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Techniques for mitigation of radio frequency interference in radio astronomy

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Radio astronomy



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(2007-2013)

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1 Introduction

Mitigation techniques fall into three general categories:

- Preventing radio frequency interference (RFI) signals from entering the astronomical data, including reduction of the Observatory's vulnerability to RFI signals (§ 4)
- Removing RFI signals from the data in real time (§§ 5.1, 5.2, 8.1, 8.2)
- Removing or reducing the impact of RFI off line, following completion of the observing (§§ 5.3, 5.4, 8.3, 8.4).

1.1 Definition and characteristics of radio frequency interference

To a radio astronomer, RFI is any unwanted addition to the cosmic signal that has the potential to degrade or prevent the successful conduct of an observation. The term RFI will be used in this sense throughout this Report. Unlike thermal noise, which has stable temporal stochastic properties (white noise) and can be dealt with through radiometric detection (i.e. long integration times and on-source minus off-source subtraction), an RFI signal is temporally, spatially or spectrally structured and can obscure a deep-space signal or produce a false positive detection.

1.2 Characteristics of astronomical signals

Astronomical signals are many factors of ten below the noise floor of the receiving system. Hence the power level at which RFI begins to be detrimental is far lower for radio astronomy than it is for other radiocommunication services. The variety of potential RFI sources is hence very large. They include personal wireless devices, radar glints from aircraft, satellite transponders, commercial broadcast services, automobile spark plugs and many others.

1.3 Dealing with radio frequency interference

The working assumption for most astronomical observations is that RFI-corrupted data are unusable. The most common method for dealing with RFI is to excise spectral or temporal segments of a data set that are known to be corrupted.

There are powerful motivations to move beyond throwing away data. Methods that remove or mitigate RFI, thus enabling scientific usage of data that would otherwise be discarded, are becoming more and more essential and feasible. Automated procedures have become ever more necessary.

There is:

- 1) an explosion of wireless communications services, with a consequent increase in the number of RFI sources;
- 2) rapid growth in the number of astronomical observations that need to be made outside protected radio astronomy bands;

- 3) an increased availability of signal processing hardware and algorithms; and
- 4) a dramatic increase in the size of data sets with increasing computer power, so automated procedures have become ever more necessary.

The aim of mitigation techniques is to enable astronomical observations to be conducted in densely occupied bands and heavily used radio environments.

1.4 ITU Standards

The threshold levels of detrimental interference in radio astronomy bands are given in Recommendation ITU-R RA.769. The percentage of permissible data loss resulting from emissions above these thresholds is specified in Recommendation ITU-R RA.1513.

In the exclusive primary bands listed in RR No. **5.340**, all emissions are prohibited. In the other radio astronomy bands, listed in RR No. **5.149**, administrations are urged to take all practicable steps to protect the radio astronomy service from harmful interference.

1.5 Adoption of mitigation methods

Despite much research on RFI mitigation over the last ten years or so, methods other than filtering and simple excision of RFI-contaminated data are not at present widely used in radio astronomy. This is primarily because more complex forms of mitigation require costly hardware, challenging software development, and/or expert-user capability to exploit during or after an observation. In addition radio astronomers want to keep control over their data and are hesitant to adopt black box methods of mitigation. Some proposed methods are not suitable for real-time operation, but require access to large data sets of recorded signals in a post-acquisition processing mode. Though many mitigation techniques have been tested, it is not possible for any of them to address every issue posed by the diverse variety of RFI sources, radio astronomy observations are made with many different aims that require a variety of different techniques and equipment.

1.6 Effective observing techniques

For many observing applications, the standard observing modes and signal processing techniques have provided an inherent degree of interference mitigation that proved adequate to obtaining useful astronomical data in the presence of some interference.

For aperture synthesis instruments, “fringe stopping” typically decorrelates the RFI received at widely-separated antennas. This tends to suppress the RFI in the associated correlation products (Thompson, 1982). In the case of some synthesis radio telescopes, such interference may still result in a spurious bright source appearing in the maps at the celestial pole, which makes high declination observations difficult or impossible.

Similarly pulsars produce pulses of broadband noise, so a significant receiver bandwidth is needed to achieve a useful signal-to-noise ratio. The noise making up the pulses is subject to frequency-dependent dispersion as it propagates through the rarefied plasmas in the interstellar medium. When observing a pulsar with a radio telescope, the pulse is deliberately de-dispersed using a combination of hardware and software, to recover an accurate (non-dispersed) representation of the intrinsic pulse profile. This process tends to reduce RFI, because the process of de-dispersing the pulsar signal consequently disperses the RFI. However, only limited mitigation is provided by these processes.

Data are always degraded when interference is present.

New aperture array instruments under development, such as LOFAR in the Netherlands, are beginning to adopt advanced techniques such as spatial nulling (Boonstra, 2005). This is necessary

because of its wide, full-sky field of view, its siting in well-populated regions, and its operation in unprotected HF and VHF bands that are crowded with broadcast and wireless radio services.

Perhaps the most vulnerable radio astronomy service (RAS) observations are those made with single-dish radio telescopes (continuum or spectroscopy), since no “fringe stopping” decorrelation is available for these observers. The improvement in sensitivity to astronomical signals afforded by increasing integration time then leads to a proportional increase in sensitivity to RFI signals.

The impact of RFI extends beyond simply preventing or degrading certain observations or types of observation. It also limits the overall productivity of the radio astronomy station by making desirable observations prohibitively difficult or expensive in terms of observing time requirements, processing complexity and operational overheads. An example is the increasing need to replace manual post-observation editing of data to remove RFI, which is routinely practiced in aperture synthesis imaging (Lane *et al.*, 2005). Such editing procedures are currently being incorporated into automated pipeline routines that are necessitated by the dramatic increase in data volumes.

2 RFI mitigation methodology – Layers of mitigation

As indicated in § 1, the techniques for data mitigation can be divided into three general categories. In any practical implementation, particular techniques are likely to be implemented at different stages in the data acquisition and processing. The technique to be used at any particular stage depends on the type of observation undertaken (single dish, single interferometer, interferometer network, phased-array, etc., and also on the type of radio sources being observed. The probable types of mitigation and stages at which it takes place are:

- 1) Pre-detection methods applied in the receiver system itself, possibly in connection with the data-taking backend.
- 2) Digital excision and RFI removal methods may be used before correlation. With the advent of software (SW) correlation, these digital methods may also be incorporated into the correlation process.
- 3) The application of digital methods after correlation and after data integration or data buffering.
- 4) Excision and flagging of the collected astronomical data to eliminate the effects of known and unknown sources of RFI.

The performance of all of these methods depends on the interference-to-noise ratio (INR), i.e. on the strength of the RFI relative to the system noise, or on the ratio of system-noise variance to RFI variance. Most methods are only effective when the RFI is clearly detectable within the data, and its effects can usually only be removed down to a level corresponding to the instantaneous noise. A figure of merit for these methods is the processing gain after RFI suppression or reduction, which can be expressed as the ratio of the signal-to-noise ratio (SNR) after processing to the SNR before processing.

The success of any technique depends on the required level of suppression and also on any loss of the signal-of-interest (SOI). The occupied bandwidth of an astronomical signal relative to that of the RFI must also be considered, particularly when considering the cumulative effects of mitigation from several stages. It is to be noted that each applied method can introduce a measure of toxicity (i.e. damage to the data), which results in an incremental degradation of the data quality. The total damage done to data, as a measure of the data loss resulting from (subsequent) mitigation processing is quantified by the ratio of the SNR (after processing) to the SNR (in the absence of RFI).

3 Techniques for mitigating RFI

The development of techniques for mitigating RFI present in the analog output of radio telescope receivers has been a rapidly developing field in recent years, spurred on by technological advances that enable real-time signal processing approaches to RFI mitigation. Helpful introductions are provided by review papers (Bell *et al.*, 2000; Fridman & Baan, 2001; Ellingson, 2005, Briggs & Kocz, 2005; Baan, 2010; Kesteven, 2010), as well as in conference presentations and summaries (RFI2004, RFI2010).

For the purposes of this Report, a concise taxonomy of mitigation techniques follows:

- 1) *Pro-active measures*, to change the local RFI environment by means of regulatory or coordination measures. In addition, some modifications to receiving systems may be possible in some circumstances to exclude RFI from observational data by using filters and robust receiver designs.
- 2) *Spatial nulling*, or adaptive spatial filtering, mitigates persistent RFI by using array beam-forming techniques to orient pattern nulls towards sources of RFI. This distorts the nominal instrument beam pattern(s), but in many cases, such as when interference arrives from the direction of the deep sidelobe response, nulls can be formed with no loss of data from the signal of interest. Challenges include the difficulty of accurately estimating the spatial properties of interference, which limits the achieved null depth.
- 3) *Waveform subtraction*, in the sense of “subtracting” RFI from the telescope output. This form of adaptive noise cancellation is potentially superior to temporal excision in the sense that the RFI is removed with no impact on the astronomy. This provides a “look through” capability that is nominally freed of the artifacts associated with a simple “cutting out” of data. In addition, methods that use the statistical properties of the data may achieve similar results. However, the tradeoff with respect to temporal excision is usually that suppression is limited by the quality of the estimate of the interference received by the radio telescope.
- 4) *Anti-coincidence*, broadly meaning the discrimination of RFI by exploiting the fact that widely-separated antennas perceive identical astronomical signals, but differing RFI. Thus RFI makes a contribution to the background noise level at each antenna rather than to the correlated signals.
- 5) *Excision in the temporal and frequency domain*, in the sense of “cutting out” RFI from the data. For example, RFI consisting of brief pulses in the time domain may be mitigated by blanking the data (or stopping the data taking process) when the pulse is present. In addition, digital methods allow excision of RFI in both the time and frequency domains. A common property of all excision techniques is the loss of astronomical data, with the possible distortion of the remaining data by artifacts introduced by the excision process or left over from the RFI signature.

Though found frequently in the literature, we will avoid using generic terms such as “cancelation” or “mitigation” to classify specific algorithms in the following discussion since these descriptors can ambiguously refer to several of the categories listed above.

The pro-active methods are described in § 4. Spatial nulling (§ 5) and methods involving waveform subtraction (§ 6) have been demonstrated using real or simulated astronomical data, but are in most cases under further development or used only in special circumstances. Anti-coincidence techniques (§ 7) provide a very effective means for identifying data contaminated by RFI that cannot strictly be classified as mitigation, but are rather a means for identifying data that should be removed by temporal excision. Finally, mitigation methods that are frequently or routinely used at observatories are generally based on temporal excision, i.e. deletion of data that is believed to be contaminated by RFI. These methods are described in § 8.

4 Pro-active measures – Changing the RFI environment

4.1 Regulatory and coordination measures

Coordination with active users and the application of national and international regulations may reduce both the occurrence of RFI at a radio astronomy station and its impact on observations. Improving and strengthening the regulatory framework at national, regional, and international levels plays an important role in protecting passive use of the spectrum: resources in support of this approach are to be found in the ITU-R Handbook on Radio Astronomy (2013), Recommendations ITU-R RA.769 and ITU-R RA.1513, and the CRAF Handbook (Cohen *et al.*, 2005).

Coordination zones and radio quiet zones can be used to control RFI from terrestrial sources. Report ITU-R RA.2259 describes the general characteristics, requirements, and implementation considerations for a radio quiet zone, and provides, in its annexes, numerous examples of specific radio quiet zones. Many observatories have local and national regulations that prevent the installation of transmitters in the immediate proximity (within 2-6 kilometers) of an observatory. Large-scale coordination and quiet zones have been implemented for several sites, such as the Mid West Radio Quiet Zone in Western Australia (MWRQZ, 2007), the National Radio Quiet Zone around Green Bank, WV (NRQZ, 1958) and the Puerto Rico Coordination Zone around the Arecibo Observatory, PR (PRCZ, 1998). The environments for new telescopes, such as ALMA in Chile and the two sites for the Square Kilometer Array, are being controlled by forward-looking, national regulations to facilitate the most sensitive observations.

Since it is better to solve RFI issues before implementation, it is important to identify both existing and prospective new transmitters that may affect portions of the radio spectrum of interest to an observatory, keep up with changes in local licensing rules, and recognize trends in spectrum use. Spectrum monitoring may be used to identify nearby transmitters, to locate potential problems, and to perceive trends in the radio environment.

4.2 Local measures

Experience shows that observatories are themselves often significant sources of RFI. Computing hardware and electronic installations required for the telescope buildings generate harmonic and broadband emissions that can enter a telescope's detection system. Identification and elimination of interference from these sources is a high priority for every observatory. RFI-shielded cabinets and Faraday cages for electronics and computing equipment, as well as the reduction of human activity (remote observing) and limitations on the use of consumer electronics all contribute to making an observatory "radio-quiet" (Rogers *et al.*, 2005).

4.3 Pre-detection & post-detection measures

A standard method for excising RFI in the frequency domain is to install a bandpass or high/low pass filter in a receiver, which results in an insertion loss and substantially raises the system temperature at frequencies close to a band-edge. Super-conducting filter technology can significantly decrease the impact of such filters. Filtering of RAS bands serves to prevent damage due to strong signals outside the bands. It also results in data loss for continuum observations, though it is often essential to enable spectral line observations when RFI occurs at a critical frequency within a receiver's passband.

Much research has been applied to the design of robust receivers with a high degree of linearity, so that harsh RFI environments do not affect them. Broadband observations are possible when receiver systems are sufficiently linear that no aliasing occurs, no inter-modulation products are generated, and no overloading occurs (Weber *et al.*, 1997; Weber *et al.*, 2002; Clerc *et al.*, 2002, Tuccari *et al.*, 2004).

5 Spatial excision (nulling)

5.1 Multi-antenna systems

Every multiple-antenna array has sidelobes and nulls in its beam pattern that can be used to reduce signals from localized sources of RFI. Manipulation of the antenna outputs may create a spatial response null in the direction of incident RFI (Van Veen & Buckley, 1988). Such methods as a group are known variously as adaptive array processing, adaptive beamforming, statistically optimal beamforming, or adaptive cancelling. A variety of specific algorithms including maximum SNR, linearly constrained minimum variance (LCMV), subspace projection, Wiener filtering, and multiple sidelobe cancelling (Van Trees, 2002; Van Veen & Buckley, 1988) have been studied by a number of researchers for application to radio astronomical observing (Boonstra, 2005; Boonstra & Van der Tol, 2005; Bower, 2005; Ellingson, 2003; Ellingson & Hampson, 2002; Hansen *et al.*, 2005; Jeffs *et al.*, 2005; Landon *et al.*, 2011; Leshem *et al.*, 2000; Leshem & Van der Veen, 2000; Nagel, 2007; Raza *et al.*, 2002; Van der Tol & Van der Veen, 2005).

In general, an adaptive system using a beam-forming algorithm requires a high INR and is limited to a small number of RFI targets to be tracked during an observation. The RFI sources also need to remain stable and predictable through an observation. Spatial filtering in beam-forming mode for a limited number of RFI sources generally does not degrade the image generated by the main beam.

The basic technique is well known from its applications in military “anti-jam” communications as well as commercial cellular telecommunications applications (Liberti & Rappaport, 1999). In principle, the same techniques are applicable to radio astronomy. In practice, however, there are complicating factors. First is the fact that in radio astronomy, unlike traditional commercial and military applications, RFI is damaging even when the INR $\ll 1$. Thus, to be effective, null-forming algorithms must successfully detect and localize RFI at these levels. In contrast, RFI in commercial and military applications is typically not problematic until the INR is ~ 1 . For this reason, most null-forming algorithms developed in the context of military and commercial applications are based on the Wiener filter strategy (which includes so-called “power minimization” and “minimum variance” algorithms), which perform poorly for INR < 1 (Ellingson & Hampson, 2002).

It is known that techniques based on Wiener filtering are limited to reducing the INR in proportion to the INR; i.e. it is straightforward to suppress RFI to a level of an INR ~ 1 , and relatively difficult to reduce it further. Thus, to make such techniques effective for radio astronomy, additional measures are typically required to increase the apparent INR delivered to the mitigation algorithm; a few of these are discussed below. It is possible to improve nulling performance if auxiliary antenna signals are available to provide a direct look at the interferer with a higher INR (Briggs *et al.*, 2000; Jeffs *et al.*, 2005).

Radio astronomical observations depend upon the antenna performance (e.g. gain, beam profile, side-lobe distribution). Traditionally, this has been achieved by precise measurement and attention to ensuring that these parameters do not change with time. Variations in the sidelobe pattern may confound the self-calibration algorithms used to produce high-dynamic range images in aperture synthesis interferometry. Maintaining or at least knowing the variation in these parameters as the antenna beam and sidelobe pattern are modulated in order to mitigate interference is a challenge for the signal processing and antenna control systems now in widespread use.

5.2 Subspace projections

An alternative to traditional Wiener filter-based null-forming techniques is the class of techniques based on “subspace projections”. The basic idea in subspace projection is that interference can be identified in terms of correlations between the array elements, which in turn can be used to determine beamforming coefficients that result in patterns which reject the interference with little or

no effect on the main lobe characteristics. In mathematical terms, subspace projection is a two-step process of:

- identifying the eigenvectors of the spatial covariance matrix (the set of pair-wise correlations between elements) followed by;
- making the vector of beam forming coefficients orthogonal (the “projection” operation) to the eigenvector associated with the interference (the interference “subspace”).

Normally, it is assumed that the interference dominates the power received by the array, so that the interference subspace is always the one associated with the largest eigenvalue of the spatial covariance. This leads to problems when the interference is relatively weak, especially if the $\text{INR} < 1$ (Ellingson and Hampson, 2002). Nevertheless, subspace projection has been shown to have significant advantages for radio astronomy when properly employed (Raza *et al.*, 2002). Such techniques are not a panacea for the problem of poor detection and localization performance, but they do offer reduced distortion of the antenna pattern and, to some extent, behaviour that is easier to anticipate and modify. Distortion introduced by this class of techniques can even be corrected in aperture synthesis imaging as a post-processing operation (Leshem *et al.*, 2000). A method to eliminate beam pattern distortion in power spectral density estimation, while nulling a moving interference source, has also been demonstrated (Jefferies & Warnick, 2008b). Another type of bias distortion caused by nulling beamformers when the interferer is narrowband has recently been identified (Jefferies & Warnick, 2009).

Even though the null is intended to attenuate only signals from a single direction, the temporal spectrum of the SOI is “notched out” at the same frequency as the interferer using an algorithmic solution. It has recently been shown that if sufficient computational resources are available to store and process a several seconds window of data, much deeper nulls can be formed, even with rapidly moving interference, by fitting the time-varying interference covariance structure to a matrix polynomial model (Landon *et al.*, 2011).

In general, null-forming is most applicable to mitigation of RFI from satellites, and can be expected to be somewhat less effective against terrestrial RFI. This is because terrestrial RFI is often scattered by intervening terrain, and often arrives at the radio telescope as a dynamically-varying and complex wavefront with apparent direction of incidence spread out over a significant angular range. Traditional null-forming techniques are typically degraded in the presence of angle spread, and the problem gets worse with decreasing INR.

5.3 Post-correlation beamforming

An alternative to the implementation of spatial nulling in real time is to implement “post-correlation” beamforming. Particularly for sparse arrays, with relatively long baselines, correlation may be performed first and the beams synthesized afterwards. “Correlation” in this sense refers to the cross-multiplication of independent antenna outputs (e.g. polarizations, or separate antennas in an array), followed by averaging of the spectrum of the products. It is common for single dish radio telescopes to correlate to obtain Stokes parameters and for arrays of dishes to cross-correlate dishes as a step in synthesizing images. The same beamforming weights, which are used with the time series samples of the array output to form the beam, can instead be applied directly to the integrated correlations to obtain an effective total-power-per-beam-per-frequency-channel spectrometer result that is identical to an integrating spectrometer applied to the time series output of the adaptive beamformer. Assuming the RFI sources are localized, their suppression with this method is then achieved by processing short time intervals of the data stream, and applying complex weighting during image processing (Harp, 2005). Computer simulations of post-correlation spatial filtering show that cleaning with an RFI-corrected beam can be effective (Leshem & Van der Veen, 2000). Also included in this category are aperture synthesis imaging

techniques, which exploit the correlation products already available to similar ends (see Cornwell *et al.*, 2004 for a recent example).

This method is effective in total power or spectrometer observations, but not for time sequence dependent applications such as pulsar processing. It has the advantages that the same correlation computations can be used both to calculate the beamforming weights and then to compute the corresponding beamformer output power for those weights. This can all be done after the fact in post processing using stored, integrated correlations.

5.4 Reference antennas and reference beams

Auxiliary reference antennas can be cross-correlated with the primary antennas. As long as the auxiliary antennas receive the desired astronomical signals with very low SNR, it is a simple matter to correct the RFI-corrupted correlation products using the hybrid (telescope output correlated with auxiliary antenna) correlation products. The technique was first described by (Briggs *et al.*, 2000), and was later shown to be essentially equivalent to time-domain (“pre-correlation”) cancellation, with the exception that additional INR is obtained with no special effort through the integration of the correlation products.

Successful experiments using this approach have been done using one of the 14 antennas of the Westerbork Synthesis Radio Telescope as a reference antenna (Fridman & Baan, 2001). This technique shows great promise for the emerging generation of radio telescope arrays, for which it should be possible to synthesize high-gain auxiliary beams from the same antennas, as opposed to requiring additional “physical” antenna elements.

Correlators for modern radio telescopes are extraordinarily complex and expensive systems. So this approach requires a significant increase in the capacity of the correlator in order to compute the required additional correlation products and apply them to achieve RFI cancellation. Furthermore, the dynamic nature of most RFI signals limits the amount of integration that can be applied for effective use of this technique: “dump times” on the order of tens of ms may be required to mitigate satellite signals or signals which experience multi-path fading. The necessary increase in the capacity of correlators combined with reduced dump times may increase cost and complexity beyond practical limits, and the increased degree of data processing will result in some degree of data degradation.

Smart antenna techniques, using multiple sensors in radar and communication systems, are used to determine the direction-of-arrival and to implement beam-forming algorithms. Similarly, multiple-sensor, new-generation telescopes with a direct view of identified RFI sources (such as LOFAR and the Murchison Widefield Array) allow the beam-forming process to be optimized to include real-time, adaptive nulling and spatial filtering of these distinct RFI sources (Van Ardenne *et al.*, 2000; Bregman, 2000). In a practical implementation, one hundred LOFAR antennas were used to generate two separate beams, while placing a permanent null at one position 15 degrees above the horizon (Leshem *et al.*, 2000). Well-calibrated, multi-sensor, phased arrays offer the possibility of steering a null to track a satellite, while maintaining a high-gain beam on a target field (Fridman, 2005). However, the processing complexity increases rapidly when coping with a multi-satellite system.

Focal plane array (FPA) systems and multi-beam receivers provide new opportunities for spatial filtering, as each of the component feeds has an independent sky signal together with the common RFI signal (Boonstra & Van der Tol, 2005; Hansen *et al.*, 2005; Kocz, Briggs & Reynolds, 2010). In addition, one of the feeds in a multi-beam system can always be used as a reference antenna.

Overall, spatial nulling techniques remain largely untested due to their high complexity and the large engineering costs associated with development and implementation. Even in the most favourable situations, the data obtained will not be of the quality that would have been the case in the absence of interference.

6 Waveform subtraction

As adaptive noise cancellation (ANC) is often used in both communications and military technology, there is a considerable body of experience in the use of waveform subtraction algorithms (Haykin, 2001). The basic principle of temporal adaptive filtering is to make a FFT from the incoming data, perform an adaptation operation on the frequency bins, and then return to the frequency domain via an inverse FFT. This method, based on Wiener filtering, works for interfering signals with a significant INR, i.e. when the RFI dominates the system noise. The suppression of the interfering signal can be about equal to its instantaneous INR. Adaptive filters are effective when spectral information is unimportant, such as in pulsar (Kesteven, 2005) and continuum studies. An equivalent process can also be implemented in the frequency domain.

An optimal single-dish temporal cancellation algorithm involves the following steps:

Step 1: Detection and estimation of the RFI waveform.

Step 2: Synthesis of a noise-free version of the RFI waveform.

Step 3: Subtraction of the synthesized RFI waveform from the afflicted data.

This strategy was investigated first in the context of radio astronomy by Barnbaum & Bradley (1998), who used a “least mean squares” (LMS) algorithm with a technique based on Wiener filter principles. But the applicability of this technology to radio astronomy is limited by the need for an input $\text{INR} > 1$ in order to achieve significant benefit. To achieve an output $\text{INR} \ll 1$ using this method, it is usually necessary to implement some means to receive the RFI with an INR greater than the INR perceived by the primary instrument. One way to achieve this is to use a separate directional antenna to receive the RFI (Barnbaum & Bradley, 1998). Since most large dishes have a sidelobe gain that is approximately isotropic in the far sidelobes, the INR can be improved approximately in proportion to the forward gain of the auxiliary antenna used to receive the RFI. Thus, for example, a yagi with a 20 dB gain could improve the INR available to the cancellation algorithm by about 20 dB, which could then reduce INR at the telescope output by a comparable factor. Subsequent work (Jeffs *et al.*, 2005) describes the extension of this “reference signal” approach to achieve better performance against RFI from satellites by using multiple auxiliary signals from dishes with gains on the order of 30 dB.

Another perspective on this performance issue from a more theoretical viewpoint is provided by (Ellingson, 2002), who found that the suppression achieved by a cancellation algorithm is approximately upper bounded by the product of the input INR and L , the number of samples used to estimate the waveform parameters, assuming a noise bandwidth equal to the Nyquist bandwidth, and is otherwise scaled by the ratio of the noise bandwidth to the Nyquist bandwidth. So, for example, to suppress a signal with INR equal to -20 dB by an additional 20 dB requires analysis of at least 10 000 Nyquist-rate samples, and proportionally more if the noise bandwidth is less than the Nyquist rate. Of course, the signal characteristics must also be stationary over this timeframe, so this can easily become the limiting factor.

A limitation of cancellation techniques that employ auxiliary antennas to obtain a reference signal with high INR is that such techniques can easily degrade into excision. For example, a single-dish radio telescope combined with a high gain auxiliary antenna can behave as a two-element array, with the result that the cancellation algorithm may synthesize a pattern null in the direction of the RFI, with the same consequences as those described above that are associated with null-forming. Yet another consideration is that it is a potentially onerous task to localize and point reference antennas for every source of RFI that affects an observation.

An alternative temporal cancellation approach that avoids these difficulties is to synthesize distinct reference signals directly from the telescope output itself, by exploiting *a priori* knowledge of the modulation characteristics. For example (Ellingson *et al.*, 2001) demonstrated a technique for mitigation of RFI from a GLONASS satellite by partially demodulating the signal and then

re-modulating the result to obtain a noise-free estimate of the RFI. They demonstrated a reduction of the INR by more than 20 dB despite the fact that the RFI was received with INR on the order of -20 dB. In this case, the INR “deficit” was overcome by the effective increase in INR associated with the process of demodulation. It should be noted that this same technique could also be used to further improve the INR obtained by using auxiliary antennas.

Unfortunately, signal modulations of the type used by GLONASS (i.e. direct sequence spread spectrum) represent only the “low hanging fruit” with respect to one’s ability to obtain large INR improvements through partial demodulation. Most other signals do not exhibit such large improvements with similar processing, and less can be done if the modulation is analog or has unknown structure. For example, work by (Roshi, 2002) on a similar strategy for analog TV signals achieved only about 12 dB suppression despite beginning with an initially large INR, and work by (Ellingson & Hampson, 2002) demonstrated suppression on the order of 16 dB against radar pulses using an estimate-synthesize-subtract strategy. A recent implementation of adaptive filtering techniques aims to remove the signature of the L3 transmission from a single GPS satellite at the Arecibo Observatory (Nigra *et al.*, 2010).

This cancellation methodology has also been used effectively with multi-feed or focal plane arrays on single dishes. A variation on adaptive filtering is to subtract a reference data-channel from a signal data-channel using a copy of the RFI itself, by comparing on-source plus RFI and off-source plus RFI signals.

In summary, while nominally more desirable than excision, temporal cancellation involves a significant risk that the waveform is not properly estimated, and therefore not completely removed when the synthesized waveform is subtracted. Whereas the performance of excision is limited primarily by one’s ability to detect RFI, the performance of cancellation is limited primarily by one’s ability to estimate the RFI waveform. The price paid for the benefit of the “look through” capability offered by cancellation is performance that is potentially limited and less-robust than comparable excision techniques. Yet, innovative and useful work continues in this area: the productive use of adaptive cancellation has been demonstrated in pulsar astronomy (Kesteven, 2005), and the use of real-time hardware has been demonstrated for implementing adaptive cancellation (Poulsen, 2003).

The ability to cancel interference by waveform subtraction is limited by the quality of the cancellation waveform as an estimate of the interference waveform received by the radio telescope. Any shortcoming in this estimation process results in some degree of data degradation.

7 Anti-coincidence methods

Instead of mitigating RFI, anti-coincidence techniques detect its presence in data. These techniques exploit the fact that widely-separated antennas perceive astronomical signals identically, but RFI differently. The primary use of this technique is in searches for astronomical transients, which are otherwise severely limited in practice by impulsive RFI. Depending on the range of the interfering signals, separations on the order of hundreds of kilometres may be required: this is of course an awkward strategy to use, except in the rare cases where similar telescopes are suitably separated while sharing the same field of view. Cancellation cannot be perfect, and residual random fluctuations do result in data degradation. Nevertheless, this technique has been successfully applied to all-sky transient searches (Katz, 2003) and to searches for one-time “giant” pulses from pulsars (Bhat *et al.*, 2005).

8 Temporal excision (blanking and flagging)

8.1 Temporal blanking

Temporal blanking is perhaps the oldest and best-known strategy for real-time mitigation of pulsed RFI, which is used as a response to ground-based aviation radars operating in the 1 215-1 400 MHz band. These typically transmit pulsed fixed-frequency or chirped sinusoidal waveforms with pulse lengths of 2-400 μ s with 1-27 msec between transmitted pulses and bandwidths on the order of 1 MHz.

These pulses are often detectable through the sidelobes of radio telescopes situated hundreds of kilometres away. Although the transmission duty cycle is relatively low (typically less than 0.1%), accurate blanking is made difficult by the short interval between pulses, as well as by multi-path reflections from terrain features and aircraft generate additional copies of the pulse, which arrive long after the “direct path” pulse (see, e.g. appendix of [Ellingson and Hampson, 2003]). It is common for multi-path pulses to be strong enough to corrupt the astronomical observations even though they are too weak to be detected reliably. Thus, a blanking interval triggered by a detected pulse must typically be many times longer than the detected pulse, in order to ensure that all of the multi-path copies are blanked. Blanking intervals with lengths up to 100’s of microseconds (i.e. 10-100 times the pulse duration) are typically required (Ellingson and Hampson, 2003).

A number of real-time techniques for temporal blanking or cessation of the data-taking process have been developed to various degrees (Fridman, 1996; Weber *et al.*, 1997; and Leshem *et al.*, 2000). The National Astronomy and Ionosphere Center (NAIC) has developed a device for real-time mitigation of strong pulses from the local airport radar at the Arecibo Observatory (Puerto Rico). This works by tracking the arrival time of the leading edge of the pulses, and then blanking the output of the receiver in a time window around the expected pulse arrival times, tailored to encompass the consequent radar artifacts from terrain and multi-path scattering. More recent work in this area, including experimental results, is described in Ellingson & Hampson (2003), Fisher *et al.* (2005), and Zheng *et al.* (2005), with the last two references addressing the similar problem of pulsed interference from aviation distance measuring equipment (DME).

The primary limitation for the blanking approach is detection performance, since an RFI pulse is detected, it can be completely removed by blanking. However, it is inevitable that some fraction of weak pulses will not be detected. Over the time-scale of a single pulse, however, astronomical signals routinely have a signal-to-noise ratio (SNR) $\ll 1$, so RFI must be reliably detected at these levels in order to be effectively suppressed in the integrated output.

This is quite difficult: the recent successes cited above are attributable to detailed advanced knowledge of the RFI waveform, which is used to compensate for an inadequate SNR in detecting the radar pulses.

Further improvements in detection performance appear to be feasible using aspects of the RFI waveform that can be exploited without specific knowledge of the waveform. Thus cyclo-stationarity has been applied by Britteil & Weber (2005) to the HIBLCO2 (Iridium) Satellite signals, while Dong *et al.* (2005), have applied Kalman tracking to aviation radar, which also improves detection performance at lower interference to noise ratios (INR). Another challenging problem is presented in determining exactly how to set detection thresholds and blanking window lengths so as to achieve an acceptable tradeoff between robust RFI mitigation (which suggests low thresholds and long windows) and limiting degradation of sensitivity and the introduction of blanking artifacts (which suggests high thresholds and short windows). This problem was studied by (Niamsuwan *et al.*, 2005). Nevertheless, “blanked” time is lost observing time that requires an increase in the observational time to achieve the desired sensitivity.

8.2 Antenna-based digital processing

Real-time digital processing may be implemented as part of the IF processing of a single-dish radio telescope (RT), and as part of the station processing and/or beamforming process for array instruments. This cost-effective method works well for impulsive (transient) RFI and requires fast data sampling as well as the availability of sufficient computing cycles at each of the stations (Fridman & Baan, 2001; Niamsuwan *et al.*, 2005; Ellingson & Hampson, 2003). The amount of data loss is determined by the transient nature of the RFI. Real-time, IF-based flagging and excising minimizes the data loss incurred by the flagging – excision method by only dealing with the RFI-infected time and frequency segments; this should not inflict collateral damage on neighbouring time and frequency intervals. This differs from post-correlation processing (next section), which is more vigorous as integrated data samples are used for baseline and antenna flagging and excising. Thresholding in both the temporal and frequency domains may be applied when the RFI in sampled data is strong and identifiable, and the spectral occupancy of the RFI is relatively low. Thresholding was first used to remove RFI at the Ratan 600 m telescope (Berlin & Fridman, 1996). A recent application was at the Westerbork Synthesis Radio Telescope (WSRT), where 20 MHz dual-polarization IF data from each of the fourteen telescopes was processed in real-time (Baan *et al.*, 2004; Baan *et al.*, 2010). This thresholding method has also been applied to pulsar data prior to period folding (Fridman 2009; Fridman, 2010).

Another form of sub-space excision exploits the probability distribution analysis of signals. Since the RFI contribution changes the power spectrum to a non-central (chi-square) distribution, as determined by its higher moments, it can be removed from data (Fridman & Baan, 2001; Fridman, 2001). A similar approach exploits kurtosis (4th moment of the power spectrum) to identify and remove the RFI component. Kurtosis has been used as the RFI discriminant for single-dish real-time solar observations by Nita *et al.* (2007), & Gary *et al.* (2010), and by (Deller 2010) for post correlation processing in a software correlation environment. Median filtering and taking advantage of the median properties of a multi-feed system, also exploit the statistical properties of data and are effective in the real-time mitigation of RFI in spectral-line data (Kalberla, 2010; Flöer *et al.*, 2010).

Pre-correlation mitigation methods that involve the removal of data samples necessarily change the gain calibration of data. So the use of these methods requires accurate bookkeeping to determine their effect on data and associated data loss. On the other hand replacing affected data in the frequency (or time) domain with a fitted baseline only affects the rms of affected channels.

8.3 Digital excision at correlation

As part of the correlation process, digitized data are generally integrated over time intervals ranging from the sampling time up to seconds, which significantly raises the INR. In consequence, persistent but weak RFI, that could not be treated in real-time, and weak (spectral) remnants of earlier mitigation operations become accessible for processing. On the other hand, significant peaks of a time-varying RFI signal may also be reduced in strength by the integration process. For array instruments, spatial filtering resulting from delay (fringe) tracking of a celestial source also reduces the strength of terrestrial RFI in cross-correlated data.

At this point in the data taking process, anti-coincidence protocols may be incorporated to identify the RFI components, as well as digital mitigation processing and the utilization of data from a reference antenna. New generation software correlators permit the integration of kurtosis-based flagging applications before and after FX (Fourier Transform before multiplication) correlation and stacking protocols (Deller, 2010). Mitigation at several processing stages is being implemented for LOFAR (Bentum *et al.*, 2008). In the case of single-dish instruments the correlation processing of (multiple) single bands may incorporate both thresholding or statistical methods and noise cancellation with a reference antenna.

Subspace filtering methods may also be implemented in a digital correlation system to search for a particular signature in the RFI power component of data in order to identify and remove it. A particularly successful application is the search for cyclo-stationarity within data, which works well for digitally modulated RFI signals (Weber *et al.*, 2007; Feliachi *et al.*, 2009, 2010).

Deploying digital processing and input from reference antennas during software correlation is equivalent to their use in baseband pre-correlation processing. But the implementation of these algorithms into pre-existing hardware backends requires the addition of both special hardware and software.

8.4 Post-correlation – Before or during imaging

Traditional post-correlation processing consists of flagging and excising, which is time consuming and often done by hand (Lane *et al.*, 2005). Because this operation is performed on integrated and correlated data, the data loss resulting from flagging can be quite significant, the more so as whole time-slots, whole baselines, and/or whole antennas may be flagged. This differs from antenna-based IF flagging or excising where small subsets are flagged, which inherently results in a smaller proportion of data loss overall.

On-line or off-line processing of (integrated) correlated data makes it possible to incorporate automated flagging and excision (Middelberg, 2006; Offringa *et al.*, 2010, 2012; Keating *et al.*, 2010; Sirothia *et al.*, 2009ab), as more sophisticated statistical or sub-space processing (see § 8.2) can be implemented to remove the RFI component without as much data loss.

Indeed, a reference antenna has been implemented at the post-correlation stage to remove the signal from a well-defined RFI source using the available closure relations (Briggs *et al.*, 2000).

Array instruments employ fringe-stopping and delay-compensation techniques to keep a zero fringe rate at the central observing position during observations. As a result the stationary (terrestrial) and satellite RFI components in data distinguish themselves by fringing faster than components from astronomical sources. This distinctive (relative) motion allows the off-line identification and elimination of stationary RFI sources from both the correlated data and the image plane without causing data loss (Wijnholds *et al.*, 2004; Cornwell *et al.*, 2004; Athreya, 2009). The coding for this operation from the GMRT is now incorporated into AIPS (Kogan & Owen, 2010).

9 Implementation at the telescopes – A strategy

The data acquisition process of radio astronomy observatories is evolving to cope with the rapidly changing technological environment. Analog to digital conversion of signals now occurs as early as possible in the data-handling scheme, which allows digital processing throughout most of the data chain. Increased instrumental capabilities allows for the processing of larger bandwidth data, with higher time-resolution and higher frequency (< kHz) resolution.

Many current backends do not allow the implementation of mitigation at early stages of the data handling chain without incurring (severe) hardware modifications. By contrast, new-generation backends and software correlation facilitate such schemes at different stages of the processing.

Since every mitigation method requires a definite INR threshold for its operation, removal of most of the RFI requires a layered application of methods to exploit the progressive integration of the data and its increasing INR. While no method can remove RFI below the noise floor it encounters, subsequent mitigation steps may remove remnants of the mitigated RFI, as well as weak RFI that is only apparent after integration.

The implementation of auxiliary antennas for array instruments depends on the possibility of incorporating their output into the processing system (most particularly) at the correlator. Directed reference antennas generally cope with particular RFI sources and are less effective in a complicated environment.

Human intervention in the RFI mitigation process currently plays an important role in practical operations. Thus real-time on-line processing that is adaptable to a variety of RFI signatures may be preferred to the restrictive use of reference antennas and/or spatial filtering for known and fixed transmitters. This is likely to be the case until an artificial intelligence controller can be invoked to guide and dictate the RFI mitigation scheme.

Interferometers are less vulnerable to RFI. Fringe-stopping and de-correlation by delay compensation provide for its natural suppression on the longer baselines. However, strong RFI still adds to the system noise, and still affects the calibration and the complex visibilities of a station. VLBI stations and distributed sensor networks can implement mitigation at every individual station to reduce the impact of local RFI on the whole system.

To correctly calibrate a system, accurate bookkeeping is required for all affected data in order to obtain the correct weights for later self-calibration, cleaning and imaging procedures.

Future mitigation implementations need to consider more sophisticated methods than the simple (kurtosis or other) RFI flagging and excising algorithms that are generally current at this time. The use of statistical methods using higher moments opens the possibility of removing RFI components without affecting the rest of the data, and there are methods that allow partial restoration of data that reduce data loss. Adaptive filtering of spread-spectrum systems may become possible when their digital keying schemes are known.

10 Conclusions

RFI mitigation technology appears to offer significant benefits to radio astronomy, but more work remains to develop technology that is practical and applicable in routine operations. It also seems clear that RFI mitigation technology cannot be regarded as a standalone fix for the external RFI problems experienced by present day and future radio telescopes. Inevitably, the effectiveness of any given technique depends on:

- the architecture of the instrument or its configuration for a particular observation;
- the observing mode (e.g. spectroscopy, continuum, aperture synthesis imaging, pulsar dispersion searching);
- the nature of the RFI itself (e.g. persistent or intermittent, spatially coherent or scattered by multi-path, etc.);
- availability of resources needed to implement computationally intensive algorithms;
- the comfort level of astronomers to use these new techniques. Since many methods do not have an established track record, most scientists are reluctant to risk precious observing time to try new algorithms that could affect their data sets in unknown or unfamiliar ways.

Mitigation merely reduces the degree to which data are degraded or obliterated by interference, and increases operational costs. The near-term path to bring RFI mitigation into practical use is for researchers in signal processing to work together with astronomers to identify specific, high-value science observations which currently cannot be undertaken due to RFI, for which mitigation algorithms can be applied and tested. It should be noted, however, that no, single technique can address all possible scenarios for radio astronomy observations, nor is one thought to be possible.

Both on-line and off-line data processing has been successful in mitigating the RFI environment of radio astronomy observatories. While there is an increasing variety of successful mitigation options, the choice of method depends strongly on the RFI characteristics, the type of radio telescope, and the type of observation. In particular, on-line real-time data-processing may be preferred in a variable RFI environment, while special measures such as reference antennas and spatial filtering may be preferred for known and fixed sources of RFI. In addition to these factors, the absence of human involvement may also render automated on-line processing a more attractive option.

No universal method exists for mitigating RFI in astronomical data and no method can identify or remove RFI within the noise of the system. The effective suppression of RFI depends on the INR and its temporal and spectral characteristics. A quantitative evaluation of the method used is not always possible because mitigation algorithms are generally non-linear processes that also affect the noise characteristics and the gain calibration. The toxicity of the method used, i.e. the negative effect of its invocation on data by the deployed method, and the amount of data loss resulting from the method, are other factors that guide the evaluation of the choice of method.

Multiple methods need to be applied to deal with a more general RFI environment. Because RFI characteristics change after each mitigation step and with increasing integration of the data, the cumulative effect of RFI mitigation at subsequent stages is not a linear sum of what each method can do, but rather the sum of what is practical and possible at each step.

The cost of computing hardware capability and of digitizing components at radio astronomy observatories is rapidly changing. Both upgrades of existing facilities and the introduction of newly constructed instruments provide opportunities for implementing and automating RFI mitigation algorithms. These capabilities also permit increased bandwidth, higher time resolution, and higher spectral resolution. The resulting, increasingly large data volumes will force the introduction of automated data reduction pipelines. Future data volumes are likely to force the acceptance of automated RFI mitigation at radio observatories.

New telecommunication and broadcasting technologies are reaching the market place, many in the form of unlicensed mobile devices. Since their ever-changing locations are impossible to control, they will rapidly affect observatory operations. Algorithmic research is needed to eliminate their signals from astronomical data. In particular, spread spectrum (ultra-wide band) devices will pose problems for passive services, as their digital modulation schemes do not respect the boundaries of spectrum allocations. Current estimates suggest that the number of transmitting devices used by each person is set to increase dramatically and many of these will rely on dynamic spectrum access.

The discovery space for radio astronomy is determined to a significant degree by the technical characteristics of the observing system and by limiting factors such as the RFI environment. While new generation telescopes are located at the most pristine possible sites, existing facilities must coexist with their local conditions. In order to prevent RFI becoming the limiting factor for existing facilities, spectrum management, both internal and external, has to be accorded a very high priority. Both observatory management and astronomers should regard RFI issues as critical.

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