The Current Status of RFI Mitigation in Radioastronomy

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1 Introduction

Over the past ten years the reviews of this topic have been increasingly positive, since a variety of techniques have been shown to be viable. In a number of cases the work has advanced to the point of successful field trials. However, the take-up has been modest. Few observatories offer on-line, real-time rfi mitigation.

This paper provides a brief summary of the nature and status of different techniques; it then explores the take-up issue.

2 RFI categories

RFI comes in a wide variety of frequencies and intensities.

2.1 Satellites

Satellites are potentially a serious problem as far as RFI is concerned. However, there are some mitigating factors: their orbits are known so observations could be scheduled to minimise the disruption. In some cases their frequencies are not critical to an astronomical observation.

The signals from the constellations (GPS, GLONASS, IRIDIUM) are probably always present at a low level (via weak sidelobes), so their frequencies may well be a lost cause.

The geostationary arc is a challenge; while it is true that no part of the astronomical sky is lost to all astronomers, it is the case that each observatory will be blinded, at the downlink frequencies, at some particular azimuths and elevations.

Some satellites are a serious problem. Cloudsat [2], for example, at 94 GHz, is powerful enough to damage a sensitive receiver system if an overlap of the satellite and the telescope beams were to occur. The damage has been contained by careful coordination between Cloudsat and the mm-wave observatories.

2.2 Aircraft

Transmissions from passing aircraft are a transient problem, and so may not represent a problem when the observations are averaged over an extended period of time. However, their appearance is not readily predicted, which will preclude evasive strategies. The probable increase in mobile and network traffic from aircraft suggest that the problem is likely to get worse.

2.3 Ground-based

The RFI from ground-based installations tracks the population density, which is why observatories tend to be located in remote sites. Some protective measures can be taken - these are discussed below in section 3

2.4 Observatory-based

As far as the radiotelescope is concerned, the establishment of its observatory has a down-side: it provides a focus for high-end computing and high-speed electronics, along with an increase of more pedestrian sources of RFI such as faulty appliances and faulty contactors.

Ensuring that the observatory itself is radio-quiet is a full-time task.

2.5 Comments

Sensitive observations are generally based on observations of long duration (measured in hours). This means that transient episodes of RFI may be manageable when averaged over the entire observation. However, such observations will also contain short calibration observations. An unlucky coincidence of a calibration observation with a transient burst of RFI could compromise the calibration and all the observations which depend on it - the cost of the RFI could be high.

Elimination of the RFI is the astronomer's preference; predictablity of the RFI occurrence is a poor second option, but it is preferable to complete ignorance.

3 Pro-active Mitigation Strategies

Pro-active strategies provide the best defense of all, keeping the spectrum clean by removing the sources of RFI.

3.1 Regulation

The international community through the International Telecommunication Union (ITU-R) has made substantial efforts to balance the needs of the community for all forms of wireless communication with the requests of the radioastronomers for reserved spectral bands. The ITU-R Recommendation ITU-R RA-769 [5] outlines the protection criteria and defines the harmful limits. The CRAF *Handbook for Radio Astronomy* (Cohen [20]) provides an excellent discussion of the details. See also the ITU *Handbook on Radio Astronomy* [29].

To maintain the ITU-R protection for radioastronomy it is essential that this effort in ITU-R groups and processes is continued by the international community.

3.2 Radio Quiet Zones

Many observatories have been granted some protection by their local licensing authority. See, for example, [3]. In general, this requires users to coordinate their operations (frequencies, power levels) with the observatory. The area of protection is generally modest - 1 or 2 km radius around the observatory.

A number of observatories are located in radio-quiet regions, where local topography provides some protection from RFI. The NRAO Green Bank observatory is in a shielded valley in West Virginia, USA; the DRAO Penticton observatory is in a protected valley in British Columbia, Canada.

Further protection has been provided by some national licensing authorities who have declared “Radio Quiet Zones” around specific observatories. The National Radio Quiet Zone was established in 1958 for the Green Bank Observatory (see NRQZ [4]). The Australian government has taken similar steps to protect the Radio Astronomy Park set up by the state government of Western Australia. Chile has defined a RQZ for the ALMA site. South Africa has defined a RQZ for the KAT site.

This strategy cannot provide protection from satellite downlinks, or from airborne radar.

3.3 The Observatory Environment

Bitter experience has shown that observatories themselves are responsible for a significant fraction of the RFI. Sources include modern computers and high speed electronics within observatory receiver systems. Remedies include eternal vigilance and aggressive monitoring of all new equipment for sound design and RFI containment practices. The correlators at the Parkes observatory, for example, are housed in RFI-tight cabinets with a high RFI-attenuation rating (95+ dB). The main control complex at Green Bank has extensive RFI shielding. The Penticton observatory has RFI-shielding around the entire main office; further, most of the computers are housed in a screened room within the main building.

Rogers [37] provides an interesting discussion of the efforts required to provide a quiet environment for a sensitive experiment.

3.4 Summary

Many observatories still operate satisfactorily with these pro-active strategies. They can find satisfactorily clean spectral bands for their observations, or they can find suitable quiet times. Few observatories have found it necessary to provide on-line RFI cancellation procedures.

The evidence is mounting that the conditions are changing for the worse. There is more RFI; experiments are more challenging, with less tolerance to RFI; and telescopes are becoming ever more sensitive. Already some low frequency cosmological experiments can only be performed in the newly defined Radio Quiet Zones; see, for example, the discussion in Chippendale [18].

4 Reactive Mitigation Strategies

In **reactive** RFI mitigation we identify the RFI in the data stream and remove it, so that the subsequent processing machinery is presented with RFI-free data. This ideal is rarely achieved, but substantial progress has been made.

Robust receivers

In everything that follows there is an underlying assumption that the receiver’s response is linear. This puts a requirement on the receiver designers to provide adequate reserve against overloading. (Clerc et al [19], Weber et al [40], Tuccari et al [39]).

One class of RFI mitigation operates by determining the RFI-free condition; it then becomes possible to identify the times when RFI is present, and to take remedial action - blanking, for example. This may have an astronomical cost - a reduction in the number of independent samples available for processing will reduce the sensitivity, and it may also reduce the image quality.

An alternative approach is to target the RFI explicitly and cancel it, removing just the RFI from the data stream. In principle this is the preferred path, as there should be no reduction in the number of astronomical data points.

Figure 1 is typical of the quality of mitigation that can be achieved. This particular example shows an on-line adaptive filter applied to a pulsar observation. The RFI (digital television) has effectively doubled the system noise. The real-time filter provides about 20 dB attenuation. The top row shows the IF band-pass; the second row shows the data folded at the pulsar period. The bottom row is a frequency-pulsar period plot.

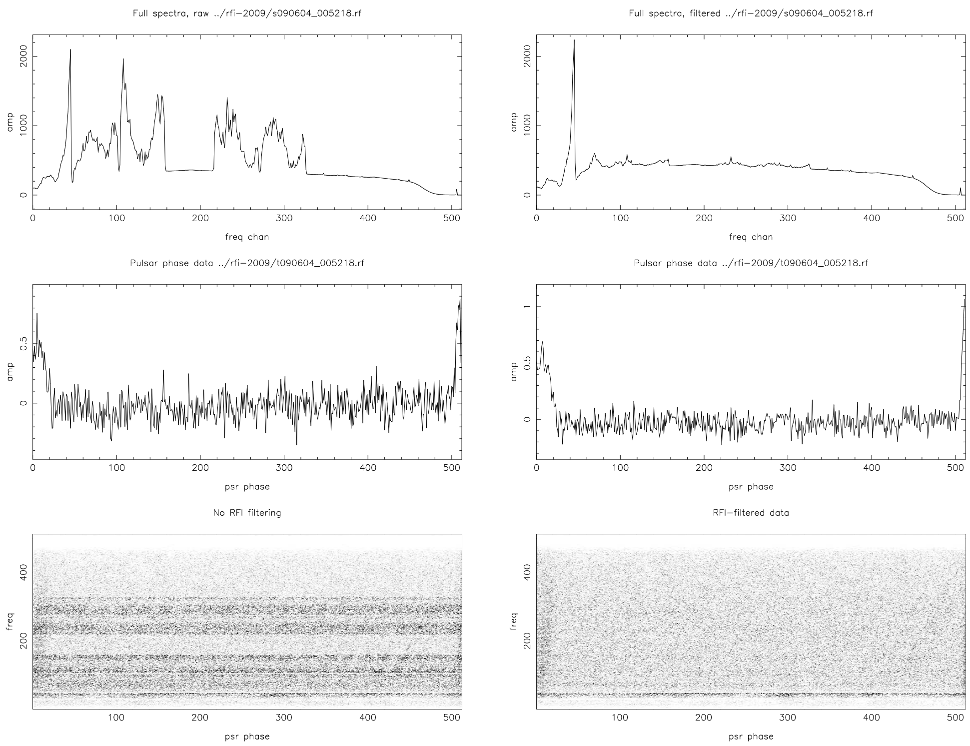

Figure 1: RFI mitigation applied to single antenna (the Parkes 64m) pulsar data

4.1 Blanking in time

This is the time-honoured technique, relevant to impulsive interference. The observer establishes a threshold to distinguish the RFI from the RFI-free state. Data exceeding the threshold is deleted.

The operation can take place on the raw IF voltages, or on the post-detection data.

It is an attractive option, as it is simple to implement, it lends itself well to automatic operation. It is cost-effective if the duty cycle is low.

The technical demands are substantial, since astronomers inevitably wish to use as much bandwidth as the processing electronics can support. Bandwidths of several 100 MHz are common in the centimetre-class bands where RFI is most likely to occur. As a result, the processor will need to operate on digitised data streams with several hundred MSamples/sec.

The process does compromise the astronomical data since we blank astronomy as well as RFI, so it is important to examine the balance sheet:

* Impulsive RFI is handled well. Large excursions are removed at a modest cost in the number of affected samples. This can be very cost effective since the signal-to-noise (SNR) is proportional to the square root of the integration time (that is, the number of useful samples retained for processing).

* It would be a waste of time attempting to blank continuous broad-band RFI.

* Strong narrow band RFI may have an impact right across the spectrum if there are non-linearities in the system, or if the processing results in frequency aliasing. Blanking in frequency is therefore of questionable value unless care is taken with the processing which occurs ahead of the blanking: it requires a linear system, a digitiser with adequate sampling bits and a spectrometer with well-defined spectral channels.

It is now possible, with modern digital processing, to perform quite sophisticated blanking. The incoming data stream could be processed in blocks of samples, so that the noise characteristics could be derived on the fly; further, the blanking window could be tailored to remove low level RFI which is known to accompany bursts of RFI. See, for example, Niamsuwan [36], Ellingson [23] Blanking can, of course, be applied to the telescopes in a radiotelescope array. In this case there is the further possibility of identifying the RFI that is coherent between antennas, thereby refining the process of identifying the RFI. Baan, Fridman and Millenaar[13] have described an impressive RFI mitigation machine installed on the Westerbork Array.

The effectiveness of this process is set by the Interference-to-Noise Ratio (INR); that is, by the extent to which the RFI dominates the system noise. Some experiments require long integrations in order to detect weak objects, and it is here that low level RFI could be a problem: it is too weak to excise, and only shows up at the end of the experiment.

4.2 Blanking post-correlation data - flagging

Flagging is the traditional RFI excision strategy, operating on the post-correlation data. It can be fearfully labour intensive (Lane [32]).

It will be effective to the extent that the RFI is impulsive so that useful RFI-free times can be identified. Algorithms have now been devised that can largely automate the procedure (Middelberg [34]).

4.3 Blanking in frequency

The strategy here is to identify the spectral regions which are free of RFI. There are a few caveats: the spectral occupancy should low enough that the achievable sensitivity is still useful; and, clearly, observations locked to specific frequencies have no recourse if the RFI overlaps that band.

LOFAR ([15]) exploits this strategy dynamically.

4.4 Null Steering

Any phased array will have sidelobes and nulls in its reception pattern. This property has long been exploited (outside radioastronomy) to position the nulls on known sources of interference. Under some circumstances (anti-jamming, for example), with arrays explicitly designed to exploit this technique (regular antenna spacing) this can produce spectacular automatic adaptively adjusted nulling. The adaptive algorithms require high Interference-to-Noise ratios, and they work best if the array is set up to track a small number of specific target directions (in a beamforming mode).

Only one astronomical array (to date) has explored this technique, the Allen Telescope [11]. In order to avoid interference from satellites known to transmit in the observing band the complex weights used in the beamformer will be adjusted to provide a null covering the RFI band in the direction of the satellite, while maintaining high gain in the direction of the target, Harp [27]. This null steering is critically dependent on an accurate calibration of the array (the receiver gains, delays and phases), as the steering is done in "open-loop" mode.

Most modern radiotelescope arrays operate in imaging mode in which there is no beamformer; this precludes null steering in its standard mode. Nonetheless, recent work with adaptive filters has brought null-forming back. The filters cancel all the signals from the RFI direction, so the array in insensitive in that direction. The procedures described in the next sections demonstrate that the null steering is as broad-band as the RFI, and is generally achieved without compromising the imaging properties of the main beam.

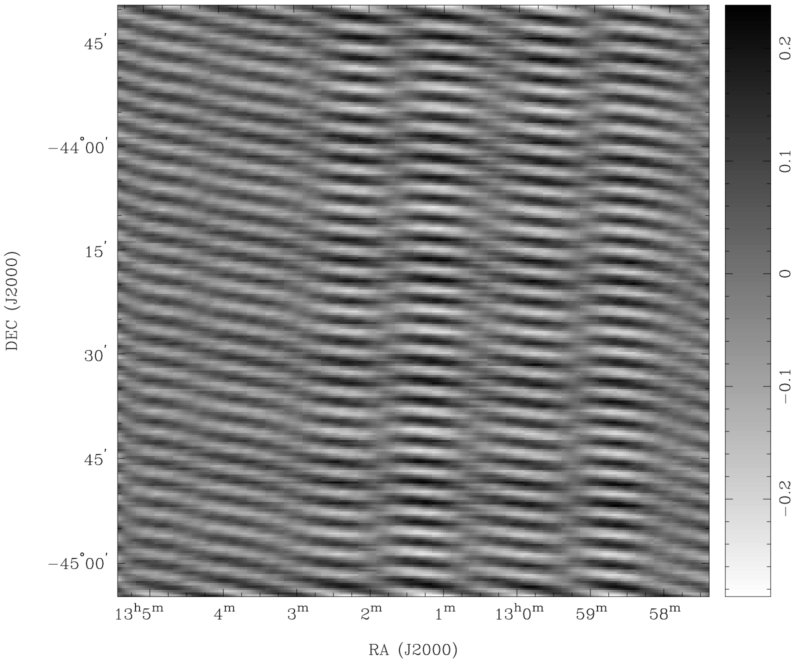

Figure 2: Image based on the raw, unfiltered data

4.5 Adaptive Filters

Adaptive filters are an option if a copy of the RFI is available. For example, a modest antenna directed towards a nearby TV tower could provide such a copy. The filter can operate in real-time or in the post-detector stage.

The canonical adaptive filter (Haykin [28]) is a powerful tool for removing RFI. It was introduced to the radioastronomical community in 1998 (Barnbaum [14]). The filter is able to remove RFI from a corrupted data channel once it is given an independent copy of the RFI. The filter will reduce the RFI (voltage) in the astronomy IF by a factor $\frac{1}{(1+INR)}$, where INR is the interference-to-noise ratio in the reference channel. In addition, a fraction of the reference channel's receiver noise will be added to the filter output. This will be equal, in magnitude, to $\frac{1}{\sqrt{(1+INR)}}$. This will appear, to the astronomer, as a spectral echo of the RFI: it will have the same spectral distribution as the RFI, although it

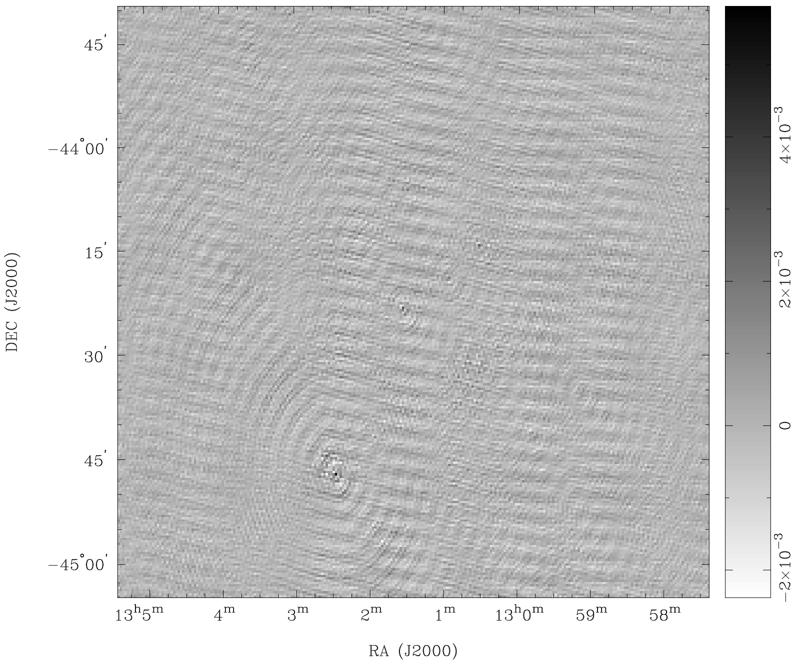

Figure 3: Image based on the filtered data

will be quite uncorrelated with the RFI. A long integration, the traditional method of improving the detectability of weak signals, will not remove the echo - it will simply reduce the noise in the baseline and in the echo. This class of filter can also play a role in telescope arrays with the filter operating on the IF output from individual antennas; in this case the spectral echo will not be a problem because it contains receiver noise which will not be coherent between antennas.

The adaptive filter also has a valuable role to play in areas where the spectral distribution is not an issue - in pulsar astronomy, for example, the filter is able to reduce the RFI's impact on SNR, provided only that the RFI has no periodicities commensurate with the pulsar (Kesteven [31]).

The adaptive filter can be applied to a synthesis array; an example is shown in figures 2 and 3. Figure 2 shows the image based on badly affected data, with the filter disabled; figure 3 is the image that is obtained when the adaptive filter is enabled. The field is essentially empty; 3 faint sources can be identified by their signature, the set of concentric ellipses.

4.6 RFI mitigation in the array imaging stage

Several groups have demonstrated that RFI can be identified and removed within the image processing operation (Wijnholds [42], Cornwell [21]). The advantage is that there is then no need for a separate reference antenna that would provide the clean copy of the RFI. The distinguishing feature that identifies the RFI is the known movement of the RFI relative to the imaged sky. (In the VLA case [21] the target was stationary with respect to the array. A moving RFI source - a satellite, for example - could be accomodated in this formulation, provided that the trajectory were known with some precision).

LOFAR has exploited this strategy in an elegant manner - exploiting the RFI to refine the array calibration, and then removing the RFI from the data.

4.7 Subspace filtering

The ideal strategy in this class of mitigation would dispense with the RFI copy, and identify the RFI in the data itself.

The goal here is to find some statistical signature that distinguishes RFI from RFI-free data. Cyclostationarity is one such signature : see, for example, Weber [41], Feliachi [24].

4.8 Generalised Spatial filtering

A more general and elegant scheme has been described by Leshem et al [33]. The basic idea is to exploit the fact that the RFI, if it is a problem, must stand out. Noise from a receiver is generally white, uncorrelated from one sample to the next, and quite uncorrelated from one receiver to the next. RFI has a variety of correlations - in time and between antennas. Astronomy signals share these types of correlation, but at a lower level. Spatial filtering attempts to categorise the samples via the correlation properties, and then discard the RFI.

Given an array of N antennas, we form the correlation matrix **R** over all N(N+1)/2 antenna combinations over some time interval τ. **R** describes the array's response to the astronomy within the field of view, to the RFI, and, along the diagonal, to the receiver noise. To the extent that the RFI is stronger than the astronomy component, an eigen decomposition will recover the RFI vector, so that a projection operation could remove the RFI.

RFI excision exacts a computing penalty, because the array's response to a point source varies over the field of view. However, the benefits of the better defined procedure for identifying the RFI make this an attractive option.

5 RFI Mitigation Metrics

The next stage in the development of RFI mitigation strategies has to be the formulation of suitable metrics. The international community through the International Telecommunication Union (ITU-R) has made substantial efforts to balance the needs of the community for all forms of wireless communication with the requests of the radioastronomers for reserved spectral bands. The ITU-R Recommendation ITU-R RA-769 [5] outlines the protection criteria and defines the harmful limits. The arguments in RA-769 that lead to the definition of the limits provide a useful starting point in establishing metrics for the RFI mitigation techniques.

RA-769 identifies some typical experiments (detection of weak radiosources with a single, large antenna, for example); the harmful RFI is defined to be the level that compromises the experiment at the 10% level. The harmful levels are given in Tables 1, 2 and 3 of ITU-R RA.769-2. Perhaps we could test the RFI mitigation techniques against these tables.

As a simple example, consider the real-time adaptive filter ([31]). It will remove the RFI, at the cost of some residual noise : $T_{resid} = \xi T_{sys-ref} \frac{INR}{1+INR}$, where INR is the Interference-to-Noise ratio in the reference channel, and ξ is the ratio of RFI powers, in the astronomy and reference antenna's IFs. We use the RA769 argument to compute ξ – the RFI enters the astronomy IF via a 0 dBi sidelobe (see section 1.3, RA 769), and with the RFI in the main beam of the reference antenna. This leads to an estimate of $T_{resid} \sim 6mK$ for the Parkes adaptive filter at high levels of RFI, reducing gracefully as the RFI reduces.

A problem for most of the techniques described in this note is that they depend on identifying the RFI in real time. In general this means the scheme will cease to be effective when the RFI is comparable to the system noise. Low level RFI, although well above the RA769 benchmark, will escape mitigation.

It is worth noting that the adaptive filter uses a separate antenna explicitly directed towards the RFI, and this gives it a substantial advantage (often around 40 dB) in the detection of the RFI.

6 Low Level of Uptake

It is an interesting state of affairs that all observatories report the presence of RFI at some level, yet very few have implemented on-line, routine RFI mitigation strategies. It is certainly true that serious efforts are made to contain or remove sources of RFI within the observatory, but there seems little effort to actively mitigate the external RFI. Blanking, discarding badly affected data blocks, or rescheduling seem to be the fallback positions.

Some possible reasons:

- The situation is not bad enough that science cannot be done. The effort and cost of developing a mitigation strategy is greater than the cost of doing nothing (ie, the cost of lost time; of manual blanking/flagging).
- The situation is already so bad that the only safe option is to find a new, quiet observatory. This is indeed the case at the low-frequency end of the spectrum: several teams exploring the Epoch of Reionisation have elected to install their equipment at the Murchison Radio Observatory (MRO).
- The techniques are new, so there are concerns about the unknown - might it affect the calibration, for example.
- There is no universal mitigation technique - specialised “niche” instrumentation might not sit well with the observatory business model.

The day may yet come when the right conditions will obtain:

- the RFI is so bad that useful observations cannot be made.

- the experiment cannot be made at an adjacent RFI-free band.

- the experiment cannot be done elsewhere.

Until then, these proven techniques will probably not be widely adopted.

7 Is there a role for RFI Mitigation in the SKA era?

The SKA, in the short-term, looks to be an unlikely candidate for RFI mitigation.

- The SKA is making substantial efforts to find a site with very low levels of RFI, thereby making mitigation unecessary.

- The SKA will be seriously challenged by the computational effort involved. Adding an extra layer to support RFI mitigation may not be encouraged.

This leads to the somewhat pessimistic conclusion: it is important that research in RFI mitigation technology continue, since the RFI levels are bound to rise; but the researchers are unlikely to see their efforts applied to routine operations in the near term.

References

[1] www.atnf.csiro.au/projects/askap

[2] www.cloudsat.atmos.colostate.edu/

[3] www.craf.eu/quiet.htm

[4] www.gb.nrao.edu/nrqz/nrqz.html

[5] www.itu.int/pub/R-REC/en

[6] www.kat.ac.za

[7] www.lofar.org

[8] www.narrabri.atnf.csiro.au

[9] www.nrao.edu/GBT/GBT.shtml

[10] www.parkes.atnf.csiro.au

[11] www.seti.org

[12] www.skatelescope.org

[13] W.A. Baan, P.A. Fridman and R.P. Millenaar, "Radio Frequency Interference Mitigation at the Westerbork Synthesis Array: Algorithms, Test observations and System Implementation" *The Astronomical Journal*, vol. 128, pp. 993-949, 2004.

[14] C. Barnbaum and R.F. Bradley, "A new approach to interference excison in radio astronomy: Real-time adaptive filtering," *Astronomical Journal*, vol. 116, pp. 2598–2614, 1998.

[15] M. Bentum, A-J. Boonstra, R. Millenaar and A. Gunst, "Implementation of LOFAR RFI mitigation strategy," URSI General Assembly 2008, Chicago, USA.

[16] F.H. Briggs, J.F. Bell, and M.J. Kesteven, "Removing radio interference from contaminated astronomical spectra using an independent reference signal and closure relations," *Astronomical Journal*, vol. 120, pp. 3351–3365, 2000.

[17] F.H. Briggs and J. Kocz, "Overview of Technical Approaches to Radio Frequency Mitigation" *Radio Science*, vol. 40, no. 5, RS5S02, 2005.

[18] A.P. Chippendale, R. Subrahmanyan and R.D. Ekers, "Effects of Interference on the ATNF Cosmological Reinionization Experiment at Mileura" *Proceedings of the XXIXth General Assembly of the International Union of Radio Science*, Delhi, 23-29 October 2005.

[19] V. Clerc, R. Weber, L. Denis and C. Rosolen, "High Performance Receiver for RFI Mitigation in Radio Astronomy: Application at Decameter Wavelengths," *EUSPICO'02*, Toulouse, France, 2002.

[20] J. Cohen, T. Spoelstra, R. Ambrosini and Wim van Diel, "CRAF Handbook for Radio Astronomy (Third Edition)," *European Science Foundation, Strasbourg, France*, 2005.

[21] T.J. Cornwell, R.A. Perley, K. Golap, and S Bhatnagar, "Rfi excision in synthesis imaging without a reference signal," *EVLA memo series 86*, 2004.

[22] S.W. Ellingson, "Techniques for Mitigation of Radio Frequency Interference in Radio Astronomy," *The Square Kilometre Array: An Engineering Perspective*, ed. P. Hall, Springer, pp. 261-269, 2005

[23] S.W. Ellingson and G.A. Hampson, "Mitigation of Radar Interference in L-Band Radio Astronomy," *Atrophys. J. Suppl. Ser*, 147, pp 167-176, 2003.

[24] R. Feliachi, R. Weber and A-J. Boonstra, "Cyclic Spatial Filteringin Radio Astronomy: Application to LOFAR Data", EUSPICO'09, Glasgow, UK, August 2009

[25] P.A. Fridman and W.A. Baan, "RFI Mitigation Methods in Radio Astronomy," *Astronomy and Astrophysics*, vol. 378, pp. 327-344, 2001.

[26] R.N. Ghose, *Interference Mitigation: Theory and Application*, IEEE Press, New York, 1996.

[27] G.R Harp, "The ATA digital processing requirements are driven by rfi concerns," *Radio Science*, vol. 40, no. 5, RS5S18, 2005.

[28] Simon Haykin, *Adaptive Filter Theory*, Prentice-Hall, New York, 1986.

[29] International Telecommunication Union, "ITU-R Handbook on Radio Astronomy," *ITU-R Radiocommunications Bureau, Geneva, Switzerland*, 2003.

[30] M. Kesteven, " New Technologies in VLBI, 2002, Gyeong-Yu, Korea." *ASP Conference series CS-307, 93, 2003.*

[31] M. Kesteven, G. Hobbs, R. Clement, B. Dawson, R. Manchester, T. Uppal, "Adaptive Filters Revisited - RFI Mitigation in Pulsar Observations" *Radio Science*, vol. 40, no. 5, RS5S06, 2005.

[32] W.M. Lane, A.S. Cohen, N.E. Kassim, T.J.W Lazio, R.A. Perley, W.D. Cotton, and E.W. Greisen, "Postcorrelation radio frequency interference excision at low frequencies" *Radio Science*, vol. 40, no. 5, RS5S05, 2005.

[33] Amir Leshem and Alle-Jan van der Veen, "Radio astronomical imaging in the presence of strong radio interference," *IEEE Transactions on Information Technology*, vol. IT-46, no. 5, pp. 1730–1747, 2000.

[34] E. Middelberg "Automated Editing of Radio Interferometer Data with Pieflag" *Proceedings of the Astronomical Society of Australia*, vol. 23, 2006.

[35] P. Napier, A. R. Thompson, and R. D. Ekers, "The very large array: Design and performance of a modern synthesis radio telescope," *Proceedings of the IEEE*, vol. 71, pp. 1295–1320, 1983.

[36] N. Niamsuwan, J.T. Johnson and S.W. Ellingson "Examination of a simple pulse-blanking technique for radio frequency interference mitigation," *Radio Science*, vol. 40, no. 5, 2005

[37] A.E.E.Rogers, P. Pratap, J.C. Carter and M.A. Diaz "Radiofrequency Interference Shielding and Mitigation techniques for a Sensitive Search for the 327 MHz Line of Deuterium, " *Radio Science*, vol. 40, No. 5, 2005

[38] A. R. Thompson, "The response of a radio astronomy synthesis array to interfering signals," *IEEE Transactions on Antennas and Propagation*, vol. AP-30, pp. 450–456, 1982.

[39] G. Tuccari, A. Caddemi, G. Nicotra, F. Consoli, "Cryogenic Filters for RFI Mitigation in Radioastronomy," *Proc. 7th European VLBI Network Symposium.* Toledo, Spain, 2004.

[40] R. Weber, V. Clerc, L. Denis and C. Rosolen, "Robust Receiver for RFI Mitigation in Radio Astronomy," *Proceedings of the XXVII General Assembly, International Union of Radio Science*, Maastricht, The Netherlands, 2002.

[41] R. Weber, P.Zarka, V.B. Ryabov, R. Feliachi, J.M. Griessmeier, L. Denis, R.V. Kozhyn, V.V. Vinogradov and P. Ravier. "Data Preprocesing for Decametre Wavelength Exoplanet Detection: an Example of Cyclostationary RFI Detector," EUSPICO'07, Poznan, September 2007

[42] S.J. Wijnholds, J.D. Bregman, and A-J Boonstra, "Sky noise limited snapshot imaging in the presence of rfi with lofar's initial test station," in *RFI2004* Penticton, Canada, 2004.