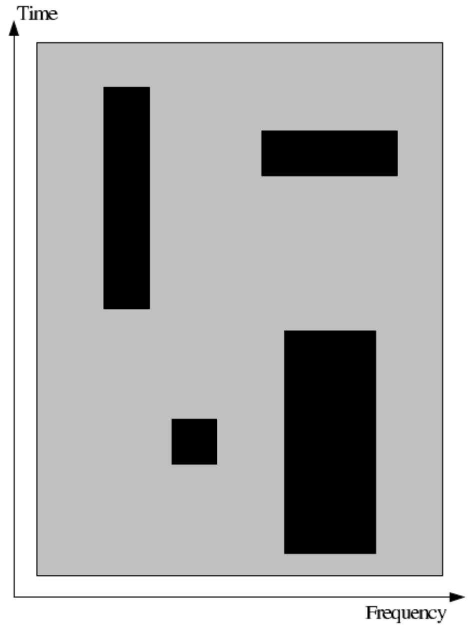


Figure 3: The output after thresholding. Black indicates RFI, gray is actual astronomical data. This image is taken from [2]

The thresholding algorithm can run in linear time ($O(n)$), making it fast enough to be used in online processing.

Naive thresholding such as described here works best for stationary impulse-like bursts of RFI. As the threshold is usually set by taking the median of a frequency sub-band, short spikes within this band are easily identified.

The ability to detect long narrow-band RFI is largely dependent on the chosen size of the subband. If the threshold is set by taking the median of a subband which is completely occupied by interference, the threshold will be too high and let the RFI through. If, however,the subbands encompass a larger spectrum than is polluted by the interference, the median of the subband will be low enough to reject the RFI.

Transient RFI is also a problem for thresholding. These signals start out low powered, ramp up and then power down again. Thresholding will only flag the highest part within the transient.

Multiple solutions have been proposed for the transient problem. A very simple one is to drop a range of samples around any thresholded value. A smarter approach is Combinatorial Thresholding, described in paragraph 6.1.1.

5.2 Long narrow-band RFI

5.2.1 Spatial filtering with eigenvalue decomposition

This section is based on papers [8], [5].

Spatial filtering concerns the removal of all data coming from a certain direction. This algorithm is therefore most useful in situations where there is a constant source of RFI from a single direction.

The first step in this algorithm is to obtain a covariance matrix of the astronomical sources, plus any random noise. A covariance matrix describes the variances of the variables along the main diagonal, meaning that it indicates how much each pair of variables in the input matrix variate.

The covariance matrix of just the astronomical sources and noise, so without any interference, is like a baseline which describes how the values within the matrix should relate. Whenever there is any interference, there will be a mismatch between these variations, as some of the values in the input will increase.

By calculating the eigenvalues and eigenvectors of the contaminated matrix, it is possible to deduce the number and direction of interferers. Once this is known, a projection matrix can be made which effectively nulls out all signals coming from the direction of the interference, i.e. discarding any tainted data.

Spatial filtering clearly works best on stationary RFI. Blanking out all data emanating from a certain direction will not work if the source of the interference is moving.

If a baseline completely clear of interference can be obtained, this method will however work for all types of stationary RFI. Both pulsing as well as constant RFI will cause the covariance matrix to change, allowing for the detection of the number and direction of interferers.

Blanking out a certain direction completely may however be more suited for constant RFI, as all data from this direction will be blanked. For pulsing interference this might be too much, especially if the pulses are far apart. Filtering a direction in that case may lead to unnecessarily losing too much actual data.

Creating a covariance matrix is a computationally expensive operation, but should only have to be done once. However, calculating the eigenvalues and eigenvectors could at best be done in $O(n^3)$ time, which is too expensive for on-line operation. There is however research being done in parallelizing eigenvalue/vector algorithms, which could make this method applicable for online processing [11]. It would require fairly large amounts of hardware though, as each receiver would need its own parallel architecture to be able to run this algorithm efficiently.

It is however possible to do this operation completely in hardware instead of in software. This would speed up the operation enough to be able to do online processing. Using hardware is not always an option though, especially when retrofitting this algorithm into an existing telescope pipeline.

5.2.2 Adaptive cancellation with a reference antenna

This section is based on paper [3].

Adaptive cancellation with a reference antenna is a technique to mitigate RFI that uses an extra piece of hardware, a reference antenna. The idea is that while the telescope, called the *primary channel*, receives both radio waves from the astronomical source and any interference, the reference antenna is tuned such that it receives nothing but interference.

The output of the reference antenna is then correlated to the interference in the primary channel and subtracted, leaving only the astronomical data.

This is however a lot easier in theory than in practice, as calculating the correlation is difficult, and changes constantly. This change is caused by the sources of interference moving, reflection, changes in the environment etc.

The value to subtract from the primary channel is calculated by applying a series of weights to a series of input samples from the reference antenna. The weights are chosen to minimize the total power output of the primary channel minus the weights times the samples.

In an optimal situation in which the source of the interference is stationary and constant the weights do not change. In real life however, this is not the case. To account for this, an adaptive approach is needed.

The adaptive approach uses a Least Means Squared algorithm based on the weights and samples from the previous time interval. This algorithm allows the weights to be updated, causing them to "track" the minimum of the power output function.

Figure 4 shows the basic architecture of this method.

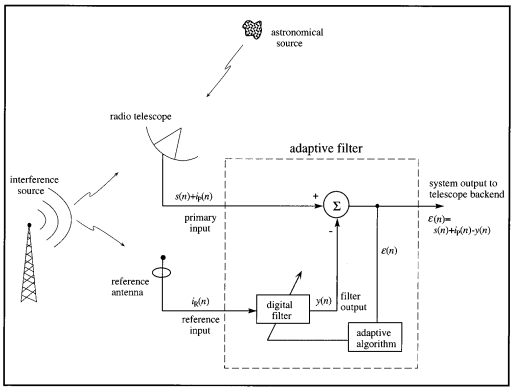


Figure 4: Architecture of a system using a reference antenna. The radio telescope receives the astronomical signal $s(n)$ plus the interference $i_p(n)$, while the reference antenna receives only the interference $i_R(n)$ which differs from $i_p(n)$ because of the physical differences in receivers, gains etc. $i_p(n)$ and $i_R(n)$ are correlated in an unknown way. The digital filter uses weights supplied by the adaptive algorithm to correlate the two sources of interference resulting in $y(n)$ which is then subtracted from the primary input. The adaptive algorithm uses this new $\eta(n)$ to adapt the weights if the interference changes. This image is taken from [3]

Adaptive cancellation is a technique that is very well suited to on-line pre-correlation, as all the required operations are performed in hardware. The downside is the need for extra equipment at each node, namely the reference antenna.

If the updating of the filters cannot be done in hardware, this method is still suited for online processing. The Least Mean Square algorithm is not very computationally expensive, as it runs in linear $(O(n))$ time [4], allowing it to be implemented in software instead.

Because of the adaptive part of this algorithm this method is suitable for both stationary and non-stationary interference. It does however work best on long narrow-band RFI, because of the adaptivity. The algorithm tries to track the interference which is much easier and therefore much more accurate if the signal is at least somewhat stable. Short bursts will cause the filter to lag behind reality and make it impossible to filter it out.

5.2.3 Fringe Fitting

This section is based on paper [1].

Fringe fitting is a clever way to distinguish RFI from actual astronomical data by making use of what could be considered a bug in the correlation phase. It is important to realize though that this method is only applicable to stationary sources of RFI.

Because most radio telescopes consists of many different receivers, all on different positions on Earth, each telescope will receive slightly different data when inspecting the same piece of sky. This is caused by the rotational movement of the Earth, which affects the time and phase at which radio signals reach the receiver.

To correct for this, each value produced by a telescope is fringe-stopped. This means that all values are multiplied by the formula $v_f(t) = -\omega_E U_\lambda(t) cos\delta(t)$, to correct for the movement of the earth and the distance to the inspected area. As mentioned, this formula is applied to *all* values, including those tainted by RFI.

However, while the distance from a telescope to the sky is influenced by the Earth's rotation, the distance to any stationary RFI sources is not. The application of the formula to these stationary sources of interference causes them to create a sinusoidal pattern in the correlated data. If the interference then remains constant for a long enough time, a sinus can be fitted over the sinus caused by the RFI.

Finally, the fitted sinus can then be extracted from the correlated data, removing all stationary constant RFI.

Because this method makes use of a phenomenon that only occurs after correlation, it is clearly unsuited for pre-correlation processing. However, as the interval over which the sinoid is to be fitted can be specified by the user, fitting the sinoid is a relatively simple linear $(O(n))$ process, making it suitable for online processing.

5.3 Combined RFI

5.3.1 Singular value decomposition

This section is based on papers [13], [14].

Singular Value Decomposition is a mathematical tool which can be used for the detection of RFI in a matrix after correlation. SVD consists of finding a decomposition of an MxN matrix A into an MxM matrix U, an NxN matrix V and an MxN matrix Σ such that $A = U\Sigma V^T$.

It is then assumed that the highest values in Σ represent RFI within the original matrix. These values are then set to zero and $\hat{A}$ is then reconstructed from U, V and Σ.

The problem here is naturally deciding how many of the highest values, if any at all, are RFI and which are simply actual data. Fortunately, this is often fairly simple, as RFI causes large outliers. By plotting the sorted singular values, a strong break can be seen when the data contains RFI. Any values before this break can be classified as RFI and nulled in Σ, as can be seen in figure 5.

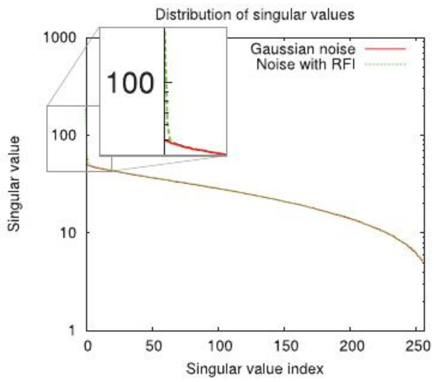


Figure 5: This plot contains two artificial measurements: one containing nothing but Gaussian noise, and one with Gaussian noise affected by broad-band RFI. The first five singular values form a clear break with the rest of the distribution, allowing them to be flagged as RFI. This image is taken from [13]

There are however quite a few properties that must be fulfilled for this method to work. First of all, the RFI must be fairly strong. If not, finding the break between the RFI values and the actual signal becomes very difficult if not impossible.

Secondly, the RFI columns must be fully linearly dependent or fully orthogonal. In other words, the RFI should either be concentrated on a small frequency band, or within a small time slot. If not, only part of the RFI will be removed. The rest will not have a high enough singular value to be noticed as RFI.

Finally, the columns or rows containing RFI have to be orthogonal to the actual signal, or more simply, the RFI in a row times the signal strength within a row must equal zero.

Conforming to the final requirement can be helped by iteratively fitting and subtracting a surface, as discussed in section 6.2.1.

Singular value decomposition is unfortunately a computationally expensive process. According to [9] computing the SVD can be done in $O(mn^2)$, in which n and m are the dimensions of the input matrix. This complexity is likely too expensive for online computation.

6 Non-stationary RFI

Non-stationary RFI is interference originating from a source that is moving relative to the receiver. Because of the movement, this type of signal is never situated within a single frequency sub-band. This is caused by the Doppler effect. As a result, this section does not include a long narrow-band RFI subsection, as there is no such thing when dealing with a moving source.

Non-stationary RFI can however be divided in impulse-like RFI and constant RFI, which is what is used here.

Sources of non-stationary RFI include airplanes, cars and satellites.

6.1 Impulse-like RFI

6.1.1 Combinatorial Thresholding

This section is based on paper [13].

Combinatorial thresholding is a more intelligent expansion on simple thresholding explained in section 5.1.1. This method makes use of the fact that RFI bursts often affect neighbouring samples, either in frequency or in time.

As an example, take two neighbouring samples Q and R both affected by RFI. Neither of the two exceeds the threshold set by the frequency median χ_1 individually, but they can still be flagged if both exceeds a slightly lower threshold χ_2. If not, the algorithm can look at the next neighbour S and detect whether they exceed the even lower threshold χ_3 etcetera.

Like ordinary thresholding, Combinatorial Thresholding runs in linear ($O(n)$) time, making it suitable for online pre-correlation processing.

Unlike the simple thresholding however, this method is much more capable of dealing with non-stationary RFI. Non-stationary RFI causes transients of which the naive method can only detect the peaks, while the combinatorial variant will successfully flag all contaminated samples.

Like regular thresholding, the applicability to long narrow-band interference depends on the size of the frequency subbands and the width of the interference. If the interference occupies the entire width of the subband, the median will be set too high, allowing RFI to pass through.

6.2 Constant RFI

6.2.1 Surface Fitting

This section is based on paper [16].

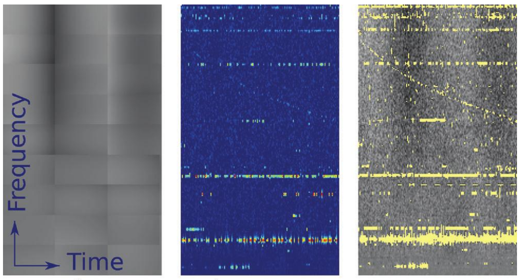
The surface fitting algorithm is a more advanced version of the thresholding algorithm. The basic idea is to form a fit over the data, i.e. an expectation for a value at a certain point. Anything that exceeds this value by too much is classed as RFI and removed.

The fit can be created in several ways, but the most accurate results are achieved when using a "sliding window". In this method, each value's fit is calculated by taking the average of N by M samples surrounding it. Whenever a value exceeds a certain threshold, based on this average, it is flagged and will not be used when computing the average.

This means that the algorithm needs several iterations, as more and more values get flagged. The iteration stopping condition is given by minimizing an error function.

A possible improvement to the algorithm is replacing the simple average by a weighted average, in which a value's weight increases the closer it is to the current centre of the window.

Once the fit is determined, the residuals between the fit and the data contain the RFI and can then be thresholded and removed.



(a) $\hat{V}(\nu, t)$ (b) $\hat{V}(\nu, t) - V(\nu, t)$ (c) Thresholded

Figure 6: Panel (a) shows the tiled fit of the astronomical data. In this instance a fixed amount of tiles instead of the sliding window described is used. Panel (b) shows the difference between the observed signal and the fitted astronomical data, while panel (c) shows the flagged values on top of the original signal. This image is taken from [16]

Because the algorithm fits a window in both time and frequency directions it is able to detect nearly any source of RFI. There is one caveat however, as it assumes that the astronomical signal does not contain any sudden spikes. This assumption is however incorrect when studying strong line sources or strong pulsars.

This algorithm's complexity is based on the number of iterations necessary to minimize the error function, as each iteration requires N operations. The paper mentions however that in practice less than five iterations are necessary, making this algorithm a practical candidate for online processing.

6.2.2 SumThreshold

This section is based on paper [13].

The SumThreshold method is, like the previous algorithm, an extension of the simple threshold algorithm. Instead of working with a single, fixed threshold like the naive version however, SumThreshold works with a series of decreasing thresholds.

The SumThreshold method is based on the Combinatorial Threshold method. Both methods make use of the fact that RFI burst often affect multiple samples in the same time or frequency slot. While thresholding only flags values above a certain threshold, Combinatorial Thresholding will inspect groups of neighbouring values. If a single sample does not exceed threshold χ_1, it could still be flagged if, when examined with a neighbour, both exceed a slightly lower threshold χ_2. If three neighbours exceed χ_3 they are also flagged, etc.

The Combinatorial method might however flag too many samples. Consider a vector of [0,0,5,6,0,0]. If $\chi_6 = 1.8$, all values will be flagged, while in fact on the two middle values are caused by RFI.

The SumThreshold method aims to correct for this. It works in a very similar manner, but sums all the values inspected. When a sample has already been flagged by a lower χ threshold, it is replaced with the current χ value. Only if the sum then exceeds the χ threshold times the amount of inspected values are all the samples flagged.

Returning to the previous example containing six values, SumThreshold would calculate the sum $0+0+\chi_2+\chi_2+0+0$. As this is lower than χ_6, the zero-samples will not be flagged. Assuming that $5+6 > 2\chi_2$ the 5 and 6 samples *will* be flagged correctly.

SumThreshold, like ordinary Thresholding and Combinatorial Thresholding, is a linear ($O(n)$) operation, making it very suitable for online processing.

7 Discussion

	Stationary impulse-like	Stationary long narrow-band	Stationary combined	Non-stationary impulse-like	Non-stationary constant
Thresholding	✓	✓†	✓†	✓	✓
Spatial filtering	✓*	✓	✓*		
Adaptive cancellation		✓	✓*	✓*	✓*
Fringe fitting	✓	✓	✓		
SVD			✓		
Combinatorial thresh.	✓	✓†	✓†	✓	✓
Surface fitting	✓	✓	✓	✓	✓
SumThreshold	✓	✓†	✓†	✓	✓

Table 1: *: This algorithm will work, but is likely to throw out significant amounts of actual data together with the RFI. †: Depending on the size of the frequency subbands.

	Complexity	Pre-cor	Post-cor
Thesholding	$O(n)$	✓	✓
Spatial filtering	$O(n^3)$	✓	
Adaptive cancellation	$O(n)$	✓	
Fringe Fitting	$O(n)$		✓
SVD	$O(mn^3)*$		✓
Combinatorial thresh.	$O(n)$	✓	✓
Surface fitting	$O(n)$		✓
SumThreshold	$O(n)$	✓	✓

Table 2: The algorithmic complexities of all the methods and their applicability to pre- and post-correlation stages. *: m and n pertain to the width and height of the input matrix, which might be different.

As can be seen in table 1 , there are ways to deal with every type of known radio frequency interference encountered in radio astronomy. However some problems with these methods remain, which should be investigated in follow up research.

First of all, all these methods will need to be able to run on-line. If this is not the case, the rate of data generation is larger than the rate of processing, causing a backlog of uncleaned data that can never be overtaken by the RFI mitigation algorithms. This is less of a problem if the telescopes are only used for short periods of time, but this scenario is unlikely. Most telescopes will be used non-stop, always generating data.

We assume that in order for a method to be run online its complexity cannot exceed $O(n)$. Algorithmic complexities for all algorithms can be found in table 2. This rules out the Spatial Filtering and Singular Value Decomposition methods. Fortunately the types of RFI mitigated by these algorithms can all be dealt with in different ways as well.

Table 2 also shows which algorithms are suitable for post- and pre-correlation phases. This is based on [13].

Secondly, the precision of these algorithms is outside the scope of this paper. In order for a method to be a viable candidate, its precision must be known and compared to other alternatives. This asks for a more detailed comparison of these algorithms.

8 Conclusion

RFI mitigation is a difficult problem within the field of radio astronomy. Because of the great sensitivity of modern telescopes, interference can corrupt the weak data obtained from space. Furthermore, RFI is not simply RFI: it manifests in several distinct ways.

Fortunately, as this literature survey demonstrates, there are methods capable of dealing with each type of interference. While their precision is not within the scope of this paper, at least there exists methods that in theory should be able to cope with all manifestations of RFI.

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