Interference Mitigation in Radio Astronomy

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Abstract

This thesis investigates techniques and algorithms for mitigating radio frequency interference (RFI) affecting radio astronomy observations. In the past radio astronomy has generally been performed in radio-quiet geographical locations and unused parts of the radio spectrum, including small protected frequency bands. The increasing use of the entire spectrum and global transmitters such as satellites are forcing the astronomy community to begin implementing active interference cancelling. The amount of harmful interference affecting observations will also increase as future instruments such as the Square Kilometre Array (SKA) are required to use larger bandwidths to reach up to 100 times the current sensitivity levels, and as spectral line observations require observing in bands licensed to other spectrum users.

Particular attention is paid to interference cancellation algorithms which make use of reference beams. This has proven to be successful in removing interference from the contaminated astronomical data. Reference antenna cancellers are closely analysed, leading to filters and techniques that can offer improved RFI excision for some important applications. It is shown that pre- and post-correlation reference antenna cancellers give similar results, and an important aspect of the cancellers is the use of a second reference signal when the reference interference-to-noise ratio is low. These modified filters can theoretically offer infinite interference suppression in the voltage domain, equivalent to that of post-correlation interference cancellers, and their internal structure can offer an understanding of the residual RFI and added receiver noise components of a variety of reference antenna techniques. The effect of variable geometric delays is also considered and various filters are compared as a function of the geometric fringe rate.
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Statement of Originality

This thesis describes work carried out between 2000 and 2004 in the Department of Astrophysics at the University of Sydney and at CSIRO's Australia Telescope National Facility. Three months were also spent at the Radio Astronomy Lab of the University of California at Berkeley in 2001. The work presented in this thesis is my own, except where specifically acknowledged. Many of the ideas expressed came from discussions with my supervisors and other collaborators, and here I will outline specific contributions.

One of the aims of this thesis is to provide a cohesive review and comparison of interference mitigation techniques and to formulate the problem with respect to radio astronomy in a single framework. While many of the interpretations and modifications are mine, most of the mathematics behind the various techniques come from the literature. All of the simulations and data processing were carried out by me (except for built-in MATLAB functions such as Fast Fourier Transforms and Eigen and SVD decompositions), although all of the genuine voltage data from the ATCA is from Bell et al. (2001). Also:

- The RFI survey from section 3.1 was performed by me and Robin Wark from the ATNF, and I analysed most of the data using the methods and pre-existing software described in McKay (1997). The case study in section 3.3 was performed by me and the initial interpretation of the processes occurring involved Mike Kesteven, Bob Sault and Lawrence Cram. Identification of the RFI source was aided and confirmed with the assistance of Aaron Gosschalk from the Australian Communications Authority and Simone Buck from Vodaphone.

- Most of chapter 4 involves reviewing and developing spatial filter theory based entirely on previous work. The discussion relating to the projection modification leading to (4.44) in section 4.3.2, came from my investigations, however I later found similar comments in Leshem and van der Veen (1999a). The investigations in 4.3.3, as well as all other simulations were all performed by me using MATLAB The Mathworks, Inc. (1998).

- Chapter 5 contains a fair amount of background and original work. Most of the single reference signal theory is from the literature, restated in the framework of the thesis. However the investigations into the residual components, for example
given in (5.32) and derived in appendix A were all my own. All of the analyses of
dual-reference pre-correlation cancellers were mine, including 5.5.2, 5.6 and 5.8.1,
although many useful early discussions on the meaning of the cancellers was had
with Mike Kestone, Geoff Bower and Bob Sault. Similar investigations were
also being carried out independently by Frank Briggs (for example Briggs and
Kestone, 2002). The post-correlation technique in section 5.10 was originally
developed by Briggs et al. (2000).

• All of the analyses in chapter 6 are mine, although some of the algorithms were
developed in earlier chapters based on existing literature.
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Chapter 1

Introduction

From a cosmic source of electromagnetic radiation — for example a galaxy consisting of objects such as gas and dust clouds, stars and black holes — we receive on Earth information covering the entire electromagnetic spectrum. While most people are familiar only with the visible optical sky, there is an enormous amount of information in other spectral regions. Of particular note here is the radio spectrum from frequencies of 10s of MHz up to 10s of GHz (metre wavelengths down to millimetre wavelengths). Much of the information seen at radio frequencies is a result of entirely different emission processes than seen at other wavelengths. For example, light from stellar photospheres often dominates in the optical case, while radio waves come from processes such as synchrotron radiation from high energy particles spiralling into magnetic fields, pulsars (beams of photons emitted by neutron stars), and the cosmic microwave background (see, for example, Verschuur and Kellermann, 1998). Radio astronomy has the advantage of being able to see through much of the dust that obscures optical observations. However, as in the optical case, other strong electromagnetic sources can interfere with radio observations and obscure a cosmic source; a good example in both regions of the spectrum is solar interference.

1.1 Radio Frequency Interference (RFI)

Radio observations are seriously affected by human-generated interference. This interference can be local to the observing facility, for example from digital computing equipment and internal clocks, or it can be external, for example satellite navigation downlinks, television and FM radio broadcasts. There is a large range of external signals that interfere with radio telescopes, see for example, Goris (1998); Ekers and Bell (1999); Fridman and Baan (2001). All interference in the radio spectrum is collectively referred to as radio frequency interference (RFI).

One thing to note early on — since it is at the heart of the issue — is that the interference is in one way or another different from the cosmic sources that we wish
to study. In the past, and to a large extent still to this day, one could avoid much interference by observing in unused or protected bands (important frequency bands such as the band surrounding the emission frequency of neutral atomic hydrogen (HI), 1400-1427 MHz, or the hydroxyl (OH) maser line emissions, 1610.6-1613.8, 1660-1670, and 1718.8-1722.2 MHz, are protected by the International Telecommunications Union, see International Telecommunication Union 1995 or Committee on Radio Astronomy Frequencies 1997), or by building observatories in radio-quiet locations such as valleys which block radiation at the horizon. However, the ability to look further back to the high redshift universe means that spectral lines no longer fall in the fixed narrow protected bands, unused bands are becoming rarer (in the past radio astronomers moved to higher frequencies, but that trend is constantly being followed by other users of the spectrum), and transmissions from satellites make it much more difficult to find radio quiet locations, so it is becoming increasingly more difficult to make observations.

At the same time as the communication revolution progresses and interfering signals engulf more of the radio spectrum (both in density and coverage), future radio telescopes such as the Square Kilometre Array (SKA) are being designed to reach sensitivity levels that are orders of magnitudes below those of current instruments. In many respects the advancement and proliferation of radio technologies is essential for reaching the goals of these next generation observing facilities. While the signal-to-noise ratio of many types of RFI signals is likely to remain fairly constant, since the antenna side-lobe levels through which most RFI signals enter astronomical receivers today will be similar for the next generation of facilities with large collecting areas, the sensitivity limit for cosmic signals in the primary beam will be much lower than they currently are, and weak interference which is below the noise level of current observations will be revealed and could limit many of the advantages which these new facilities offer.

In general, astronomical observations are affected in two main ways. Spectral line observations (of, for example, emission lines, absorption lines, or in a sense structure in the cosmic microwave background radiation) require measuring spectral features which may be located over a large range of the spectrum (and the frequency at which the detail occurs is usually extremely important). If the detail happens to overlap with the interference, interpreting the observation may be impossible. Continuum observations of cosmic sources with intensities that are approximately constant over frequency require collecting data over large bandwidths to reach the required sensitivity levels. This means that astronomers need to detect across a large amount of RFI-contaminated spectrum. Future radio telescopes (and some upgrades of current instruments) must have mechanisms to deal with RFI if these problems are to be overcome.

If one wants to remove the RFI from the collected data samples, it is important to know what the form of the RFI is: Is it narrow-band or wide-band, continuous in time or impulsive, strong or weak? Knowing these parameters can make the difference between recovering most of the cosmic signal from the RFI and recovering nothing. To know what sort of interfering signals are being encountered it is important to survey regularly or monitor the local RFI environment (Fridman and Baan, 2001). RFI surveys offer a
glimpse at the spectrum and may allow one to observe in the most radio-quiet band (see section 3.1). For more detailed research on RFI, emissions from common sources of interference can be recorded and analysed. This has been happening for several years and raw voltage data containing various types of RFI have been collected and archived from several radio astronomy facilities around the world. This “RFI Atlas” is part of a software radio telescope project which allows various RFI mitigation algorithms to be tested and compared off-line with real astronomical data (see Bell et al., 2001).

Interference generated locally at the observing facility frequently originates in the actual observing and processing equipment, and has the form of narrow-band signals at the frequency and harmonic frequencies of the digital equipment (there are exceptions such as observatory cars and microwave ovens which might cause more broad-band interference). Of course, steps will have been taken to shield or remove local sources of interference where possible, and the main focus in this thesis will be on external interference. There are many different types of human-generated external interfering signals, which enter and affect the receiving system in a variety of ways. A good overview with a radio astronomy perspective is given in Goris (1998). Two types of particularly challenging transmissions of increasing concern are those from satellites (which decorrelate during integrations in arrays but are nevertheless hard to avoid at any geographical site and can be close to the primary beams) and weak spread-spectrum signals (which can look much like cosmic signals and may not be detectable until after long integrations). The way in which different types of interference affect an observation is of course dependent on the instrument, as described below.

1.2 Types of Observations

While the types of interference can be quite varied, there are also a number of different types of observations, for example those described in radio astronomy texts such as Thompson et al. (1986), Taylor et al. (1999), and Smolders and Haarlem (1999). As well as classifying observations based on the target astrophysical objective (for example, spectral line or continuum), they can be classified based on the type of observing facility used, for example; a single dish, a phased array, an interferometric (or synthesis) array, or a very long baseline interferometry (VLBI) array (e.g. Fridman and Baan, 2001). These are loosely listed in order of decreasing susceptibility to RFI, and briefly discussed below.

- Single dish observations typically measure the total power received at the antenna feed. Any RFI will be 100% present in the output power and thus single dish observations give the worst-case scenario for harmful RFI, Thompson et al. (1986). Single antennae have some natural defences against RFI. For example, there is some chance that the RFI is in the antenna side-lobes, the receiver polarisation might not match that of the RFI, and most transmitters are a long distance away and obscured by terrain. These are defences available for the antennae used for
the other types of observations. The main defence against interference is that the main beam sensitivity can be many orders of magnitude greater than the gain of the side-lobes through which the RFI enters. Of course, this is a very simplistic view of single dish astronomy. There are observing modes and instrumentation that do tend to reduce the effects of RFI in single dish observations, as well as techniques to actively confront the RFI, some of which are discussed in later chapters.

- Phased-array observations in the simplest case measure the total power of the sum of the voltages from an array of feeds, phased so that signals from a particular direction are added (this is known as beamforming or a tied array). The beam of the phased array is smaller than the individual antenna beams, however if small single dishes are used in the array, the beam size may be comparable to that of a large single dish. The main advantage of phased-arrays, apart from the adaptive beamforming techniques discussed in chapter 4, is that moving sources are constantly changing their positions and therefore require steady adjustment of the phases required for beamforming. Since sources of RFI are usually moving relative to the cosmic sources being tracked, their signals will suffer decorrelation in the output power. Signals with large bandwidths will also decorrelate due to differential phase delay across the band as the signal travels from one antenna to the next.

- Synthesis array observations also measure the power in beams, specifically the cross-correlation of voltages from pairs of antennae. These represent points on the plane that is the 2-dimensional Fourier transform of the sky. Once an adequate number of points has been collected, the Fourier transform plane can be transformed to form the sky image (the total power of many beams on the sky; see, for example, Thompson et al., 1986, or chapter 2). Signals from sources moving relative to the cosmic sources or with large bandwidths decorrelate for synthesis arrays in the same way that a tied array will decorrelate.

- VLBI arrays are synthesis arrays with the antennae separated by hundreds or thousands of kilometres. Most sources of interference are local to individual antennae, and so will not add correlated power to the cross-correlations. RFI results only in an increase in the system noise level, Thompson et al. (1986). For signals that do reach a pair of antennae, for example satellite signals, the motion of the transmitter relative to the cosmic sources during a correlation and the bandwidth will usually completely decorrelate the signal (both types of decorrelation are functions of antenna separation).

One should note that with arrays, individual antennae need to be calibrated for gain and phase. This will be compromised in the presence of RFI, Fridman and Baan (2001).
1.3 Methods for Excising RFI

Ekers and Bell (1999) list a hierarchy of strategies for removing interference from astronomical observations. The list begins with removal of the interference before it is generated, for example locating and shielding self-generated interference. One can also negotiate with the users of interfering signals and attempt to find a compromise (for example, since many proposed arrays will have optical fibre running underground for hundreds of kilometres, it has been suggested that users of radio links near the remote sites could replace much of their radio usage with a higher quality fibre connection). Another step towards avoiding interference is moving to the most radio-quiet location and frequency. This may include standards being set down for, and the creation of, protected frequency bands and geographical regions (radio quiet zones). Further steps to take in avoiding interference include using front-end filtering to block known sources of strong interference which will drive the receivers into non-linearity, and blocking particular directions, for example the horizon.

After all avenues for avoiding interference have been taken, steps for removing as much of the remaining interference as possible (under various constraints) need to be taken. To do this successfully robust receivers that will remain linear and continue to digitise the noise in the presence of strong interference are required, otherwise the astronomy signals will be lost during sampling (see, for example, Gough 2001). When an observed data sample is contaminated with interference, it is sometimes possible to find dimensions of the observing parameter space (for example, time, frequency, direction of arrival, polarisation) in which the interference differs greatly from the cosmic sources being observed. An example which is used in all telescopes is passband filtering, which stops signals from all parts of the electromagnetic spectrum that are not in the band of interest, although out of band emissions can be a problem. Other techniques that deal with signals in the passband are discussed below.

The first group of techniques involve data blanking or data clipping. Two parameters that are commonly blanked are frequency (for example, notch filters) and time. These techniques involve performing a statistical analysis of the data samples and removing those that contain RFI, revealed through significant departure from the average properties (see, for example, Leshem and van der Veen 1999b; Leshem et al. 2000; Fridman and Baan 2001; Fridman 2002). Blanking in the frequency domain involves removing contaminated spectral channels from a data set and therefore can work well for narrow-band signals (that is, much narrower than the overall observing bandwidth). It is particularly suited to observations of continuum sources, where, in the absence of interference, the background statistics are slowly varying with frequency. Blanking in the time domain is used to eliminate pulsed signals such as radar and many communication signals. It often involves removing voltage samples with amplitudes greater than a set threshold. To minimise the amount of astronomy signal that is thrown away, one can blank the data in the combined time-frequency domain (i.e. perform time blanking in individual spectral channels). Fridman and Baan (2001) give examples of both forms of blanking, and for their applications, time-frequency domain thresholding for
continuum sources works well when less than 5-10% of the data is contaminated. When interference is removed by blanking, contaminated samples are simply discarded (one could replace them with random noise which has similar statistics to the neighbouring samples, but the astronomy signal is still thrown away). However, it is possible to transform the data so that the part of the data set that is orthogonal to (i.e., uncorrelated with) the RFI contains a greater fraction of the astronomy signal. An example is the Fourier transform, where narrow-band interference is contained in a few spectral channels. Other techniques are briefly mentioned now, expanded on in section 1.4, and form the bulk of the thesis.

One category of techniques, commonly referred to as spatial filters, applies to phased arrays and is the focus of chapter 4. The application of spatial filters can be broken up into “null steering” (discussed in section 4.2), where the voltage response of the antennae are orthogonalised in space to the interference, and the post-correlation version known as “subspace projections” (discussed in section 4.3), where the spatial covariance matrix of the antennae voltages is transformed so that it is orthogonal to the interference (the spatial covariance matrix contains the auto and cross correlations of the voltages from all of the antennae in an array). An overview of adaptive beamformer applications can be found in Widrow and Stearns (1985). Specific radio astronomy applications can be found in, for example, Smolders and Hampson (1999), Welch and Dreher (1999), Ellingson and Cazemier (2003), Ellingson (2003) and Bower (2001b). An overview of subspace projections can found in Leshem and van der Veen (1999b) and Leshem et al. (2000).

A fundamentally important concept reinforced in this thesis is the fact that spatial filtering is similar to, and in some cases identical to, forming a second beam towards the interference which, appropriately scaled, is subtracted from the main beam leaving the required null in the beam pattern. Similar are the techniques that use auxiliary reference antennae with zero gain towards any of the cosmic sources of interest to form the beam response to the interference, resulting in minimal effect on the primary cosmic beam. As with spatial filters, reference antenna cancellers are applicable to interference subtraction from the antennae voltages (“adaptive noise cancelling” discussed in section 5.3), or subtraction from the antennae covariances (“post-correlation cancelling” discussed in section 5.9). An overview of voltage domain cancellers, and current applications, can be found in Widrow and Stearns (1985), Haykin (1996), and Solo and Kong (1995). For example, the acoustic signal from a microphone placed near a pregnant woman’s heart has been used as a reference signal to cancel her heartbeat from the primary acoustic signal from the fetus. Examples of applications in radio astronomy can be found in, for example, Barnbaum and Bradley (1998) and Bower (2001a) for adaptive noise cancelling, and Briggs et al. (2000) for post-correlation cancelling.

Post-correlation methods are extremely important because they are applied on time scales of 10s or 100s of milliseconds, rather than time scales of 10s or 100s of nanoseconds (the astronomy signal is random noise which has important statistics, but unimportant modulation). However, since time domain techniques are applied on much
shorter time scales they are able to deal with signals that have fast changing statistical properties. There are also other ways to form the interference reference signal, such as fitting the voltages to parameters of a known interferer (e.g. Ellingson et al. 2001 and Ellingson and Hampson 2003). At a more fundamental level, robust statistics can be used which are less susceptible to RFI (as a simple example taking the median of a data set is affected less by strong interference than taking the mean). These topics are outside the scope of this thesis, and left for future work. The topics which are covered in the thesis and some of the important results are now reviewed.

1.4 Thesis Outline and Summary

This thesis is focused on techniques and algorithms for mitigating interference affecting radio astronomy observations, with particular attention to cancellation using interference reference beams. Most significantly, reference antennae cancellers are analysed in the context of radio astronomy, leading to new cancellers and techniques which can offer improved RFI removal for some important applications. It includes a modified adaptive canceller which can theoretically offer infinite RFI suppression in the voltage domain. Analysis of this canceller also offers an understanding of the residual power components of a variety of reference antenna cancellers. Although the modified canceller injects a larger amount of noise into an astronomy signal path, a double filter is proposed which averages this noise from the output power spectrum. The resulting spectrum is equivalent to that produced by the post-correlation cancelling technique. These points are now briefly expanded, and major issues are highlighted.

Before moving into the interference suppression theory and analyses, the first part of the thesis gives an introduction to radio interferometry and interfering signals. In chapter 2 the radio astronomy theory and mathematics relevant to RFI mitigation is reviewed. This starts with interferometers and methods for measuring the power spectra from stationary radio sources, and then discusses how these measurements can be decorrelated by the relative motion of a transmitter to the cosmic sources. Since these effects can limit the quality of interference suppression algorithms discussed in later chapters, they are central in dealing with interference. To put some of the theory and the interfering signals themselves into context, chapter 3 gives an illustrative look at the RFI environment. Various types of RFI are described using an interference survey from the Australia Telescope Compact Array. Some of the sampled voltage data sets used in later chapters and available for research purposes are summarised. Chapter 3 also looks at some of the processes that can affect an interfering signal with a real-world example, where the decorrelation of Low Earth Orbit satellite signals due to transmitter motion is investigated.

The bulk of the thesis then lies in the next three chapters. Spatial filters are investigated in chapter 4 and adaptive noise and post-correlation cancellers are investigated in chapter 5. Although there are many processes that can limit the effectiveness of these
algorithms, these two chapters mainly deal with ideal situations. In particular, it is assumed that the entire receiving system remains linear and that the interference is stationary relative to the array (over an appropriate time interval). Assumptions about the polarisation state of the interference vary for different mitigation schemes. For example one model for the dual reference antenna cancellers requires that the interfering signal is completely polarised, but that the polarisation state is not orthogonal to either of the reference receivers (this situation occurs when one chooses to use reference signals from orthogonally polarised receivers, both of which must contain the interference). It should also be noted that most of these algorithms deal with short segments of a larger observation (in time, frequency, direction of arrival and polarisation). For example, if one is accumulating voltage correlations to create a synthesis image, the techniques are applied independently to each correlation measurement (and in some cases at much shorter time intervals before the correlations are constructed). The main topics covered and results are now briefly summarised.

Chapter 4 analyses spatial filtering with respect to radio astronomy. Forming beams out of the signals from an array of antennae is widely used in communications, radar, sonar, etc., and radio astronomy, and many of the planned arrays for the next generation of radio astronomy facilities will require a substantial amount of beamforming (see, for example, Smolders and Haarlem 1999). For example, array stations consisting of many antenna elements with wide beams can be phased-up in a particular direction, effectively acting as a single large antenna. Beams from many array stations could then be used to form beams with a higher spatial resolution or to form a synthesis array. Two advantages of beamforming are that multiple instantaneous beams can be formed anywhere in the wide beams of the individual antenna elements (permitting multiple simultaneous observations), and the beamforming process can be altered to spatially filter out signals from certain, unwanted directions.

Section 4.2 reviews ways of spatially filtering the unwanted directions from the voltages which are being added to form a beam. This can be viewed as either a projection of the voltages on to the null-subspace of the unwanted directions, or a projection onto the subspace of the unwanted directions themselves (the interference directions), to create interference beams which can then be subtracted from the main astronomy beam. Section 4.3 discusses how these projections can be applied directly to the cross-power spectra of the sampled voltages. Since in radio astronomy these power spectra are often all that is required (the actual structure of the voltages is usually of little interest), projecting the interference out of these averages at a rate which is much less than the sampling rate has obvious computational advantages. The power spectra projections can also be thought of as projecting onto the interference subspace, and then subtracting the interference away to give the orthogonal projection. The coefficients for the projections are often calculated using short samples of the interference, since the antenna side-lobe amplitudes and phases are usually not accurately known, and as the interference becomes weak relative to the system noise the coefficients become incorrect. At the same time, a problem with both the voltage and power spectra projection techniques is that of astronomy signal “bleed-through”, where some of the
cosmic signals in the main astronomy beam leak into the interference beams and are therefore also projected out of the data set. One way to deal with this is to create a situation where there is no astronomy signal whatsoever in the interference beam. A way of attempting to achieve this – which is the topic of chapter 5 – is to use separate antennae as reference antennae with no gain towards the cosmic signals, to collect a copy of the interference and create an astronomy-free interference beam.

Chapter 5 follows directly from the spatial filtering discussions to investigate interference mitigation techniques which modify signals from auxiliary reference antennae to model and cancel interference from an astronomical observation. These techniques can also be applied in two domains; they can be applied in the time domain, where the RFI voltage is modelled and subtracted from the astronomy signal path (adaptive noise cancelling, covered in sections 5.3 through 5.8), or they can be applied to the auto- and cross-correlated voltage spectra in the frequency domain (post-correlation cancelling, covered in section 5.9).

Using a single reference signal to model the RFI in the astronomy signal path results in biased cancellation due to receiver noise in the reference signal. While any astronomy signals make their way through the canceller untouched, the canceller output is no longer completely orthogonalised to the interference (the filter is also attempting to orthogonalise its output to the reference receiver noise). For many applications in communications and radio astronomy this is not a concern since a strong reference copy of the interference is available. The larger the reference interference power is relative to the reference receiver noise power, the more the filter will concentrate on cancelling the interference. When a strong reference copy (relative to the receiver noise) is not available, a method of removing the noise bias is required. This is achieved naturally for the post-correlation canceller where the cross-correlation of two references with independent reference receiver noise is used. The cross-correlation has a zero-mean noise floor which will not affect the orthogonalisation. A dual-reference filter can also be used in the voltage domain adaptive noise canceller, and a double filter setup with independent references leads to the same output power as that of the dual-reference post-correlation canceller. For a single, statistically stationary, interfering signal and ideal receivers with uncorrelated system noise, both of the dual-reference techniques give complete removal of the interference.

Two caveats are discussed in chapter 5. First, when the interference power in the reference antennae becomes much less than the receiver noise power, dual-reference cancellers can become unstable and need a mechanism to turn off (this is discussed in section 5.10). Single-reference cancellers do not have this problem since the receiver noise bias mentioned above gradually turns the cancellers off as the interference drops below the noise. The second caveat concerns the amount of reference receiver noise added during cancelling. Even though both dual-reference cancellers completely remove the interference power, they both add more reference system noise during cancelling than the equivalent single-reference cancellers. This noise is uncorrelated for the post-correlation canceller and averages away as one continues to integrate (it reduces with
the interference power-to-noise ratio and square root of the number of samples). When a power spectrum is required, a double filter system can be set up for the voltage domain technique, as discussed in section 5.6, leading to a spectrum which is equivalent to that of the post-correlation technique. However, if the voltage sequence is required, there will be more noise power for dual-reference cancellers than for single-reference cancellers (but no residual interference). It should also be pointed out that the residual interference in the output of the single-reference cancellers will continue to correlate and not average away as one continues to integrate.

As mentioned previously, the post-correlation method has the advantage of being applied on longer time scales rather than at the sampling rate. However, since the cancellers use cross-correlated power measurements in the deduction of the interference in the main astronomy signal path, if the transmitter location changes during the time integration, the varying phase differences cause decorrelation of the cross-power measurements which can limit the effectiveness of the algorithms. In section 6.3 it is shown that if the decorrelation is not too severe it can be corrected, at the expense of a noise increase. However, as discussed in section 5.3, time domain adaptive cancellers are allowed to slightly vary their internal coefficients at the RF sampling rate. Section 6.2 demonstrates how the weights adapt to the changing phases to avoid the decorrelation problem, but the freedom to move also results in a noise increase. These issues form the discussion in chapter 6.

Other limitations and subtleties are discussed in chapter 7. In particular this chapter contains discussions on bandwidth smearing of an interfering signal, time scales and correlation lengths, quantised sampling and the effect on mitigation, multiple interferers and correlated system noise. The main conclusions are then given in chapter 8.

1.5 Common Nomenclature and Symbols

A glossary of regularly used terms, mathematical nomenclature, abbreviations and acronyms, is given in appendix B. As a general outline, throughout the thesis, unless otherwise stated, the following nomenclature is used:

- \textbf{a, A, ...} Bold characters generally refer to complex variables.
- \textit{a, A, ...} An arrowed overline denotes a vector (always a column vector unless explicitly stated otherwise).
- \hat{a}, \hat{A}, ... A hat denotes a unit vector.
- \underline{a, A, ...} An underline denotes a matrix.
- a, \textit{a}, ... When the distinction needs to be clear, lower-case characters represent time-domain processes (for example voltage streams), and
- A, \textbf{A}, ... upper-case characters represent frequency-domain processes.