PROCEEDINGS OF SCIENCE

Overview of RFI mitigation methods in existing and new systems

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Significant progress has been made in developing techniques for RFI mitigation. A number of these techniques have had successful demonstrations and field trials. However the take-up at the observatories has been low. At the present time the strategy of choice is simple editing. This paper assesses the new techniques and explores the reasons for the low level of support by the astronomers

RFI mitigation workshop - RFI2010,
March 29-31, 2010
Groningen, the Netherlands

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PoS(RFI2010)007

1. Introduction

Radiofrequency interference (RFI) has challenged astronomers for decades. In recent years the problem has reached the point where mitigation strategies need to be formulated. In essence, astronomers can choose either to discard contaminated material, including target data along with RFI, or they can excise the RFI without damage to other data. By blanking they can identify the data compromised by RFI and flag the data as bad, but it is obviously preferable to characterise the RFI and remove it (and it alone) from the data.

Over the past decade a number of mitigation schemes have been trialled, and shown to work. At the present time however, blanking is, to a very large degree, the only strategy in use.

The issue of the low takeup of advanced algorithms needs to be understood.

2. The Challenge

It has long been clear that there is no universal solution, as the scope of the problem is substantial :

- There are different types of RFI

  TV/Communications
  Satellites
  Observatory-based

- There are different types of telescopes

  Single dish
  Arrays of antennas

- There are different observing regimes

  Low frequency
  High frequency
  VLBI
  Pulsars
  Spectral line
  Continuum

2.1 The benchmark - ITU RA-769

A.R.Thompson provided a useful framework to describe the impact of RFI. In essence, this document attempts to relate the RFI levels to the impact on the science. Of interest here is the link between the observation mode and the RFI levels: single antenna operation, for example, is much more vulnerable to RFI than is a VLBI operation.

We need to recognise that RFI entering the main beam of a telescope (LOFAR apart) is generally a lost cause, and pitch the debate at RFI in the far sidelobes - at the level corresponding to a 0 dBi gain.

The criterion is that the observation be degraded by no more than 10%. This allows us to define the harmful levels of RFI. The argument can be extended to the different mitigation techniques - are they worth their cost?

2.2 The ideal RFI mitigation strategy

We need machinery to reduce the impact of the RFI which is damaging the astronomer's data.

It should be automatic, reliable and robust.

It should not introduce artefacts which mimic real results.

The cost (to the budget, to the science, and in time involved) of applying the machinery should be predictable.

The cost should be less than the cost of doing nothing.

3. Pro-active mitigation : Avoid the RFI

3.1 Regulation

The spectrum management authorities have a difficult task balancing the commercial, military and scientific requests for spectrum access. Radioastronomy has benefited in a number of ways: with some reserved bands, and legislated radio quiet zones, where the licensing of transmitters is limited.

3.2 Good observatory discipline

Observatories are potentially a rich source of RFI, with their substantial inventory of high speed electronics and computers. It requires a serious commitment of time and effort to keep the observatory quiet. See, for example, the Greenbank experience [4]).

3.3 Remote Locations

There is a clear link between population density and RFI. (see figure 1). The next generation of radiotelescopes will likely be built in remote areas with a low population, where there is little or no RFI.

4. Re-active mitigation : remove the RFI from the data

This comes in two flavours : Discard those parts of the astronomical data space which contain RFI (excision), or identify and remove the RFI while leaving the astronomy untouched (cancellation).

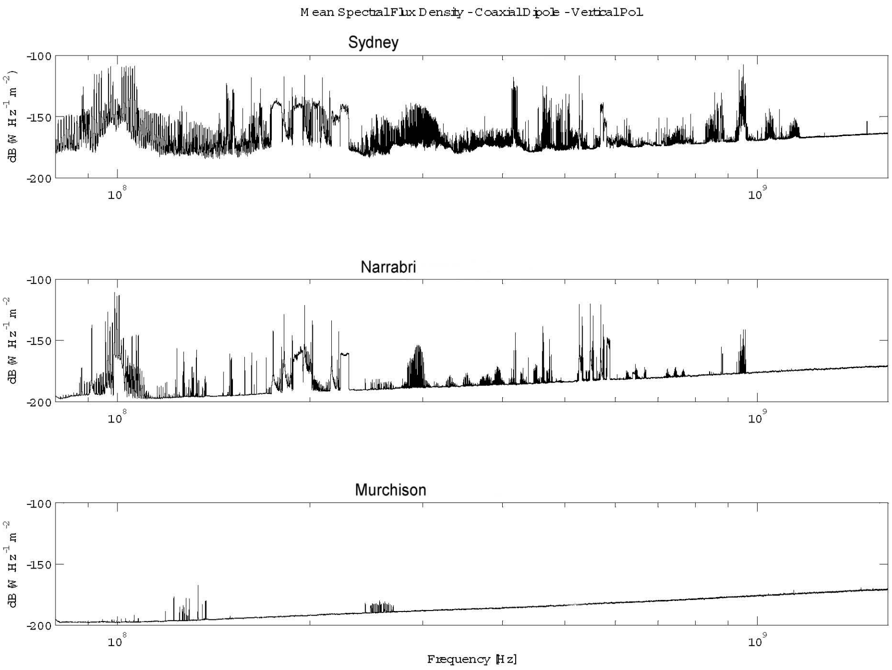

Figure 1: RFI levels - from a metropolis to the Murchison desert

5. Excision

This is the current mitigation strategy of choice. It is attractive to observers because it is simple and its consequences are predictable:

- The loss in sensitivity is related to the amount of data discarded.
- The effect on the image quality can be estimated.
- It is straightforward in its implementation, and can easily be automated.

The strategy is predicated on two factors:

The RFI events must occupy a small fraction of the data space, to keep the cost (reduction in sensitivity) acceptable.

Each RFI event has to be readily detectable (as otherwise good data will be discarded). This means that the Interference-to-Noise Ratio (INR) should be high.

5.1 Real-time (hardware) blanking

Blanking has become increasingly attractive with modern high speed samplers and their associated electronics. It is realistic to accumulate a buffer of samples and apply sophisticated tests on the data before delivering it to the subsequent processing stages. The buffer needs to be long enough to allow a reliable separation of the RFI from non-RFI. The general approach is to assume that the normal data is white noise, and look for statistically significant departures.

The buffer allows further options. One could blank a known pulse shape, for example, once the RFI event has been identified. A number of observatories have installed hardware (on-line) blanking devices.

Arecibo, for example, addresses the serious RFI from neighbouring radar. The known timing details of the pulsing assists the blanking trigger.

ASTRON, at the WSRT, have demonstrated an impressive unit built around digital processing boards which, amongst many capabilities, can provide on-line blanking.

5.2 Post-correlation Flagging

The traditional RFI mitigation strategy is to flag the data: to instruct the downstream imaging/processing machinery to ignore the corrupt samples. This is the RFI-mitigation strategy of last resort. It is tedious when done manually (although this has not deterred generations of astronomers); automated scripts are now available. When blanking is applied to the correlator output data, the minimum quantum of rejected data is the size of the correlator dump cycle.

5.3 Frequency Flagging

Discarding data in frequency space is a variant of this approach: modern high speed processing allows fine on-line spectral analysis, so that corrupted channels can be identified and excised. This is an option if the discarded fraction of frequency space is modest compared to the overall bandwidth.

LOFAR includes this in its armoury.

5.4 Excision Issues

The technique relies on the ability to detect RFI from a small number of samples (or from prior information). It generally requires a good INR. Long integrations with low INR will be compromised, as the RFI will remain undetected until the processing is complete. INR > 10 is a rough guide. There may be little to be gained by integration if the RFI is pulsed, as the INR is essentially based on a relatively small number of samples. (Periodic RFI is a separate case).

Care is needed to ensure that the downstream processing is not compromised. The blanking must replace the RFI-affected samples with benign data - noise that mimics the system noise.

Discarding data in synthesis arrays will affect the (u,v) plane data distribution and may therefore compromise the imaging quality.

This can be a viable technique if the cost to science is modest; that is, if only a small fraction of data is lost. A loss of 10% of the data has a small effect on the science outcome.

6. Cancellation

This is the more ambitious approach:

- Identify and characterise the RFI.
- Subtract the RFI from the data, to give the astronomer an RFI-free dataset.

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6.1 The image-plane filter

Cornwell, [2] has created an elegant scheme for a synthesis array. It looks for signals which do not follow the celestial rotation during the observation. It solves the RFI identification problem in the image plane.

Consider a simple interferometer tracking an astronomical field. Every source in the field will be seen with a phase trajectory set by its position on the sky. The RFI from a fixed location on the ground, by contrast, will be seen at a constant phase. A source at the celestial pole shares this signature.

The algorithm exploits this feature. A whole sky image is made (at least in concept). The image will show the field of interest – an antenna beamwidth centred on the field, along with the RFI at the pole. A Clean/Self-calibration stage is required to account for the actual location of the RFI. Its phase is constant in time, and its value is set by the location the RFI relative to each baseline.

The actual clean/self-calibration operation runs two parallel chains: one for the field of interest, and the second for the RFI at the pole.

Once the RFI has been fully characterised it can be removed.

The scheme has been shown to work, but it does have some limitations :

- It will require rapid correlator dumps, in order to prevent dilution of the RFI by the fringe tracking;
- The Clean/Self-Calibration requires access to the entire data set, which will preclude on-the-fly RFI mitigation;

Its strength is that it does not require additional hardware. It makes few *a priori* assumptions about the RFI.

6.2 Spatial Filtering

Each object within the field of view of the array will add a specific signature to the full set of correlation products between the antennas. An eigenvalue decomposition of the product matrix will isolate the strongest sources. A projection operation can then remove the RFI sources.

This scheme has a long history (Leshem [7]), and most recently it has been successfully demonstrated in the LOFAR trials.

Its strength is that it operates on an integration-by-integration basis, and so is suitable for on-the-fly operation. A weakness is that it requires strong RFI.

6.3 LOFAR snapshot variant

The LOFAR array operates in an RFI-rich environment, so RFI management has a high priority (Bentum, [8]).

An interesting variant of the spatial filtering has been demonstrated (Wijnholds, [9]): Within each widefield (whole sky) snapshot the strong RFI point sources (as found by spatial filtering) are identified and removed. This cleans the snapshot down to sky noise.

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Stacking the sky-aligned snapshots builds the SNR on the astronomical objects while dissolving the remaining RFI.

The computing load for a detailed spatial filtering operation may be a limiting factor.

6.4 Cyclostationary Filters

The concept here is to identify the RFI by its temporal signature, cyclostationarity. This attribute is specific to RFI. The classical spatial filtering matrix is replaced by a variant which is matched to a cyclic frequency. The projection operation then proceeds as before, to remove the RFI.

This scheme has had some initial (promising) trials on LOFAR (Feliachi [3]).

6.5 Null Steering

The ATA is an array of 42 antennas that includes a beamformer mode of operation, with each beam directed to a potential target. This opens the possibility of adjusting the beamformer weights to position nulls in the direction of known RFI sources, fixed or mobile.

Wide-band nulls may be required (and have been demonstrated).

The process works well (Harp, [5]), but has serious implications for the bandwidth of the phase tracking machinery.

6.6 Adaptive Filters

The starting point is to obtain a copy of the RFI – typically with a separate antenna pointed directly at the source of RFI. The adaptive filter manipulates this copy until the RFI matches (in amplitude and phase) the RFI in the astronomy IF. A subtraction operation provides an RFI-free IF for subsequent processing.

The scheme can work to low levels of RFI, since the machinery to identify the RFI is separate from the astronomy antenna, and can be optimised to detect the RFI.

The filter can be implemented in hardware (Kesteven, [6]) or in software, operating on the correlator products (Briggs, [1]). Figure 2 shows an example of a filter in action.

The post-correlation filter has been demonstrated to be effective for both single dish and synthesis array operation.

7. The Low INR Problem

The mitigation schemes generally work on short sections of data, but the astronomer works with the entire dataset. This means that low level RFI could be a problem: too weak to trigger the mitigation machinery, but able to show up in the final product. This domain has yet to be tested. All the trials to date have been concerned with significant levels of RFI.

In addition, future arrays may have too much data to allow RFI mitigation predicated on the entire dataset, thereby precluding the use of some of these mitigation schemes.

None of the mitigation schemes described here are able to reduce the RFI to levels approaching the standards of ITU RA-769. This makes the radio quiet zones such as the Karoo and the Murchison increasingly attractive.

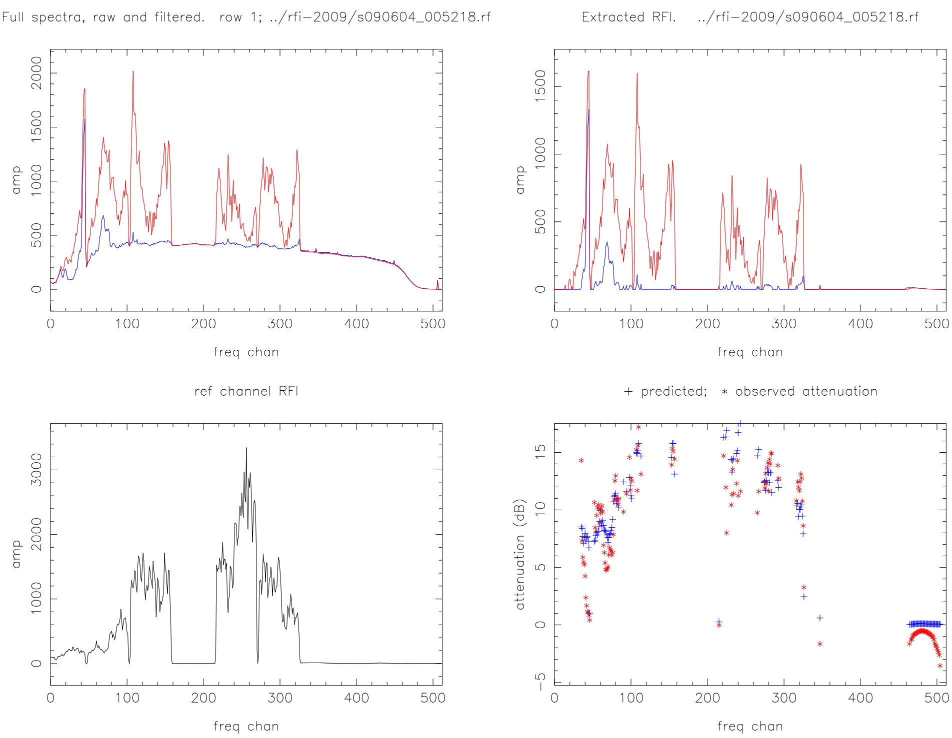

Figure 2: Adaptive filter in action. The top left panel shows the unfiltered IF (red) and the filtered IF (blue). The lower left panel shows the RFI in the reference antenna's IF. The top right shows the RFI (the IF from which the underlying system bandpass has been removed. The lower right panel shows the measured attenuation (red), and predicted (blue).

8. The Low Takeup Problem

Astronomers have been reluctant users of the advanced RFI mitigation schemes, preferring the traditional blanking schemes. This suggests that the RFI is not a serious issue. The modest improvements achievable with a sophisticated scheme are marginal, and do not outweigh the uncertainties inherent in new techniques.

Those instances where the new techniques are taken seriously are indeed associated with challenging RFI. LOFAR operates in a RFI-hostile environment, and is exploring all the recent RFI mitigation schemes. The pulsar group at Parkes needed the adaptive filter once the digital TV had swamped the observing band.

It is possible that the time is approaching when RFI mitigation will be automatically embedded in the observing machinery.

9. Conclusion

A number of effective RFI mitigation techniques have been demonstrated to be workable. In coming years the RFI conditions at many established observatories will deteriorate to the state where RFI mitigation will be a routine tool.

New observatories will probably explore the option of a remote site, free of RFI.

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