

Radio frequency interference monitoring and mitigation for astronomy with phased array feeds

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Prof. Tara Murphy

1st November 2024

Inyarrimanha Ilgari Bundara

“sharing sky and stars”

Abstract

Despite progress in radio frequency interference (RFI) algorithms and techniques in radio astronomy, much work remains to implement these techniques as part of a holistic strategy in routine, large-scale telescope operations. To that end, this thesis combines RFI monitoring and mitigation, first of a self-generated interferer and then providing forward predictions of the effects of oblique projection on more complicated interferers.

The characterisation of RFI using flagged (discarded) data compiled from over 5000 observations (1500 h) using the ASKAP radio telescope is presented. The average amount of flagged data due to radio frequency interference across the routinely-used ‘clean’ continuum science bands is 3 %. ASKAP survey science projects lose most of their data to the FIXED/MOBILE (cellular) services in the low-band and aeronautical service in the mid-band. For at least some of these services the percentage of discarded data has been increasing year-on-year.

Subspace projection spatial filtering techniques applied at the beamformer have been implemented in the ASKAP codebase for a self-generated interferer. We find that the unwanted signal can be suppressed by at least 31 dB using oblique projection to the noise floor of an 880 s integration, with a typical degradation of 1.2 K in system-temperature-over-efficiency (T_{sys}/η) to that 1 MHz channel. Interferometric measurements of system equivalent flux density showed an increase of no more than 4 %. Furthermore, no significant change to the gain in the main beam was confirmed using holography within ± 0.4 % on average about the half power point.

The final chapter presents the first steps in extending the static case to moving RFI. A set of tools is under development to identify RFI-affected channels, estimate their RFI subspace and forward predict the performance of oblique projection. Subspace estimation using

the median absolute deviation is extended by considering the eigenvalues of neighbouring frequency channels. Forward predictions of the performance of the mitigation are made using the correlation of maxSNR beamformer weights with individual spatial signature vectors, the Y-Factor, and the singular value decomposition of the projection matrix based on a small population of ASKAP array covariance matrices. This is the first time RFI and its directionality have been analyzed at this scale using actual telescope data.

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This thesis was primarily written at my home and at the University of Sydney, on the land of the Gadigal people of the Eora nation.

The work presented in this thesis uses observations from the Australian SKA Pathfinder, which stands on the land of the Wajarri Yamatji people.

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Acronyms

ACM: array covariance matrix
AIC: Akaike information criterion
ACMA: Australian Communications and Media Authority
ADS-B: Automatic Dependent Surveillance–Broadcast
ALMA: Atacama Large Millimeter/submillimeter Array
APERTIF: APERTure Tile in Focus
ARQZWA: Australian Radio Quiet Zone – Western Australia
ASKAP: Australian SKA Pathfinder
ATCA: Australia Telescope Compact Array
ATNF: Australia Telescope National Facility
BETA: Boolardy Engineering Test Array
BYU: Brigham Young University
CASDA: CSIRO Australian SKA Pathfinder (ASKAP) Science Data Archive
CCIR: International Consultative Committee on Radio
COPUOS: Committee on the Peaceful Uses of Outer Space
CORF: Committee on Radio Frequencies
COSPAR: Committee on Space Research
CPS: IAU Centre for the Protection of the Dark and Quiet Sky from Satellite Constellation

Interference

CRAF: Committee on Radio Astronomy Frequencies of the European Science Foundation
CSIRO: Commonwealth Scientific and Industrial Research Organisation
DME: Distance Measuring Equipment
DRAO: Dominion Radio Astrophysical Observatory
EM: electromagnetic
EMU: Evolutionary Map of the Universe
EVD: Eigenvalue Decomposition
FAST: Five-hundred-meter Aperture Spherical radio Telescope
FoV: field-of-view
FPA: focal plane array
FPGA: field programmable gate array
FRB: Fast Radio Burst

GLONASS: GLObalnaya NAvigatsionnaya Sputnikovaya Sistema
GPS: Global Positioning Satellite
GPU: graphical processing unit
GUI: Graphical User Interface
HI: hydrogen line
OH: hydroxal
OST: Outer Space Treaty
IAU: International Astronomical Union
IEEE: Institute of Electrical and Electronics Engineers
IUCAF: Scientific Committee on Frequency Allocations for Radio Astronomy and Space Science
ITU: International Telecommunication Union
LEO: Low Earth Orbit
LOFAR: Low-Frequency Array
LNA: low noise amplifier
MAD: median absolute deviation
MDL: minimum description length
MEO: Medium Earth Orbit
MJD: Modified Julian Date
MRO: Murchison Radio-astronomy Observatory
MWA: Murchison Widefield Array
NRAO: U.S. National Radio Astronomy Observatory
NSF: National Science Foundation
ODC: On-Dish Calibrator
PAF: phased array feed
PCA: principal component analysis
POSSUM: POLarisation Sky Survey of the Universe's Magnetism
RACS: Rapid ASKAP Continuum Survey
RAFCAP: Radio Astronomy Frequency Committee in the Asia-Pacific region
RAS: radio astronomy service
REMP: Radio Emissions Management Plan
RFI: radio frequency interference
RR: Radio Regulation
SAURON: Scheduling Autonomously Under Reactive Observational Needs
SVD: singular value decomposition
SKAO: SKA Observatory
SEFD: system equivalent flux density
SETI: the search for extraterrestrial intelligence
SMART: "Survey and Monitoring of ASKAP's RFI environment and Trends"

SNR: signal-to-noise ratio

SOI: source-of-interest

SSP: survey science project

SSV: spatial signature vector

UEMR: unintended electromagnetic radiation

UHF: Ultra-High Frequency

UN: United Nations

UNESCO: United Nations (UN) Educational, Scientific, and Cultural Organization

URSI: International Union of Radio Science

UTC: Coordinated Universal Time

VAST: ASKAP survey for Variables and Slow Transients

VLA: Karl G. Jansky Very Large Array

VLBI: very-long-baseline interferometry

WARC: World Administrative Radio Conference

WRC: World Radio Conference

WSRT: Westerbork Synthesis Radio Telescope

Nomenclature

$\langle \cdot \rangle_T$	Time average operator
$\mathbf{A}^H$	Conjugate transpose of $\mathbf{A}$
$\mathbf{A}^T$	Transpose of $\mathbf{A}$
h	Planck's constant
k_b	Boltzmann constant

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CHAPTER 1

Introduction

It has been said that astronomy is a humbling and character-building experience. [...] To me, it underscores our responsibility to deal more kindly with one another, and to preserve and cherish the pale blue dot, the only home we've ever known.

Carl Sagan

Pale Blue Dot, 1994

Non-destructive radio frequency interference (RFI) mitigation techniques are preferable to flagging (discarding) data. However, their effects on astronomical figures of merit must be understood, predicted (where possible) and communicated to astronomers and observatory staff. Mitigation via spatial filtering, now with over 20 years of research, is of particular interest. Spatial filters introduce deep nulls into the beampattern (gain as a function of direction), which significantly attenuates the contribution of radio frequency interference (RFI) before it is correlated or processed into science-ready data products. Despite promising research into spatial nulling and subspace projection [1–10] (see §2.3.4 for the full literature review) much work remains to implement these techniques in routine, large-scale telescope operations combined with ‘traditional’ RFI mitigation techniques. This thesis begins to address this gap. This thesis also aims to bring together what are often practically treated as individual problems, monitoring and mitigation as part of a holistic RFI strategy.

Phased array feeds (PAFs) provide increased information about interfering signal(s), in particular their direction, which can be used, alongside a suite of other techniques, to mitigate the interference [6]. These methods mitigate RFI by exploiting the spatial signature of the interferers and placing a null in their direction. They are particularly suited to phased arrays and PAFs. The challenge in deploying and implementing active RFI mitigation techniques – using spatial filters – is first understanding the RFI environment (§3) and then identifying suitable RFI candidates for mitigation. In the case of spatial nulling, the number and direction of interferers affecting an observation must be determined from the array covariance matrix (ACM) (§5). After modelling and implementing an RFI mitigation technique, engineers need to understand the effects of the algorithm on the science and communicate the effects to the astronomers (§4). Astronomers require very stable and well-characterized beampatterns. Using simulations and experimentally obtained measurements, including system-temperature-over-efficiency (T_{sys}/η), holography [11], and system equivalent flux density [12] (§4) provide estimates of the expected impact of subspace projection on the astronomical response and calibration of the telescope required for the adoption of adaptive mitigation on radio telescopes during science observations.

A holistic approach to managing RFI in an evolving radio spectrum would include:

- continuously **identifying and characterising** RFI (based on their frequency, duration, and temporal properties) using RFI monitoring equipment and the telescope itself in as close to real-time as possible;
- **assessing the impact** of RFI on the instrument and scientific observations, including how much data is discarded/flagged and long-term trends based on historical (archived) data to make **ongoing improvements**, for example:
 - calibrate RFI monitoring equipment;
 - predict (and avoid) RFI using ‘smart’ autonomous observation scheduling;
- implementing **active, non-destructive, RFI mitigation techniques**, such as spatial nulling, throughout the signal chain, instead of flagging, to recover data whenever possible;

- providing each other with feedback; not only should active mitigation be informed by monitoring data, but monitoring should also quantify the effects of mitigation techniques and the data those techniques have recovered, i.e., **evaluate the mitigation**;
- communicating the effects of RFI on science and the observatory with relevant stakeholders, including **collaboration across the RFI community** (spectrum managers, astronomers, engineers and observatory operations) and
- increased cooperation, not only within the astronomy community but with other services and users of the radio spectrum, is essential.

This thesis realises the first step toward this vision of a holistic approach to managing RFI. A two-part RFI strategy is presented herein. The first describes the routine monitoring and analysis of RFI-affected data from the telescope that has been implemented based on flagged data over the last five years across multiple surveys. The second describes the evaluation and implementation of active RFI mitigation via spatial nulling, in particular with oblique projection, using the Australian SKA Pathfinder (ASKAP)’s PAF to mitigate a persistent (static) self-generated interferer originating in ASKAP’s digital receiver building on work done by Chippendale and Hellbourg using a modified ASKAP MKII PAF on Murriyang, the Parkes radio telescope. This RFI spatial signature remains constant throughout the observation and is suppressed by modifying PAF beamformer weights once at the start of the observation. This static case is an important intermediate step toward mitigating more pernicious forms of RFI from satellite and aviation systems that are dynamic (moving relative to the PAF). Finally, suitable candidates for further mitigation are identified based on techniques to determine the number of interferers, the RFI subspace and its orthogonality to a set of beamformer weights from the ACM. Ultimately, this thesis aims to build on work done by Hellbourg and Bannister using Boolardy Engineering Test Array (BETA) [13] and eventually porting spatial nulling to CSIRO’s new receiver for Murriyang at Parkes the cryoPAF [14].

The remainder of this chapter provides a general introduction to radio astronomy and is optional for readers already familiar with the topic.

I begin with an overview of radio waves and astronomy and explain the relevant history. I then introduce categories of instrumentation and how they work, both single-dish telescopes and different types of arrays, including interferometers, phased arrays and phased array feeds (PAFs). Most relevant to this thesis, I move on to a summary of radio frequency interference (RFI) and present different categories of interference and the challenges they pose for radio astronomy in the context of an evolving set of radio spectrum services. Finally, I describe mitigation strategies to prevent or minimize effects of RFI, including protecting certain frequency bands or radio-quiet zones through legislation, flagging and its limits.

The chapter concludes with the research motivation, a list of publications and conferences I have presented at and an outline of the remainder of the thesis. The aim is to familiarize the reader with the main concepts, terminology and instrumentation pertinent to the thesis.

1.1 Radio waves and radio astronomy

Radio astronomy uses radio waves to study the physics and nature of celestial objects. Radio waves are a type of electromagnetic (EM) radiation. Based on the properties of radiation as a function of frequency, the EM spectrum is coarsely divided into bands (a range of frequencies). These bands are, from low to high frequencies; radio, microwave, infrared, visible, ultraviolet, X-ray and gamma rays. The Earth's atmosphere is largely opaque to most of the EM spectrum, except for a few windows (see Figure 1.1) where EM radiation passes through the atmosphere unattenuated to the Earth's surface.

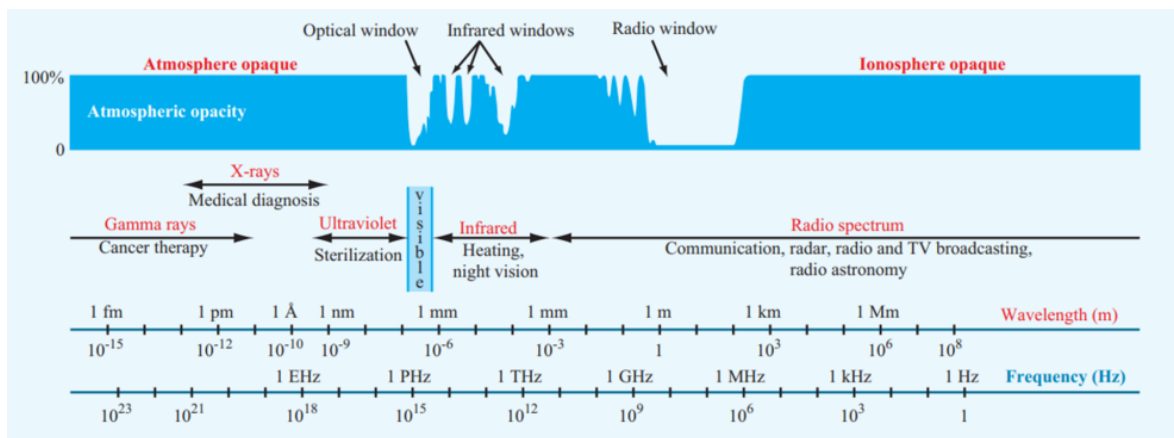


FIGURE 1.1. ‘Windows’ of frequencies — based on the opacity of the Earth’s atmosphere — allow EM radiation to pass through the atmosphere unattenuated. Ground-based astronomy is, therefore, only possible at these specific bands of frequencies. The radio window is the widest of the windows. Credit [15]

These windows are radio, infrared¹ and optical. Radio waves frequencies range from 3 Hz to 3 THz, as defined by the International Telecommunication Union (ITU) Radio Regulations (RRs) [16]. Radio astronomers are further limited to a smaller frequency range due to ionospheric and atmospheric effects, which attenuate the signal outside the approximate range from 10 MHz to 10 GHz.

¹Sub-millimetre astronomy, 2 THz and above in the microwave to far-infrared, is possible with ground-based telescopes only at high altitudes. An example of this kind of instrument is the Atacama Large Millimeter/submillimeter Array (ALMA).

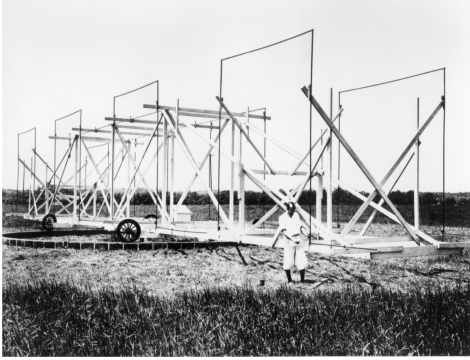


FIGURE 1.2. 1933 is the start of radio astronomy when Karl Jansky detected radio waves from the Milky Way [17]. Credit: NRAO/AUI/NSF

Astronomers were limited by their instruments to observing only visible light until 1933. While investigating interference for radio voice communications, Karl Jansky (Figure 1.2), a Bell laboratory radio engineer, discovered the first extraterrestrial radio emission, the centre of our Galaxy [17]. Jansky made this discovery while investigating sources of static that could interfere with transatlantic radio telephone service. Radio astronomy therefore was born of a careful study of RFI [18]. Since then, radio astronomy has led to excit-

ing discoveries invisible in other EM bands, including the cosmic microwave background [19] and new types of celestial objects, e.g. pulsars [20].

The frequencies emitted by a cosmic source-of-interest (radio waves) depend on the physical processes within it; in the radio spectrum, these include thermal and synchrotron radiation. Synchrotron radiation is the motion of particles and the acceleration of relativistically charged particles perpendicular to their velocity. Cosmic sources of interest are characterised either spectrally, spatially or temporally, in other words, by their frequency, position or direction, and in time.

Spectrally, radio astronomy is generally broken down as being either broadband or narrowband in frequency, i.e. continuum emission or spectral line, respectively.

- **Continuum** (emission) is broadband radiation that varies slowly as a function of frequency. Continuum observations are used to study a wide range of astrophysical phenomena, including star formation, galaxy formation/evolution, and active galactic nuclei.
- **Spectral** line, in contrast, refers to narrowband radio emission or absorption due to changes in atomic or molecular excitation. This can provide information about

the composition and physical state of both the signal source and intervening matter. The hydrogen line (HI), the most prevalent atomic example, is a radio emission at 1420 MHz used to observe galaxy kinematics and the evolution of physical conditions in the early universe. Hydroxal (OH) lines are an example of molecular spectral lines.

Radio waves may change frequency due to the Doppler effect and redshift. Radio waves may also undergo dispersion, where different frequencies travel through an ionised medium at different speeds.

Spatially, sources of interest may have a large area in the sky with low-surface-brightness which astronomers describe as diffuse or conversely compact. Sources of interest also differ in their brightness, intrinsically or otherwise— for example, their distance, shown in the next section.

Temporally, cosmic sources-of-interest are dynamic and evolving in time at different rates. Fainter and more distant continuum sources necessitate significantly longer observations (and integration times). Other phenomena may require multiple follow-up observations at cadences of weeks, months or even years to monitor their evolution. High-energy fast flashes and periodic bursts may require extremely high time-resolution observations at short notice. Dating astronomical observations is often done using the Modified Julian Date (MJD) number or Coordinated Universal Time (UTC) to avoid ambiguity.

Ground-based astronomy is cheaper than space-based astronomy due to the costs associated with launching space telescopes (only possible since the 1970s) into orbit. Other benefits of ground-based instruments are their comparative ease of maintenance and upgrade compared to space telescopes and the ability to build larger apertures.

Information on the physics and nature of celestial objects is available across the entirety of the EM spectrum. In particular, the radio spectrum spans several decades compared to the

optical window and is transparent to the atmosphere, making it an invaluable resource to the larger field of astronomy.

Radio astronomy should be considered complementary to astronomy in the other EM bands toward understanding the nature of celestial objects, called multi-wavelength astronomy. Multi-messenger astronomy further generalises this approach to astronomy to include gravitational waves, neutrinos, and cosmic rays to obtain an increasingly comprehensive picture of the universe. The following resource [21] is recommended for a more in-depth introduction to radio astronomy.

1.2 Radio astronomy instrumentation

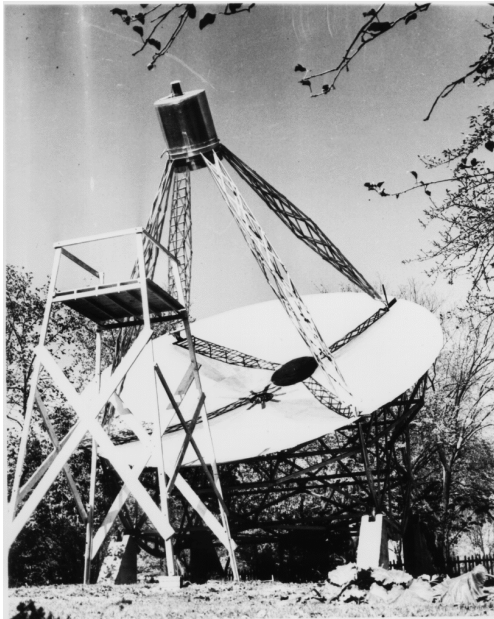


FIGURE 1.3. The first parabolic radio telescope built by Grote Reber in Illinois in 1937.

Maxwell's equations, published in the 1860s [22], demonstrated that EM radiation could exist at any wavelength. Early attempts during the 1890s by Lodge and Wilsing & Scheimer to detect radio emission from the Sun were unsuccessful due to the technical limitations of their instruments [23, 24]. Early radio telescopes — those used by Jansky (Figure 1.2) and Wilsing & Scheiner, for example — did not use a single-dish, high-gain paraboloidal reflectors reminiscent of radar antennas operating only in the passive mode, which we often associate with radio telescopes and radio astronomy. In 1937, Grote Reber built the first single-dish parabolic radio telescope and performed the first sky survey [23] at 160 MHz. After

the Second World War, as radar engineers pivoted their efforts to radio astronomy, we began

to see increased interest and substantial advancements in radio astronomy. Increased budgets from national observatories [25] through the 1940s – 1960s also helped to further the field.

Particularly significant developments for radio astronomy occurred in Australia during this time, where Pawsey (who coined the term ‘radio astronomy’) and radio engineer Payne-Scott conducted pioneering research at the Radiophysics Laboratory of the (later) Commonwealth Scientific and Industrial Research Organisation (CSIRO) [26, 27]. Specifically, Payne-Scott and Pawsey were the first to formulate (and then implement using interferometry) aperture synthesis in 1946 [27].

How radio telescopes work

At a very high level, radio telescopes aim to maximise the signal-to-noise ratio (SNR)

$$SNR = \frac{P_{\text{signal}}}{P_{\text{noise}}}. \quad (1.1)$$

The ratio of the average power of the desired signal - the cosmic sources of interest - to the average power of the background. Maximising the SNR, as seen in the equation above, can either be done by increasing the power of the signal received (by increasing the collecting area or integrating over a longer period) or by reducing the noise.

A dish like the one in Figure 1.3 collects radio waves that have passed through the atmosphere unattenuated. The shape of the reflector focuses the incident radio waves on to a receiver at the focus of the dish. The larger the collecting area of the telescope, the more signal it can collect. The collecting area can be increased by building a larger reflector or by combining multiple reflectors, or in fact any kind of antenna, in arrays.

In practice, radio telescopes measure flux density (S_ν). Flux density is the spectral power received per unit area of a surface, in our case, the reflector. It is measured in Janskys $J = 10^{-26} \text{ W m}^{-2} \text{ Hz}^{-1}$ and defined by the integral of radio brightness over the solid angle

of a radio source

$$S_v \equiv \int_{\text{source}} I_v(\theta, \phi) \cos\theta \, d\Omega. \quad (1.2)$$

$I_v(\theta, \phi)$ is the specific/spectral intensity (radio brightness) intrinsic to the source per unit frequency; expressed as a function of its position, and measured over some solid angle ($d\Omega$) on the sky [28]. The inverse square law relates the Flux density to the spectral luminosity (L_v) — power (WHz^{-1}) — radiated by the source at frequency v ,

$$S_v = \frac{L_v}{4\pi D^2} \quad (1.3)$$

where D are often large distances between cosmic sources-of-interest and the Earth. Also,

$$S_v \propto \frac{1}{D^2} \text{ because } \int_{\text{source}} d\Omega \propto \frac{1}{D^2}$$

As such, (increasingly) sensitive radio telescopes that maximise the SNR are required to detect, collect and amplify the weak (distant) astronomical signals.

Two popular types of radio astronomy instruments are single-dish and array telescopes. Each is discussed further in turn in the subsequent subsections.

Single-dish telescopes

Single-dish telescopes have an often large and parabolic² [29] reflector that focuses the incident radio plane waves onto a receiver at the reflector's focus.

Examples of large (and still operational) single-dish telescopes built over the decades include:

- the 75 m Lowell telescope (50s),
- Murriyang, the 64 m radio telescope at the Parkes Observatory (60s, Figure 1.4),
- the 100 m Effelsberg telescope (70s), and
- the 100 m $\times$ 110 m Green Bank Telescope (2000).

²Other optical designs/geometries of telescopes, of which there are many, are not described in this thesis.



FIGURE 1.4. Murriyang, the 64 m radio telescope at the Parkes Observatory is an example of a single-dish telescope with a paraboloid reflector and receiver at the focus. Photo[©] Shaun Amy

Steerable single-dish radio telescopes like the ones listed above have an upper limit to the angular resolution they can achieve due to constraints in increasing their diameter³, becoming more challenging at diameters greater than around 100 m. Images are made by slewing the reflector in a raster scan, one pixel at a time and stitching those measurements together, resulting in a slow survey speed. The size of the grid that is scanned determines the size of the image. A smaller beam can resolve finer detail; therefore, the reflector's diameter determines image resolution. Kraus [28] and Baars [29] are recommended for more details.

Array telescopes

There are different types of array telescopes, synthesis imaging arrays, phased arrays and focal plane arrays.

Figure 1.5 shows how, to overcome the single-dish diameter constraint, multiple single-dish telescopes (an array) work together as a single telescope (called an interferometer) with a much larger 'diameter', resulting in higher angular resolution. The 'diameter' for an

³Larger fixed single-dish telescopes, for example, the 500 m Five-hundred-meter Aperture Spherical radio Telescope (FAST), are possible if built into natural sinkholes and basins.



FIGURE 1.5. CSIRO's Australian SKA Pathfinder (ASKAP) telescope. Credit: CSIRO

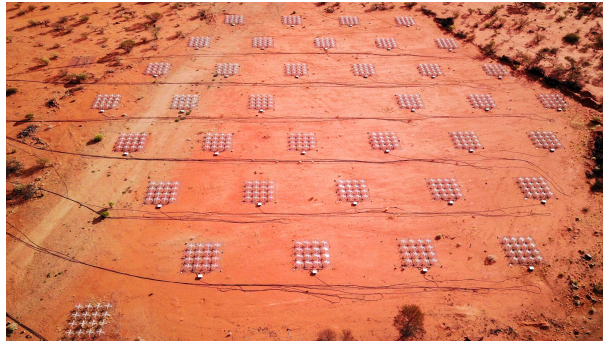


FIGURE 1.6. The Murchison Widefield Array (MWA) is an example of an array of phased array antennas. Credit: ICRAR/Curtin

interferometer is the longest baseline (the distance between antenna pairs). Gaps between antennas mean an interferometer has less collecting area than a single-dish of the same diameter. Interferometers measure the correlation of signals between antenna pairs. Each antenna receives roughly the same signal but with a phase delay, the resulting interference pattern creates an interference (or fringe) pattern on the sky. Complex ‘visibilities’ denote the amplitude of the correlation and the delay (phase) on which an inverse Fourier transform is performed to reconstruct an image. Fourier synthesis imaging [30] (or aperture synthesis) was made practical by computers, first with east-west interferometers (1-D Fourier transform) using earth rotation synthesis. Examples of this type of telescope include:

- Westerbork Synthesis Radio Telescope (WSRT) (70s),
- the One-Mile (60s) and 5 km Ryle (70s) telescopes⁴,
- and the CSIRO's Australia Telescope Compact Array (ATCA) (80s).

Nowadays, interferometers with 2D configurations like the Karl G. Jansky Very Large Array (VLA), MeerKAT and ASKAP are the norm. Very-long-baseline interferometry (VLBI) with continent-wide, earth-wide and even orbital baselines have also become commonplace. The use of supercomputers has become central to cope with imaging and calibration with ever increasing numbers of baselines, frequency channels, field of view, and image resolution.

⁴operation discontinued in 2006.

For a comprehensive overview of synthesis imaging and interferometry, Thompson, Moran and Swenson [31] and Taylor, Carilli and Perley [32] are recommended. More information is given in §2.3 on interferometry and ASKAP.

As previously explained, radio telescopes need not have a reflector. An example of this type of telescope array is a phased (aperture) array, where the antenna elements point directly toward the sky without a dish, Figure 1.6. There is, however, a trade-off between the mechanical costs of large telescopes with reflectors and the additional costs associated with phased arrays due to the processing required from the many signal paths [33]. These telescopes were quite prevalent in early radio astronomy [34]. Nowadays, they constitute many antenna elements (typically dipoles) or arrays of antenna elements called stations and used at low frequencies. Examples of low frequency phased array telescopes include:

- The Low-Frequency Array (LOFAR) [35],
- Murchison Widefield Array (MWA) (Figure 1.6) [36], and
- SKA⁵-Low (under construction).

These systems use *Beamforming*, a signal processing technique in which antenna array elements are combined (using different algorithms and methods) to create a beam (or beams) in the desired direction, discussed further in §2.3.4.

Receivers

As described in the previous sections, paraboloid reflectors focus the incident radio waves. At the focus of each dish is a receiver, nominally a feed horn. The receiver (antenna elements and electronics) convert radio waves into electrical signals. The degree to which noise in the

⁵The [SKA Observatory](#) is an international collaboration headquartered in the United Kingdom, currently constructing two radio telescope arrays; SKA-low in Western Australia and SKA-mid in South Africa, with 131,072 and 197 planned antenna elements respectively.

receiver is minimised will increase the SNR and, in turn, the sensitivity and efficiency. Single-feed horns have well-characterised gain patterns and do not require complicated software to operate: however, one downside, is that they have slow survey speeds.

A focal plane array (FPA) at the reflector's focus can increase survey speeds. One type of FPA is a multibeam receiver like the Parkes multibeam [37], which used thirteen traditional waveguide feed horn antennas. Multibeam feeds can be expensive but are not suitable for smaller dishes due to their large size.

Another example of focal plane arrays (FPAs) are phased array feeds (PAFs). A PAF is a dense array of antenna elements at the focus of a dish from which elements are combined to make PAF beams. Operated and maintained by CSIRO, ASKAP is the first synthesis imaging array designed explicitly from its outset to use PAF technology [38], shown in Figure 1.7.



FIGURE 1.7. ASKAP phased array feed (PAF) at the focus of an antenna, Credit: CSIRO

PAFs are not too dissimilar to the phased array (pointing directly at the sky) described in the previous section. At mid-high frequencies PAFs are more cost effective because the number of aperture array elements goes up as the square of a reducing wavelength [33]. A dense phased array of closely spaced, small low-gain elements is positioned at the focus of the dish(es), whether on a single dish or within an interferometer effectively creating an

array (interferometer) of arrays (PAF). The reflector ‘concentrates’ the energy intercepted by the larger reflector aperture onto the smaller aperture of the PAF, allowing the signal to be collected and processed with a smaller array.

Throughout its history, radio astronomy has placed extreme performance demands on its instrumentation. PAFs are one of the most recent examples of this trend, offering several advantages over existing feed horn technologies. Primarily, PAFs allows for multiple simultaneous steered beams resulting in a wide field-of-view (FoV), and in turn, faster survey speeds thus increasing the number of astronomical sources detected in significantly less time [39]. ASKAP and its PAFs are described in more detail in the next chapter. PAFs can also adapt to their changing environment in their flexibility to optimise beam patterns between or even during observations. Most notably for this project, introducing deep nulls into the beam pattern (gain as a function of direction) to eliminate the contribution of RFI before it is correlated or processed into science-ready data products.

1.3 Radio frequency interference

Radio astronomers consider all unwanted radio signals that corrupt or negatively affect radio astronomy data (and the instrument) as RFI. Often RFI is used to mean human-made radio transmitters. Legislatively, each radio service has specific frequency allocations, RFI (in any service) is only classified as such when transmissions by one service exceed certain thresholds [40, 41] outside their allocation in the radio spectrum. Services include the radio astronomy service (RAS), the aeronautical radionavigation service, the broadcasting service and the fixed/mobile service. In Australia, this is under the jurisdiction of the Australian Communications and Media Authority (ACMA) and the International Telecommunication Union (ITU) treaty implemented by way of a set of Radio Regulations (RRs) [16]. The RAS-protected bands and RRs are described further in §2. Most of ASKAP’s operating bandwidth, 700 MHz to 1800 MHz, is shared with other services [42]. Passive services, including RAS⁶,

⁶RAS is the only completely passive service. I.e. it does not transmit.

receive protection in only 3 % (including primary, shared, and secondary allocations) of the radio spectrum below 30 GHz [43]. In principle, RFI for radio astronomy is only considered as such in that subset of the spectrum, but in practice, observatories and astronomers are not limited to these bands, and neither is ‘their’ definition/perception of RFI.

RFI, then, is a variety of radio communication applications transmitting and receiving at different frequencies. Primarily, the appeal of radio communications is that radio waves allow wireless transmission of information, often over long distances. Due to advancements in radio communication technologies, the radio spectrum is very different today compared to the early days of radio astronomy. The radio spectrum is continuously evolving. Figure 1.8 shows some familiar technological developments that (increasingly) compete for allocations in the radio spectrum. New services are continually being added or superseded; 1978 and 1979 saw the first satellite-based navigation systems and mobile networks respectively. The rate of this change is also impressive. While the first television broadcast globally was in 1927 five years before Jansky’s discovery; television broadcasts did not start in Australia until 1956, 27 years. In 2019 Starlink launched its first 66 satellites, in less than a fifth of the same amount of time, it has exceeded 5000 satellites. Looking forward, the largest mega-constellation filed with the ITU is for upward of 300 000 satellite units [44]. Despite many protections (detailed in the next chapter), at the instrument’s sensitivity limit, the availability of an entirely interference-free spectrum is expected to degrade over time due to growth in population and spectrum usage [43].

These technologies have undoubtedly improved our lives but pose a significant challenge for radio astronomy because

- radio waves from active services can propagate such vast distances;
- radio astronomy routinely observes outside of its protected bands;
- radio telescopes are increasingly more sensitive; and
- radio waves from cosmic sources are faint.

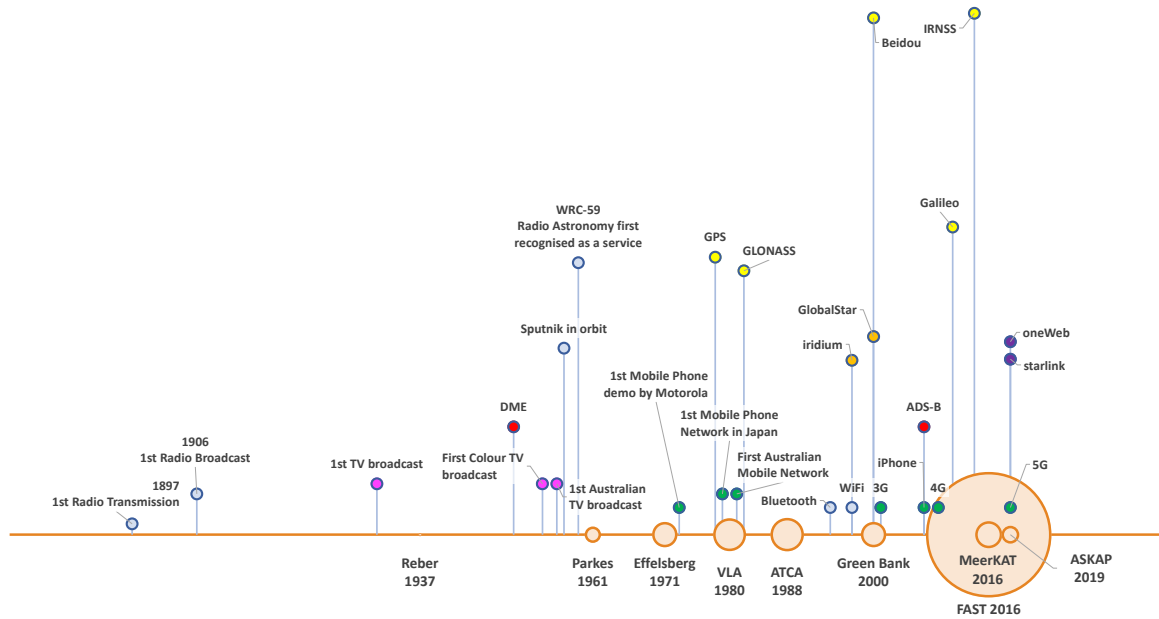


FIGURE 1.8. Timeline of some developments in radio transmitters, i.e. RFI. The completion year of some radio telescopes and their corresponding collecting area (size) shown along the bottom give a time reference. Developments are grouped together by colour: Aircraft Navigation (red), mobile phone-related (green), satellite navigation (yellow), communication satellites (orange) and internet satellites (purple). The height of the markers is loosely indicative of the height/orbit of the transmitter.

On the one hand, since the earliest days of radio astronomy, RFI has evolved in parallel with radio astronomy, and the radio astronomy community has innovated with the ever developing challenge. Primarily, protection has come from locating the most sensitive telescopes in radio-quiet zones like the Australian Radio Quiet Zone – Western Australia (ARQZWA)[45, 46], thus significantly restricting the amount of RFI from ground-based transmitters. Until recently, radio-quiet zones have been adequate to make science observations out to high redshifts⁷ possible outside the RAS bands. Satellite transmission – in particular, an imminent future of multiple Low Earth Orbit (LEO) satellite mega-constellations – is an unprecedented challenge for the future of radio astronomy.

⁷Cosmological *Redshift* is a phenomenon related to the expansion of the universe. The term describes the observed shift of electromagnetic radiation toward lower frequencies (longer wavelengths) as it travels through the expanding universe away from the observer.

The problem for radio astronomy is the ubiquity and variety of RFI and therefore the unpredictable behaviour. These interferers also frequently have power many orders of magnitude greater than the astronomical source of interest. Strong RFI can saturate or even damage the telescope receiver. Two particularly pernicious challenges for radio astronomy are:

- Current radio-quiet zone legislation is insufficient to protect against increased satellite interference [47] which, at its limit, risks shutting down observatories for extended periods. For example, some satellite RFI results from unintended electromagnetic radiation (UEMR)⁸ [47, 48]. Furthermore, radio-quiet zones are typically under state legislation, meaning they provide radio astronomy with protection from ground-based sources of RFI; they do not protect from orbiting satellites and aircraft [47], that are under national or international governance. There is an asymmetry worth explicitly pointing out compared to historic RFI challenges; once in orbit, it is significantly more difficult to mitigate the RFI at its source.
- Differentiating/identifying (in particular weak) RFI, such as discriminating some forms of RFI from astronomical sources-of-interest, is exceptionally difficult⁹. There is probably no better instance of this than the case of ‘peryttons’. First observed by [49] using Murriyang, ‘peryttons’ mimic the dispersion of Fast Radio Bursts (FRBs). Later ‘peryttons’ were shown to be RFI due to microwave ovens at the Parkes Observatory [50].

So far, we have limited the definition/discussion of RFI to interference external to the observatory; in practice, RFI can originate from interference within the observatory. Efforts to reduce unintended and unwanted transmission on-site are therefore required, for example shielding. RFI originating from the instrument itself (See §3) or within the observatory is called self-generated RFI¹⁰. Furthermore, not all interference is necessarily human-made:

⁸UEMR is different a type of RFI which is emission outside the service allocation and not due to the transmitter. The RRs define the rules for transmission frequencies, not incidental RFI from the rest of the satellite for example.

⁹This is also the key challenge for the search for extraterrestrial intelligence (SETI)

¹⁰sometimes termed Electromagnetic Interference (EMI) and dealing with it comes under designing for Electromagnetic Compatibility (EMC).

lightning and the sun can be significant sources of interference for radio telescopes. The moon and atmosphere can also reflect human-made RFI.

In summary, RFI may be categorised as follows. Note the mitigation proposed in this thesis is best suited for the bolded items in the subsequent list of RFI,

1) Human-made and outside the RAS allocation:

- activity on-site and self-generated,
 - consumer electronics (phones, laptops, microwaves, Bluetooth/WiFi etc.),
 - * visitors centers;
 - on-site maintenance (welding, spark plugs etc.);
 - **electronics in the system signal chain (clocks);**
- **ground based** (mobile base station, radio and television broadcasting),
- out-of-band and spurious emission from adjacent bands,
- outside radio-quiet zone legislation,
 - **aircraft**,
 - * Automatic Dependent Surveillance–Broadcast (ADS-B);
 - * Distance Measuring Equipment (DME);
 - **orbiting satellites**,
 - * satellite navigation systems (GPS, GLONASS etc.);
 - * satellite communications (Iridium, Thuraya, GlobalStar);
 - * satellite internet mega-constellations (oneWeb, Starlink),
 - unintended electromagnetic radiation (UEMR);
 - Maritime communications.

2) Naturally occurring:

- solar interference,
- lightning,
- naturally occurring phenomena which refract/reflect radio waves,

- tropospheric *ducting* [51], a phenomenon whereby radio waves can propagate much farther distances by ‘bouncing’ between the atmosphere and ground under certain meteorological conditions (described further in §2). Mobile base stations and maritime communications would otherwise not be detected in a large enough radio-quiet zone;
- reflected terrestrial RFI from the Moon.

Many of the above-mentioned human-made interferers we are interested in mitigating are modulated signals. Unlike astronomical sources, RFI is typically not noise-like. Weak RFI (below the noise floor), left unidentified, will therefore corrupt telescope data.

As radio spectrum usage evolves, so must radio astronomy. To ensure the sustainability of ground-based radio astronomy amid a constantly evolving radio spectrum – in particular, from satellite transmitters outside the protection of radio-quiet zones, there is a growing need for active RFI mitigation strategies that preserve the astronomical signal and data whilst alleviating the adverse effects of RFI on radio astronomy described thus far.

1.4 RFI monitoring and mitigation

RFI monitoring involves identifying and characterising RFI; observatories often perform this task using RFI monitoring equipment, such as spectrum analysers. Modulated RFI signals can also be decoded to help identify their source of origin. RFI mitigation, in the broadest sense, will be defined in this thesis as any techniques and strategies used to reduce the impact of the interference on observations, scientific conclusions and data-products.

There are many approaches to RFI mitigation, with a more detailed overview provided in §2.2. Proactive passive RFI mitigation is the first line of defence to minimise the effects of RFI. First, at the level of the observatory, measures include site selection and protective legislation such as restricted air space and radio-quiet zones (as discussed above and further in §2.3.1), aiming to prevent, to the degree that it is possible, RFI from reaching and affecting the

site in the first place. Then, at the level of the instrument, ‘shielding’ electric components and filters before the low noise amplifiers (LNAs) such that RFI is not introduced (or amplified) in the downstream signal output by the instrument. RFI mitigation should then be considered throughout the signal chain [52], including notch filters, time/frequency blanking, reference subtraction, adaptive beamforming (see §2.3.4) and post-correlation (in an interferometer) mitigation techniques. Indeed, any specific RFI mitigation technique will only work for a subset of RFI.

The RFI environment can be complex, which requires a suite of solutions that work together. Constraints in the hardware and the RFI’s properties determine a technique’s appropriateness. Fridman & Baan [53] and the ITU-R report RA.2126-1 [54] review different mitigation strategies. Flagging, the process of discarding RFI-affected data in time and frequency, is currently the most synonymous and representative form of typical RFI mitigation.

Discarding data should be a last resort, yet, this is the predominant method of RFI ‘mitigation’ (this is a misnomer because no attempt is being made to reduce the RFI). Radio astronomers currently flag and discard RFI-affected data to ensure the accuracy of scientific conclusions. Unfortunately, this reduces the measurement sensitivity, and the discarded data may contain valuable information from cosmic sources of interest. Discarding data also affects the instrumental response in ways that may require further consideration when drawing scientific conclusions. For example, discarding data impacts UV coverage and, thereby, the point spread function of a synthesis imaging array like ASKAP.

1.5 Thesis outline

Chapter 2 is a comprehensive background and literature review, beginning with a discussion on the legal protections afforded to radio astronomy via the radio regulations and radio-quiet zones. It then considers a holistic approach to RFI mitigation including proactive and intervention opportunities at different stages of the signal chain. The chapter further describes the ASKAP radio telescope, its RFI environment, hardware, signal path. Finally, ASKAP's approach to beamforming and a description of subspace projection is given, including the orthogonal and oblique projections.

Chapter 3 describes the implementation of the `flagstats` software to routinely monitor flagged (discarded) data. Based on over 1500 h of ASKAP science data, statistics about the amount of discarded data is presented.

Chapter 4 describes and presents the evaluation of active RFI mitigation using oblique projection based on how they affect the sensitivity and the beam shape for a static narrow-band self-generated interferer.

Chapter 5 begins to extend Chapter 3 to the more typical but significantly more challenging case of RFI moving with respect to the PAF.

Chapter 6 concludes the thesis and discusses future work. The thesis is supplemented with appendices that revisit radio regulations in more detail, address the specific problem of RFI from LEO satellites, describe the development of PAFs for radio astronomy, and examine the effects of phase changes on spatial nulling.

1.6 Publications & Conferences

Publications

- L. Lourenço, A. P. Chippendale, B. Indermüehle, V. A. Moss, Tara Murphy, T. J. Galvin, G. Hellbourg, A. W. Hotan, E. Lenc, and M. T. Whiting, “*Survey and Monitoring of ASKAP’s RFI Environment and Trends I: Flagging Statistics*”. Publications of the Astronomical Society of Australia. [2024:1-14](#). [doi:10.1017/pasa.2024.4](#)”.
- L. Lourenço and A. P. Chippendale, “*Mitigation of self-generated RFI with an ASKAP phased array feed*”. Publications of the Astronomical Society of Australia. [arXiv:2405.16309](#)”.

Conferences

- L. Lourenço, “*Developments in RFI monitoring and mitigation using ASKAP.*”, URSI AT-RASC, Gran Canaria, Spain, May 20-24, 2024.
- L. Lourenço and A. P. Chippendale, “*Identifying RFI affected channels and estimating RFI spatial signatures vectors for spatial nulling with ASKAP using the oblique projector.*”, phased array feed & Advanced Receivers Workshop, Provo, USA, Apr 22-24, 2024.
- L. Lourenço, “*Monitoring and Mitigating Radio Frequency Interference using the ASKAP radio telescope.*”, AIP ANZCOP Summer Meeting, Canberra, Australia, Dec 3-8, 2023.
- L. Lourenço and A. P. Chippendale, “*Mitigation of self-generated interference via spatial nulling with ASKAP.*”, URSI GASS, Sapporo, Japan, Aug 19-26, 2023.
- L. Lourenço, “*Statistical analysis of aggregated ASKAP flagging data due to RFI.*”, ACAMAR, Perth, Australia, Jul 31 - Aug 2, 2023.
- L. Lourenço and A. P. Chippendale, “*Mitigation of self-generated interference with ASKAP PAF.*” phased array feed & Advanced Receivers Workshop, Sydney, Australia, Nov 15-17, 2022.

- L. Lourenço and A. P. Chippendale, “*Radio frequency interference mitigation for astronomy with phased array feeds.*”, URSI RFI2022, Online, Feb 14 - 18-2022.
- L. Lourenço and A. P. Chippendale, “*Active Mitigation of self-generated interference with ASKAP’s phased array feeds.*”, URSI AT-AP-RASC, Online, May 29 - 3 Jun, 2022.

Background and Literature Review

Building on the previous chapter, this chapter revisits the radio spectrum, focusing on the legal measures to safeguard radio astronomy from RFI through the RR, the international legal framework that governs the allocation and use of radio spectrum. Radio-quiet zones, specially designated areas where strict controls are placed on radio emissions to protect sensitive astronomical observations, are then discussed.

Moving beyond legal frameworks, the chapter emphasises a holistic approach to RFI mitigation. Techniques for mitigating RFI at various stages of the signal processing chain are introduced. This includes mitigation at the antenna, before correlation and processing, and at the correlation and post-correlation stages.

An in-depth description of the Australian SKA Pathfinder (ASKAP) radio telescope is given next, describing ASKAP's RFI environment, detailing the types of interference encountered. An overview of ASKAP's hardware and signal path is given, followed by a discussion of the signal model and beamforming techniques used to enhance signal quality and, in the future, mitigate interference.

The chapter concludes by introducing subspace projection techniques for arrays. This section explains the principles and applications of orthogonal projection and oblique projection, highlighting their roles in effective RFI mitigation.

2.1 Legal protection

The literature review for this section relies heavily on the International Telecommunication Union (ITU) [55] *Handbook on Radio Astronomy* and Committee on Radio Astronomy Frequencies of the European Science Foundation (CRAF) *Handbook for Radio Astronomy* [43], as well as the Committee on Radio Frequencies (CORF) *Handbook of Frequency Allocations and Spectrum Protection for Scientific Uses* [56].

Radio astronomy uses radio waves to explore the formation, evolution, dynamics and characteristics of celestial sources-of-interest [43]. The radio spectrum — ITU bands 1 through 12, from 3 Hz to 3 THz — is a finite resource that has to be shared among a variety of services and technologies for a range of applications; cellular mobile communications, radar, satellite navigation and communication. As a result, a compelling case for why radio astronomy should get dedicated frequency allocations has to be made.

Some phenomena, for example, the 21 cm hydrogen line (HI), are only detectable in the radio, highlighting the scientific significance of the dedicated RAS allocations. The ITU Handbook [55] also cites radio astronomy’s economic, societal, and astronomy’s cultural (including religious) significance more broadly; see Venkatesan, Neilson and Noon [57–59]. Economically, [55] gives examples of technologies developed in radio astronomy but applied elsewhere, the most notable example being Wi-Fi [60]. Indeed, the relationship between radio astronomy and radio communications has been mutual [43]. Innovations developed for radio astronomy, such as large steerable antennas and low-noise amplifiers, often find applications in radio communication [55], particularly space communications, and vice versa. Another reason for the need for dedicated allocation is that CRAF states there is increasingly more competition than cooperation in the radio spectrum [43].

A drawback to sharing the radio spectrum with human-made radio transmitters is that it results in RFI for radio astronomy, which is ultimately why the designation of radio astronomy service (RAS) in 1959 was so crucial [55]. Human-made transmitters have a rich history

dating back to 1888, when Heinrich Hertz was the first to produce EM waves [61] and in 1901, when Guglielmo Marconi first transmitted radio waves across the Atlantic [62].

From a spectrum management point of view, there is less flexibility to choose a RAS frequency allocation compared to other services because the ‘transmitter’ in radio astronomy is fixed by nature. For example, in the case of spectral line observations, the rest frequency of the spectral line dictates the allocation [43]. From a hardware point of view, unlike active services, radio astronomers cannot change the nature of the received signal character or emitted power or encode the signal to make detection easier. Astronomical signals are also weak, resembling (Gaussian) thermal noise [43]. Improving the SNR therefore, is only possible through extended integration and more sensitive receivers [43]. As a result of these constraints, RAS has very different requirements from the radio spectrum compared to the other services and, therefore, requires additional dedicated protection and compliance from other services. Radio Regulations (RRs) define the sharing of the spectrum and service allocations.

2.1.1 Radio Regulations

Sharing of the radio spectrum is managed by the International Telecommunication Union (ITU) via the Radio Regulations (RRs). These are developed at successive World Radio Conferences (WRCs) and become treaty obligations of ITU member states.

The ITU includes 193 (voting) member countries and other members, including businesses¹, academic, regional and international organisations. The ITU is a specialised United Nations agency tasked with allocating the global radio spectrum and orbits [64]. The ITU

¹Business members of the ITU in Australia are SingTel Optus Pty Limited and Telstra Limited [63].

comprises three sectors, of which the ITU radio communication sector (ITU-R) specifically, regulates the radio spectrum [56].

The frequency allocations themselves are contained in Volume 1, Chapter II, Article 5 of the RRs [55]. Allocations, in order of decreasing levels of protection, are: primary, secondary, or shared. For readers interested in more details of the specific legislation relating to RAS, see Appendix A.

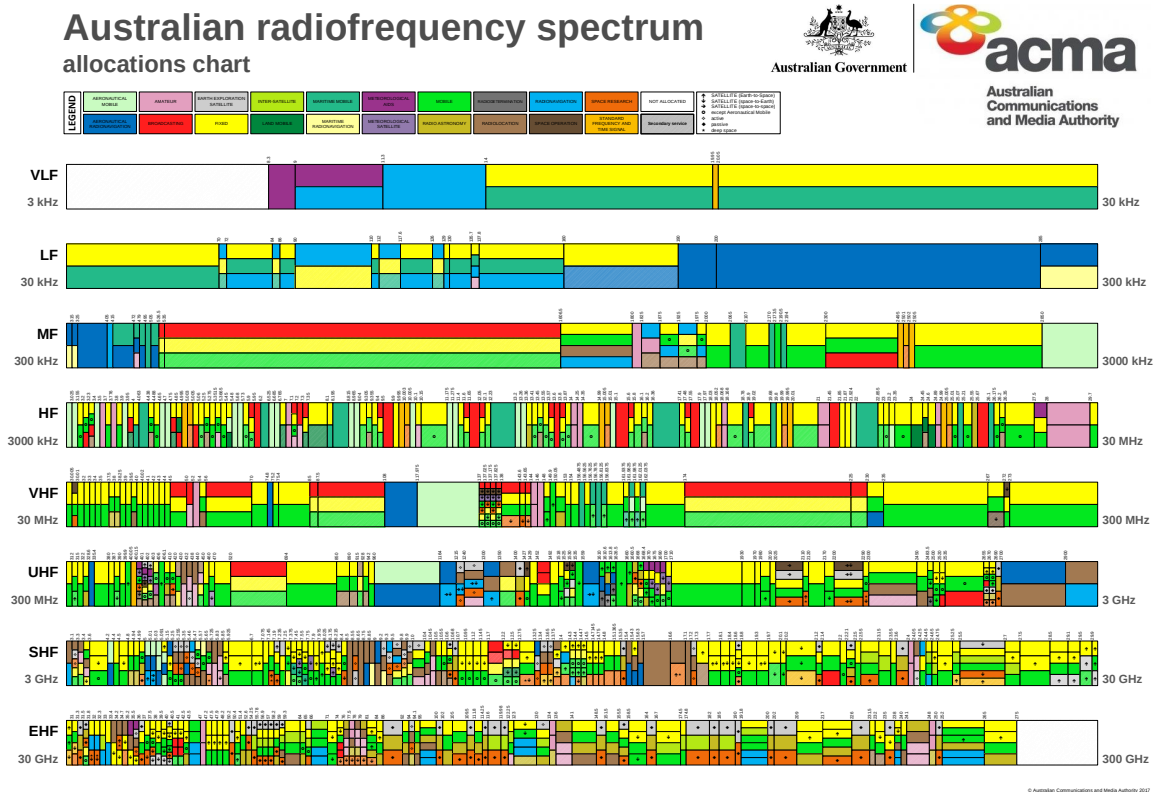


FIGURE 2.1. Radio Regulations (RRs) in Australia are under the administration of Australian Communications and Media Authority (ACMA). Visually, RRs are often depicted as a frequency allocation chart. Article 1, Section III of the ITU RRs define approximately 40 radio services of which the radio astronomy service (RAS) service is one. Credit: [65]

As a member state, Australia must fulfil its international obligations. The radio spectrum is under the administration of Australian Communications and Media Authority (ACMA) by way of federal legislation, in particular, the Radiocommunications Act 1992 [66]. Visually,

RRs are often depicted as a frequency allocation chart. The ACMA Australian radiofrequency spectrum is shown below in Figure 2.1.

Article 1, Section III of the ITU RRs defines roughly forty radio services, of which the radio astronomy service (RAS) is one [16]. RAS is also the only completely passive service. A feature worth pointing out in Figure 2.1 is the division of the radio spectrum in decades². RAS has approximately double the bandwidth in each decade starting from the HF band [43].

Appendix A describes the organisation and structure by which astronomy is represented from a spectrum management point of view in more detail. It sets out the different levels of protection [67], how RFI is defined legally with respect to various thresholds, and some of the mechanisms by which RFI affects RAS protected bands. Appendix A outlines many protections for RAS, for example Footnote 5.340 states that “all emissions are prohibited”. However, an exclusive primary allocation does not ensure complete protection from RFI [43] because as stated in Article 4.6 of the RRs, *“For the purpose of resolving cases of harmful interference, the radio astronomy service shall be treated as a radiocommunication service. However, with regard to emissions from services operating in other bands, it shall be afforded the same degree of protection as such services are afforded vis-à-vis each other.”* [16].

RAS receives protection in only 3 % (including primary, shared, and secondary allocations) of the radio spectrum below 30 GHz [43], Figure 2.2.

Ultimately, radio telescopes must be located in radio-quiet zones to operate in bands outside the RAS allocations, as well as to ensure the least amount of RFI within protected RAS bands.

²The ITU and the Institute of Electrical and Electronics Engineers (IEEE) are two organisations that have established standards in defining the radio spectrum and its bands. The radio spectrum is divided into bands and further divided into subbands. For example, ITU defines Ultra-High Frequency (UHF) as the frequency range from 300 kHz to 3000 MHz. The IEEE breaks this same frequency range into the UHF, L and S (radar) bands.

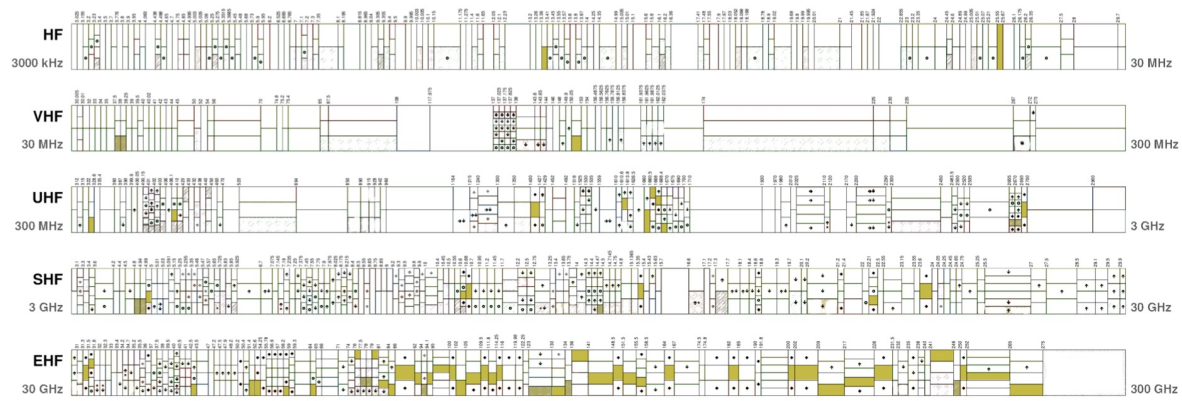


FIGURE 2.2. Excerpt of the Australian Communications and Media Authority (ACMA) frequency allocation chart showing only RAS allocations. RAS receives protection in only 3 % (including primary, shared, and secondary allocations) of the radio spectrum below 30 GHz [43]. Credit: [65]

2.1.2 Radio-quiet zones

Allocation sharing and radio astronomy's unique requirements as a passive service are practically realised in the form of radio-quiet zones. Radio-quiet zones typically refer to geographic areas around ground-based telescopes and observatories; however, they need not be limited to the Earth's surface, for example ITU-R RA.4749-4 (2003) protecting the shielded zone of the moon and ITU-R RA.1417-2 (2007) protecting the L2 Sun-Earth Lagrange point. [68]. Radio-quiet zones are defined in [55] as "a recognized geographical area where the usual spectrum management procedures are modified for the specific purpose of reducing or avoiding interference to radio telescopes." Table 9.1 in [55] and recommendation ITU-R RA.2259 [69] gives a list of various controls and measures employed in radio-quiet zones globally.

Radio-quiet zones are implemented legislatively by national³ and state regulators. These zones are often far from heavily populated areas and can have inherent protection from

³An interesting example of the limits of the quiet zone (due to the borders between nations) is the 'coordination zone for ALMA', where the legislation by the Chilean regulator SubTel does not extend across the Bolivian and Argentinian borders, resulting in only approximately half of an outer concentric shell of coordination zone and even the inner protected zone has a chord across the north, slightly northeast, due to the Bolivian border. There is currently no legislation less than 30 km directly north of the centre of the protected, quiet zone around ALMA [70].

topographical features. Transmitters may be permitted outside the frequencies used by the telescope. Varying levels of protection as a function of distance from the centre of the radio-quiet zone are realised in a series of concentric shells with specific criteria for each ring. The CRAF says that radio-quiet zones are most effective when established early [43].

One limit to the protection from radio-quiet zones is that they are restricted to terrestrial emitters, i.e., there is no volume in the zone. Footnote 5.149 illustrates this point and urges administrations to take steps to protect RAS, especially from emission by satellites, spacecraft or airborne transmission [16]. In addition to a radio-quiet zone, restricted air space around observatories is desirable for reducing RFI from aeronautical radio navigation [69, 71]. Currently, no radio-quiet zone restricts satellite transmission [55]. The particular threat to astronomy from satellites is presented in Appendix B.

Another limitation is RFI due to natural phenomena⁴. This may be either completely natural like lightning or solar interference; or phenomena that propagate human-made transmitters farther than normal called (tropospheric) ducting.

The troposphere is the lowest layer of the atmosphere. Under certain circumstances, temperature increases with altitude (rather than the usual decrease) and causes a higher refractive index. This bends the radio waves in a way that creates a “duct” of enhanced propagation. Radio signals that enter the duct can travel hundreds of kilometres with very low propagation losses [51]. A tropospheric duct can last between a few minutes and several hours. The effect of ducting on a radio-quiet zone is that it effectively moves a far away radio transmitter, that would have been outside the protected area, hundreds of kilometers closer.

Protected, radio-quiet zones around observatories are essential for radio astronomy outside of RAS bands. As [55] points out, even with respect to terrestrial transmission, a radio-quiet zone “does not imply the complete absence of radio transmission”, it is a ‘buffer-zone’

⁴This was the focus of Karl Jansky’s research; he was investigating natural sources of RFI in long-distance telephone communication over shortwave radio when he discovered the cosmic radio emission. [18]

intended to mitigate the worst effects of terrestrial RFI on the telescope. Co-existence with other services will always be necessary.

Examples of current radio-quiet zones⁵ are (with a comprehensive list in [55] and ITU-R RA.2259-1 [69]):

- coordination zone for ALMA ,[43],
- Karoo Central Astronomy Advantage Area [72],
- National Radio Quiet Zone in Green Bank, West Virginia [56], and
- Australian Radio Quiet Zone – Western Australia (ARQZWA) [45, 46].

The Australian Radio Quiet Zone – Western Australia (ARQZWA) specifically surrounding the observatory and ASKAP, is discussed separately in detail in Section 2.3.1.

Radio dynamic zones, like radio-quiet zones, are geographically bounded areas. Instead of prohibiting transmission, radio dynamic zones are experimenting with more sophisticated sharing of the radio spectrum to maximise its use via mutual spectrum awareness and coordination from both the observatory and the transmitter [73]. In this regime, satellite internet providers would have automated access to relevant telemetry from the observatory regarding the observing frequency range and pointing, for example, to steer their beams away from the antenna or operate at different frequencies [73]. *Pseudonymity* could allow improved compliance in which interferers can be identified from a watermark and notified through a shared database to stop their operation, thus protecting passive service observations [74]. The most notable example of dynamic spectrum sharing is in the United States where the National Science Foundation and Starlink [75] have collaborated to not only reduce optical brightness but have committed not to illuminate the U.S. National Radio Astronomy Observatory (NRAO) with their main beam, a test bed for the future National Radio Dynamic Zone [76]. This is a good example of Articles VI and VII of the Outer Space Treaty [77] in practice and foreshadows the recent WRC 2027 and Committee on the Peaceful Uses of Outer

⁵Annex 10 of Recommendation ITU-R RA.2259-1 describes protection of the MeerKAT/SKA radio telescope in South Africa [69]

Space’s Scientific and Technical Subcommittee agenda items regarding satellite constellation (discussed in Appendix B) scaled out, in particular, to existing (SKA) radio-quiet zones.

2.2 Thinking about RFI mitigation holistically

There have now been many reviews of RFI mitigation (removal or reduction) techniques [52–54, 78–82]. One of the more cited review papers is Fridman and Baan 2001 [53]. I recommend the updated and more recent 2019 review paper by Baan [52] which is broadened to include both RAS and the Earth Exploration Service and is structured not by mitigation technique (as in [53]) but by where the technique can be used in the signal chain and provides a framework for what I will call a ‘holistic’ approach to RFI mitigation, management and monitoring. The latter covers all the same techniques as the former but also emphasises the need for automated RFI mitigation and new active non-destructive techniques. The ITU-R RA.2126-1 *Techniques for mitigation of radio frequency interference in radio astronomy* (2013) [54] first published in 2007 is also recommended.

Typically, any mitigation strategy involves the following: distinguishing the RFI from the source of interest by finding dimensions in the parameter space (time, frequency, power, direction, polarisation, or other statistical properties), and exploiting those differences to remove or attenuate the unwanted signal.

Baan [52] advocates for a multi-layer RFI mitigation strategy in which techniques fall into three categories;

- prevention,
- real-time mitigation,
- and offline mitigation.

He identifies four opportunities to intervene in the signal chain:

- (1) At the antenna/station - Pro-active and **pre-detection** interventions;
- (2) Antenna/station mitigation **at the detection system**;
- (3) Antenna/station mitigation **before correlation⁶ and processing**;
- (4) Central mitigation **at correlation and post-correlation**;

I will follow a similar structure throughout this section after some general remarks.

Baan [52, 53] and Ekers [78] explain that there is no universal method of mitigation and that the suitability of any of the techniques presented below is based on the type of science, type of instrument and the characteristics of the interference (hence the structure of Chapter 1). This section presents the broader suite of RFI mitigation techniques discussed in the literature. A more comprehensive literature review on the chronological developments of spatial nulling, is outlined in §2.4 and its implementation for ASKAP is the subject of Chapters 4 and 5.

In general, single-dish telescopes are more affected by RFI than arrays [53]. Broadband interference raises the instrument noise floor thereby reducing the sensitivity. Narrow band RFI may imitate spectral line sources-of-interest and in both cases can obscure a signal of interest or lead to false scientific conclusions [52]. Baan [52, 53] suggests some overarching principle: it is better to remove RFI as early as possible in the signal chain and at the highest time and frequency resolution. Mitigation in the time domain is generally best suited for strong short interference, and mitigation in the frequency domain is better suited for long lasting RFI.

Baan [52] also points out that time/frequency excision, specifically flagging has been the standard – and preferred – method for dealing with corrupted data. There is a working assumption in the community that RFI corrupted data is either partially or completely unusable. Filtering and excision are simple, and their consequences, from the astronomers’ point of view, are predictable. This sentiment is echoed in the literature in different forms. RA.2126 states that astronomers are “hesitant to adopt black box methods of mitigation” [54] and in

⁶Correlators in radio astronomy combine signals received from different antennas.

Kesteven that "the modest improvements achievable with a sophisticated scheme are marginal and do not outweigh the uncertainties inherent in new techniques" [83]. While the claim is not explicitly made in the research, there is clearly an adoption issue [84]. Baan [52] also claims that the threat of RFI has been underestimated and that mitigation efforts have typically been considered an after thought. It is therefore incumbent on those of us who implement and design these mitigation techniques to better communicate the effects on the instrument and its science outputs. In this vein, Baan [52] recommends detailed bookkeeping, in an autonomous multi-tiered mitigation scheme, to detail what has been done with regards to mitigation at every point of the signal chain. He emphasises that with an increasingly congested RFI environment, larger big-data style outputs, a suite of automated particularly non-destructive RFI mitigation techniques must be implemented as a matter of priority. RA.2126 [54] reiterates this point. Friedman and Baan [53] also campaign for an RFI database at each facility that would provide guidance for observational procedures and for choosing appropriate RFI mitigation methods. Chapter 3 is a step in this direction, statistics about the amount of discarded data due to RFI, based on over 1500 h of ASKAP science data, is presented.

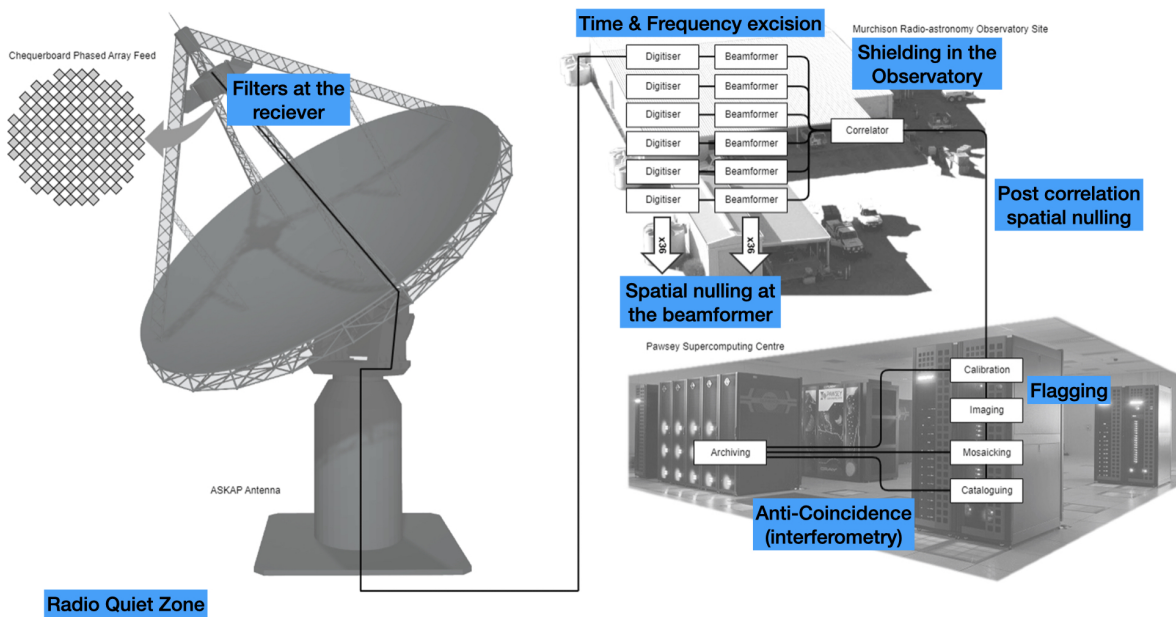


FIGURE 2.3. Reproduced from [38], annotations show opportunities for RFI mitigation across ASKAP's signal chain.

Figure 2.3 shows ASKAP’s signal chain as an example, with annotations of RFI mitigation techniques shortlisted in ITU-R RA.2126 and where they can be applied in the signal chain.

2.2.1 Pro-active and pre-detection interventions

Baan [52] defines these techniques as preventing RFI from entering the detector or reducing their strength at the detector. Where possible, interferers should be removed [78]. RA.2126 [54] describes proactive measures including ongoing identification and elimination of RFI on-site. Baan [52] refers to this as ‘cleaning the site’. Before construction, an RFI survey is typically conducted to determine the risk of RFI in the instrument(s) operating bandwidth (for example, [42, 85, 86]) and identifying clean subbands. Observatories are often sources of RFI. This can be reduced through RFI-shielding (aka screening) [78, 87], remote observing, and limiting the number of visitors and electric devices. Chapter 4 addresses the mitigation of a self-generated source of interference originating from the telescope backend electronics.

Proactive measures also include regulation of dedicated RAS bands [16, 78] as discussed in the previous section. Baan [52] does emphasise that these rules are not always respected. Observations outside of the protected allocations require radio-quiet zones and restricted airspace (also discussed in the previous section). Screening or blocking terrestrial interferers on the horizon can be realised through topographical features [78]. ‘Smart’ scheduling of observations which considers telescope pointing could also be used to avoid known sources of RFI. Finally, coordination and negotiation [75, 88] with radio network operators and service providers is becoming increasingly necessary. Locally, Ekers [78] gives another example where replacing nearby radio links with fibre removes RFI and improves connectivity for users. Similarly, transmitters can move to different frequencies as at the SKA-low site [78, 89]

2.2.2 Antenna/station mitigation at the detection system

This primarily includes robust high dynamic range linear receivers with enough headroom to ensure the receiver does not saturate and enter the non-linear regime [54, 78, 90, 91]. Filters are also imperative in the receiver electronics, including band edge and notch filters (good for constant known signals) [52, 78, 82, 92]. All telescopes have a ‘natural’ filter built-in, that is the frequency range in which they operate, also known as the passband [93]. An [82] identifies the drawbacks with filtering are insertion loss, increased system temperatures near band-edges. They point out filtering is essential for spectral line observations but presents a trade off for continuum observations.

2.2.3 Antenna/station mitigation before correlation and processing

Fridman & Baan, An and RA.2126 [52–54, 78, 82] describe time and frequency excision in the passband in its various forms – clipping, blanking and thresholding – as useful for impulsive RFI in real-time, at baseband and as close to the sampling speed as possible. In other words, removing the voltage samples with amplitudes greater than some threshold [87, 94–96]. In this case, the underlying astronomical data is also lost, and artifacts may remain or be introduced. Usually interference affected samples are discarded, but they can also be replaced with random noise with similar statistical properties, this still however discards the astronomical signal [93]. Blanking in the frequency domain is best suited for narrow band RFI and particularly suited for continuum observations where features vary slowly in frequency [52, 93].

Removing the RFI signature is possible using waveform subtraction methods [52–54]. Waveform subtraction requires a copy of the interferer which can be subtracted from the telescope output, often using a reference antenna [97, 98] or an alternate communications channel [99]. In theory, the RFI is removed without affecting the source data, in practice, suppression is limited by the quality of the estimate of the RFI. This approach assumes the

source of interest and RFI are additive and uncorrelated signals. This method can be used for both arrays and single dishes [100]. Examples of waveform subtraction are Autoclean [52, 53] without a reference antenna and Adaptive Noise Cancellation with reference antennas [4, 98, 101]. Adaptive Noise Cancellation involves thresholding using convolution kernels in the frequency domain and returning back to the temporal domain before the data is fed to the correlator. RA.2126 [54] has the most comprehensive overview of waveform subtraction and the use of reference antennas/beams.

Baan [52] describes the use of higher-order statistics and probability analysis to separate two superimposed signals such as RFI on a known spectral line. This approach leverages the statistical properties of thermal (white) stochastic processes, system noise and signal of interest and how the distribution is altered in the presence of RFI.

The final pre-correlation strategy Baan [52] highlights the potential of is RFI mitigation with multi-element and phased-array systems before correlation which consider the RFI's direction.

2.2.3.1 Pre-correlation adaptive/spatial filters

Adaptive filtering makes use of various beamforming algorithms [102, 103].

Beamforming is described in more detail in Section 2.3.4, but it is worth mentioning a few features of a beam here. Phased-array beams can most easily be understood as a weighted sum of the antenna element patterns, resulting in a high gain main lobe in the direction of the wanted astronomical source (shown by the peaks in the left panel of Figure 2.4). Different beamforming algorithms exist, yielding different beampatterns, as illustrated by the different colours in Figure 2.4. Some, like the green curve, are specifically designed to introduce nulls (zero gain) in the direction of an interferer (the red dashed curve) and reduce its contribution (interference) to astronomical data.

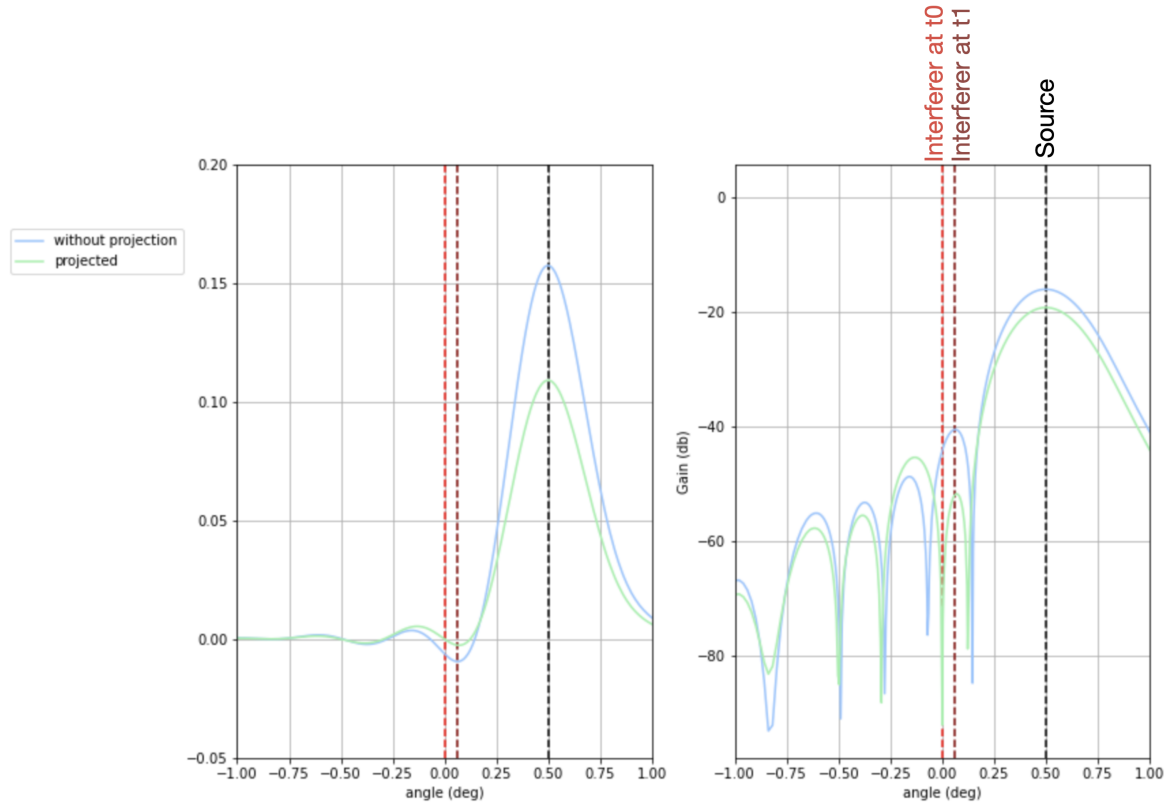


FIGURE 2.4. Comparison of a beam pattern with and without mitigation using orthogonal projection. The left image shows the linear gain and the right image shows the gain in dB.

Spatial filtering techniques have been developed to avoid interference in telecommunication and radar antenna array systems [104]. For optimal utilisation of these techniques, multi-element systems should be able to adjust antenna phases and amplitudes [53]. Spatial filters at the beamformer are effective in mitigating a limited number of strong temporally stable and predictable interferers [7, 52].

Adaptive filtering using one array element (per interferer) as a reference channel is not suited to sparse arrays [52]. Using a reference antenna with a direct view of the interferer and a higher SNR can significantly enhance nulling performance [4, 105]. On the other hand regularly spaced and dense phased arrays, with element spacing $d \approx \lambda/2$, are well suited to these techniques — in particular subspace projection [1, 102, 106]. PAFs at higher frequencies are also well suited to spatial nulling [5, 7, 98].

Figure 2.4 shows two beamforming mitigation strategies, the blue curve is without mitigation and the green curve is with mitigation. The right panel in Figure 2.4 at the red dashed curve shows that the blue curve has a higher gain than the green curve. The local maximas to the left (and right, not shown) of the highest peak (the main lobe) are called sidelobes. Although the gain is less in the sidelobes the much stronger interferers entering the sidelobes would result in the unwanted signal corrupting the recorded output data and therefore have to be discarded.

Spatial nulling using projection (green curve) introduces one or more nulls in the beam-pattern in the direction of the interferer, shown at the red dashed line in the right panel of Figure 2.4. The left panel however clearly shows a distortion to the main beam using this particular projection, the gain is lower in the green curve compared to the blue curve. This undesirable effect is reduced when using oblique projection [6, 107, 108]. Oblique projection is the specific beamforming RFI mitigation technique used in later chapters of this thesis.

The right panel of Figure 2.4 also shows another challenge of using subspace projection. The null was calculated at the direction of the interferer at time zero (t_0), but some time later (t_1) the relative motion between the array and the interferer means that that the interferer is no longer in the null but rather (again) in the green sidelobe. The rate at which new beamformer weights can be calculated and then applied, the width of the null [10], and the relative motion between interferer and antenna are therefore important considerations in implementation. Another challenge in implementing this subspace projection is estimating the interferer's spatial signature (direction) [109]. Fridman and Baan [53] caution that spatial filters presume RFI is well localised in space even though this is not always the case.

More background on spatial nulling is given in §2.4.

2.2.4 Mitigation at correlation and post-correlation

Correlators in interferometry combine signals received from different antennas. Correlation usually involves integration over longer time intervals which can increase the interference signal level. In interferometers, (another round of) spatial filtering is possible at the correlator to remove weak RFI [6], again possible with a reference antenna [110].

Interferometers allow for natural rejection of incoherent signals [31, 78, 82]. Anti-coincidence — minimising coherent signals — relies on the fact that sources of RFI are typically much closer than the source of interest. Widely-separated antennas receive the same signal from the source but differing RFI and are therefore negligible in the correlated astronomy [54, 111]. This approach may not be suitable for dense array tiled stations or phased array feeds.

Post correlation time and frequency excision is mainly in the form of *flagging*, the process of discarding corrupted data.

2.2.4.1 Flagging: discarding RFI-affected data

Flagging is the most widely practiced RFI mitigation technique in radio astronomy [52]. It involves analysing visibilities (correlated measurements of amplitude and phase) for outliers and removing the outliers using a mask (marking the visibility as ‘corrupted’) so that they do not affect scientific conclusions. The removal of data unfortunately decreases sensitivity and also impacts synthesis beam of a synthesis array. The specific methodology for determining which visibilities to flag depends on the flagger. Some examples of flaggers include AOflagger⁷ [112], cflag⁸, tricolor⁹ [113]. Some common approaches to identifying RFI-affected channels by the flaggers include statistical, frequency, time-domain analyses

⁷<https://sourceforge.net/p/aoflagger/wiki/Home/>

⁸<https://www.atnf.csiro.au/computing/software/askapsoft/sdp/docs/current/calim/cflag.html>

⁹<https://github.com/ratt-ru/tricolour>

and offline visual inspection, or a combination thereof. Flagging is also often done iteratively during calibration and imaging [32].

More recently a statistical view of the RFI environment of an observatory based on flagging data has been explored. The earliest of these is Offringa et al.[114] using the MWA phased array looking at the low frequency environment (72.3 MHz - 230.8 MHz) of Inyarrimanha Ilgari Bundara, the CSIRO Murchison Radio-astronomy Observatory over 10 nights. Offringa et al. also conduct, to a more limited degree, an analysis of flagged data using the PAF Apertif between 1280 MHz and 1370 MHz on the WSRT [115]. Zhang et al. [116] ≈ 300 h of FAST data from 1000 - 1500 MHz. Finally Sihlangu et al. [117] did a very comprehensive study of RFI occupancy including pointing occupancy using 1500 h of MeerKAT data covering from 800 - 1700 MHz. §3 performs a similar analysis of ASKAP data using over 2000 h of observing time.

2.3 The Australian SKA Pathfinder

A full description of the Australian SKA Pathfinder (ASKAP) is given by Hotan et al. [38]. ASKAP is located in Inyarrimanha Ilgari Bundara, the CSIRO Murchison Radio-astronomy Observatory¹⁰, Figure 2.5.

2.3.1 ASKAP RFI environment

The observatory is located in a remote area to avoid human-made RFI, state and federal legislation protect an area of 260 km from the observatory site centre known as the Australian Radio Quiet Zone – Western Australia (ARQZWA) established by Australian Communications and Media Authority (ACMA) [45, 46].

¹⁰In addition to ASKAP, the observatory is home to the MWA [36], EDGES [118], and SKA-Low[119] telescopes.

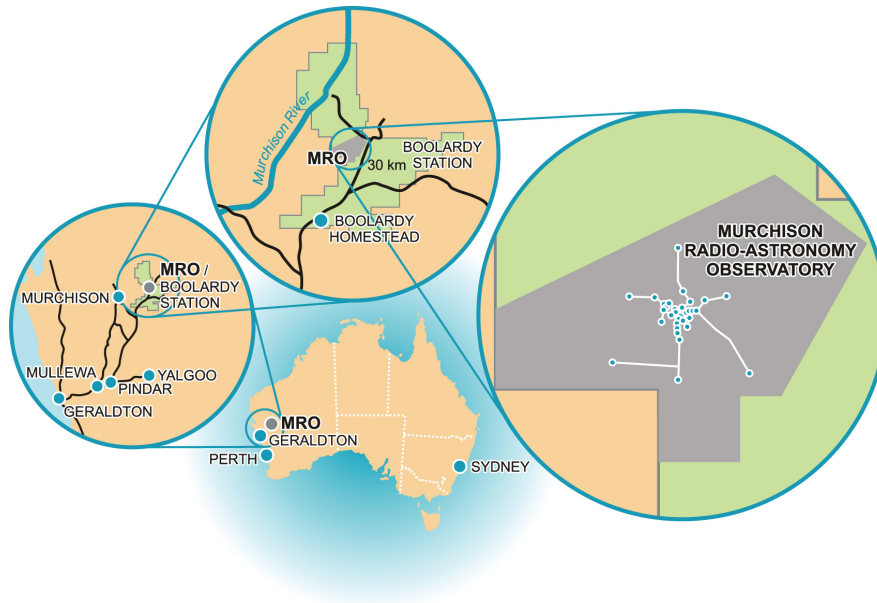


FIGURE 2.5. Diagram showing the relative location and size of Inyarrimanha Ilgari Bundara, the CSIRO Murchison Radio-astronomy Observatory. The final inset shows ASKAP antennas as blue dots and service tracks as white lines.

Reproduced from [38],

pre dual name Inyarrimanha Ilgari Bundara [120].

Operating a radio transmitter in the ARQZWA requires varying licences based on the distance from the centre of the radio-quiet zone. The ARQZWA comprises three zones [121]:

- the inner zone from 0 km to 70 km;
- the outer zone from 70 km to 150 km; and
- the coordination zone from 150 km to 260 km.

Within the inner zone “*Radio astronomy is the primary user of radiofrequency spectrum in this zone*” and in the outer zone “*the governments endeavour to maximise opportunities for coexistence between radio astronomy and other activities ...*” [121].

However, as we have seen, radio-quiet zones — outside the coordination zone — do not protect from orbiting satellites, aircraft safety equipment, and radio services with a primary

allocation (Figure 2.6) undergoing tropospheric ducting. A request for restricted airspace over the observatory has been filed [71].

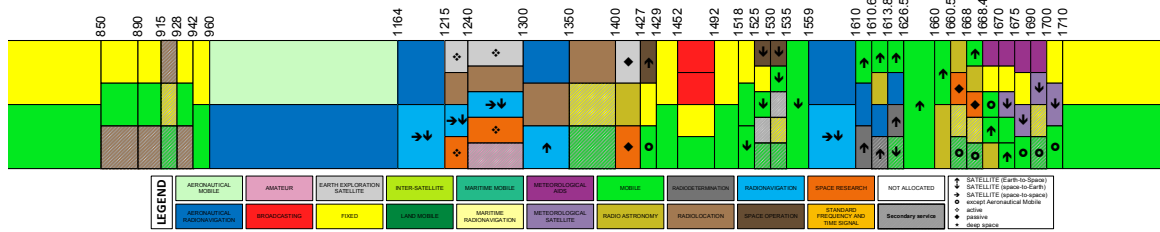


FIGURE 2.6. Excerpt of the Australian Communications and Media Authority (ACMA) frequency allocation chart showing services in ASKAP's frequency range. Credit: ACMA [65]

Figure 2.6 shows that ASKAP operates in frequency bands of services with primary allocations associated with communication services (yellow and green), aeronautical services (dark blue), various satellite services (orange, light blue and purple), broadcasting (red) and radar (brown and grey). The gold allocations are RAS protected bands, which are always shared by other passive services (indicated by a diamond) or satellite uplink (up arrows).

In 2016 Sokolowski observed evidence of tropospheric ducting identifying RFI from distances much farther away than expected at the observatory site in up to 37 out of 131 nights (28 %) between 70 MHz and 300 [122]. Note that ducting events at lower frequencies foreshadow ducting in the ASKAP frequency range [42]. Also at low frequencies Offringa et al. in 2015, over 10 nights of observations, showed evidence of RFI based on flagged data from the MWA [114] in at least 1.1 % of data in the 72 MHz to 231 MHz range. Most recently in 2020 Tingay et al. conducted an FM band RFI survey at the observatory over the course of three days from 33 994 all-sky dual polarisation images and detected approximately 40 000 RFI events [123].

Indermüehle in 2017 conducted an RFI survey using the 6-antenna BETA array (preceding ASKAP) and various other RFI detection equipment [42] and compiled a list of RFI transmitters affecting ASKAP's observing range. Services identified included mobile telephony basestations (up to 550 km away) and aeronautical safety equipment. They found 15 % of the

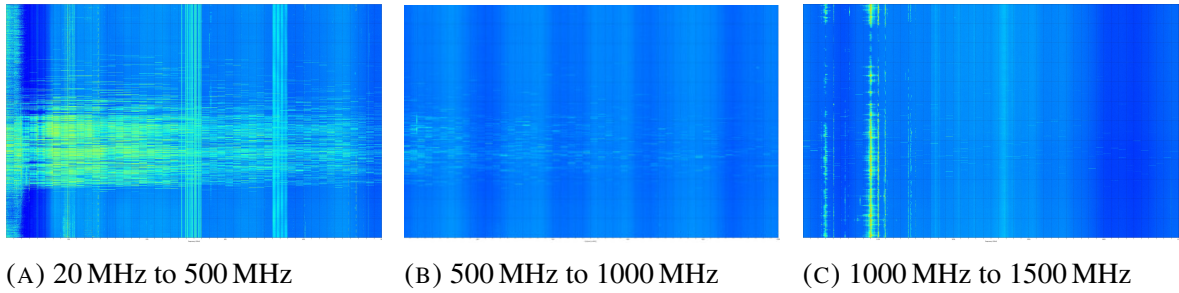


FIGURE 2.7. Measurements from RFI monitoring equipment at the observatory from the 5 March 2024 showing strong narrowband (vertical lines) from human-made RFI and lightning (horizontal lines). Frequency along the x-axis and time of day along the y. Panels B and C are in ASKAPs frequency range. Panel c shows strong RFI from aircraft. Credit: Dr Balthasar Indermüehle.

spectrum was lost to RFI. 90 % of the RFI was deemed to be external broadband emission (≥ 5 MHz bandwidth) and 10 % narrowband self-generated emission (< 5 MHz bandwidth) including faulty correlator cards and water pumps used for cooling (both replaced with the completion of ASKAP).

RFI monitoring equipment at the observatory is outlined in [42, 124]. In short there are two separate RFI monitors used at the observatory, the first has a slower scanning rate and longer integration time. It is better suited for detection of faint signals often seen from satellites, distant transmitters such as mobile base stations and localised weak RFI. The second is paired with an active antenna to make up in part for the faster scan rate. Both scan from 20 MHz to 3000 MHz, the first has finer frequency resolution, 3.125 kHz, with a sweep time of 62 s, compared to the second which scans at 100 kHz with a sweep time of 1.49 s, permitting detection of rapid transient emissions. RFI detection equipment is mounted on a 25 m high tower 170 m west of antenna ak25 (Figure 2.8). RFI monitoring data is recorded, archived and made available using a web GUI¹¹, Figure 2.7.

¹¹<https://www.atnf.csiro.au/observers/RFI/>

2.3.2 ASKAP hardware and signal path overview

ASKAP (Figure 1.5) comprises 36×12 m diameter paraboloidal reflectors, arranged as in Figure 2.8. It operates within a frequency range of 0.7 GHz to 1.8 GHz and has an instantaneous (correlated) bandwidth of 288 MHz. [38].

ASKAP is an interferometer, which means it estimates the correlation of the electric field produced at radio sources in the FoV by pairs of radio antennas [125]. The maximum separation between a pair of antennas (a baseline) is approximately 6 km [38].

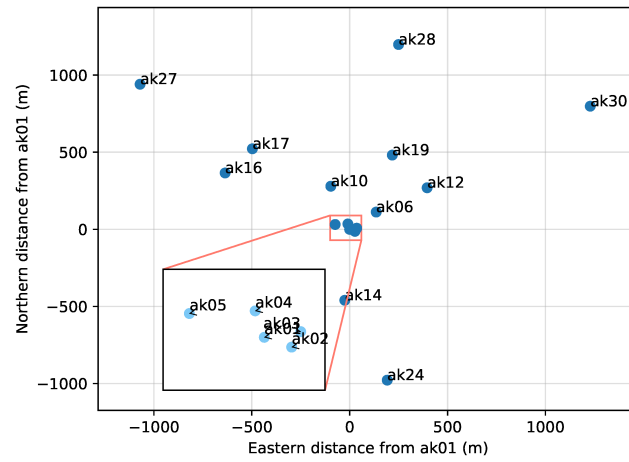


FIGURE 2.8. ASKAP antenna locations with respect to antenna ak01. Radio interferometers sample the electric field of sources in the FoV by estimating the correlations between antenna pairs. Reproduced from [126]

This means that it is highly sensitive due to the large collecting area of 4072 m^2 , has a high angular resolution due to the long baselines and can observe a 30 deg^2 FoV simultaneously

At the focus of each reflector there is a 188-element chequerboard PAF (Figure 1.7) capable of forming up to 36 independent dual-polarisation beams (94 for each polarisation) [38] arranged in different patterns on the sky called a footprint (Figure 2.9). ASKAP is the first large-scale instrument designed from its outset with PAFs in mind [7]. Beamforming is the process of combining the PAF elements in weighted sums resulting in beams with the desired shape, stability and sensitivity [127]. Beamforming with PAFs presents more challenges

compared to the conventional single feed horn as outlined by Jeffs [5]. More detail on the development of PAFs for radio astronomy is given in Appendix C.

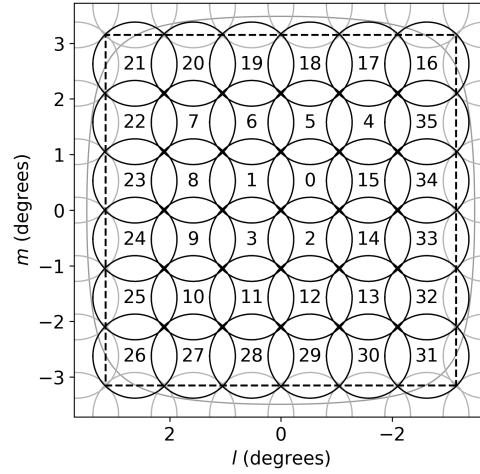


FIGURE 2.9. ASKAP PAFs allow multiple dual-polarisation beams arranged on the sky in a footprint, resulting in a large FoV. Reproduced from [12]

Plane waves from a source arrive at each antenna at slightly different times, resulting in a geometric delay between the two measurements of an antenna pair. The plane wave is focused on the receiver inducing voltages across pairs of PAF dipole elements.

Voltages induced across PAF dipole pairs are amplified, filtered, and prepared for bulk transport in the focus package by 94 modules called “dominos” [128]. Each domino has three layers:

- (1) bottom, the low noise amplifier (LNA);
- (2) middle, three selectable RF bandpass filters (500/600/400 MHz bandwidth); and
- (3) top, an RF-over-Fibre transmitter with low relative intensity noise laser diode.

This first stage of signal processing is the analog part of the system and ensures minimal signal degradation from the antennas to an RFI shielded building located 7 km away. Two proprietary digital signal processing boards – Dragonfly and Redback – use field programmable

gate arrays (FPGAs) to perform analog-to-digital conversion¹², coarse (336 x 1 MHz channel) filtering using an oversampled polyphase filter bank [130], correlation¹³, fine 18.5 kHz filtering and beamforming. Specifically 16 Redback boards per antenna computes the array covariance matrix (ACM) (Figure 2.10) and performs beamforming [38, 131].

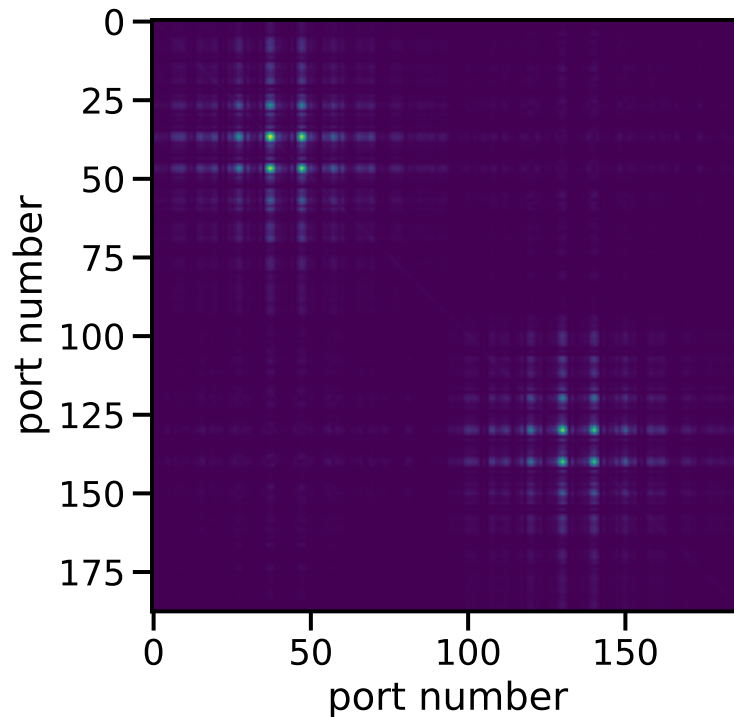


FIGURE 2.10. 1 MHz beamforming ACM (short observations tracking the Sun) for the 1030 MHz channel from a single antenna, for a single beam. Considering the quadrants in clockwise order from the top left: I and III are the cross correlations of each PAF port with itself for the XX and YY polarisation respectively. The diagonal show the auto correlation, total power of each port. II and IV show the YX and XY correlations (leakage). This is an on-source beamforming ACM with a bright source illuminating the PAF.

ASKAP's Redback boards calculate ACMs — the pairwise correlations of all antenna elements in the array — for each of the 336, 1 MHz coarse channels. Complex beamformer weights are estimated using the Maximum Signal-to-Noise Ratio (maxSNR) beamforming algorithm, see §9 of the ASKAP system description [38] for more information.

¹²Analog-to-digital conversion is actually performed by external ADC chips that are connected to the FPGAs [129].

¹³also delay tracking and fringe stopping

An on-dish calibrator can be used to estimate changes in the complex gain of PAF elements and update beamformer weights to ensure that the primary beam is stable and remains stable [38].

Corresponding Beamformed outputs (i.e. those pointing in the same direction) from all PAFs on all antennas are correlated (multiplied and averaged) to provide complex visibilities for each baseline and define the response of the interferometer. A Fourier transform relationship exists between the visibilities and the source brightness distribution, which is used to create downstream images. The visibilities are streamed from the observatory to the Pawsey Supercomputing centre 600 km away, where a real-time ingest pipeline prepares the data for further (offline) processing, including flagging, calibration, imaging formation, and beam deconvolution [132] as seen in Figure 2.3.

2.3.3 ASKAP signal model

Let $\mathbf{x}[n]$ be the sampled output vector of complex voltages of a single PAF. Given an array with M elements $\mathbf{x}[n]$ is an $M \times 1$ column vector for the k^{th} narrow-band frequency channel of K channels ($K = 336$ for ASKAP). The model comprises three terms corresponding to the contributions of the source of interest (SOI), RFI and a total noise term

$$\mathbf{x}[n] = x_{\text{SOI}}[n]\mathbf{a}_{\text{SOI}} + x_{\text{RFI}}[n]\mathbf{a}_{\text{RFI}} + \mathbf{x}_z[n]. \quad (2.1)$$

Here $x_{\text{SOI}}[n]$, $x_{\text{RFI}}[n]$, $\mathbf{x}_z[n]$ are the source-of-interest, RFI and noise signal vector at sample n . $\mathbf{a}_{\text{SOI}}$ and $\mathbf{a}_{\text{RFI}}$ are the associated (direction) spatial signature vectors (SSVs), also known as steering vectors, at sample n . This model is extended to multiple interferes in Chapter 5. The noise term is the sum of all noise, including thermal noise, sky noise (atmosphere, celestial noise e.g. cosmic microwave and galactic backgrounds), spillover noise (ground), thermal and receiver/electronic noise and is always present in the data. For beamformed beams on different antennas, this noise is random, always uncorrelated and has a mean of zero¹⁴. The

¹⁴For a dense PAF array where there is coupling between the elements.

significance of this is that when averaged over time, no ‘signal’ emerges from the noise; it simply averages out¹⁵.

An ACM can then be calculated as follows

$$\mathbf{R} = \langle \mathbf{x}[n] \cdot \mathbf{x}[n]^H \rangle = \mathbf{R}_{SOI} + \mathbf{R}_{RFI} + \mathbf{R}_n \quad (2.2)$$

where $(\cdot)^H$ is the conjugate transpose or Hermitian and $\langle \cdot \rangle$ denotes the time average operator.

2.3.4 ASKAP Beamforming

Monzingo or Van Trees [104, 133] are recommended as thorough references to array signal processing and beamforming.

Digital beamforming is a signal-processing technique used to control the directionality of an antenna array. It involves adjusting the phase and/or amplitude of signals transmitted or received by each antenna element to steer the main beam in a specific direction.

Weights can be calculated and applied to the vector $\mathbf{x}[n]$ to form an arbitrary number of beams in the desired direction as shown in Figure 4.9. The output vector at the beamformer is given by [134, 135]:

$$\mathbf{y}_k[n] = \mathbf{w}_k^H \mathbf{x}_k[n] \quad (2.3)$$

where $\mathbf{w}_k$ is a set of complex beamformer weights for a single beamformer frequency channel. Although there are a different types of beamformers [133] only the maximum signal-to-noise ratio (maxSNR) beamformer is described below, as it is very frequently used in radio astronomy where sensitivity is of primary concern. Two ACMss are required in order to perform maxSNR beamforming, $\mathbf{R}_{off}$ and $\mathbf{R}_{on}$, that is, one pointing at the empty sky (off source i.e. noise) and one pointing at an astronomical source (on source i.e. noise + source). The maxSNR algorithm estimates the dominant solution $\mathbf{v}_0$ by performing an eigenvalue

¹⁵in the case of cross-correlations for an interferometer with widely separated antennas. In single-dish telescopes, the noise has to be calibrated/subtracted out.

decomposition:

$$(\mathbf{R}_{on} - \mathbf{R}_{off})\mathbf{v} = \lambda\mathbf{v} \quad (2.4)$$

we subtract the noise to isolate the signal. In the presence of no or negligible RFI this will yield a set of weights with high gain in the direction of the source.

From which the beamformed weights are then computed:

$$\mathbf{w}_k = \mathbf{R}_{off}^{-1}\mathbf{v}_{1k} \quad (2.5)$$

Figure 2.4, shows in dark blue an example of a beampattern created to have a high gain in the direction of a source at 0.5 degrees from boresight. There are a couple of features worth noting, The main lobe, the side lobes and nulls. The purpose of the techniques described in the next section are to introduce nulls into the side lobes in the direction of the interferer as shown by the green curve of Figure 2.4.

2.4 Subspace projections techniques for arrays

Section 4 and 5 present the effects on astronomy of RFI mitigation using subspace projection. Subspace projection aims to project the data in the ACM onto a subspace that is orthogonal to the RFI subspace but still in the direction of the source-of-interest, this parallel subspace (the projected subspace) contains only contributions from the source-of-interest. Astronomical sources-of-interest have power orders of magnitude weaker than the instruments noise floor mitigation of the RFI. This necessitates deep nulls in the beamformed pattern in the direction of the much stronger interferer.

Leshem and van der Veen first recommended subspace projections techniques for this purpose in 2000 [79], they analysed the effects of orthogonal projection on synthesis imaging and proposed how to integrate them into standard imaging practices using multiple sensors. They then went on to show how [1]: from short-term ACMs comprised of the source-of-interest, RFI and noise subspaces (Equation 5.2) — in the case where strong RFI is present —

the RFI spatial signature can be estimated using eigenvalue decomposition (Equation 4.4) of the affected channel [6, 39].

2.4.1 Orthogonal projection

After estimating the RFI subspace, $\mathbf{A}_{\text{est}}$; the dominant columns acquired from the eigenvalue decomposition of R with columns that span the RFI subspace. We obtain the projection matrix as follows

$$\mathbf{P} = \mathbf{A}_{\text{est}}(\mathbf{A}_{\text{est}}^H \mathbf{A}_{\text{est}})^{-1} \mathbf{A}_{\text{est}}^H. \quad (2.6)$$

The Orthogonal projection $\mathbf{P}_{\perp}$ is obtained by subtracting the projection matrix $\mathbf{P}$ from the identity matrix $\mathbf{I}$

$$\mathbf{P}_{\perp} = \mathbf{I} - \mathbf{P}. \quad (2.7)$$

Premultiplying an ACM by the orthogonal projection matrix will project its columns onto a subspace that is orthogonal to the RFI, essentially filtering the RFI out of the matrix by representing it on a basis that does not support the RFI.

Orthogonal projection matrices have either “0” (null Space) or “1” (range space) eigenvalues and hermitian symmetry (conjugate symmetry) [6].

Instead of applying the projection to the ACMs, they may be applied via modified or “projected” beamformer weights

$$\mathbf{w}'_{\perp} = \mathbf{P}_{\perp} \mathbf{w}_0 \quad (2.8)$$

where $\mathbf{w}_0$ are the original (maxSNR) weights and $\mathbf{w}'_{\perp}$ are the mitigated (orthogonal) weights.

Radio Astronomy requires stable and carefully calibrated beams, therefore, projections should ideally be done without changing the beampattern, such that the signal of the source-of-interest is unattenuated (maintains constant gain). Unfortunately orthogonal projection modifies the beam’s main lobe and boresight gain. Raza et al., using a phased array, applied a

correction to obtain an unbiased estimates of the RFI and noise subspaces for continuously present RFI [2] and later van der Tol extended this to time-varying signals [136].

In 2005, Boonstra demonstrated how subspace projection would be implemented at LOFAR [3]. In the same year, Jeffs et al. (Bringham Young University (BYU)/NRAO) showed how existing large-scale interferometers could perform subspace projection using a reference antennas [4] and their implementation in PAFs using a single reflector [108]. They then introduced a new method for power spectral density estimation bias error correction in narrowband RFI when cancelling using subspace projection and other common adaptive array processing techniques [137, 138]. Efficiency metrics from single-feed recievers are extended to PAFs and validated using simulations and experimental data using a 19-element PAF on the Green Bank 20 m telescope [139].

2.4.2 Oblique projection

To overcome having to use corrections to the orthogonal projection Hellbourg showed how oblique projection [107] could be applied to phased array systems [6]. Oblique projection in addition to creating deep nulls in the direction of the RFI using orthogonal projection, preserves the gain in the direction of the source-of-interest, defined by the unbiased [8] maxSNR weights

$$\mathbf{P}_{\text{oblique}} = \mathbf{w}_0(\mathbf{w}_0^H \mathbf{P}_{\perp} \mathbf{w}_0)^{-1} \mathbf{w}_0^H \mathbf{P}_{\perp}. \quad (2.9)$$

Updated beamformer weights can be calculated as follows

$$\mathbf{w}'_{\text{oblique}} = \mathbf{P}_{\text{oblique}} \mathbf{w}_0. \quad (2.10)$$

The different effects on the beampattern between the two projections, in particular the main lobe, are presented in Section 4.

2.4.2.1 Subspace estimation

Subspace estimation refers to the process of identifying the eigenvalue modes of an RFI-affected ACM that correspond to the RFI. The number of contributing eigenmodes depends on the number of interferers as well as their relative motion to the receiving array during the integration cycle called subspace smearing. Subspace smearing [109, 140] describes the increase in the RFI subspace due to motion during an integration time of the ACM. Furthermore, the faster the relative motion the closer to real-time the SSVs must be estimated and the mitigation ultimately applied. An upper limit of at least an 8 s delay is expected based on [13] for ASKAP. Subspace smearing impedes accurate estimation of SSVs, meaning the nulls could be in the wrong spot or, more likely, wider and shallower. Because the subspace estimates are higher order than they need to be, more information is projected out than necessary and (likely) results in greater impacts on beam quality (shape and sensitivity) than would be the case with the correct lower order SSV that might be obtained if subspace smearing could be avoided.

In short the degree to which a viable interference RFI SSV can be estimated limits the effectiveness of the mitigation. Methods to improve subspace estimation using auxiliary antennas [4, 110] or cached ACMs [10, 141] have been considered in the research but are not currently possible for ASKAP. The challenge of subspace estimation using ASKAP is discussed the topic of Chapter 5.

2.4.2.2 Subspace Projection using an ASKAP PAF

In 2015 Black [7] showed that it is most effective to perform RFI mitigation at the PAF beamformers. In 2016 a modified ASKAP PAF was tested on Parkes [142] and achieved mitigation of up to 20 dB, but the mitigation depth reduced rapidly after each beamformer weight update due to the relative motion of the telescope and the RFI source [8, 143]. Hellbourg and Bannister also successfully imaged a celestial source in a 1 MHz channel that was otherwise saturated by interference from GPS L2 over 200 times stronger than the desired

signal on a single beam of ASKAP BETA [13]. Finally, Heyminck [144] has demonstrated RFI-mitigation using spatial nulling using a modified ASKAP PAF at the Effelsberg 100 m telescope.

Flagging statistics

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This chapter establishes a baseline of ASKAP RFI-affected data, against which changes either from a worsening RFI environment or successful mitigation can be evaluated.

Abstract

We present an initial analysis of radio frequency interference (RFI) flagging statistics from archived Australian SKA Pathfinder (ASKAP) observations for the “Survey and Monitoring of ASKAP’s RFI environment and Trends” (SMART) project. SMART is a two-part observatory-led project combining analysis of archived observations with a dedicated, comprehensive RFI survey. The survey component covers ASKAP’s full 700 MHz to 1800 MHz frequency range, including bands not typically used due to severe RFI. Observations are underway to capture a detailed snapshot of the ASKAP RFI environment over representative 24 h periods. In addition to this dedicated survey, we routinely archive and analyse flagging statistics for all scientific observations to monitor the observatory’s RFI environment in near real-time. We use the telescope itself as a very sensitive RFI monitor and directly assess the fraction of scientific observations impacted by RFI. To this end, flag tables are now automatically ingested and aggregated as part of routine ASKAP operations for all science observations, as a function of frequency and time. The data presented in this paper come from processing all archived data for several ASKAP survey science projects (SSPs). We found that the average amount of flagging due to RFI across the routinely-used ‘clean’ continuum science bands is 3 % . The ‘clean’ mid band from 1293 MHz to 1437 MHz (excluding the 144 MHz below 1293 MHz impacted by radionavigation-satellites which is discarded before processing) is the least affected by RFI, followed by the ‘clean’ low band from 742 MHz to 1085 MHz. ASKAP SSPs lose most of their data to the mobile service in the low band, aeronautical service in the mid band and satellite navigation service in the 1510 MHz to 1797 MHz high band. We also show that for some of these services, the percentage of discarded data has been increasing year-on-year. SMART provides a unique opportunity to study ASKAP’s changing RFI environment, including understanding and updating the default flagging behaviour, inferring the suitability of and calibrating RFI monitoring equipment, monitoring spectrum management compliance in the Australian Radio Quiet Zone – Western Australia (ARQZWA), and informing the implementation of a suite of RFI mitigation techniques.

3.1 Introduction

Powerful human-generated transmissions corrupt weaker radio signals from cosmic sources. Balancing the advantages of wireless communication, satellite navigation, consumer electronics, weather forecasting and air transport with novel techniques [73] to manage radio frequency interference (RFI) is essential in keeping scientific research in radio astronomy sustainable in the future. The challenge for radio astronomy is not only the comparative power of these unwanted signals but also their increasing prevalence [43]. From a scientific perspective, all undesired signals are described as RFI. However, practically (and legislatively) emissions are only classified as RFI if they impinge on the authorised user of bands allocated (or shared) amongst different services (e.g. the radio astronomy service (RAS), aeronautical radionavigation service, broadcasting service, fixed/mobile service, etc.). In Australia this is under the jurisdiction of the Australian Communications and Media Authority (ACMA), and of the International Telecommunication Union (ITU) treaty, implemented by way of the Radio Regulations (RRs) [16, 52]. To further complicate the issue some RFI is a result of unintended electromagnetic radiation, emission outside the service allocation of the intended transmission and therefore not subject to the same regulations stipulated above [47, 48].

There are many methods of RFI mitigation [52–54, 83] depending on the type of RFI and instrument. Indeed, observatories have to use a variety of techniques at different stages in the signal chain to manage RFI [52]. Flagging is the most common strategy to mitigate the effects of RFI in radio astronomy; it is the process of identifying and discarding corrupt data in the frequency or time domain. Flagging can be conducted manually but is increasingly done by more sophisticated flagging software [146, 147]. Unfortunately, flagging reduces measurement sensitivity and the discarded data may contain valuable information from astronomical sources. Flagging also impacts the instrumental response in ways that may require consideration when drawing scientific conclusions. An example is that flagging impacts the UV coverage and thereby the point spread function of a synthesis imaging array like the Australian SKA Pathfinder (ASKAP). Furthermore, newer generations of radio telescopes with increased sensitivity, larger bandwidths and wider fields of view — designed

to keep up with contemporary science goals — are more severely affected by RFI, resulting in even more flagging.

The ASKAP telescope, operated by the CSIRO, is one such instrument [38]. ASKAP operates over the 700 MHz to 1800 MHz band of which less than 4 % is allocated to the radio astronomy service (RAS) on a primary basis in three small protected bands:

- (1) 1400 MHz to 1427 MHz (Hydrogen line),
- (2) 1610.6 MHz to 1613.8 MHz (OH line), and
- (3) 1660 MHz to 1670 MHz (OH line).

The remainder of the frequencies ASKAP operates are in use by the fixed/mobile service, the radio location service, the aeronautical mobile service, the aeronautical radionavigation service, and the radionavigation-satellite service [16, 42, 148].

RAS has secondary allocation for spectral line observations from 1718.8 MHz to 1722.2 MHz and some minimal protection is afforded from 1710 MHz to 1930 MHz via footnote 5.149 in the RRs, stating “[..]administrations are urged to take all practicable steps to protect the radio astronomy service from harmful interference” [16]. The radio spectrum is therefore a finite resource supporting a diversity of vital services. Current and future radio telescopes operating in large bandwidths outside of the RAS protected bands, where usage purely for astronomy purposes is not possible, need to monitor and coexist with other services.

ASKAP is comprised of 36×12 m antennas with a 188-element checkerboard phased array feed at the focus of each dish, allowing up to 36 independent dual-polarisation beams to be formed on the sky [38]. The maximum separation between antenna pairs (baseline length) is approximately 6 km. Because low RFI environments are required for radio astronomy, the ASKAP telescope was built about 600 km north-east of Perth, at Inyarrimanha Ilgari Bundara, the CSIRO Murchison Radio-astronomy Observatory. State and federal legislation has established a protected area known as the Australian Radio Quiet Zone – Western

Australia (ARQZWA) established by ACMA [45, 46], a circular region of 260 km radius from the observatory centre. However, the regulation does not protect ASKAP from orbiting satellites (of particular concern for the planned deployment of several low earth orbit mega-constellations), air traffic navigation, or mobile communication towers outside the ARQZWA. The latter of which cause interference during tropospheric ducting events. Ducting is an anomalous propagation phenomenon that can cause the refractive index of the atmosphere to match that of the curvature of the earth, and thereby enables radio waves to refract and travel much farther than usual [42, 51].

An holistic strategy to manage the effects of RFI, must include legislation, spectrum management, cooperation, avoidance, flagging, and active RFI mitigation [6, 7, 13] but also continued monitoring and evaluation of RFI’s impact on the observatory [42]. To this end, observatories and telescopes have started to perform statistical analysis of flagging data [114, 116, 117]. In this paper, we present our analysis of 1 MHz resolution flagged data from the ASKAP radio telescope’s data processing pipeline as a function of frequency and time. Section 3.2 describes ASKAP’s data products and processing as well as the RFI environment at the observatory. Section 3.3 describes the implementation of the flagged statistics pipeline. We present an analysis of the effect of RFI on ASKAP science, based on over 1500 h of ASKAP observations in Section 3.4. Finally, future work and concluding remarks are presented in Sections 3.5 and 3.6 respectively.

3.2 ASKAP data and inferring RFI through flagged data

The data collected for this project is from processed and archived ASKAP continuum observations from April 2019 to August 2023. Archived ASKAP visibilities are stored with 1 MHz frequency channels and 10 s integration time resolution. ASKAP survey science projects (SSPs) typically observe over three ‘clean’ bands, below 1085 MHz, 1293 MHz to 1437 MHz (excluding 1149 MHz to 1293 MHz severely impacted by radio navigation-satellites which is observed but discarded before processing) and above 1510 MHz, which we

refer to as the ‘clean’ low, mid and high bands respectively. For a full description of ASKAP, including the technical specifications and overview of science operations, see [38].

ASKAP operates primarily as an automatically-scheduled telescope to carry out observations, with the autonomous scheduler SAURON (Scheduling Autonomously Under Reactive Observational Needs) communicating to the telescope operating system [TOS, 149] via parameter specifications [38, Moss et al. in prep]. SAURON conducts system and environment checks as part of the scheduling decision-making, but RFI is largely not included as a factor. The exception to this is ducting avoidance, where some SSPs have elected to not to observe if there is active ducting due to the impacts on data quality (mainly loss of sensitivity or bandwidth coverage)¹. Observations for these SSPs are not scheduled during active ducting, and if ducting starts during an observation, SAURON will interrupt the observation. Further discussion on the severity of ducting is presented in Section 3.4. The other most problematic sources of RFI are relatively consistent, meaning that active avoidance has not been necessary. The dramatic rise in solar activity approaching the solar maximum (and observed impacts on ASKAP calibration and science data) are likely to result in more active consideration of solar activity as part of future upgrades to SAURON. Similarly, it has been discussed whether active satellite avoidance as a constraint may be beneficial to especially the mid band observations, but to date the SSPs and observatory have instead elected to remove the RFI-corrupted lower 144 MHz bandwidth from 1149 MHz to 1293 MHz. Work is currently underway as part of the Collaborative Intelligence Future Science Platform collaboration to implement machine learning anomaly detection on ASKAP raw data diagnostics. This work will identify and characterise outliers in the data, including RFI, and it is expected that the first version of this will be in production before the end of 2023. Note that while RFI due to increased solar activity does negatively affect science observations and operations, it does not trigger the flagger and therefore the results presented here are not accounted for by solar interference.

¹Data from the SSPs used in this paper do not use ducting avoidance.

ASKAP operates primarily as an automatically-scheduled telescope to carry out observations, with the autonomous scheduler SAURON (Scheduling Autonomously Under Reactive Observational Needs) communicating to the telescope operating system [TOS, 149] via parameter specifications [38, Moss et al. in prep]. SAURON conducts system and environment checks as part of the scheduling decision-making, but RFI is largely not included as a factor. The exception to this is ducting avoidance, where some SSPs have elected to not to observe if there is active ducting due to the impacts on data quality (mainly loss of sensitivity or bandwidth coverage)². Observations for these SSPs are not scheduled during active ducting, and if ducting starts during an observation, SAURON will interrupt the observation. Further discussion on the severity of ducting is presented in Section 3.4. The other most problematic sources of RFI are relatively consistent, meaning that active avoidance has not been necessary. The dramatic rise in solar activity approaching the solar maximum (and observed impacts on ASKAP calibration and science data) are likely to result in more active consideration of solar activity as part of future upgrades to SAURON. Similarly, it has been discussed whether active satellite avoidance as a constraint may be beneficial to especially the mid band observations, but to date the SSPs and observatory have instead elected to remove the RFI-corrupted lower 144 MHz bandwidth from 1149 MHz to 1293 MHz. Work is currently underway as part of the Collaborative Intelligence Future Science Platform collaboration to implement machine learning anomaly detection on ASKAP raw data diagnostics. This work will identify and characterise outliers in the data, including RFI, and it is expected that the first version of this will be in production before the end of 2023. Note that while RFI due to increased solar activity does negatively affect science observations and operations, it does not trigger the flagger and therefore the results presented here are not accounted for by solar interference.

The ASKAPsoft pipeline [132, 150] is the collection of software required to process ASKAP data end-to-end including calibration, ingest, flagging, averaging, imaging, source-finding and archiving. ASKAP data is processed at the Pawsey Supercomputing Centre where each of ASKAP’s 36 beams are processed in parallel [38]. There are two processes in the

²Data from the SSPs used in this paper do not use ducting avoidance.

pipeline involved in flagging. First, before the data is averaged to 1 MHz, known RFI is excised based on an RFI database, and then on-the-fly detection and excision occurs [132]. The RFI database used, is an internally developed table of known transmitters affecting the observatory [42]. Averaged coarse-resolution 1 MHz data may be flagged again before being imaged and archived [38]. Flaggers generally use fixed and dynamic thresholds in amplitude (or using circular polarisation) to remove anomalous samples in the calibrator and science data. This approach works because many sources of RFI have amplitudes much higher than the noise and astronomical signal [12]. Weak noise-like RFI, however, can still be missed in the flagging process. The default flagging algorithm embedded in the ASKAPsoft pipeline is CFLAG [151], but the specification parameters also allow the alternative use of AOFLAGGER [112, 146]. Resulting data products from ASKAPsoft are stored in the CSIRO ASKAP Science Data Archive (CASDA)³[152, 153]. Flagging data is stored alongside visibility data in CASA-style Measurement Sets [38, 154]. ASKAPsoft also outputs diagnostic and quality information throughout the pipeline, including a summary of flagged data per observation.

Our research builds on the existing flag summary reports generated by ASKAPsoft. We establish a baseline of flagged data against which to compare and predict the expected amount of flagged data. We also contribute to the body of research outlining the RFI environment at the observatory [42, 114, 122, 123] and recreate a statistical approach to monitoring of RFI flagging which is becoming more widespread in large-scale telescope operations. [114] describes the low-frequency environment at the observatory using ten nights of Murchison Widefield Array (MWA) data. Similar approaches at other observatories, include [116] with the Five-hundred-meter Aperture Spherical radio Telescope (FAST) in China using approximately 300 h across 45 days, and in South Africa using the MeerKAT telescope where [117] implemented a counter-based solution (which we have also used) using approximately 1500 h of data. Flagging statistics can be used to monitor long-term changes in the RFI environment, monitor spectrum compliance and improve the planning of observations such that the impact of RFI is minimised. Finally, this work will inform the ongoing development

³<https://research.csiro.au/casda/>

of active RFI mitigation [7, 8, 141] and subsequently monitor the efficacy of these techniques [6] in reducing flagging.

We have used flag tables to infer the effects of RFI on ASKAP science and to monitor changes in the RFI environment as a function of frequency and time. We developed software to routinely extract, aggregate, analyse and visualise flagged data from ASKAP in near real-time. We opted for a bespoke software solution to systematically aggregate and analyse flagged data because to our knowledge, no compatible open-source software existed. As such, we created the `flagstats` library based on available Python libraries and existing scripts in ASKAP’s pipeline that interrogate ASKAP measurement sets and summarise flagged data. The `flagstats` library is broken into four main components *StatsWriter*, *StatsReader*, *StageStats* and *StatsGUI*. Figure 3.1 shows the high-level sequence of those components as well as their input and output data products.

3.3 Approach and implementation: `flagstats`

3.3.1 StatsWriter

StatsWriter takes a set of ASKAP measurement sets as an input and outputs a file containing the flagging tables from each beam for the duration of the observation and relevant metadata extracted using `dask-ms`⁴. Flagging for all four polarisation products (XX, XY, YX, and YY) are recorded in the original measurement set, but, flagging across polarisations is currently the same for ASKAP, therefore to reduce the size of the output only the XX polarisation flagging table is stored. A benefit of having these relatively smaller individual `flagsummary.nc`⁵ files (per observation) is that users can query them to get comprehensive statistics about the flagging (and RFI) affecting a specified observation using *StatsReader*.

⁴<https://dask-ms.readthedocs.io/en/latest/>

⁵<https://www.unidata.ucar.edu/software/netcdf/>

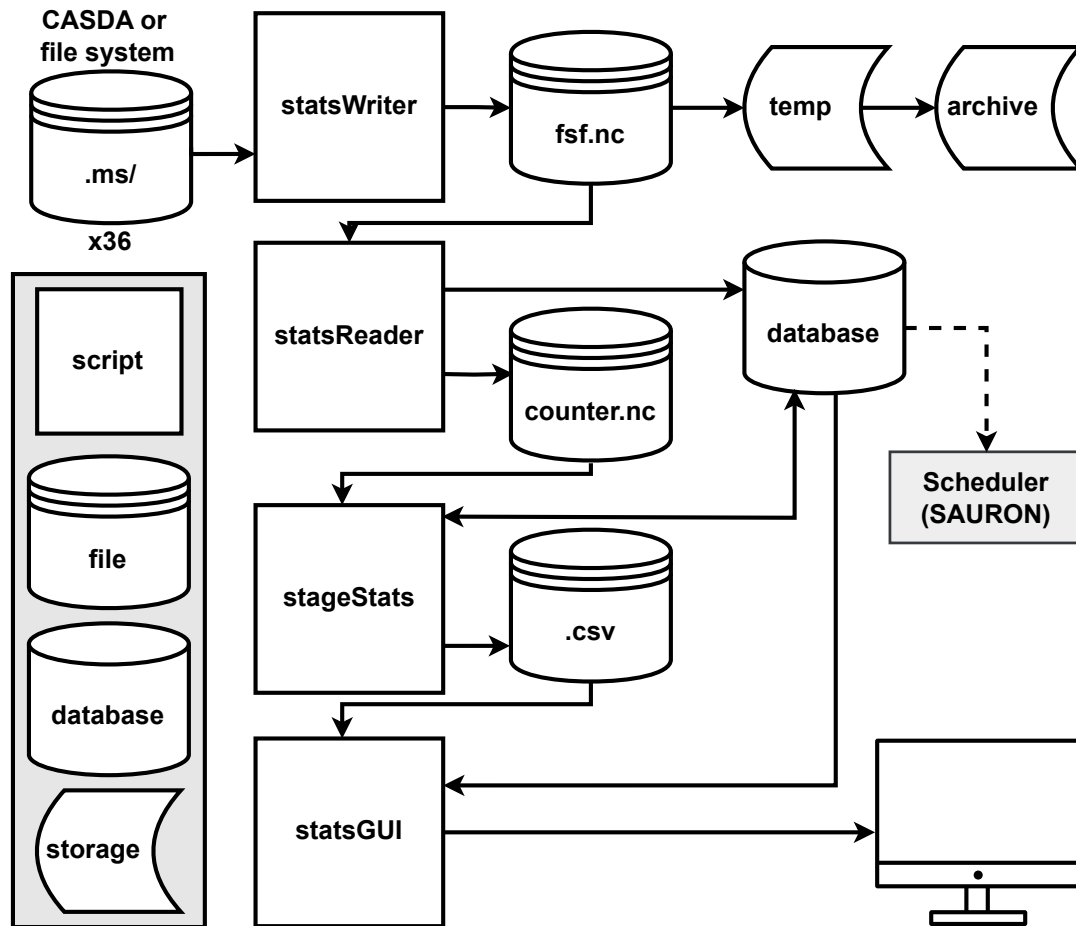
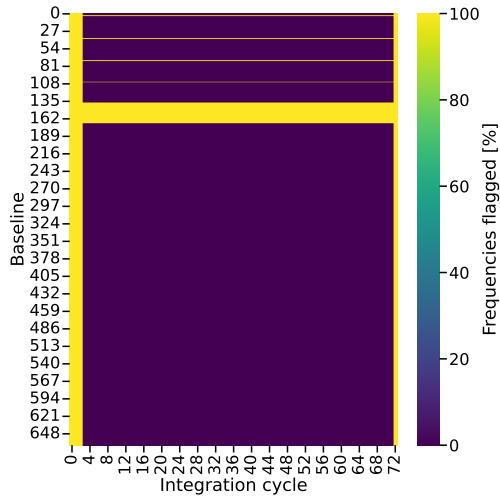


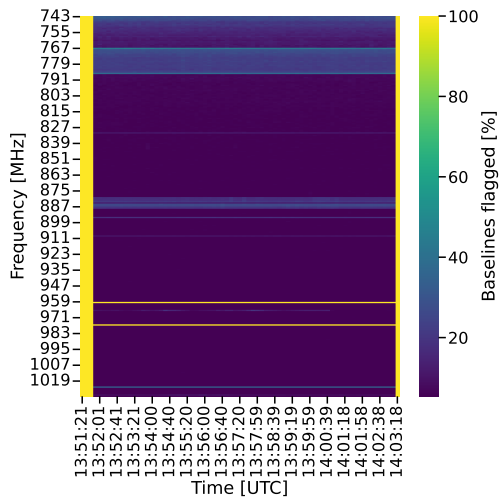
FIGURE 3.1. Components of the `flagstats` library and their data inputs and outputs. *StatsWriter* extracts flags, *StatsReader* aggregates them, *StageStats* further aggregates, performs analysis and prepares files that serve the GUI, *statsGUI* for interactive visualisation of flags and aggregated data.

3.3.2 StatsReader

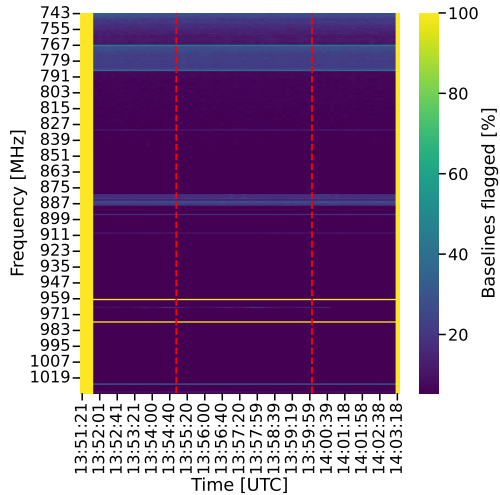
StatsReader is the key component of the `flagstats` library. It first cleans (removes non-RFI-related) flagged data stored in the previous step. A series of ‘counter’ files are created if they do not exist. Data is binned for each observation, in turn. The appropriate counter is updated to aggregate flagged data from multiple observations. Counters from which statistics are computed are updated with the flagged and total number of contributing samples of each bin similar to [117].



(A) Before cleaning: Horizontal lines show baselines where all frequencies are flagged as a result of a faulty antenna, in this case, antenna 05. Vertical lines show time cycles flagged for reasons other than RFI. e.g. slewing.



(B) Before cleaning: Faulty antennas introduce an offset in the amount of flagged data, note the min value in the colour bar is non-zero. i.e. 5.4 % of flagging due to other causes.



(C) After cleaning: Percentage of baselines flagged after removing faulty antennas gives a better estimate of flagged data due to RFI. Data will be time-binned into 5 min bins (overlaid as vertical dashed red lines).

FIGURE 3.2. Sub-figures (a) and (b) show the flag cube before removing faulty antennas. (c) shows the 'cleaned' cube with a more accurate estimate of flags due to RFI.

Consider a single beam from an ASKAP observation, where the flag table from the measurement set is reshaped and stored into a 3-dimensional array of shape, $n_{\text{freq}} \times n_{\text{cycles}} \times n_{\text{baselines}}$. Figure 3.2a shows the percentage of flagged frequency channels in the observation as a function of time (in integration cycles) on the x-axis and baseline on the y-axis. Figure 3.2b, is the same cube but shows the percentage of flagged baselines in the observation as a function of time (in UTC) on the x-axis and 1 MHz frequency channels on the y-axis. We call Figure 3.2a and Figure 3.2b the ‘dirty’ cube because faulty and intermittent antennas have not yet been removed. ASKAP currently uses boolean flags which are `True` when the data is discarded/flagged. One of *StatsReader*’s functions is to identify (and remove) flags that are not due to RFI. The vertical yellow lines in Figure 3.2a show time cycles for which all frequency channels are flagged, similarly horizontal lines show baselines for which all frequency channels are flagged throughout the observation. For the latter, an antenna can be mapped to a set of baselines due to a faulty antenna(s), in this case antenna ak05. For the former, flags are from timing issues (slewing time if all antennas are not in the ‘tracking’ state and latency of data flow through the digital systems). *StatsReader* will disregard flags where all frequencies are affected over either all baselines or all integration cycles because they are not from RFI. *StatsReader* also cleans antennas that ‘drop out’ mid-observation.

Figure 3.2c shows the same cube but masked, i.e. without the bad integration cycles and antennas, that we refer to as the ‘clean’ cube, which yields a better upper estimate of the flags due to RFI. Using the Radio Regulations [16], spectrum plan [148], and known RFI affecting ASKAP [42] we can map features in Figure 3.2c to likely sources of RFI. It should be noted however that the 1 MHz frequency resolution is coarse compared to the bandwidth of many interferers, limiting the accuracy with which we can map flags to services. Furthermore, multiple interferers may also affect the same 1 MHz channel. Brighter horizontal lines in Figure 3.2c show channels for which more (or all remaining) baselines/antennas are affected by RFI. Two red vertical dashed lines demarcate the three bins that this observation would be divided into. Starting from the top of the plot, this 12 min observation is corrupted by mixed fixed cellular interference below 787 MHz [42]. In the frequency range of this observation, there are many mobile base stations that routinely trigger `CFLAG` due to ducting, discussed

further in Section 3.4 (see Figure 3.9). For example, we know of two Vodafone base stations (identified by decoding RFI monitoring equipment) that operate in a frequency range of the affected channels in Figure 3.2c [42]: the first in the Northampton Shire, 267 km south-west of ASKAP and the second in Carnarvon, 357 km north-west of ASKAP. In this case 960 MHz, like the 976 MHz flagged channel above it, the origin of the RFI is likely self-generated.

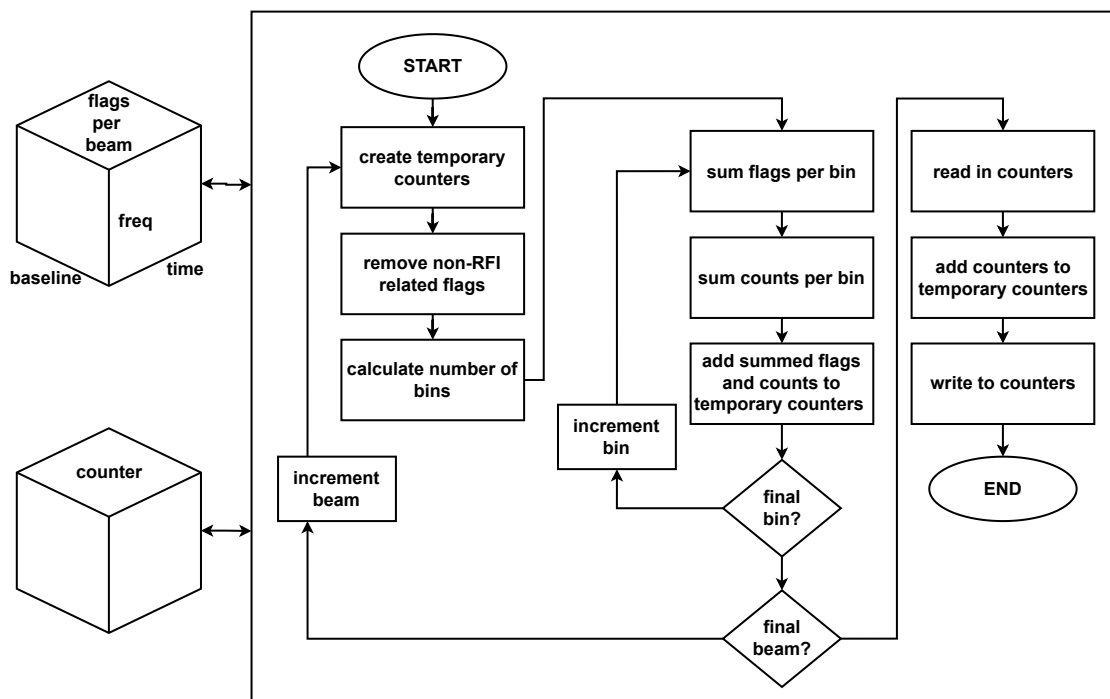


FIGURE 3.3. *StatsReader* takes an array of each beam’s flags in turn, creates a counter if one does not already exist, cleans the flag cube, bins the data, and updates the appropriate counter. This process is repeated for every observation. There are counters for all permutations based on the metric calculated, year and data source (science, bandpass, RFI survey). Science data is further divided by the different survey science projects (SSPs) processed (EMU, POSSUM, RACS, VAST).

An overview of the steps involved in *StatsReader* for an arbitrary counter are depicted in Figure 3.3. Each `counter.nc` file has three groups⁶, one for each of the following counters:

- The `flag` counter, tallies flags flagged as `True`, per bin.

⁶<https://docs.xarray.dev/en/stable/>

- the `count` counter, tallies the total number of samples per bin, i.e. flagged as `True` or `False`.
- The `int_time` counter, scales the count by the integration time of each observation to keep track of the flagging per unit time (typically represented in hours but stored in minutes).

We have implemented a series of counters as opposed to a single counter [117]. First, for each metric we want to interrogate, there are individual counter files:

- Time of Day, arrays in this counter have shape $1100 \times 666 \times 288$: 1100×1 MHz frequency bins, 666 baseline pairs from ASKAP's 36 antennas and 288×5 min time bins in a day. Figure 3.2c shows these bins with two red vertical dashed lines.
- Day of Week, arrays in this counter have shape $1100 \times 666 \times 168$; frequency, baseline and 168×1 h time bins in a week.
- Week of Year, arrays in this counter have shape $1100 \times 666 \times 53$; frequency, baseline, 52 complete weeks in a year and one incomplete week. Week zero is the week inclusive of the 4th of January using the ISO week date system.

The above set of counter files is created for each permutation of year and type of data. SSPs are further divided by the different surveys processed: EMU, POSSUM, RACS, VAST (see Section 3.4). *StatsReader* uses metadata stored in the extracted flags by *StatsWriter* to locate and update the appropriate counter files. This approach makes it easy to add new metrics, types of data or surveys by simply adding the associated counters. In addition to aggregating, cleaning, binning and updating counters, Figure 3.1 shows that *StatsReader* writes high-level data, per observation to a database table. This table is used to keep track of the observations processed and includes the percentage of total flagged data (including bad antennas), percentage of flagged data due to RFI, duration, field of observation, data source and survey name. At this point, counters per metric for each observation are aggregated in their respective counters - by year, type of data and science survey - but not aggregated with each other.

3.3.3 StageStats

In order to create aggregated statistics for each metric, across different years, surveys and observing modes, counters of the same type must be added together. First, vertically, the counters created and updated by *StatsReader* in the lowest directory of the file hierarchy are added together by *StageStats* and placed at the level of the file structure above it until there is one counter per metric per year. Then counters are added horizontally until there is one counter per metric per type of data. Finally, counters from every year are added together. *StageStats* has three other processes:

- Create tables from these ‘top-level’ counters and store them in the database with local copies to serve the Graphical User Interface (GUI).
- Calculate high-level statistics based on the files processed by *StageReader* (Table 3.1). We also use this database table to infer observations affected by ducting, based on excess flagging.
- Perform analysis of the aggregated data (see Section 3.4):
 - Compare flagging between day and night (Figure 3.8).
 - Aggregate data from RFI monitoring equipment.
 - Compare flagged and RFI monitoring equipment data.
 - Map flagged data to corresponding radio service(s).
 - Calculate losses per service (Figure 3.6).
 - Calculate losses per service year-on-year (Figure 3.7).
 - Infer observations affected by ducting based on ‘excess’ flagging.

Finally, *StageStats* summarises statistics per metric (time of day, week and year), to reduce the computation required for the interactive GUI.

3.3.4 StatsGUI

The *StatsGUI* is an interactive GUI that allows users to explore aggregated flagged data. It also matches RFI probabilities to radio services and known transmitters in the same 1 MHz channel using a click callback. Users first select a metric to view (by default it is ‘time of day’), they can then use a series of filters to select data from a particular year, survey and/or observation type. We are in the process of automating the individual parts of the `flagstats` library. So far *StatsWriter* is fully implemented to extract flags from all bandpass and continuum science observations as soon as the processing is completed.

3.3.5 Automation

The ASKAP telescope is increasingly becoming an autonomous system building upon SAURON, a dynamic observation scheduling system [Moss et al. in prep], and `Process Manager`, an event-based triggered workflow manager. `Process Manager` has been designed to allow the automatic triggering of a data processing pipeline (e.g. calibration and imaging) when a set of defined criteria have been met. We used the Python package `prefect`⁷ to create an extensible workflow that implements the *StatsWriter* routines, which was then registered with `Processing Manager` and configured to trigger against all science-observations once they have been processed by the larger ASKAP processing-pipeline. Hence, the flagging statistics that are currently extracted are from the calibrated measurement sets after the automated RFI flagging within the ASKAP processing pipeline have been performed. We plan to further develop our own `prefect`-based pipeline to directly run flagging procedures against the raw uncalibrated measurement set before they are processed by software in the larger ASKAP ecosystem. This improvement will gather useful statistics on sub-bands that are currently removed at the beginning of the ASKAP pipeline containing excessive RFI and therefore affecting scientific processing, for example over the frequency range 1149 MHz to 1293 MHz impacted by the radionavigation-satellite service.

⁷<https://github.com/PrefectHQ/prefect>

While we continue to test, develop, optimise and automate the software it remains internal, but we intend to explore options to generalise and make it more widely available as we further develop the software. In the next section, we present the preliminary results based on 1 MHz flagged data.

3.4 Results

In this paper, we present results based on science observations with at least 250 h per year from April 2019 to August 2023⁸.

Flags from archived science data were collected via CASDA. Recent science data were directly processed from the Pawsey Supercomputing Centre file system. Most recently this is done automatically by triggering *StatsWriter* upon completion of the ASKAP processing pipeline. Table 3.1 shows the total observing time and number of observations of science data subdivided by survey and clean band. Science data from the following SSPs and their respective pilot surveys have been included:

- the Rapid ASKAP Continuum Survey (RACS) I, II and RACS-mid [12, 155, 156],
- the ASKAP survey for Variables and Slow Transients (VAST) [157, 158],
- the POLarisation Sky Survey of the Universe’s Magnetism (POSSUM) [126]
- the Evolutionary Map of the Universe (EMU) [159]

A key outcome of this work is shown in Figure 3.4. Using the flagstats library, the data in Table 3.1 was extracted, cleaned, binned, aggregated, summed across SSP, data category and metric and analysed. Figure 3.4 shows the probabilities of flagging due to RFI as a function of frequency and time of day. The x-axis, binned to 5 min, is given in Coordinated Universal Time (UTC) in the format hh:mm.

⁸2021 and 2023 have at least 750 h and 500 h respectively.

TABLE 3.1. Hours of continuum science data by processed survey science project and band.

Project	Typical Field Duration	Clean Band	# Fields	Total Hours
RACS	0.25 h	low	864	385
		mid	1574	390
		high	18	4
VAST	0.20 h	low	2146	50
		mid	429	36
POSSUM	10 h	low	1	10
		mid	10	98
EMU	5 h or 10 h	low	77	617

The y-axis shows ASKAP's 1 MHz resolution frequency channels in ascending order. The vertical subplot to the left shows the average flagging due to RFI across the day as a function of frequency in blue. Similarly, the horizontal subplot at the bottom shows the average flagging due to RFI across the ASKAP band as a function of the time of day in blue. Both subplots show the contributing number of observing hours per bin in red.

An upper estimate on the total percentage of flagged data due to RFI across ASKAP's frequency range is 3 % . Starting from the lowest frequencies and working upwards, we will discuss the corresponding primary service allocations [148] to features in Figures 3.4 and 3.8.

Figures 3.4 and 3.8 show flagging below 787 MHz, and around 841 MHz, 884 MHz and 894 MHz which are most likely attributable to the closest mobile base stations operating at those frequencies (see Figure 3.9). Flagged data above 960 MHz to 1163 MHz range is likely due to aeronautical radionavigation. The end of ASKAP's clean low band (1085 MHz) terminates where RFI due to aeronautical radionavigation is expected to increase based on measurements by RFI monitoring equipment (middle panel, Figure 3.8).

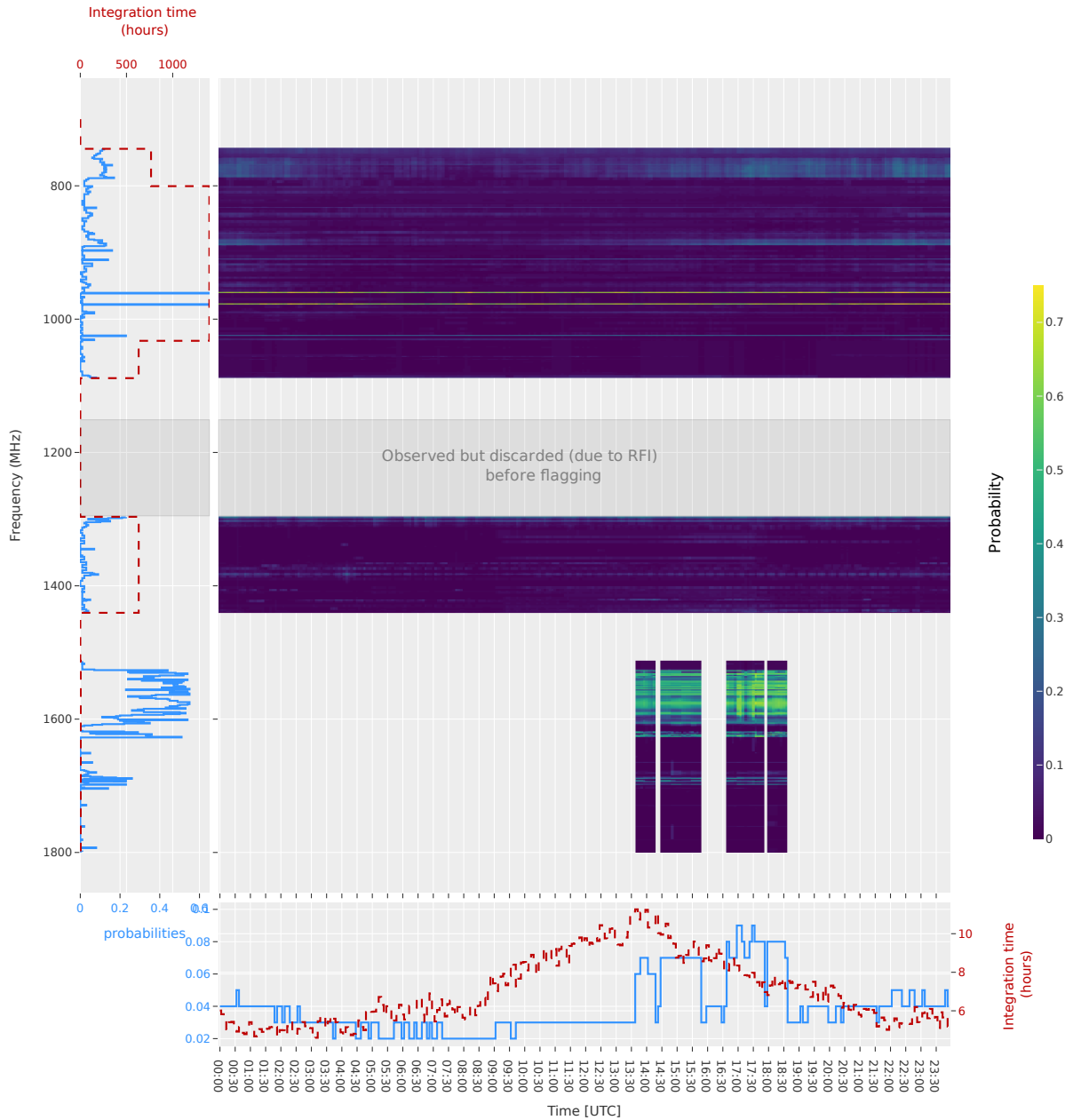


FIGURE 3.4. The central heatmap shows the probability of flagging due to RFI based on the aggregation of over 5000 scheduling blocks comprising approximately 1500 h of observing time from April 2019 to August 2023. The x-axis is binned to 5 mins, and the y-axis to 1 MHz frequency channels. The vertical subplot to the right shows the average flagging due to RFI in blue as a function of frequency. Similarly, the horizontal subplot at the bottom shows the average flagging due to RFI as a function of the time of day in blue. The red curves in both subplots show the number of hours that contributed data to that bin. Three sub-bands in which ASKAP continuum observations are most typically conducted are shown. From top to bottom, the low band shows flagging due to RFI from the fixed/mobile service exacerbated by ducting, the two most prominent peaks are likely due to self-generated interference in ASKAP’s signal chain. Aeronautical mobile and radionavigation affect the low and mid bands shown above. Note the bottom half of the mid band from 1149 MHz to 1293 MHz whilst observed is not processed or archived as it is severely affected by radionavigation-satellites. The lower half of the high band is affected by various satellite services, in addition the high band is affected by meteorological aids and satellite services as well as fixed/mobile. Both the mid and high bands have protected radio astronomy service allocations for HI and OH spectral lines respectively.

Radionavigation-satellite routinely affect the 144 MHz below 1293 MHz, although observed, this sub band is discarded before processing result in a large section of bandwidth in which no flagging data has been collected. The clean mid band from 1293 MHz to 1437 MHz is affected by flagging in corresponding to the following services: radio location service for use by the Australian Defence Force and Department of Defence from 1300 MHz to 1400 MHz and the radio astronomy service hydrogen line protected band from 1400 MHz to 1427 MHz in which the strong hydrogen line emission itself may be triggering CFLAG.

Various satellite services affect the bottom half of the high band (1510 MHz to 1797 MHz) including radionavigation-satellite satellite and radiodetermination-satellite services as well as aeronautical radionavigation. The radio astronomy service OH spectral line protected band from 1610.6 MHz to 1613.8 MHz and 1660 MHz to 1670 MHz is located between the above satellites and meteorological aids and satellite services and fixed/mobile which fills the remainder of ASKAP's frequency range.

3.4.1 ASKAP self-generated RFI

Not all RFI is external to the observatory and telescope, with ASKAP itself (and the infrastructure supporting it) capable of generating RFI, which might include power supplies and electronic components. Self-generated RFI is generally unintended and we aim to identify and ultimately reduce the impact of these unwanted sources of RFI caused within the observatory.

An example of this in early ASKAP observations/operations is the On-Dish Calibrator (ODC) a noise source used for calibrating the phased array feed (PAF) which introduced RFI (particularly in the shortest, baselines and in the low part of the band). The ODC is now only switched on as needed, during the beginning of beamforming and before an observation to update the weights, not during the observation. The ODC is designed to be broad-band and operates at about 1 % of the system temperature. It is therefore unlikely to have caused any additional flagging. Furthermore, the majority of data presented herein was collected after this issue was resolved. Shielding is also used to mitigate the effects of RFI in the

observatory control building. In some cases due to planned activities at the observatory (including maintenance and construction), the risk of RFI is increased. In these instances a Radio Emissions Management Plan (REMP) is conducted to prevent and avoid RFI as much as possible.

Another example includes some digital artifacts that impact the data like RFI but can be coherent across the array without being radiated into it due to their originating from coherent clock signals. A dominant example is a 256 MHz clock that is multiplied by 32/27 to read out the digital receiver's 1 MHz resolution oversampled coarse filter bank [129, 130]. Table 3.2 shows calculated values of harmonics of this clock signal and frequencies that they will appear at in observations due to the direct sampling architecture of ASKAP's digital receiver. This clock signal is narrowband and correlated across antennas.

TABLE 3.2. Calculated interference due to harmonics from $32/27 \times 256$ MHz coarse filterbank readout clock in ASKAP's digital receiver. Bolded frequencies are potentially triggering the flagger, strikethrough text indicates frequencies outside the available ASKAP observing band. Apparent frequencies calculated for direct sampled filter bands as defined in [129].

Harmonic	Frequency (MHz)		
	<i>RF</i>	<i>1200 MHz Filter</i>	<i>1450 MHz Filter</i>
1	303.41	976.59	1232.59
2	606.81	673.19	929.19
3	910.22	910.22	910.22
4	1213.63	1213.63	1213.63
5	1517.04	1042.96	1517.04
6	1820.44	739.56	1251.56
7	2123.85	843.85	948.15
8	2427.26	1147.26	891.26
9	2730.67	1109.33	1194.67

This signal is internal to each digital receiver card and is well shielded inside ASKAP's shielded room. It enters the signal path directly on the digitiser cards. Note the 673.19 MHz value has been struck through because it is outside of ASKAP's observing range and therefore does not see corresponding flagging in the data collected herein.

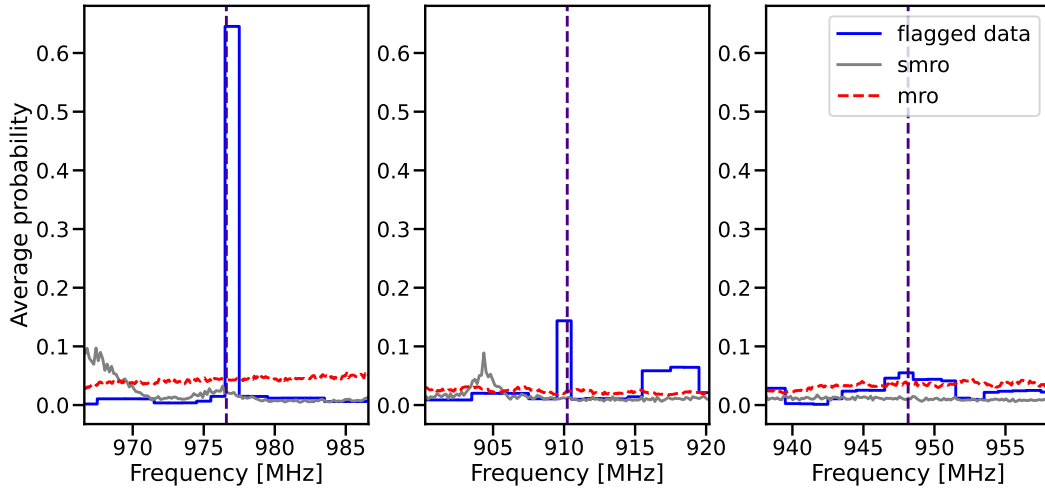


FIGURE 3.5. Mapping flagged data at the calculated harmonics of self-generated interference, overlaid are the probabilities of RFI based on the RFI monitors. For these frequencies there is no externally measured RFI but flagging, consistent with self-generated interference.

Figure 3.5 shows how by using the values in Table 3.2 we map the probabilities of flagging due to RFI to frequencies that are likely flagged due to self-generated interference. i.e. the bolded frequencies in Table 3.2 are potentially triggering the flagger. The flagged data from Figure 3.4 is shown in Figure 3.5 as a solid blue step plot, with step widths of 1 MHz. Overlaid and with a higher frequency resolution, are two separate RFI monitors used at the observatory, the first (solid grey) and the second (dashed red). The first is more sensitive owing to its slower scanning rate and thus longer integration time (‘s’ stands for sensitive in the name). It is better suited for detection of faint signals often seen from satellites, distant transmitters such as mobile base stations (See Figure 3.8), and localised weak electromagnetic interference. The faster and thus less sensitive RFI monitor is paired with an active antenna to make up in part for the faster scan rate. Both scan from 20 MHz to 3000 MHz, the first has finer frequency resolution, 3.125 kHz, with a sweep time of 62 s, compared to the second which scans at 100 kHz with a sweep time of 1.49 s, permitting detection of rapid transient emissions. More information on RFI monitoring equipment can be found in [42]. The point is that at the frequencies with flagging peaks in Figure 3.5 and no corresponding measurement by the RFI monitoring equipment, we detected three self-generated RFI candidate frequencies on which to follow up. There is a mechanism in the ASKAPsoft `inject` software, ‘on-the-fly

averaging’ based on an amplitude threshold, that should remove the underlying narrowband signal causing CFLAG to flag these 1 MHz channels; we believe these candidates are not strong enough to trigger this mechanism and are therefore subsequently flagged. An additional candidate signal of this nature not previously documented, the 960 MHz flagged channel in Figure 3.4 and 3.8 has been identified for further investigation.

3.4.2 RFI-affected science data

The elevated steps in the red vertical subplot of total integration time in Figure 3.4 (where we have accumulated more data) identify two clean bands that ASKAP regularly observes in the low and mid bands. Across the science bands flagging due to RFI is 3 %.

The average flagging in the low band is 5 % and is mostly accounted for by four primary service allocations.

Less than 0.1 MHz is lost to RFI in this band without identification of a corresponding primary service allocation. The top panel of Figure 3.6 shows the two primary service allocations that most affect the low band are both fixed/mobile allocations (green) to which combined ASKAP science loses between 6 MHz and 20 MHz. Estimated losses are calculated by multiplying the channel width (1 MHz) by the probability of flagging in that channel and summing all the channels corresponding to that service resulting in a range of expected/estimated bandwidth losses in MHz.

The average mid band flagging is 1 %. This does not include the 144 MHz below 1293 MHz discarded before processing 100 % of the time which is affected by radionavigation-satellites. Including this would increase the total flagging due to RFI across all bands to 15 %. The remainder of the mid band (as it appears in CASDA) is the least affected by flagging due to other sources of RFI. Three primary service allocations correspond to this band. The middle panel of Figure 3.6 shows that no more than 2 MHz across 75 % of the most affected channels is lost to flagging due to RFI. The three most prevalent sources of

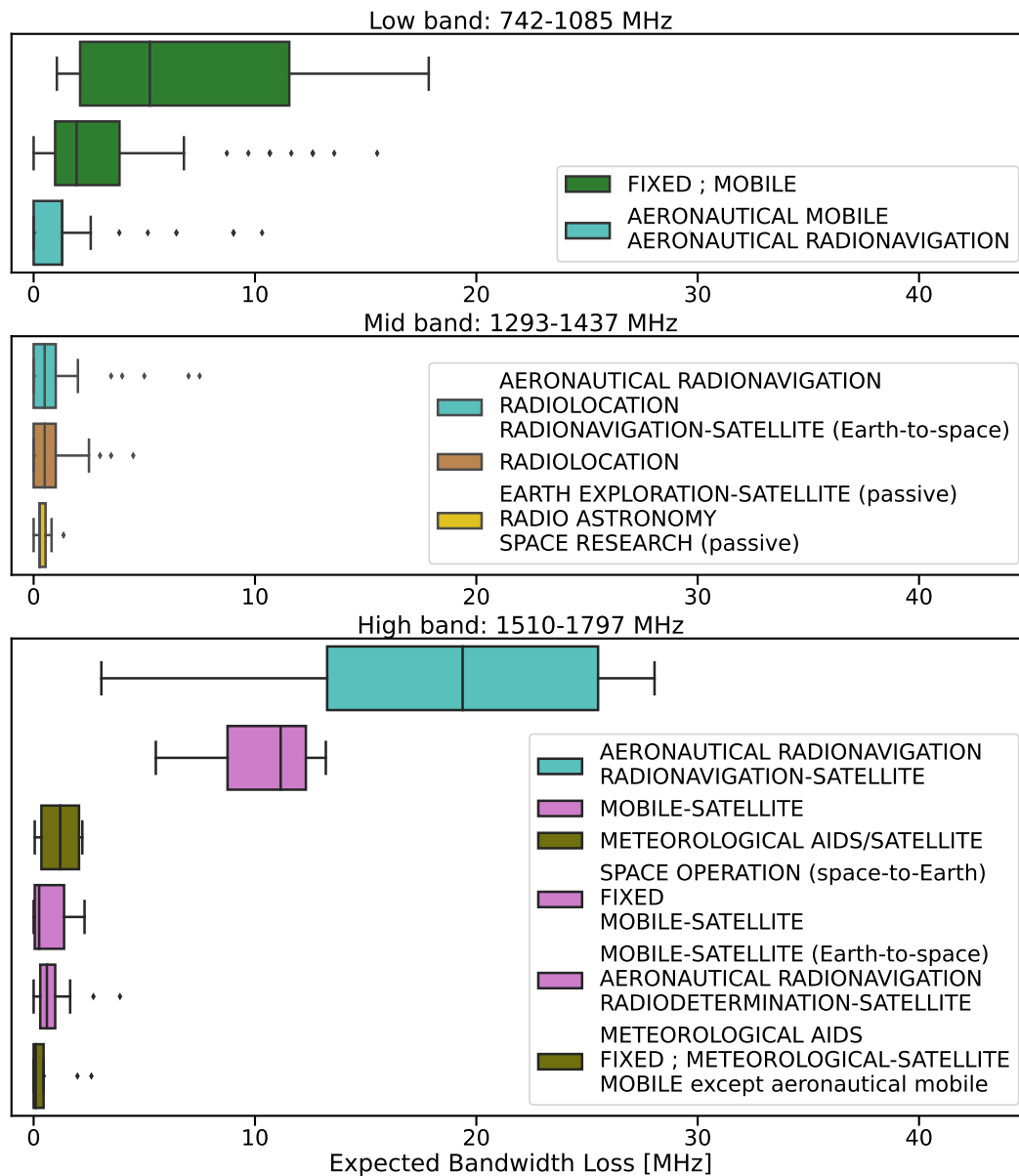


FIGURE 3.6. An estimated bandwidth loss is calculated by multiplying the channel width (1 MHz) by the probability of flagging in that channel and summing all the channels corresponding to a particular primary service allocation. For each band — ASKAP’s low (top panel), mid (middle panel) and high (bottom panel) bands — the estimated bandwidth loss of the highest average flagged services are shown. The mid band (excluding radionavigation-satellite affected data) is the least affected by RFI followed by the low and high bands. The low band is most affected in fixed/mobile (green) allocations and the high band by aeronautical (cyan) and satellite allocations (pink).

flagging correspond to transmitters in the aeronautical radionavigation, radio location and earth exploration satellite primary service allocations. ASKAP's mid band is of particular importance as it contains the biggest protected RAS allocation centered on the 1420 MHz hydrogen line. In this allocation up to 0.4 MHz is lost due to flagging; i.e 1.5 % data in the hydrogen line protected RAS allocation is flagged.

Whilst there are comparatively less data for the high band, the average flagging is 11 %. The high band is the most complex with regards to the effects of RFI. Fourteen services affect this band. The bottom panel of Figure 3.6 shows that the majority of data in the high band is lost to channels corresponding to an aeronautical radionavigation allocation (cyan) accounting for between 12 MHz to 25 MHz of average bandwidth loss. Other primary services affecting the high band are satellite (pink) and meteorological related, the former of which cumulatively accounts for a further 10 MHz loss on average. There is currently insufficient data to estimate the losses in the narrower OH spectral line RAS allocations.

We compared the estimated losses to the measured RFI monitoring occupancy, that is the average percentage of detected RFI in a channel using the RFI monitoring equipment since 2019. We find that in general, across the clean bands there is more agreement between ASKAP and the more sensitive RFI monitor. Both RFI monitors find fixed/mobile to be the most significant cause of interference in the low band. RFI monitoring equipment does however detect more interference due to aeronautical mobile and radionavigation service related interference compared to ASKAP flagging data. Similarly, in the mid band there is alignment between services and the more sensitive RFI monitor. More high band observations are required to make reliable comparisons with RFI monitoring equipment.

3.4.3 RFI trends

Several other trends in the probabilities of flagging due to RFI based on Figure 3.4 were also explored including the expected bandwidth loss per service year-on-year, differences in the

probability of flagging due to RFI in the day compared to night and the effects of ducting as compared to RFI monitoring equipment.

Year-on-year

Following on from the previous section, the estimated bandwidth loss per service can be further separated by year. There is only enough data to make this comparison in ASKAP's clean low and mid bands, shown below for a subset of primary spectrum services.

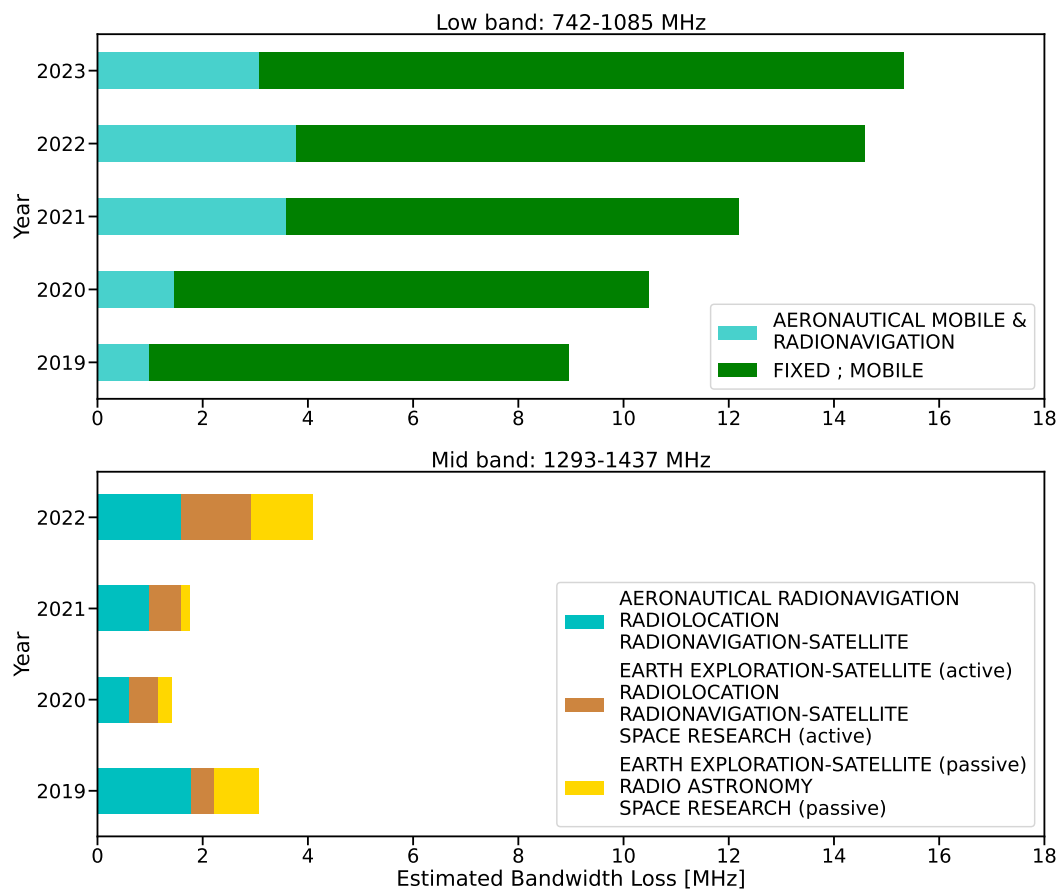


FIGURE 3.7. For the low band (top panel) and mid band (bottom panel) there is enough data to determine trends in the estimated bandwidth loss per service year-on-year. The increasing losses corresponding to fixed/mobile (green) is of concern in the low band. The (yellow) protected RAS allocations in the mid band where in previous years there have been non-negligible losses require ongoing monitoring and investigation to ascertain the source of the flagging.

Figure 3.7 again shows that the clean mid band is less affected by RFI than the low band. In the low band we see again that the primary losses are due to fixed/mobile (green). The data also shows that there is a year-on-year increase in the amount of flagged data corresponding to fixed/mobile allocations. Interestingly, in the RFI monitoring data this trend is not evident, which could suggest that the amount of interference year-on-year remains more or less constant, but since 2019 the ASKAP pipeline has improved in identifying and flagging the interference. Figure 3.7 shows less flagging in the bands corresponding to aeronautical radionavigation service allocations (cyan) in 2019 and 2020, compared to after 2020 consistent with travel restrictions due to the COVID-19 pandemic. This pattern is not as clear in the mid band aeronautical radionavigation service allocations, nor do we see any obvious increases in the modest flagging in any other services. Of concern are the (yellow) protected RAS allocations where in previous years there have been non-negligible losses. Further investigation is required using full resolution data from the “Survey and Monitoring of ASKAP’s RFI environment and Trends” (SMART) project to determine if in some cases CFLAG is flagging the 21 cm line itself or if this is due to RFI as a result of unintended electromagnetic radiation.

Day vs Night

Figure 3.4 shows some variation as a function of day and night. The red curve on the horizontal subplot is the easiest to discern by eye. Historically, it indicates that there have been more continuum science observations between 08:00 and 21:00 UTC (16:00 and 03:00 local time). This trend can be explained by maintenance on-site and beamforming occurring during the day. Going forward with full survey operations we expect this difference to be reduced. Note, ASKAP does not currently support SSPs being observed only at night. Another obvious variation between day and night is in the main plot below 800 MHz and at 900 MHz corresponding to the fixed/mobile service which shows more flagging after sunset (19:00 local time 11:00 UTC). To quantitatively determine the variations between day and night, Figure 3.8 plots probabilities due to RFI in the day (orange) and night (blue) as a

function of frequency in the top panel; i.e. the blue vertical subplot in Figure 3.4 split into flagging in the day versus night.

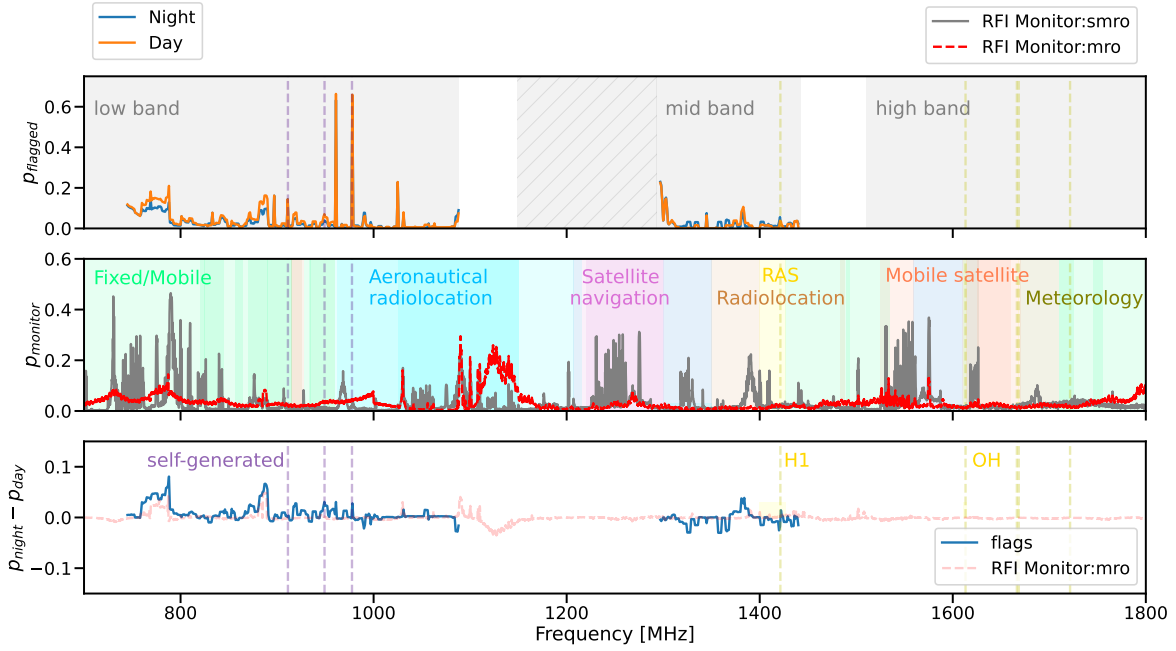


FIGURE 3.8. The top panel shows the mean probability of flagging, (from the blue vertical subplot in Figure 3.4) comparing flagging in the day (orange) versus night (blue). The middle panel shows the probability of RFI based on RFI monitors. The bottom panel shows differences in flagging between night and day (blue) and RFI monitor (opaque red dashed curve in the background). In the background of the top panel are ASKAP’s low, mid and high bands (hatched area is discarded after observing). In the background of the second panel the broad ranges of several primary allocations affecting ASKAP. Finally, the protected band (spectral lines) in yellow and the self-generated RFI in purple are shown vertically across all panels.

We have defined the daytime as 06:00 to 18:00 local time (inclusive) based on the average sunset and sunrise times across the year corresponding to 22:00 to 10:00 UTC in Figure 3.4. This division also yields two equal 12 h subsets of data with which to make the comparison. The middle panel in Figure 3.8 shows the probability of RFI based on two RFI monitors at the observatory with different integrating times. The *smro* (solid grey) RFI monitor is more sensitive to transmission from mobile base stations and satellites, the *mro* (dashed red) RFI monitor gives better estimates on transmission from aeronautical radionavigation equipment,

for example Distance Measuring Equipment (DME). The bottom panel shows the difference between day and night in flagging (blue) and the *mro* RFI monitor (red). The ranges of the clean low, mid and high bands are shown in the background of the top panel. The ranges of several primary radio allocations affecting ASKAP are also shown in the middle panel. The RAS protected bands and spectral lines are shown in yellow. Finally, the candidate self-generated RFI signals from Figure 3.5 are overlaid vertically across all three panels in purple.

The bottom panel in Figure 3.8 shows variations in flagging between day and night (the solid blue curve) are within $\pm 10\%$. This curve traces the *mro* RFI monitor. Positive values in the bottom panel indicate that the interference and flagging are worse at night and negative values indicate the interference and flagging are worse during the day. The most prominent examples of variations between day and night are in the low band, the fixed/mobile below 800 MHz and at around 870 MHz is more likely during the night. At first one might expect that RFI due to cellular interference would decrease at night when people are generally asleep. However, recall that ASKAP is located in the ARQZWA, this means that RFI from mobile base stations (see Figure 3.9) is more likely to affect ASKAP during ducting events. Indeed, upon comparison with RFI monitoring ducting predictors since 2019, ducting is 9% more likely on average at night.

Ducting

We have tried to identify the percentage of scheduling blocks affected by ducting based on ‘excess’ flagging compared to the mean across all scheduling blocks. Table 3.3 shows the percentage of scheduling blocks per band with probabilities greater than the mean, 1σ and 2σ above the mean. Across all data, day and night, and across all seasons we estimate an upper limit of 12% of the processed scheduling blocks affected by ‘excess’ flagging potentially due to ducting. There are not yet any discernible seasonal trends in ‘excess’ flagging though, across the year. [122] observed ducting in 28% of 131 nights in summer at the observatory

at low frequencies (≤ 300 MHz), with which we expect some correlation during periods of intense ducting at ASKAP's frequency range [42].

TABLE 3.3. Percentage of scheduling blocks with excess flagging.

	low band (%)	mid band (%)
$p_{\text{RFI}} > \mu$	23	39
$p_{\text{RFI}} > 1\sigma$	11	12
$p_{\text{RFI}} > 2\sigma$	4	6

Predictors for RFI ducting have been developed utilizing RFI monitoring equipment data spanning the last five years. These predictors differentiate between four levels of ducting status: none, mild, moderate, and severe. We see mild ducting 1.35 % of the time, moderate ducting 4 % of the time and severe ducting 3 % of the time. Broken up year-on-year, the percentage of time experiencing increased RFI propagation is shown in Table 3.4.

TABLE 3.4. Percentage of year experiencing increased RFI propagation.

	mild (%)	moderate (%)	severe (%)
2023	0.05	4	5
2022	3	5	2
2021	0.62	1.40	0.47
2020	1.35	2	1.18
2019	1.92	7	5

Furthermore, Figure 3.9 shows the location of mobile base stations that have been detected at the observatory since 2017. Base stations with larger circles indicate more numerous and the colour denotes the detected frequency. The majority of detected base stations correspond to the frequencies with increased flagging in the fixed/mobile service allocations below 800 MHz and at around 870 MHz at night shown in Figure 3.8. The most frequent detections of mobile base stations come from Mullewa/Geraldton (SW) and Carnarvon (NW) directions (>5000 detections). Detections from base stations this far (and further) away is only possible under circumstances in which there is severe ducting. Similarly, RFI from maritime vessels are detected when there is ducting. Work is ongoing within the observatory to better characterise and detect ducting both historically and operationally, including work to automatically identify it in the data and reliably predict significant ducting events in advance.

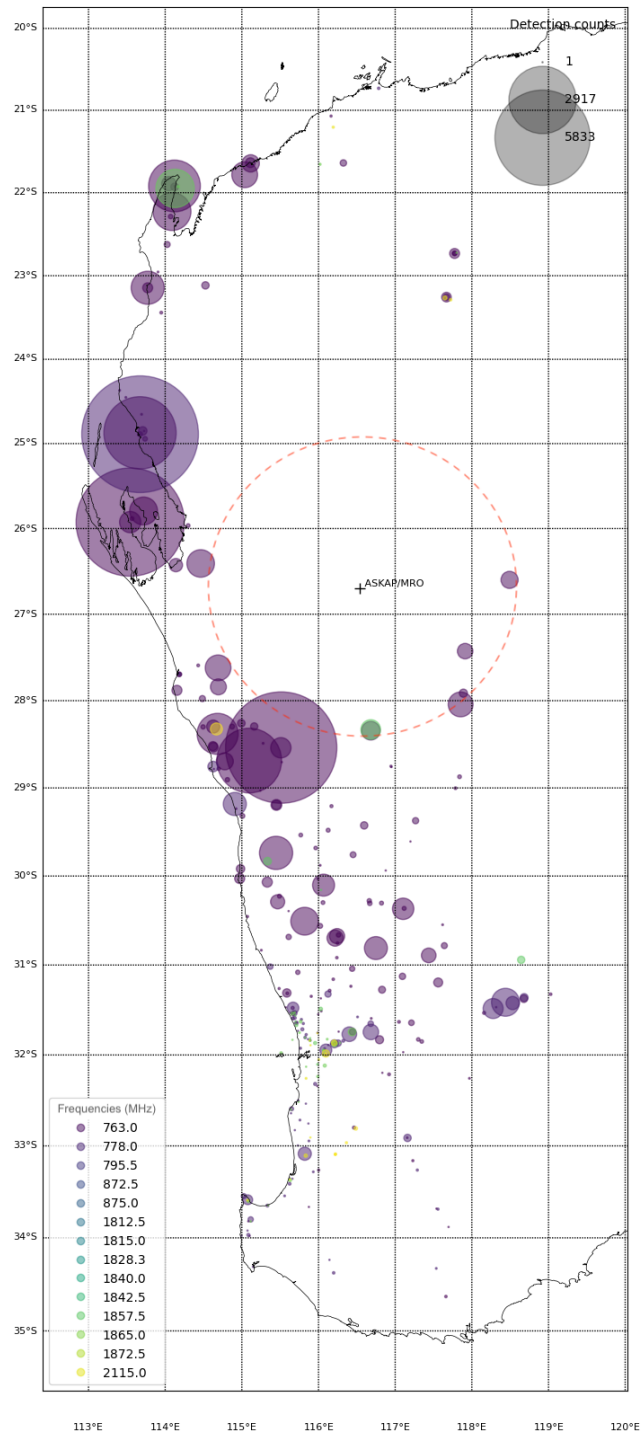


FIGURE 3.9. Map of mobile base station detections via ASKAP's RFI monitoring equipment since 2017 showing the most frequently detected mobile base stations (the largest circles) are in the Mullewa/Geraldton (SW) or Carnarvon (NW) directions. The colour of the circles denotes the detected frequency. The map has been annotated to show the approximate area of the ARQZWA.

3.5 Future Objectives

We will continue to process, aggregate and analyse archived 1 MHz data from other SSPs. We plan to conduct regular follow-up RFI surveys and are considering a mode in which we can sample the RFI with full pointing coverage in ASKAP’s fly’s-eye mode. The first epoch of the dedicated RFI survey is currently being carried out. The survey has been designed to complement our analysis of archived data. There are two primary motivations for carrying out an RFI survey as part of the SMART project.

Firstly, frequency resolution: the data used to develop the `flagstats` library - and presented here within - comes primarily from archived data. The consequence of using archived data is that most of the data has a 1 MHz frequency resolution. In contrast to narrowband RFI, 1 MHz is too wide to identify interference accurately. The dedicated survey visibilities (and flags) will help plan a mitigation strategy around the RFI affecting ASKAP. Furthermore, the survey will enable us to build out the software described in the previous section and routinely process flagged data from ASKAP 18.5 kHz resolution observations, thereby better understanding the origins of RFI impinging on ASKAP science.

Second, frequency coverage, from 1085 MHz to 1293 MHz and from 1437 MHz to 1510 MHz of the ASKAP frequency range, is either entirely or frequently discarded after observing due to RFI. As mentioned, ASKAP SSPs generally observe in the three relatively clean bands to avoid RFI caused by satellite-based radionavigation systems (GPS, Galileo, GLONASS, and BeiDou), aeronautical radio navigation (DME and ADS-B) and satellite-based radio communication systems (Iridium, Thuraya and Globalstar) [38, 42]. Collecting flagged data exclusively from SSPs results in large frequency gaps where we do not understand the RFI environment or ASKAP’s default flagging behaviour (see Figures 3.4 and 3.8).

We are currently working on extending the software presented herein to be compatible with observations in ASKAP’s nominal full-band spectral-line resolution of 18.5 kHz (i.e. excepting zoom modes), starting with this first epoch of survey data, which will allow us to

more accurately identify interferers and plan a mitigation strategy around them. We also plan to include flagged data as a function of pointing and baseline/antenna into our analysis. Full frequency survey data will be used to calibrate and infer the suitability of RFI monitoring equipment. As part of ASKAP’s holistic RFI strategy we aim to more closely integrate the `flagstats` library and RFI monitoring equipment, in particular, the full frequency telescope flagging data and high-time resolution RFI monitor data (not presented here). Finally we plan to use the RFI survey and flagged data monitoring system presented to determine and monitor the effects of RFI mitigation. This includes but is not limited to, in the short-term spatial nulling of the self-generated interferers [160] presented in Section 3.4.1, to recover these affected frequencies.

3.6 Conclusion

RFI-affected data in radio astronomy is typically thrown away in a process called flagging so as not to affect scientific conclusions. The “Survey and Monitoring of ASKAP’s RFI environment and Trends” project has generated an automated software processing pipeline that ingests flagged data upon completion of an observation. The software makes it easy to visualise flagging statistics due to RFI as a function of frequency and time and SSPs. Flagging statistics per observation are also stored and mapped to other sources of data to compare and analyse populations of observations in novel ways. We have presented here the implementation of this software and are currently undertaking the first in a series of regular epochs of an RFI survey with ASKAP.

We have shown the results from over 1500 h of 1 MHz averaged data, mapped features in flagged data to their respective radio allocation to estimate the impacts on ASKAP science by other services in the radio spectrum and self-generated interferers. We have placed an upper estimate of 3 % on the average data lost to RFI in the clean science bands. The (archived and processed) mid band is the least affected by flagging, while the low band is most affected by mobile telecommunication base stations.

The ongoing monitoring of all flagged data and regular full-frequency resolution RFI surveys, presented herein, are essential in improving the overall quality of science conducted with ASKAP amidst an increasingly dynamic and evolving radio spectrum.

Acknowledgments

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Mitigation of static self-generated RFI

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This chapter is reproduced from [160], published in the Publications of the Astronomical Society of Australia as “*Mitigation of self-generated RFI using ASKAP’s phased array feeds*”. Initiating the first processing of the SEFD at Pawsey was done by T. J. Galvin. The subsequent processing of the SEFD at Pawsey, the equation to calculate the suppression in Figure 7, executing all observations, the change from standard SEFD to use the correlation coefficient in the 3rd and 4th iteration, were done by Dr. Chippendale. All other work in this chapter is mine.

The previous chapter identified two self-generated and static interferers as the most persistent.

This chapter realises and considers the effects of oblique projection on one of these interferers.

Abstract

This paper presents the effects of radio frequency interference (RFI) mitigation on a radio telescope’s sensitivity and beam pattern. It specifically explores the impact of subspace-projection mitigation on the phased array feed (PAF) beams of the Australian SKA Pathfinder (ASKAP) telescope. The goal is to demonstrate ASKAP’s ability to make science observations during active RFI mitigation. The target interfering signal is a self-generated clock signal from the digital receivers of ASKAP’s PAFs. This signal is stationary, so we apply the mitigation projection to the beamformer weights at the beginning of the observation and hold them fixed. We suppressed the unwanted narrowband signal by 31 dB, to the noise floor of an 880 s integration on one antenna, with a typical degradation in sensitivity of just 1.5 %. Sensitivity degradation over the whole 36 antenna array of 3.1 % was then measured via interferometric assessment of system equivalent flux density (SEFD). These measurements are in line with theoretical calculation of noise increase using the correlation of the beamformer weights and RFI spatial signature. Further, degradation to the main beam’s gain is $\pm 0.4\%$ on average at the half-power point, with no significant change to the gain in the first sidelobe and no variation during extended observations; also consistent with our modelling. In summary, we present the first demonstration of mitigation via spatial nulling with PAFs on a large aperture synthesis array telescope and assess impact on sensitivity and beam shape via SEFD and holography measurements. The mitigation introduces smaller changes to sensitivity than intrinsic sensitivity differences between beams, does not preclude high dynamic range imaging and, in continuum 1 MHz mode, recovers an otherwise corrupted holography beam map and usable astronomical source correlations in the RFI-affected channel.

4.1 Introduction

For astronomers to adopt active radio frequency interference (RFI) mitigation, they need to understand the impact of mitigation on telescope performance and calibration.

Active RFI mitigation algorithms can help sensitive radio telescopes operate over scientifically interesting bandwidths in the congested modern radio spectrum. RFI continues to increase with population and technology use [43]. Telescopes are also becoming more susceptible to RFI as they are built to operate with higher sensitivities and bandwidths. The Australian SKA Pathfinder (ASKAP) telescope [38] used in this work operates over 700 MHz to 1800 MHz in frequency bands where satellite navigation, aviation, and terrestrial mobile communication base stations have a primary service allocation [16]. Active mitigation algorithms could enable the use of the 1.15 GHz to 1.3 GHz band that is largely avoided by ASKAP due to satellite navigation signals.

Radio astronomers currently mark and discard (flag) RFI-affected data so that it does not affect scientific conclusions. Unfortunately, discarding data reduces measurement sensitivity as the discarded data contains valuable information from astronomical sources. In the case of a synthesis imaging array like ASKAP, flagging also changes the secondary beam, or point spread function, and thereby image resolution and dynamic range. Although effective when carefully implemented, flagging does not exploit all the information the system provides. In particular, the interferer's spatial information is not fully considered.

Phased array feeds (PAFs) allow for the recovery of spatial information of RFI and cosmic sources. Using this spatial information, projection techniques for aperture arrays and PAFs create nulls in the direction of the RFI [1, 6, 161], which could reduce the amount of discarded and flagged data. The viability of this technique for the ASKAP PAF has already been explored in simulation [7] and demonstrated on six antennas during commissioning [13]. [7] showed that mitigation via spatial nulling at the PAF beamformer is most effective. The PAF primary beam nulls are spatially broader and, therefore, don't have to be updated as

rapidly to track moving interferers as would be the case for secondary beam nulls formed at the correlator.

Despite promising progress of active RFI mitigation radio in radio astronomy [53, 54], much work remains to implement these techniques as part of a holistic strategy in routine, large-scale telescope operations in combination with ‘traditional’ RFI mitigation techniques.

This paper begins to address this gap, building on work by [8] in which a narrowband tone generated by the PAF digital back-end was suppressed by up to 20 dB using a modified ASKAP Mk. II PAF on the 64 m Parkes telescope. In this instance, the unwanted signal is static (not moving) relative to the receiver and mitigated at the start of the observation. This static case is an essential first step toward mitigating more pernicious forms of RFI from satellite and aviation systems that are dynamic (moving) and need to be mitigated in as close to real-time as possible. Note that in cases where the interference is external to the receiver (or downstream electronics), RFI will appear dynamic from the telescope’s point of view because the telescope tracks a source on the sky.

We present simulated forward predictions of the effects of spatial nulling via PAF beam-forming on astronomical figures of merit, comparing two subspace-projection-based algorithms with attention to the impacts on sensitivity (noise), bandpass (gain), and beam shape, including polarisation response. Section 2 describes the ASKAP PAF, the signal model and an overview of the spatial filtering algorithms. Section 3 gives simulated forward predictions of the effects of the mitigation. Finally, section 4 presents the implementation and measured performance on ASKAP.

4.2 Background

The Australian SKA Pathfinder telescope comprises thirty-six 12 m parabolic reflectors at Inyarrimanha Ilgari Bundara, the CSIRO Murchison Radio-astronomy Observatory. This

unique radio-quiet site is protected by rigorous testing and shielding of observatory electronics and legislative coordination of spectrum usage up to a radius of 260 km [45]. Figure 4.1 shows the Mk. II phased array feed (PAF) at the focus of each antenna. Behind the 188 chequerboard elements (94 per polarisation) is the receiver electronics package housing the low noise amplifiers (per antenna element), three radio frequency (RF) band selection filters and RF-over-Fibre transmitter [38].



FIGURE 4.1. 12 m ASKAP antennas with PAFs at their foci at Inyarrimanha Ilgari Bundara, the CSIRO Murchison Radio-astronomy Observatory. Credit: CSIRO

The self-generated RFI is generated by a 256 MHz field programmable gate array (FPGA) clock that is multiplied by an oversampling rate of 32/27 to read out the digital receiver's 1 MHz resolution oversampled coarse filter bank [130]. Relative delays of this unwanted signal between digital ports differ significantly from relative delays of the desired astronomical signals entering via the reflector and PAF. This difference in the spatial signature allows the RFI to be cancelled at the beamformer output with little impact on the desired signal. The digital receiver is housed in the stable environment of the ASKAP's central building, so we

expect this RFI and its path into the signal chain to be stable except for resets of the digital receiver, which do not occur during observing.

The fundamental of this $32/27 \times 256 \text{ MHz} = 303.4 \text{ MHz}$ clock signal is aliased and appears at the frequency labeled

$$F_s/2 + (F_s/2 - 303.4) = 976.6 \text{ MHz}$$

when observing in ASKAP's 700 MHz to 1200 MHz band with a sampling rate of $F_s = 1280 \text{ MHz}$.

Figure 4.2 shows the clock signal in the fine filter bank power spectrum without mitigation (blue) and with mitigation (orange). The mitigation suppresses the unwanted interference, but also increases the system temperature of the 1 MHz channel in which beamformer weights were adjusted to implement the mitigation.

4.2.1 Signal model

The instantaneous output for a single ASKAP PAF (Figure 4.1) is an M -dimensional vector of complex voltages ($M = 188$)

$$\mathbf{x}[n] = x_{\text{SOI}}[n]\mathbf{a}_{\text{SOI}} + x_{\text{RFI}}[n]\mathbf{a}_{\text{RFI}} + \mathbf{x}_z[n] \quad (4.1)$$

where $x_{\text{SOI}}[n]$ and $x_{\text{RFI}}[n]$ are the scalar amplitude time samples of the astronomical source-of-interest (SOI) and RFI (unwanted signal to mitigate) respectively. $\mathbf{a}_{\text{SOI}}$ and $\mathbf{a}_{\text{RFI}}$ are the spatial signature vectors of the SOI and RFI, respectively. $\mathbf{x}_z[n]$ is the total system noise (the radio sky, feed and receiver). ASKAP's beamformer [38] computes an array covariance matrix (ACM), which is the pairwise correlation of each port with every other port for a single 1 MHz coarse filter bank channel

$$\mathbf{R} = \langle \mathbf{x}[n] \cdot \mathbf{x}[n]^H \rangle = \frac{1}{L} \sum_{n=1}^L \mathbf{x}[n]\mathbf{x}^H[n] \quad (4.2)$$

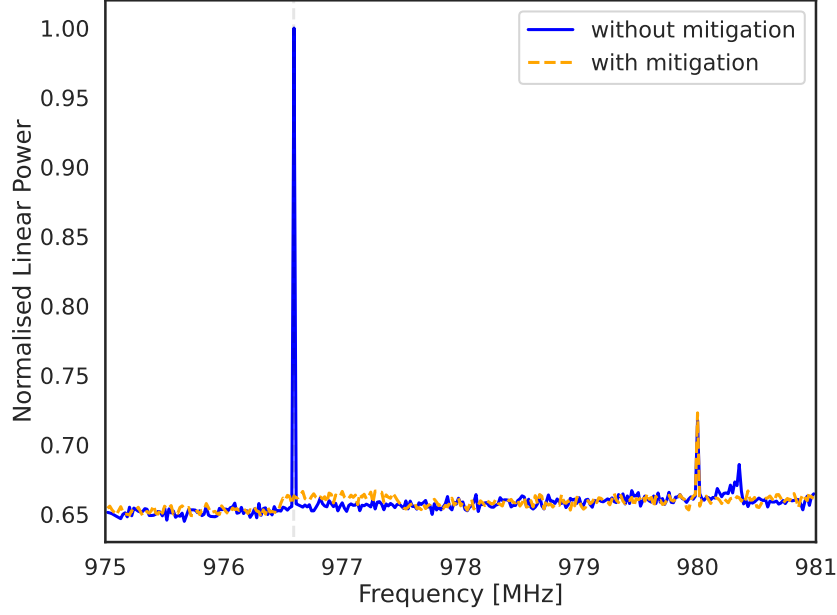


FIGURE 4.2. Beamformed single-antenna power spectra with mitigation (orange) and without (blue). Beamformer weights are fixed over each 1 MHz coarse channel before further channelisation to 18.5 kHz resolution. The 976.6 MHz unwanted clock signal is successfully mitigated but with an increase in the system temperature for that coarse channel. The difference between spectra at 980.3 MHz is due to these observations occurring at different times. The mitigation, using the oblique projection, was performed whilst observing a flux reference source, Virgo A, assuming the flux model of Ott et al. [162] using a single ASKAP antenna.

where $(.)^H$ is the Hermitian (complex conjugate) transpose, and $\langle . \rangle$ is the average operator. The spatial filtering algorithms used below use this ACM to estimate the RFI spatial signature ($\mathbf{a}_{\text{RFI}}$) and subsequently suppress its contribution. For typical moving RFI $\mathbf{a}_{\text{RFI}}$ must be estimated frequently. For the stationary clock signal being mitigated here, $\mathbf{a}_{\text{RFI}}$ can be estimated once at the beginning of an observation because it does not change with time or PAF motion¹.

Under typical operation, a set of beamforming steering vectors or “beamformer weights” are calculated at the beginning of the observation and loaded to the beamformer to create up to 36 dual-polarized beams on ASKAP. The 188 weights correspond to a weighting of each

¹due to ASKAP’s 3rd axis of rotation

PAF port and are calculated per beam, per 1 MHz channel via the ACM using a maxSNR algorithm from an on-source and off-source pointing [38]. This beamforming process is most easily understood as applying the weights as a weighted sum of the PAF array element voltages

$$\mathbf{y}[n] = \mathbf{w}^H \mathbf{x}[n]. \quad (4.3)$$

The goal is to update these beamformer weights ($\mathbf{w}$) by projecting them onto a subspace orthogonal to the interference subspace, forcing a deep null in the “direction” of the interferer but preserving beam gain in the direction of the original beam that was designed to receive the SOI.

4.2.2 Mitigation algorithm

Subspace projection refers to a subset of spatial filtering signal processing techniques involving a linear projection to cancel the unwanted signal in the beamformed output of an array. Two projections are considered in this research: orthogonal [79] and oblique [6, 107]. [6] and [39] give a full description of both projections. Both use an eigenvalue decomposition of the ACM to determine the ‘direction’ of the RFI

$$\mathbf{R} = \mathbf{U} \mathbf{\Lambda} \mathbf{U}^H. \quad (4.4)$$

Each column of $\mathbf{U}$ is an eigenvector of $\mathbf{R}$, corresponding to the eigenvalues contained along the diagonal of the matrix $\mathbf{\Lambda}$ sorted in descending power. $\mathbf{U}$ may be partitioned into columns $\mathbf{U}_{\text{RFI}}$ defining the RFI subspace and $\mathbf{U}_{\text{SOI}+z}$ defining the signal plus noise subspace

$$\mathbf{U} = [\mathbf{U}_{\text{RFI}} | \mathbf{U}_{\text{SOI}+z}]. \quad (4.5)$$

In the case of the self-generated interference, Figure 4.5a shows there is only one dominant eigenvalue. The corresponding eigenvector $\mathbf{a}_{\text{RFI}}$ comprises a one-dimensional RFI subspace $\mathbf{U}_{\text{RFI}}$.

An orthogonal projection matrix $\mathbf{P}_{\text{ortho}}$ is defined as follows, where $\mathbf{I}$ is the identity matrix

$$\mathbf{P}_{\text{ortho}} = \mathbf{I} - \mathbf{U}_{\text{RFI}} (\mathbf{U}_{\text{RFI}}^H \mathbf{U}_{\text{RFI}})^{-1} \mathbf{U}_{\text{RFI}}^H. \quad (4.6)$$

Whilst orthogonal projection mitigates the unwanted signal, it introduces undesirable distortions to the primary beam shape. Therefore, oblique projection is preferred as it better preserves the desired beam shape [6, 163]. Using the calculated maxSNR beamformer weights ($\mathbf{w}$) as our spatial signature $\mathbf{a}_{\text{SOI}}$, we determine a projection matrix $\mathbf{P}_{\text{obliq}}$, which not only mitigates the interferer but maintains the steering direction and gain

$$\mathbf{P}_{\text{obliq}} = \mathbf{a}_{\text{SOI}} (\mathbf{a}_{\text{SOI}}^H \mathbf{P}_{\text{ortho}} \mathbf{a}_{\text{SOI}})^{-1} \mathbf{a}_{\text{SOI}}^H \mathbf{P}_{\text{ortho}}. \quad (4.7)$$

To obtain updated (“mitigated”) weights, the chosen projection matrix, i.e. $\mathbf{P}_{\text{ortho}}$ or $\mathbf{P}_{\text{obliq}}$, is applied to the original weights

$$\mathbf{w}_{\text{proj}} = \mathbf{P}^H \mathbf{w} \quad (4.8)$$

before uploading them to the beamformer where they are used to calculate a beamformed voltage time series with suppressed RFI

$$\mathbf{y}_{\text{proj}}[n] = \mathbf{w}_{\text{proj}}^H \mathbf{x}[n]. \quad (4.9)$$

4.3 Simulated forward predictions

The voltage pattern of individual ASKAP PAF elements is estimated based on the geometric optics analysis of [29] for the illumination of a paraboloidal reflector by laterally offset feeds

$$A_k(l, m) = \sqrt{2.56} \int_0^1 2r F(r) J_0 \left[r \left\{ (l - sx_k)^2 + (m - sy_k)^2 \right\}^{0.5} \right] dr \quad (4.10)$$

where J_0 is the Bessel function of the first kind and order zero. The illumination function $F(r) = 1 - (1 - \tau)r^2$ based on the geometry of the reflector and PAF element positions (above). A one-dimensional slice showing the x-pol element response for the centre row (ten ports) of the ASKAP PAF is plotted in the background of Figure 4.3.

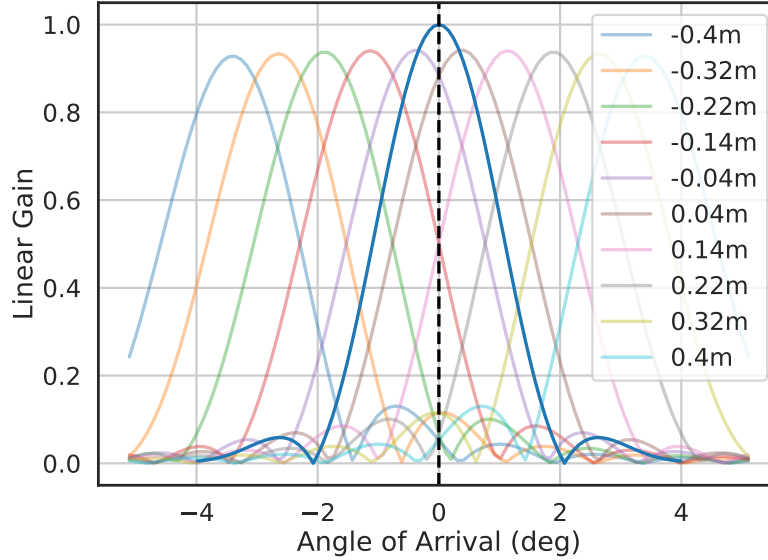


FIGURE 4.3. A model was created based on the PAF port spacing and diameter of the antenna. The background shows the x-polarisation element response for the centre row of ports using a -15 dB taper. The background curves are weighted and summed to form a beam in the foreground in a process called digital beamforming.

To create the beam ($y[n]$) at the boresight in the foreground of Figure 4.3, the model uses maximum gain weights that effect a Conjugate Field Match (CFM); that is, the intersections of the background curves with the dashed vertical line are the weights w used to steer the beam. The exact process is repeated for the y-polarisation ports but is not shown here.

PAF ports are weighted by a steering vector and summed to create beams. The beam in the foreground of Figure 4.3 shows a high-gain main lobe centred about the dotted line and terminates on either side with a null. The first and second side lobes are also discernible, separated by nulls. The model evaluates the effects of the orthogonal and oblique projection on six equally spaced beams ($\approx 0.9^\circ$ degrees apart) across the PAF for both polarisations.

This beam separation was chosen based on the close-pack square 6×6 beam footprint used by ASKAP [38].

The effects of mitigation, using an estimated 1-D RFI spatial signature of the stationary internal clock signal determined from an ASKAP ACM, were assessed on changes to model beam shape (Figure 4.4) and suppression calculated as follows

$$20 \log_{10} \frac{|\mathbf{w}^H \mathbf{U}_{\text{RFI}}|}{|\mathbf{w}_{\text{proj}}^H \mathbf{U}_{\text{RFI}}|} \text{ dB}. \quad (4.11)$$

As expected from previous experiments [8], the projection algorithms suppress the unwanted signal. The calculated predicted suppression of the unwanted signal across the six simulated beams yields an upper limit on the suppression greater than 250 dB. In other words, how orthogonal the RFI spatial signature can be made given, for example, the numeric precision of the calculations. In practice, this will be limited by the noise floor and the degree to which an accurate RFI spatial signature vector can be estimated.

Figure 4.4 shows the X and Y polarisation beamformed response in the direction -2.4° (black vertical dashed line), before and after mitigation using a measured RFI spatial signature. The rows show the linear gain, gain in decibels and gain (in decibels) with respect to the reference (unmitigated) to highlight differences in maximum gain of the main beam.

After mitigation, variations to the beam patterns were observed mostly in the outer side lobes (starting at the second null). The bottom panel of Figure 4.4 shows differences in the main beam are reduced when using oblique projection. Two instances of the self-generated interferer $\mathbf{a}_{\text{RFI}}$ were considered in the model (D); a uniform amplitude arriving at all ports with and without randomised delay/phase. That is all ports with different delay (randomised) and all ports with the same (aligned) phase, respectively. It was found that distortions to the beam were reduced when the phase of the generated signal was randomised. The estimated RFI spatial signature in Figure 4.4 is consistent with a clock signal arriving at the PAF ports with randomised phase due to differing delays in the signal path of each port. Using this property, we can start to preselect RFI, based on its phase as being a suitable candidate for

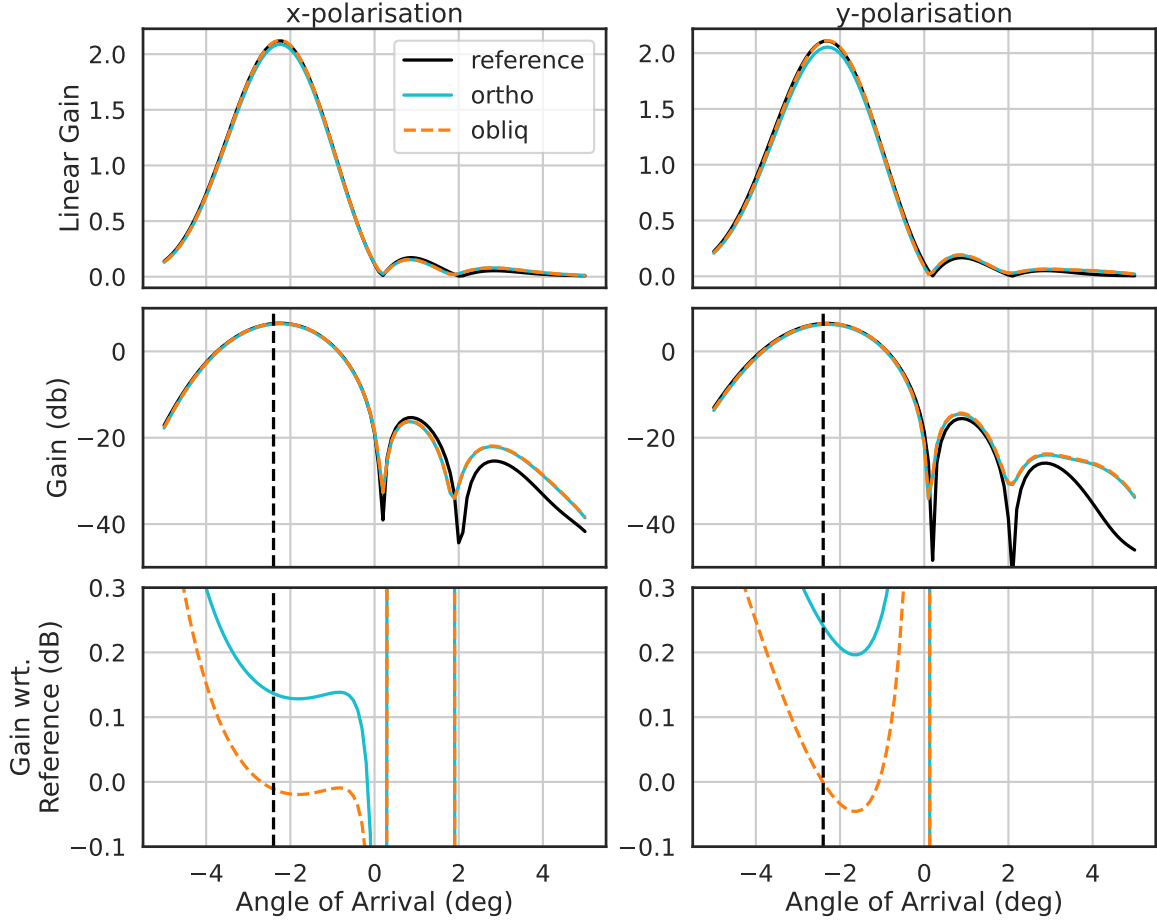


FIGURE 4.4. X and Y polarisation beamformed response in the direction -2.4° , before and after mitigation. The rows show the linear gain, gain in decibels and gain in decibels with respect to the reference (unmitigated) beam. This result is for the case where the RFI enters each PAF port with a measured RFI spatial signature. Variations to the beam shape are reduced in the main lobe when using oblique projection. In both cases, introduced variations to suppress the unwanted signal are confined to the outer lobes.

subspace projection RFI mitigation. Similarly, for a one-dimensional RFI subspace $\mathbf{u}_{\text{RFI}}$ the correlation ρ , between the estimated RFI and beamformer weights, given by their dot product

$$\rho = \frac{|\mathbf{w}^H \mathbf{u}_{\text{RFI}}|}{\|\mathbf{w}\| \|\mathbf{u}_{\text{RFI}}\|} \quad (4.12)$$

can be used to estimate the performance impact of the orthogonal and oblique projections as given by [6]. For oblique projection the increase in the noise power is

$$P_{noise} = \sigma_n^2 (1 - |\rho|^2)^{-1} \quad (4.13)$$

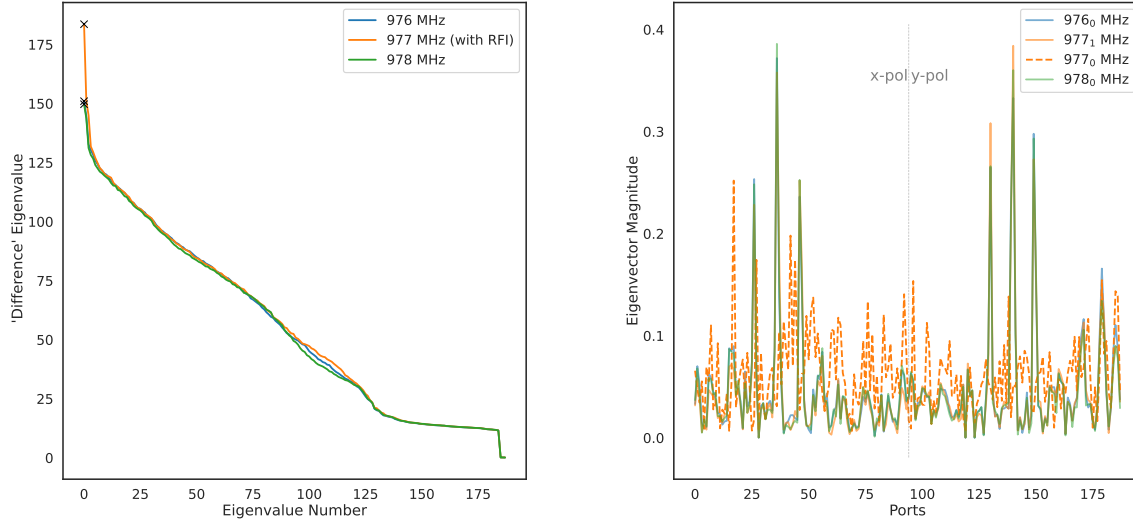
where σ_n^2 is the true noise power.

Simulating changes in T_{sys} requires a full simulation of the noise and mutual coupling. Without a full noise model, this paper uses CFM (maximum gain) weights in place of the maximum Signal-to-noise ratio (maxSNR) weights used in operational ASKAP beamforming. We, therefore, measure the mitigation's effects on sensitivity using on and off-source measurements from the telescope directly.

4.4 Measured performance on ASKAP

We conducted three experiments to assess the effects of spatial nulling via PAF beamforming on astronomical figures of merit. First, we conducted offline mitigation and calculated the suppression and sensitivity. The second experiment was conducted in real-time using on and off-source measurements whilst observing Virgo A using a single ASKAP antenna with and then without mitigation. We measured suppression limited by the noise floor and a beam equivalent system-temperature-on-efficiency T_{sys}/η across eight beams via the Y-factor ratio of beamformed power between on and off-source pointings.

Finally, we performed simultaneous measurements across the entire array, using pairs of beams in the same direction. Each beam pair comprises one beam with oblique projection and the other using maxSNR weights. We simultaneously measure the system equivalent flux density (SEFD) and perform holography on both mitigated and unmitigated beams to isolate changes due to the mitigation from other variations. This final experiment uses all antennas and a set of 36 beams to quantify the impact on telescope performance of mitigating the narrowband self-generated signal during operational observing modes.



(A) The eigenvalue spectra of three adjacent coarse ACM channels, the centre channel (977 MHz), contains the self-generated interference. The difference in the first value in the 977 MHz channel is due to the interfering clock signal.

(B) The dominant eigenvectors of the three adjacent channels, as well as the second eigenvector of the centre channel (with RFI), U_{977_1} (the dashed curve). Note how the U_{976_0} , U_{977_1} and U_{978_0} have a similar structure compared to U_{977_0} (the dashed curve meaning they have the similar weights of ports on the PAF).

FIGURE 4.5. The eigenvalue decomposition of three adjacent ACMs centred on the RFI-affected channel showing the power and ‘direction’ of the eigenmodes.

4.4.1 Implementation

Eigenvalue decomposition of the ACM is performed to isolate the one-dimensional spatial signature of the self-generated interferer (The dominant eigenvalue). RFI moving relative to the telescope would have a higher dimensional subspace [109, Lourenço & Chippendale in prep]. Looking at the eigenvalue spectra (Figure 4.5a) of three adjacent channels, we can see that when the self-generated RFI is powerful enough, the dominant eigenvalue of the centre channel is easily identifiable — the max value of the 977 MHz (orange) curve is higher — compared to the adjacent coarse 1 MHz channels.

When comparing the dominant eigenvectors (Figure 4.5b) of the same three adjacent channels (subscript $[.]_0$), as well as the second eigenvector (subscript $[.]_1$) of the centre

977 MHz channel (with RFI), we see that U_{976_0} , U_{977_1} and U_{978_0} have a similar structure compared to U_{977_0} (the dashed curve). U_{976_0} , the dashed curve, is our 1-D RFI spatial signature ($\mathbf{a}_{\text{RFI}}$). The other curves are representative of our SOI spatial signature ($\mathbf{a}_{\text{SOI}}$). This is only the case here because the ACM is an on-source beamforming ACM, so the Sun is in the field-of-view, which gives the structure in the solid curves, dominated by six highly weighted ports (i.e. the ports onto which the Sun's energy is focused by the reflector).

ASKAP calculates a weights steering vector per polarisation. Implementation of these algorithms, therefore, requires we calculate $\mathbf{a}_{\text{xRFI}}$ and $\mathbf{a}_{\text{yRFI}}$ separately to be consistent with ASKAPs existing codebase. We isolate two sub-ACMs of size 94×94 along the diagonal and perform the eigenvalue decomposition on those matrices to obtain $\mathbf{a}_{\text{xRFI}}$ (first sub-ACMs) and $\mathbf{a}_{\text{yRFI}}$ (second sub-ACMs). That is quadrants I and III of the ACM moving clockwise from the top left. In other words the first 94 ports of the ASKAP PAF (and weights) correspond to the x-polarisation and ports 95 through 188 correspond to the y-polarisation (as illustrated in Figure 4.5b) we found that we cannot simply "slice" $\mathbf{a}_{\text{RFI}}$ (U_{977_0}) into $\mathbf{a}_{\text{xRFI}}$ and $\mathbf{a}_{\text{yRFI}}$. Instead, we isolate the two sub-ACMs of size 94×94 along the diagonal and perform the eigenvalue decomposition on those matrices to obtain $\mathbf{a}_{\text{xRFI}}$ (first sub-ACMs) and $\mathbf{a}_{\text{yRFI}}$ (second sub-ACMs). That is quadrants I and III of the ACM moving clockwise from the top left

Furthermore, ASKAP varies the number of ports used in beamforming. Typically for thirty-six beams, only sixty ports per ASKAP antenna are used. The number of ports used increases as the number of beams decreases [38]. We compared the effects of using all ports vs sixty ports in simulation and found the results to be comparable.

Finally, in some cases, when the interference-to-noise power is low, the difference observed in Figure 4.5a is not substantial enough to provide an accurate estimation of $\mathbf{a}_{\text{RFI}}$ due to the low power nature of the signal. To overcome this, the ACMs of the adjacent channels were averaged and subtracted from the centre channel to isolate the spatial signature more easily. The ACM, $\mathbf{R}$ in the eigenvalue decomposition in Equation 4.4

$$\mathbf{R}' = \mathbf{R}_k - \left[\frac{\mathbf{R}_{k-1} + \mathbf{R}_{k+1}}{2} \right] \quad (4.14)$$

is modified to estimate the RFI spatial signature.

This would not be necessary for typical RFI which is much stronger than our test signal, however a useful result nevertheless for identifying and mitigating weak sources of RFI. Comparing both methods for calculating $\mathbf{a}_{\text{RFI}}$ yielded similar (and parallel determined by the dot product) vectors.

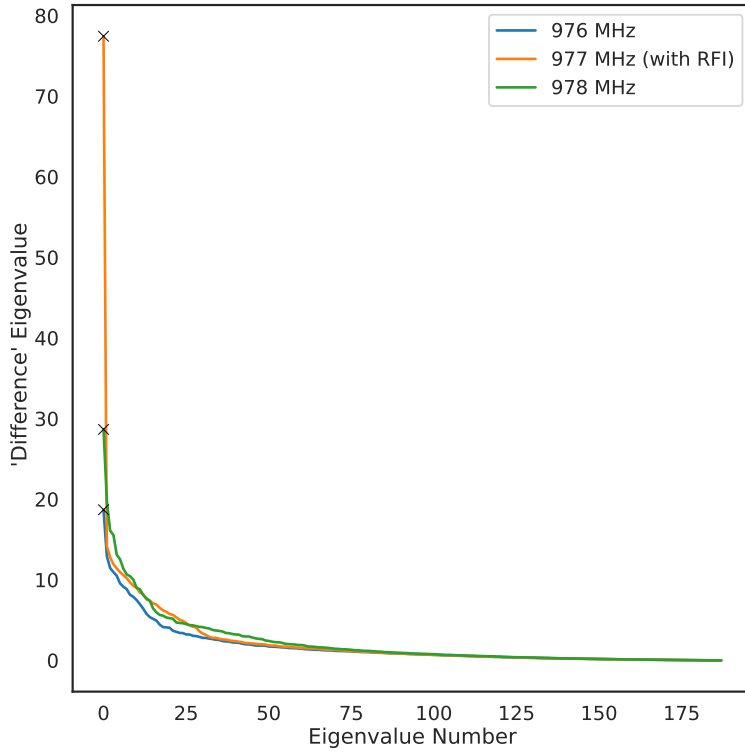


FIGURE 4.6. When the interference-to-noise power is low, by subtracting the mean of the adjacent channels it is easier to isolate an RFI- affected channel in the eigenvalue spectra.

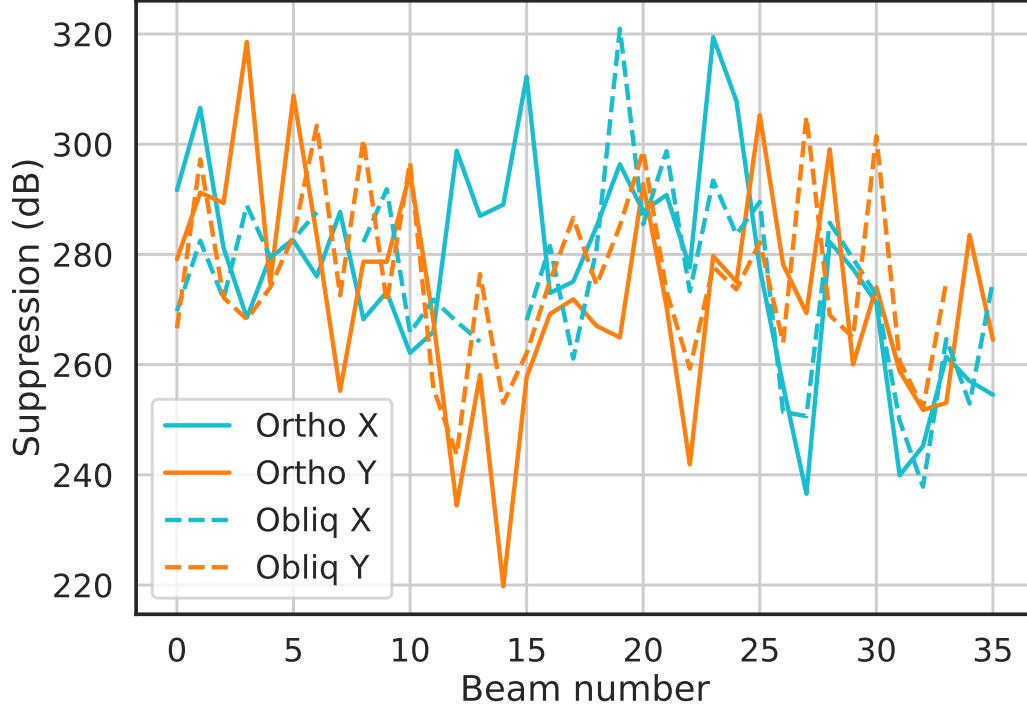


FIGURE 4.7. Calculated suppression of the unwanted signal across beams is approximately 277 dB.

4.4.2 Impact on suppression, sensitivity and beam shape

In the first experiment, the mitigation is performed offline. We use ACMs (containing the unwanted signal) and beamformed maxSNR weights from one ASKAP antenna (ak18) to determine the calculated suppression across beams. Figure 4.7 shows a maximum expected suppression of approximately 277 dB across all thirty-six beams, consistent with the model.

Using on and off-source ACMs the Y-factor (on-dish noise performance) can additionally be calculated [164]:

$$Y = \frac{\mathbf{w}^H \mathbf{R}_{on-src} \mathbf{w}}{\mathbf{w}^H \mathbf{R}_{off-src} \mathbf{w}} \quad (4.15)$$

That is, the power ratio between measurements of a known astronomical source and nearby empty sky, respectively. The off-source measurements are routinely obtained at the beginning

of a beamformer weight calibration observation and stored in the resulting ACM file. Across beams, similar results in terms of suppression were obtained using both projections, as expected. Using offline mitigation we measured a maximum increase to the Y-factor of 17 % and 15 % and an average increase of 3 % and 5 % for the x and y polarisations, respectively. Up to 6 % increase could be expected from the calculated value using Equation 4.13. Currently, on ASKAP, as the number of beams increases to the complete set of 36 dual-polarisation beams, the maximum number of ports used to form each beam reduces from 192 to 60 [38]. We assessed the expected increase in noise power using only 60 ports in the above calculation, and recall are only using the sub-ACMs to estimate $\mathbf{a}_{\text{xRFI}}$ and $\mathbf{a}_{\text{yRFI}}$. We use the indices of the same 60 ports from the beamformer weights to mask the RFI spatial signatures and then calculate the correlation coefficient.

However, the expected noise power increase is much smaller when calculating the correlation coefficient with an RFI spatial signature estimated from the full ACM and using all ports with the x and y maxSNR weights, 0.2 % and 0.4 %, respectively, on average. This result shows that the mitigation works much better for a beamformer that can work over all PAF ports of all polarisations and suggests how we could improve the mitigation on ASKAP in the future.

The second experiment conducted on 20 June 2022 captures on and off-source measurements using one antenna (ak18 again). The mitigation, using the oblique projection, was performed whilst observing a flux reference, Virgo A, assuming the flux model of [162]. Eight beams were formed. First, the antenna was pointed off-source -9° offset in declination, each beam was then subsequently directed toward Virgo A in turn, and fine filter bank data were recorded at 18.5 kHz resolution. We repeated the experiment with mitigation turned off for comparison. The sensitivity can be determined via the Y-Factor by calculating the beam equivalent system-temperature-on-efficiency as in [142] and [165, 166].

$$\frac{T_{\text{sys}}}{\eta} = \frac{A S}{2k_B(Y - 1)} \quad (4.16)$$

where A is the area of the dish, S is the known flux of the source, and k_B is Boltzmann's constant.

Figure 4.8 shows the T_{sys}/η of eight x and y polarization beams across an approximately 3 MHz frequency range centred at the 1 MHz channel containing the unwanted signal. The dashed vertical line demarcates the frequency of the mitigated interfering clock signal. There is a mean T_{sys}/η of 79.2 ± 3.7 K, 80.6 ± 3.8 K and 79.5 ± 3 K for the 976 MHz, 977 MHz and 978 MHz channels respectively across all beams. All the mitigated channels have a higher T_{sys}/η , except beam 5, due to the upward slope in the curve. In the 1 MHz channel containing the unwanted signal, across all beams, there is a maximum increase of 3.31 % or 2.66 K in T_{sys}/η and a mean increase of 1.59 % or 1.26 K. Note that these increases are smaller than the differences between beams. A mean increase of 1 % based on the correlations was expected (Equation 4.13). The rest of the band is consistent with [165]. One way to understand the increase in T_{sys}/η is that the original weights are calculated to yield a maximum signal-to-noise ratio (the lowest T_{sys}/η); any deviation from those weights will by definition be less than the maximum.

Suppression using Equation 4.11 is not limited by the noise floor. From this experiment, we were able to determine a noise floor limited suppression of 31 dB, see Figure 4.2. Importantly, we have regained a channel that is otherwise always flagged [145] and ultimately discarded.

Recall we are applying the mitigation once at the start of an observation because, in this case, the 1-D RFI spatial signature ($\mathbf{u}$) is unchanging during an observation. The similarity of the two signatures $\Re \{ \mathbf{u}_{\text{RFI}}[t1]^H \mathbf{u}_{\text{RFI}}[t2] \} \geq 0.99$, i.e. they are in the same 'direction' over a 7 min measurement.

4.4.3 Concurrent measurements with mitigation on and off

Two experiments were conducted in January 2023 to compare the effects of the projection techniques simultaneously. First measuring sensitivity across the array, we carried out a

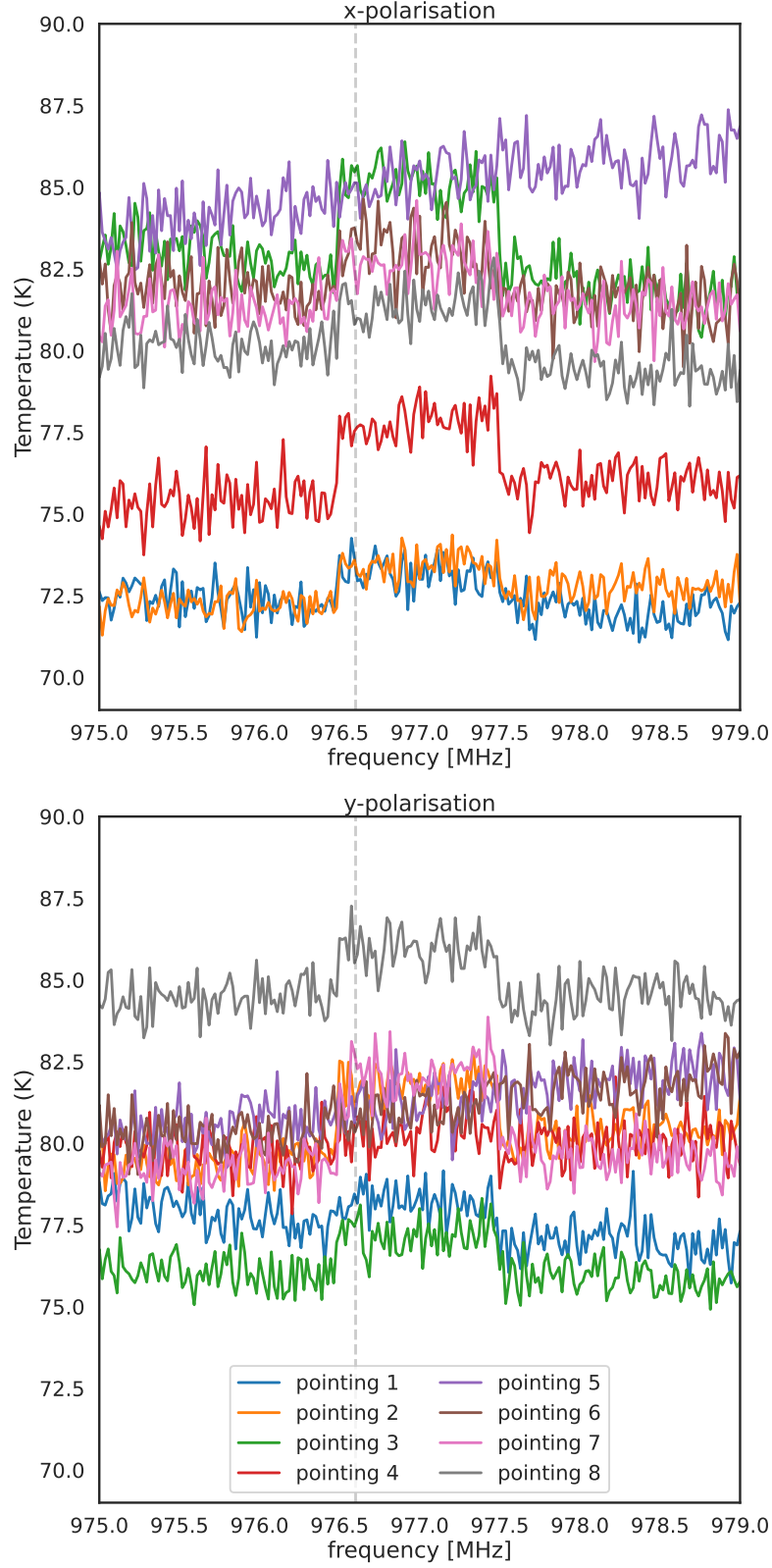


FIGURE 4.8. Sensitivity (System-temperature-over-efficiency) with mitigation, shows x-polarization on the top and y-polarization on the bottom across eight different beams. T_{sys}/η increases at the channel updated using oblique projection compared to maximum signal-to-noise ratio weights (seen in adjacent channels). Beamforming and sensitivity measurements were made using Virgo A and an off-source measurement -9° offset in declination.

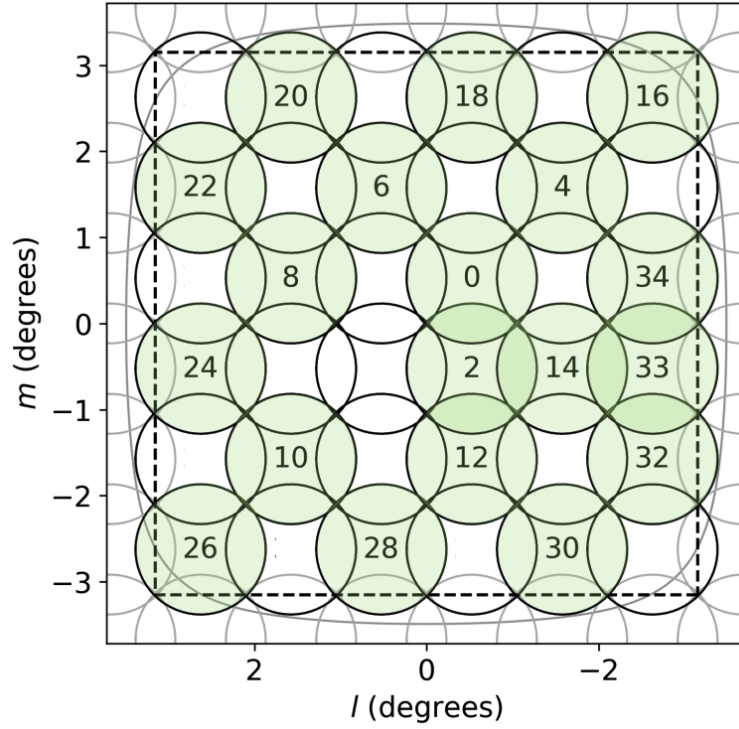


FIGURE 4.9. To simultaneously compare the effects of the projection techniques on sensitivity and beam shape, experiments were conducted using a modified close-pack square 6×6 footprint. The modified footprint consists of two beams created at each odd position (shaded in green), the first without mitigation and the 2nd with mitigation. Modified from Figure 2 in [12].

system equivalent flux density (SEFD) measurement whilst observing a flux reference, PKS B1934–638. Then we made a holography measurement to determine changes to the beam shape.

A modified ASKAP 6×6 square close-pack beam footprint was used in both experiments. The modified footprint creates pairs of beams in the even positions (highlighted in green) of the footprint shown in Figure 4.9. Thirty-six beams grouped into 18 pairs were created; odd-numbered beams used unmitigated weights, and even beams used updated weights with mitigation using oblique projection. In other words, for every beam in Figure 4.9, marked in green, there is a mitigated copy in the same position labelled with the subsequent number. Simultaneously measuring beams with and without mitigation isolates changes in the SEFD and holography to the mitigation itself.

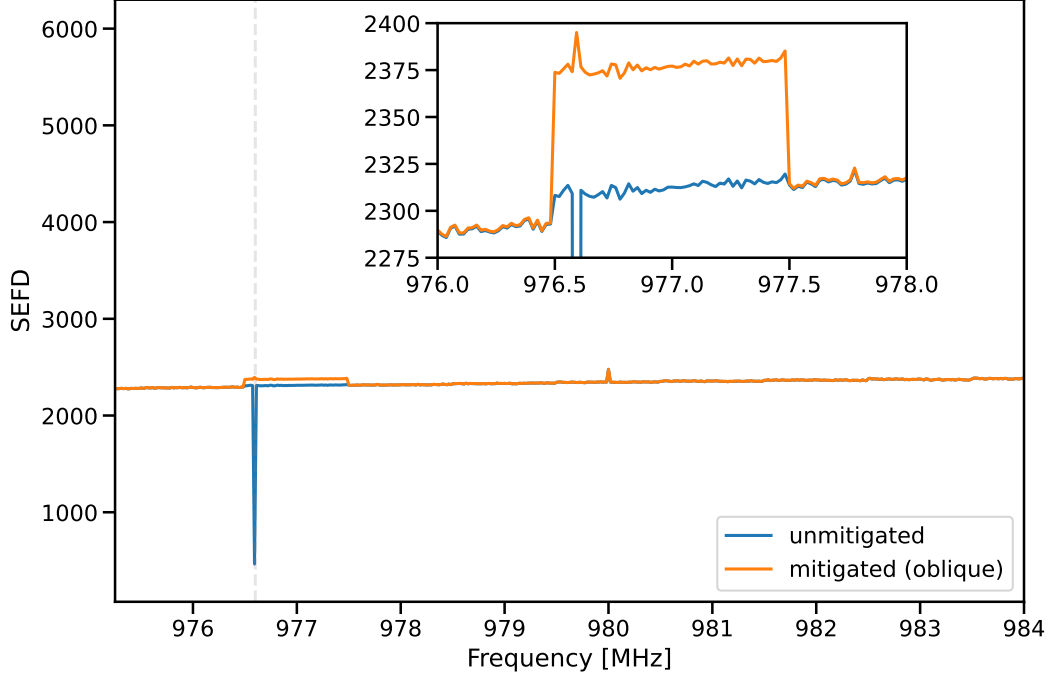


FIGURE 4.10. SEFD measurement showing unwanted clock signal with and without mitigation (orange and blue, respectively). Similar to a single antenna across the array, mitigation introduces a reduction in sensitivity to the 1 MHz channel. This plot is averaged over all beams and all antennas.

Sensitivity across the Array

The SEFD, measured in Janskys (Jy), is given by [38]

$$SEFD = \frac{2k_B T_{\text{sys}}}{A\eta} \quad (4.17)$$

and used to characterise the sensitivity of an antenna (and receiver). We use a modification of ASKAP standard SEFD which uses the correlation coefficient [167] to reduce measurement noise. SEFD measurements are a good way of comparing sensitivity between telescopes because it takes into account both the receiver system temperature (T_{sys}) and the area (A). Note the T_{sys}/η term, Equation 4.16, from the previous experiment. A lower SEFD value corresponds to an increased sensitivity.

Comparison of SEFD measurements across beams

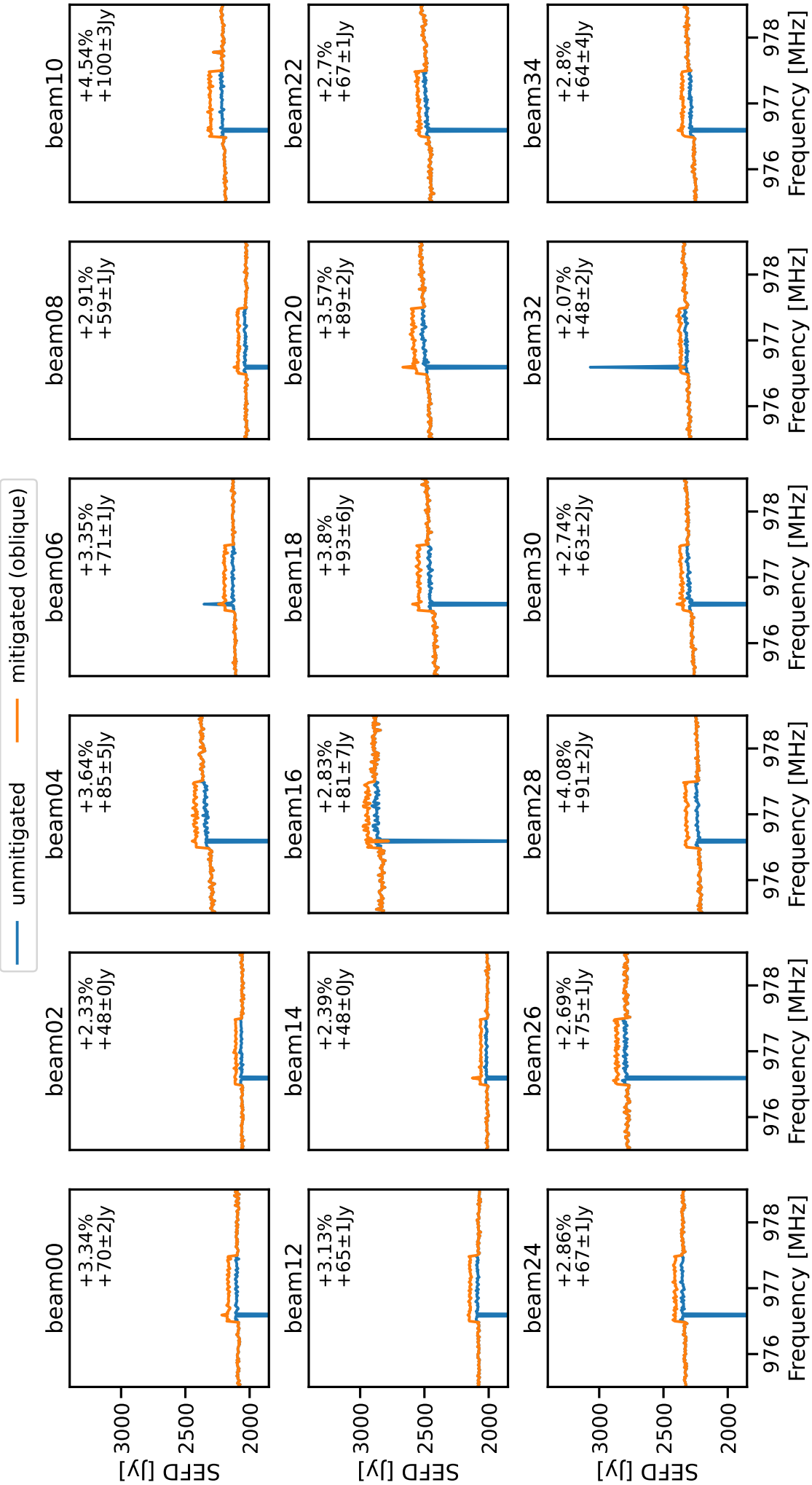


FIGURE 4.11. SEFD measurement per beam, annotations showing the percentage increase and the increase in Janskys in the mitigated channel in orange introduced by the mitigation. The unmitigated SEFD in blue. Each panel is averaged over all antennas.

Figure 4.10 shows the SEFD measurement with mitigation (orange) versus without mitigation (blue) averaged across all beams and antenna. The inset shows that similar to Figure 4.8, the subspace projection introduces a measured 3.1 % decrease in sensitivity in the mitigated channel. This increase in the system temperature is larger than what was seen in the fine filter bank test on Virgo in the previous experiment, and at the lower end of the 3 % to 5 % calculated value using the y-factor. Figure 4.11 separates out the individual beams (averaged over antennas) in the same SEFD measurement. Each panel shows the corresponding pair of mitigated (orange) and unmitigated beams (blue) showing three adjacent 1 MHz channels. In each channel containing the interferer, the offset in the mitigated channel is annotated. Offsets range from $48 \pm 0.8 \text{ Jy}$ to $100 \pm 3 \text{ Jy}$, much less than the $\approx 800 \text{ Jy}$ difference between beams. Compared to the calculated value using the correlation of the spatial signature vector and weights, the SEFD values are higher than the mean calculated value of 1 %, but all lower than the maximum calculated value of 6 %.

Measured change in beamshape

Holography was used to determine changes to the beam shape and gain using the same footprint. Figure 4.12 shows two beams located in position 0 of the footprint at 977 MHz with (bottom) and without mitigation (top). Holography measurements are performed using a raster grid while observing a calibration source. In comparison to a reference boresight beam, the sensitivity pattern of all beams in the footprint is sampled [11, 168].

The top panel of Figure 4.12 shows the effect of RFI on holography. The gross impact of RFI on beamformer weights is already corrected using frequency interpolation [8]. The degradation in the holography measurement is likely because the correlations are dominated by the correlating RFI instead of the weaker astronomical source we are doing holography on. Not only is there an order of magnitude difference in the peak values between the two panels of Figure 4.12, but there is also no discernible beam in the top panel. Furthermore, this is not the case in the adjacent 1 MHz channels free from RFI. Comparison with archived

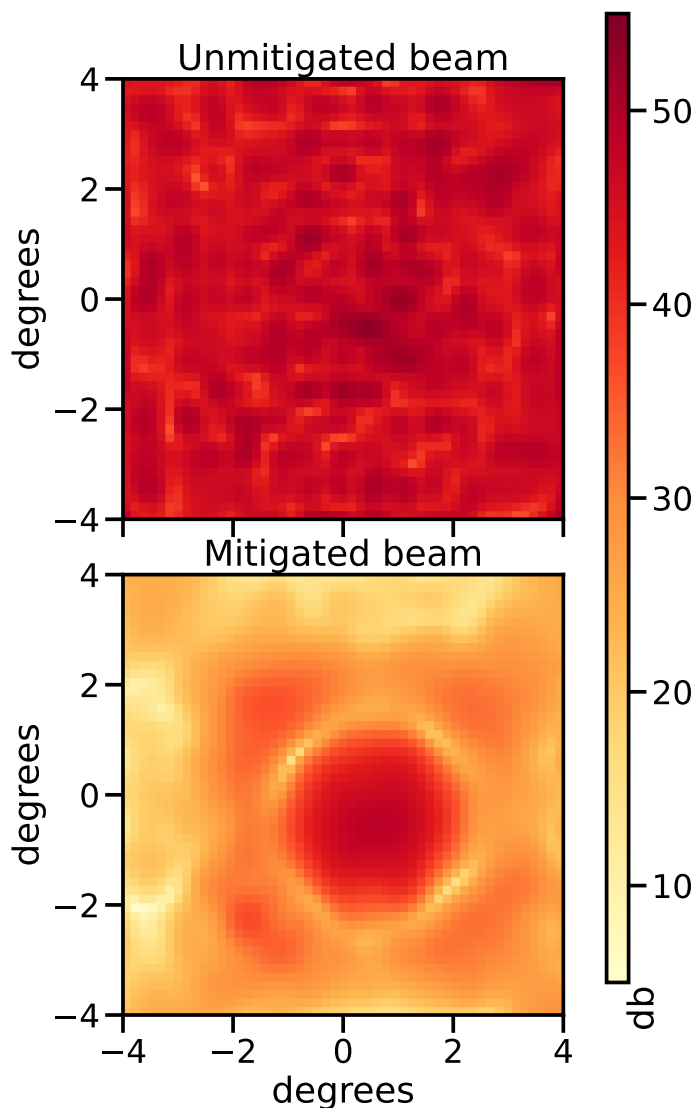


FIGURE 4.12. Holography measurement at 977 MHz with mitigation (bottom) and without mitigation (top). Beams at this frequency are routinely corrupted by RFI but can be completely recovered using the oblique projection.

holography measurements at 977 MHz shows that beam maps at this frequency are regularly corrupted.

The mitigated copy of the beam is shown in the bottom panel of Figure 4.12. The mitigated beam pattern in Figure 4.12 clearly shows the high-gain main lobe terminating in a surrounding null. We can also identify the side lobes surrounding the first null.

To quantitatively measure differences in the mitigated beam pattern, we interpolate between the adjacent channels' sensitivity patterns to establish a reference beam to which to compare, assuming the channel-to-channel variations are smooth. We then fit a Gaussian to the reference 'beam' to find the half power point, sample the reference beam and integrate around the half-power contour. We do the same for the mitigated beam and calculate the percentage difference between them at half power.

Figure 4.13 shows differences between the reference and mitigated beams across the footprint. The heatmaps in Figure 4.13 shows that there is no change (white) to the shape or gain in the main lobe. The heatmaps shows the difference between the reference and mitigated beams in dB. The half power point is marked by the red dashed circle. Green indicates suppression of the RFI in the beam pattern by oblique projection. Purple, an increase in gain, is the compensation as a result of the mitigation of introducing the (green) suppression. The purple also represents the underlying reason for the increase in the system temperature.

The subplots in Figure 4.13 (the top and right panels of each individual heatmap) show a slice across the main heatmap through the maximum of the beam identified by horizontal and vertical dashed grey lines, respectively similar to (and with the same colours as) Figure 4.4. The top and side panels show the reference beam in blue and the mitigated beam overlay in orange through that slice. The solid curves show the normalized linear gain. The dashed curves show the beamformed response in dB.

Two points worth noting; first, in Figure 4.13, had the interferer been external to ASKAP's receivers, the suppressed direction of the interferer (Green) would have been 'better defined'. Second, Figures 4.12 and 4.13 have been interpolated to a higher resolution from the original holography measurements.

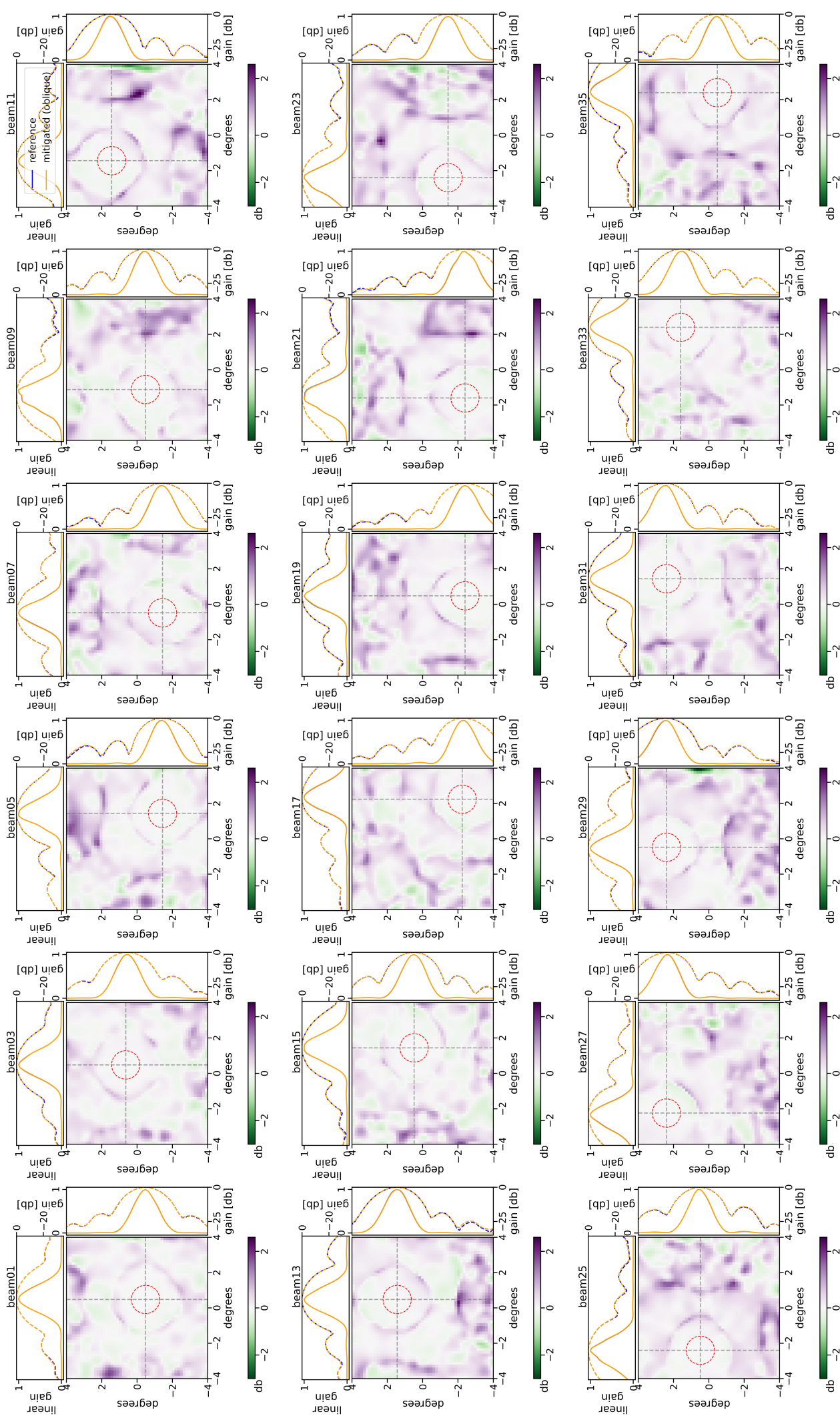


FIGURE 4.13. Comparison between the reference and mitigated beams by oblique projection across the modified close-pack square 6×6 footprint. Each beam has a central heatmap showing the difference between reference and mitigated beams in dB. The red dashed circle marks the half power point, white shows no change to the beam. Purple is an increase in gain, resulting from changes to the weights by introducing the green null (decrease in gain). All differences are within -3 dB to 2.5 dB and primarily limited to the outer lobes as predicted by the modelling. The top and side panels of each heatmap show a slice through the main beam at the grey dashed lines of each heatmap. These subplots show the reference beam (blue) and mitigated beam (overlaid in orange) with the normalized linear gain using solid curves and gain in dB using dashed curves.

On average the mitigated beam differs from the main beam about the half power point by only 0.02 %, with a range of just over 1.5 % and standard deviation of 0.4 %. Figure 4.13 shows that all differences are within -3 dB to 2.5 dB of the reference beam and, in line with our modelling, changes to the beam shape are limited to the outer sidelobes.

4.5 Future Work

We are in the process of making this operational on ASKAP. We have also found a second self-generated RFI signal in ASKAP data at 960 MHz that is persistently flagged in continuum observations [145]. This is due to the ADC read-out clock at 320 MHz being aliased by the 1280 MHz sample clock when observing with the 1200 MHz bandpass filter. We can mitigate this second signal using the exact method presented above.

We would like to provide users with information on which RFI may be successfully mitigated without exceeding specific limits on performance degradation. During observations, these impact estimates may be provided to observers and observing systems [169] to inform whether activating the mitigation will benefit science goals. The calculations from the correlation of the beam weight steering vector and the RFI spatial signature seem sufficient to predict changes to the RFI-affected channel and can therefore be recommended to guide users.

Furthermore, calculations of the expected noise power from the correlation of an estimated RFI spatial signature using the full ACM with maxSNR weights using all ports, as opposed to only 60, show potential for improved mitigation on ASKAP.

This method, applying projected beamformer weights at the beginning of observation and leaving them fixed, would also work for a phased array pointing directly at the sky, which doesn't track the source where the interferer is nearby and ground-based. In this case, there is also no relative motion between the array elements and the interferer(s). However, additional

techniques to determine the RFI subspace would be required, especially at low frequencies [170].

In order to mitigate moving interferers relative to the ASKAP — and in the future, the Murriyang (Parkes) cryogenic [14] — PAFs, we are currently developing strategies to identify RFI affected channels and determine their suitability for mitigation based on their eigenvalues (power), eigenvectors (spatial signature), and estimate performance impacts via orthogonality of the RFI eigenvectors and the maxSNR beamformer weights (Lourenço & Chippendale in prep).

4.6 Conclusion

In the growing presence of RFI, sensitive synthesis array instruments will need to rely on methods other than flagging for RFI mitigation. Mitigating self-generated interference by estimating the spatial signature of the interferer once at the beginning of the observation is a practical initial use case of ASKAP's RFI mitigation capabilities via PAF beamforming before implementing the dynamic case — adjusting beamformer weights continuously throughout the observation — required to mitigate RFI from moving sources, e.g. signals from satellites and aircraft (or static sources with a tracking telescope).

This paper presents the effects on gain, beampattern and sensitivity of RFI mitigation using subspace-projection-based spatial nulling algorithms on a self-generated stationary clock signal. Our modelling and measurements show that the impact on the main beam shape and sensitivity is small. Measured results on sensitivity and beam impacts agree with theoretical calculations via ρ (correlation between RFI subspace and beamformer weights) as well as simulations using a geometric optics model of the RFI. We have also shown a technique for estimating weak narrowband interference subspaces by taking the difference of the mean adjacent channels and the RFI-impacted channel ACMs. Suppression of the unwanted signal by over 31 dB, to our measurement noise floor, was achieved with a 1.5 % measured average

increase to the system-temperature-over-efficiency using a single antenna and a 3.1 % increase in the SEFD across the array. We modelled and measured no significant change to the gain in the main beam, ± 0.4 % on average, about the half power point. Variations to the beam pattern were limited to the outer lobes.

Acknowledgments

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RFI subspace estimation & the performance of oblique projection on dynamic RFI.

Dr Chippendale had the idea to interpolate across frequency to get a clean, noise eigenvalue surface and take the ratio between an arbitrary eigenvalue surface and the clean noise eigenvalue surface to get the RFI subspace. Dr Chippendale also pointed us in the direction of Behrens [163] as a metric to predict the noise increase due to oblique projection. All other work in this chapter is mine.

The previous chapter described the mitigation and implementation of oblique projection of stationary interferers with a 1-D RFI subspace. This chapter begins to extend oblique projection to the rest of the interferers identified in Chapter 3 that have relative motion with respect to the PAF resulting in a wider, time variable, n -D RFI subspace, making it more challenging to mitigate. The results in this chapter are a proof-of-concept, specifically concerning RFI subspace estimation and forward predicting the performance of the projection using ASKAP array covariance matrices.

5.1 Introduction and background

As we have seen throughout this thesis, RFI undermines the ability of radio telescopes, like ASKAP, to operate optimally. ASKAP's PAFs comprise of 188 elements, allowing multiple independent and flexible beams to be formed. Beamforming is a weighted sum of the PAF elements, resulting in a pattern of 36 high-gain beams 'on' the sky and a large field-of-view (FoV) [38]. The majority of ASKAP's 700 MHz to 1800 MHz operating bandwidth is shared with other radio services [16, 148]. The radio astronomy service (RAS) has protected bands corresponding to important spectral lines, however observations outside of these bands are routine. The most sensitive radio telescopes are therefore located in radio-quiet zones like the ARQZWA [45, 46], which surrounds ASKAP and the observatory, to limit the amount of RFI from ground-based transmitters. However, additional mitigation techniques are still required throughout the telescope signal chain [52], including spatial nulling at the beamformer [7]. Techniques that null the RFI but retain the uncorrupted time-frequency data relating to the source-of-interest are more desirable than flagging, which can decrease instrument sensitivity. Flagging also has potentially undesirable effects on the instrument response and does not retain any information about the sources-of-interest.

PAFs provide spatial information about the direction of the sources-of-interest and RFI in the instruments' FoV [5]. Based on this information, spatial nulling/filtering introduces deep nulls in the instruments' beampattern in the direction of the RFI [1]. Specifically, the oblique projector mitigates the RFI subspace whilst minimising distortion to the beam shape [6]. This was demonstrated in two instances:

- Using a modified ASKAP PAF on Murriyang, the 64 m CSIRO Parkes Radio Telescope [142];
- Then using the Boolardy Engineering Test Array (BETA) [13] — a test array made up of the first six ASKAP antennas — to mitigate an unwanted, strong GPS L2 signal.

Most recently, using the full ASKAP array, oblique projection has been used to mitigate a self-generated interferer [160], with a 1-D RFI subspace —shown in Chapter 4.

The RFI subspace is an estimate of the set of spatial signature vectors (SSVs) relating to the direction of the RFI. The degree to which a viable RFI subspace can be estimated limits the effectiveness of the mitigation. The RFI SSVs are typically estimated using an Eigenvalue Decomposition (EVD) of the array covariance matrix (ACM)— the pairwise correlation of all ports. Methods for subspace estimation using auxiliary antennas [4, 110] or cached ACMs [10, 141] are not currently possible using typical ASKAP operating modes.

A challenge in realising active projection-based RFI mitigation comes from the relative motion between the interferer and the PAF during an integration cycle. In the previous chapter, with no relative motion, the RFI SSV only needs to be estimated once at the beginning of an observation. A projection matrix is then calculated, and beamformer weights are updated and applied [160]. In the case of RFI with relative motion to the PAF, the RFI subspace is wider and constantly changing. The changing direction results in more RFI-affected ports and beamformer weights that need to be updated and applied continuously throughout the observation. If the update rate is too slow, by the time the mitigation is applied with a null in the beam in the direction of the interferer, the interferer has moved and is no longer in the null Figure 2.4. Subspace smearing [109, 140] describes the increase in the RFI subspace due to motion during an integration time of the ACM. The faster the relative motion, the closer to real-time the SSVs must be estimated and the mitigation applied. The experiment performed by Hellbourg and Bannister, who used BETA to mitigate an unwanted GPS signal, placed this update rate at at least 8 s [13]. Oblique projection is best suited to RFI entering the PAF through the sidelobes. In other words, RFI with a direction orthogonal to the main beam will have RFI SSVs with low correlation with the maxSNR beamformer weights, fewer overlapping highly weighted ports, and can be mitigated with only a modest decrease in sensitivity [6, 160].

This chapter begins to extend the work done in Chapter 4 to multiple moving interferers, given ASKAP's above-mentioned constraints, asking the question: What subset of interferers affecting ASKAP can active RFI mitigation, using the oblique projector, be realised? Specifically, this chapter takes a step towards robustly estimating an increasingly accurate RFI subspace of RFI-affected channels. Furthermore, we investigate what forward predictions or estimates can be made regarding the performance of the mitigation and its impact on beam sensitivity. This is required to implement oblique projection operationally in ASKAP's codebase.

5.1.1 Extending the signal model to multiple moving interferers

The sampled output of the PAF, with K interferers, is an L -dimensional ($L = 188$) vector,

$$\mathbf{x}[n] = \mathbf{a}_{\text{SOI}} x_{\text{SOI}}[n] + \sum_{k=1}^K \mathbf{a}_{\text{RFI}_k} x_{\text{RFI}_k}[n] + \mathbf{n}[n] \quad (5.1)$$

where $\mathbf{a}_{\text{SOI}}$ and $\mathbf{a}_{\text{RFI}_k}$ are the spatial signature vector (SSV) of the source-of-interest and k^{th} RFI. Similarly, $x_{\text{SOI}}[n]$ and $x_{\text{RFI}_k}[n]$ are the scalar amplitude time samples of the astronomical source-of-interest and k^{th} RFI respectively. $\mathbf{n}[n]$, is the additive noise vector (thermal, sky, spillover, and receiver).

Given the stochastic nature of the source-of-interest and $\mathbf{n}[n]$, an approximate ACM is computed by ASKAP beamformers for each 1 MHz channel,

$$\mathbf{R} = \frac{1}{L} \sum_{n=0}^{L-1} \mathbf{x}[n] \mathbf{x}^H[n] = \langle \mathbf{x}[n] \cdot \mathbf{x}[n]^H \rangle_T = \mathbf{R}_{\text{SOI}} + \sum_{k=1}^K \mathbf{R}_{\text{RFI}_k} + \mathbf{R}_n \quad (5.2)$$

where $(\cdot)^H$ is the Hermitian (complex conjugate) transpose, $\langle \cdot \rangle_T$ the time averaging operator and T the integration time ($T = 10$ s). This process is done independently by each of ASKAP's 36 antenna. Hellbourg [109] shows how the time dependence of $\mathbf{a}_{\text{RFI}_k}$ results in subspace smearing within the ACM. This results in errors in the estimates of $\mathbf{a}_{\text{RFI}_k}$ and a larger than necessary RFI subspace to be projected out and (likely) further degrades sensitivity and

introduces more beam distortion than would be the case if we projected out the minimum necessary subspace that could be identified if there were no subspace smearing.

By way of the $\mathbf{w}_{\max\text{SNR}}$ measured using the Sun and computed using ACMs $\mathbf{R}_{\text{off}}$ and the dominant eigenvalue of $\mathbf{R}_{\text{on}} - \mathbf{R}_{\text{off}}$ [38, 102, 135], the beamformed output of a single beam is given by

$$\mathbf{y}[n] = \mathbf{w}_{\max\text{SNR}}^H \mathbf{x}[n]$$

and repeated for each of ASKAP's 36 beams, resulting in a set of high-gain beams arranged on the sky in a pattern called a footprint. By replacing $\mathbf{w}_{\max\text{SNR}}$ with a set of 'mitigated' weights in the above equation $\mathbf{w}_{\text{obliq}}$ the unwanted effects of the RFI can be avoided.

As we have already seen, oblique projection is a two-step process involving first projecting $\mathbf{w}_{\max\text{SNR}}$ onto a subspace orthogonal to the interference subspace [39, 79], but then retaining the gain in the direction of $\mathbf{w}_{\max\text{SNR}}$ [6, 107]. The unwanted signals to be mitigated, $\sum_{k=1}^K \mathbf{R}_{\text{RFI}_k}$, are typically estimated from the ACM using an eigenvalue (or singular value¹) decomposition,

$$\mathbf{R} = \mathbf{U}\mathbf{\Lambda}\mathbf{U}^H$$

where $\mathbf{\Lambda} = \text{diag}(\lambda_1, \dots, \lambda_L)$ are the sorted (descending) eigenvalues and $\mathbf{U}$, their corresponding eigenvectors. $\mathbf{\Lambda} = \text{diag}(\boldsymbol{\lambda})$ is a function that returns a diagonal matrix when a column vector is given and returns the vector when a diagonal matrix is passed $\boldsymbol{\lambda} = \text{diag}(\mathbf{\Lambda})$. $\mathbf{U}$ may be partitioned into two orthonormal bases (subsets or columns) $\mathbf{U}_{\text{RFI}}$ and $\mathbf{U}_{\text{SOI+n}}$ defining the RFI and source-of-interest plus noise subspaces, assuming the noise is independent and equally distributed across all ports:

$$\mathbf{U} = [\mathbf{U}_{\text{RFI}} | \mathbf{U}_{\text{SOI+n}}]. \quad (5.3)$$

$\mathbf{U}_{\text{RFI}}$ is therefore an estimate of the minimal set of component vectors necessary to describe SSVs ($\sum_{k=1}^K \mathbf{a}_{\text{RFI}_k}$), either due to different interferers ($\mathbf{K}$) impinging on the PAF (and in turn the ACM) or due to subspace smearing, to be mitigated. Practically, as we will see in the

¹Note, in the case of an Hermitian matrix like the ACM ($\mathbf{R}$), the square root of the eigenvalues (power) are the singular values (voltage), i.e either an EVD or SVD respectively can be used to estimate the set of $\mathbf{a}_{\text{RFI}_k}$, the input to the mitigation algorithm.

next section, it is more specifically an estimate of the subset of orthogonal SSVs with power greater than the noise. The determination of $\mathbf{U}_{\text{RFI}}$, is a key constraint in making active RFI mitigation realisable using ASKAP as it is the input to the oblique projection beamformer

$$\mathbf{P}_{\text{obliq}} = \mathbf{w}_{\text{maxSNR}} (\mathbf{w}_{\text{maxSNR}}^H \mathbf{P}_{\text{ortho}} \mathbf{w}_{\text{maxSNR}})^{-1} \mathbf{w}_{\text{maxSNR}}^H \mathbf{P}_{\text{ortho}}.$$

and is estimated per frequency, with each subsequent ACM—in the presence of dynamic (having relative motion with respect to the PAF) RFI.

One of the two primary concerns of this chapter is, therefore, robustly determining the number of ‘significant’ eigenvalues (those associated with the RFI), which in turn correspond to $\mathbf{U}_{\text{RFI}}$, the eigenbasis (an estimate of the RFI SSVs) to be mitigated. Recall that the degree to which an accurate estimate of the RFI subspace can be estimated limits the effectiveness of the mitigation. The significant eigenvalues are the estimated RFI SSVs. Without a good estimate, any forward predictions or projections are pointless.

5.1.2 Estimating the RFI subspace & performance of oblique projection

The RFI SSVs are not known apriori, and must therefore be estimated. Subspace estimation utilises statistical properties of the RFI to isolate an estimate of the interferers’ SSVs from the eigenvalue spectrum of the ACM. Figure 5.1 is an example eigenvalue spectra obtained from an ASKAP ACM, used to illustrate Equation 5.3, in which the spectra must be seperated into an RFI subspace and source-of-interest plus noise subspace (demonstrated by the dashed vertical line). In other words the subspace to mitigate and suppress (orthogonal projection) and the measurement to project onto a subspace oblique to the RFI (oblique projection). The gain in the direction of a set of maxSNR beamformer weights will therefore be retained and the underlying astronomical data recovered².

The eigenvalues (λ) of the EVD (blue curve) are related to the beamformed power in the corresponding eigenvector’s direction and the ports on which the RFI was incident on the PAF.

²This does not work if the RFI enters through the main beam.

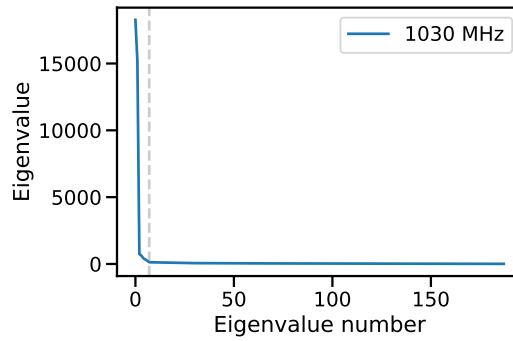


FIGURE 5.1. Eigenvalue spectra from the ACM. The dashed vertical line illustrates Equation 5.3; an estimate of where the RFI subspace ends and the source-of-interest plus noise subspace begins. The corresponding eigenvectors to the left of the dashed line are the input to the orthogonal projection.

Where to reliably position the dashed vertical line in Figure 5.1 is the crux of this chapter. We will assume a convention of having the eigenmodes sorted from strongest to weakest. An RFI-affected ACM with power above the noise will, therefore, have eigenmodes to the left of the vertical dashed curve. The challenge is empirically determining where to place the dashed grey vertical curve separating our estimated RFI subspace and source-of-interest plus noise subspace. Then, doing this for all RFI-affected frequencies, while the RFI is changing direction in time, for all antennas and across all beams fast enough to update the weights, such that the interferers are still in the null. Finding the significant values from an eigenvalue spectrum (sometimes called a scree plot) is an open but extensively researched problem in various disciplines. The problem, essentially, is one of outlier detection or finding the ‘elbow’ of the curve in Figure 5.1.

Listed below are several techniques for identifying the significant eigenvalues:

- principal component analysis (PCA) [171, 172], is primarily used for dimension reduction by transforming data into orthogonal axes based on the directions of maximum variances. This is the ‘standard’ method for finding the most significant eigenvectors from a covariance (or correlation) matrix.

- Akaike information criterion (AIC) [173, 174] and minimum description length (MDL) [174, 175], are used in statistical modelling, information theory, and machine learning for model selection and hypothesis testing.
- Median absolute deviation (MAD) is a measure of the dispersion of the dataset, but more robust to outliers than the standard deviation. It is therefore often used to ‘detect’ strong RFI in radio astronomy, where the power of the interfering signal is frequently orders of magnitude above the noise.
- Two heuristic techniques, specifically from the domain of RFI subspace estimation in radio astronomy [9] are also considered:

A $\log_{10}(\lambda)$, and fit a 3rd-order polynomial between the 10th and 83rd eigenvalues value. The RFI subspace length is given by the number of eigenvalues that exceed 10 % the fit; Bannister and Hellbourg, method A (BHA). Note that we use the 20th and 83rd eigenvalues value to accommodate for the longer RFI subspace in this example.

B the ratio of each $\log_{10}(\lambda)$ value with the previous $\log_{10}(\lambda)$ value; Bannister and Hellbourg, method B (BHB). Note that we use the index where the ratio is maximised instead of the number of ratios greater than 0.1.

How each of the above methods works in practice for identifying the RFI subspace (eigenmodes) associated with a 1 MHz RFI-affected channel are shown below in Figures 5.2–5.5.

PCA, Figure 5.2, calculates the variance contributed by each eigenmode illustrated by the blue bar plot. Note that only the first 40 eigenvalues are plotted because, as shown by the orange curve, the cumulative variance of the first 16 eigenmodes describes almost all of the variance. PCA can therefore be used to identify significant eigenvalues based on some threshold — eigenvalues to the left of the grey dashed line — in this case, eigenmodes contributing in excess of the mean-variance.

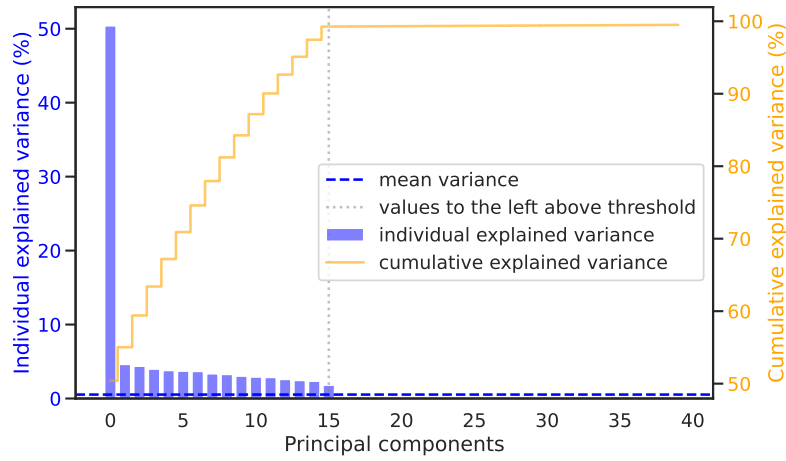


FIGURE 5.2. PCA uses the variance of the eigenmodes to isolate the RFI subspace.

AIC and MDL, Figure 5.3, are functions that can be used to identify significant eigenvalues. The RFI subspace is estimated by selecting eigenmodes up to and including the minimum

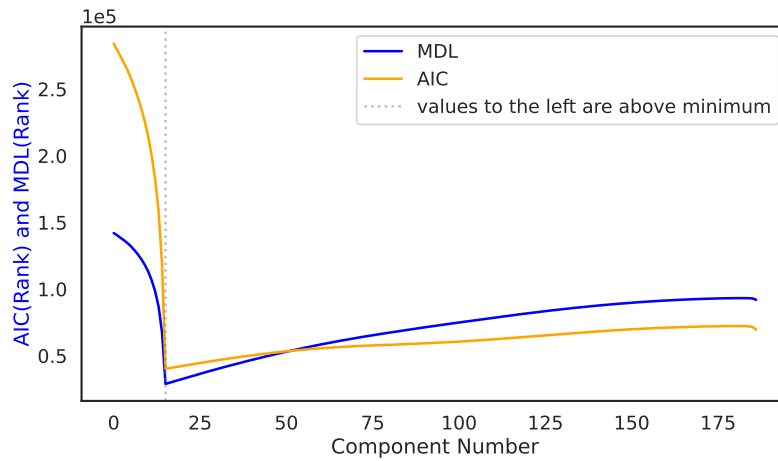


FIGURE 5.3. The index at which AIC and MDL are minimised identifies the RFI subspace length.

AIC and MDL ranks. We use the `pyspectrum` implementation of AIC and MDL ³ [176].

MAD is shown in Figure 5.4, the threshold to identify significant eigenvalues (left of the grey dotted vertical curve) is given by values that exceed the dotted horizontal line, three

³<https://pyspectrum.readthedocs.io/en/latest/index.html>

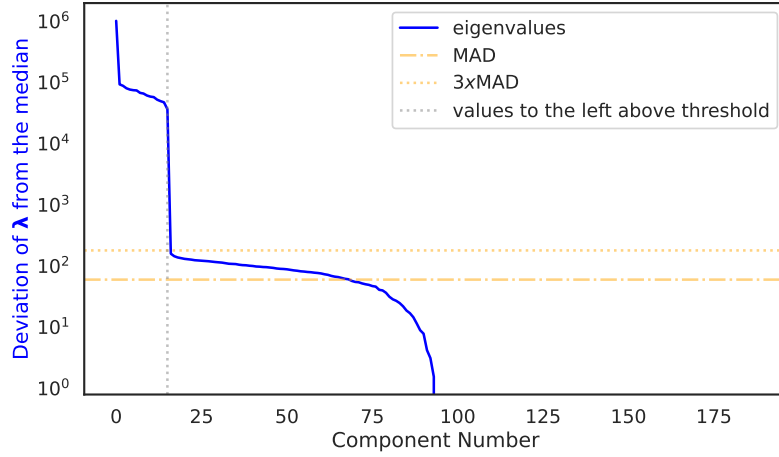


FIGURE 5.4. Using the MAD is one of the standard methods for identifying RFI-affected channels in radio astronomy.

times the MAD. The blue curve shows the deviation of λ from the median (the orange dashed curve).

Finally, the blue curves in Figure 5.5 show $\log_{10}(\lambda)$. The first method used by Bannister and Hellbourg [9] (left) establishes a threshold using a 3^{rd} order polynomial (solid orange curve) between the dashed and dotted vertical plots⁴. The elbow in the eigenvalue spectrum is identified by the first set of values that exceed the fit by 10 %.

The second method (right) considers the slope of the blue curve to determine the ‘cut off’ threshold for identifying the elbow and significant eigenvalues relating to the strong RFI.

All the above methods consider only each 1 MHz channel, however, there is useful information about the subspace length in the adjacent channels. In Section 5.3, we use MAD to identify 1 MHz channels affected by strong RFI, and extend it to include information about the adjacent frequency channels in determining the RFI subspace, shown in the next subsection. RFI-affected channels with the following properties should yield better SSV estimates and, ultimately, the best-performing spatial filter:

⁴The idea is to fit the polynomial to the smooth, noise dominated part of the eigenspectrum to help identify the sharp deviation from the smoothness at the elbow. In other words, the position of the elbow must broadly be known before using this method to fine-tuning the estimate.

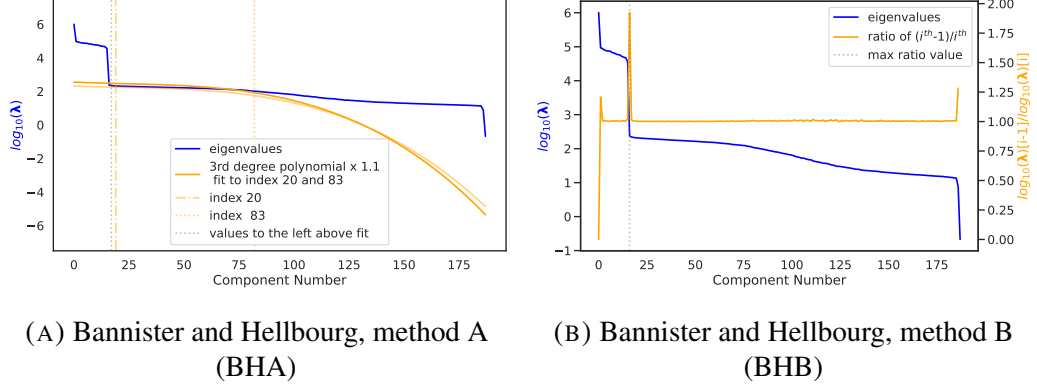


FIGURE 5.5. Heuristic techniques for determining the RFI subspace from an experiment [9] in which an unwanted, strong GPS L2 signal was successfully mitigated.

- (1) Few interferers per channel (small K),
- (2) High power so that the RFI subspace dominates the source-of-interest and noise terms in Equation 5.2,
- (3) Time-invariant,
- (4) Slow relative motion to minimize subspace smearing,
- (5) Orthogonality to beamformer weights (i.e. entering through the sidelobes as opposed to the primary beam).

We expect, therefore, that interferers with the above properties will ultimately be the most suitable candidates for mitigation.

Note that larger values for properties (1) and (4) above would increase the ‘length’ of the RFI subspace. A larger subspace, to first order, is analogous to more RFI-affected ports whose weightings need to be adjusted (disabled in the direction of the SSV) and, therefore, a higher chance of overlap with ports that are highly weighted for maxSNR beamforming in a desired direction. If the mitigated subspace is large and there is some low-level correlation between the beamformer weights, the performance will degrade incrementally with larger subspaces. The more correlated the RFI subspace with the signal subspace, the worse the degradation of the expected sensitivity may be after projection.

The other objective of this chapter is, assuming a viable RFI subspace estimate, forward predicting the degradation in performance as a result of using projected weights compared to the maxSNR weights. We first consider the orthogonality of each estimated SSV with the maxSNR beamformer weights. That is, as in the previous chapter (Equation 4.12), the correlation of each individual eigenvalue ($\mathbf{u}_{\text{RFI}}$) in the RFI subspace with the steering vector,

$$\rho = \frac{|\mathbf{w}^H \mathbf{u}_{\text{RFI}}|}{\|\mathbf{w}\| \|\mathbf{u}_{\text{RFI}}\|}$$

is used to estimate the downstream effects of oblique projection⁵ as a result of the increased the noise power: Equation 4.13 [6],

$$P_{\text{noise}} = \sigma_n^2 (1 - |\rho|^2)^{-1},$$

where σ_n^2 is the true noise power. Doing so for all eigenvectors in the RFI subspace with each set of weights that define the footprint we can see that calculating each ρ individually does not scale, given that:

- RFI is frequency dependent;
- Each of ASKAP's 36 antennas compute and store averaged ACMs from which $\mathbf{U}_{\text{RFI}}$ needs to be calculated;
- ASKAP footprints can contain up to 36 dual-polarised beams, and;
- we are now interested in RFI subspace with lengths greater than 1-D.

This is particularly true because, ideally, the goal would be to have the projection automated based on some single threshold. For example, different survey science projects (science use cases/goals) may have different tolerances for the degradation in sensitivity they are willing to accept if it means they can recover RFI-affected channels. This threshold approach would require a single value to represent the expected degradation in sensitivity.

We should therefore consider as in Chapter 4, the Y -Factor with and without mitigated weights, which yields a measurement of the total degradation as a result of the projection.

⁵This will be largely due to the dominant eigenvalue.

This is only possible because in this chapter, we use a population of beamforming ACMs including an ACM measurement of a known astronomical source (the Sun) and then an ACM measurement of the nearby empty sky (noise), on- and off- respectively. The Y -Factor again is defined as [164] (Equation 4.15):

$$Y = \frac{\mathbf{w}^H \mathbf{R}_{on-src} \mathbf{w}}{\mathbf{w}^H \mathbf{R}_{off-src} \mathbf{w}}.$$

By interchanging $\mathbf{w}_{\max\text{SNR}}$ and $\mathbf{w}_{\text{obliq}}$ for $\mathbf{w}$ in the above equation, the performance of the oblique projection can be evaluated. As also described in the previous chapter the sensitivity is related to the beam equivalent system-temperature-on-efficiency [142, 165, 166] (Equation 4.16),

$$\frac{T_{\text{sys}}}{\eta} = \frac{A S}{2k_B(Y - 1)}$$

where A is the area of the dish, S is the known flux of the source, and k_B is Boltzmann's constant.

Finally, we consider the following estimate of increase in noise power after projection between two n -D subspaces, initially presented in §6 of Behrens [163] given by⁶,

$$g_{\text{avg}} = \frac{1}{n} \sum_{i=1}^k \sigma_i^2 \quad (5.4)$$

where, g_{avg} is the the average increase in noise power gain, σ^2 are the squared singular values of the projection matrix, $\mathbf{P}_{\text{obliq}}$ for which the (up to) K interferers have been estimated as k non-zero singular values, k is therefore the length of the RFI subspace, $\mathbf{U}_{\text{RFI}}$.

In summary, this chapter aims to identify RFI-affected channels for which a viable RFI subspace can be estimated and then evaluating the performance of the mitigation using:

- the correlation coefficient,
- the Y -Factor, and;
- the singular values of the projection matrix.

⁶Behrens uses the terms structured and unstructured noise to describe what we are referring to as the RFI and noise respectively.

given a small population of ASKAP ACMs. This is the first time that ACMs have been looked at in this way with respect to spatial nulling using oblique projection.

5.2 Data: ASKAP beamforming ACMs

ACMs from ASKAP science observations are not archived due to data storage constraints, however beamforming ACMs are temporarily stored. These `ACMFiles`⁷ are shorter (≈ 10 min) observations, first off-source, then for each beam in turn, on-source, $\mathbf{R}_{\text{off}}$ and $\mathbf{R}_{\text{on}}$ respectively as described in Section 2.3.4. Each scheduling block contains separate `ACMFiles` for each beam and antenna. ASKAP’s ACMs are calculated for each 1 MHz channel over 336 channels and there is a single ACM for each 2 s integration.

TABLE 5.1. Distribution of ACM data per frequency band

Frequency band (MHz)	# SBs	# off-source ACMs	# ‘clean’ ACMs
low	12	467	301
mid ⁸	7	214	72
high	11	391	44

Data used for the results presented in this paper are selected from a pool of 30 scheduling blocks (observations) of beamforming ACMs between November 2020 and December 2023 and is distributed across ASKAP’s frequency bands as given in Table 5.1. The most representative sample of these ACMs to regular ASKAP continuum observations are the off-source ACMs measurements. These ACMs are the only ones considered in this chapter, except in Figure 5.10 where an on-source ACM is used to illustrate and introduce Figure 5.11.

Of the ACMs in Table 5.1, only one scheduling block had on-source ACMs for the full 36 dual polarisation beam footprint. Having all the on-source ACMs means that new weights can be created using a varying number of ports. Furthermore, there is a greater FoV with which to

⁷An `ACMFile` is an `.hdf5` containing all the ACMs from that observation.

⁸Mid-band `ACMFiles` contain ACMs across the full 288 channels in the band giving us a unique window into the RFI environment at those frequencies. Frequency channels at the bottom of this band are discarded before downstream processing [145].

sample the RFI. The software developed as part of this chapter and the results in Section 5.3 and 5.4 use this low-band scheduling block. The majority of the remaining scheduling blocks are beamforming boresight beams, of which some early results are presented in Section 5.5 which looks at how the software performs with other ACMs and in other frequency bands.

The last column in Table 5.1 refers to ‘clean’ ACMs, this is the number of ACMs in which the software did not identify any RFI-affected channels and as such were not considered for mitigation. However, we will see in Section 5.5 that there are still significant improvements that need to be made in identifying RFI-affected channels from ASKAP ACMs as the software continues to be developed. The first step, in realising active RFI mitigation using oblique projection is to robustly identifying RFI-affected channels and ACMs. We will consider a single example, in Section 5.3 and 5.4, of a low-band observation with RFI affecting only a single antenna to illustrate the method of identifying RFI-affected channels.

5.3 Identifying RFI-affected channels

Something that is not considered in the typical way of estimating the RFI subspace — using an EVD from an ACM of a single frequency channel — is the frequency dependence between frequency channels. In particular, the noise subspace has structure due to the instrument response. In some sense, what we propose is ‘flipping the problem on its head’ and attempting to find an estimate of the noise subspace from which the RFI subspace can then be determined. If we have a good model of the noise subspace we can more easily identify the RFI subspace.

Figure 5.6 shows the method we have used to identify RFI-affected channels from an ASKAP `ACMFile`. Each panel shows frequency on the y-axis in ascending order and the eigenmode in descending order along the x-axis. Eigenmodes with the most power have the brightest pixels. Panel A shows the median eigenvalue surface (spectrogram), that is, the median eigenvalue spectra for all frequencies calculated from ACMs at three time samples. Because the RFI is so much stronger than the noise, it is difficult to make out the structure

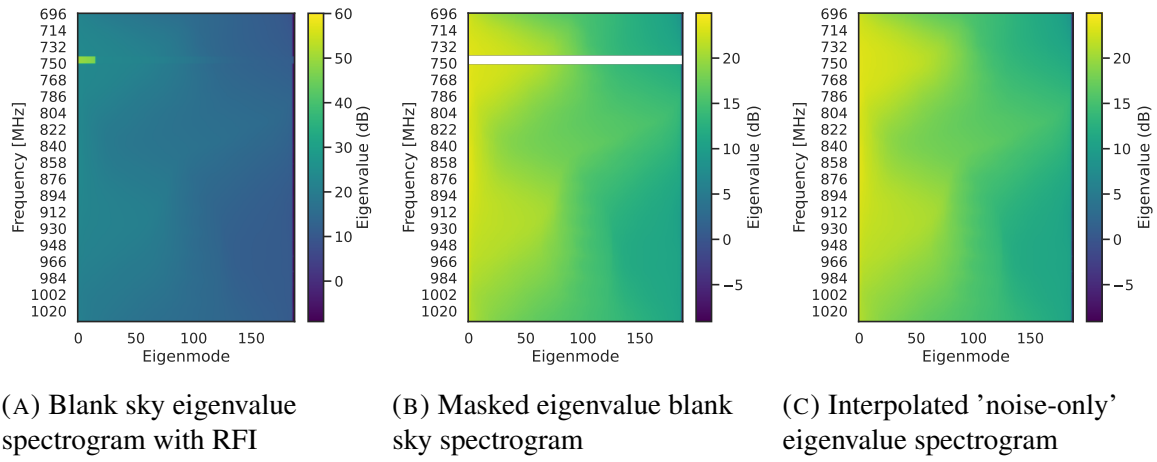


FIGURE 5.6. Method for identifying RFI-affected channels (and later the RFI subspace) which takes into account the frequency dependence of the instrument response. Panel A shows the median eigenvalue surface (spectrogram) calculated over three time samples. Panel B shows channels masked that have power $10 \times \text{MAD}$ above the median. Finally, panel C, shows the frequency interpolated eigenvalue surface.

of the eigenvalue surface in the non RFI-affected channels in Panel A. Panel B shows the channels with dominant eigenvalues $10 \times \text{MAD}$ above the median masked out. With the RFI masked out, Panel B shows more structure within the noise eigenvalue surface, resulting from the instrument response. Considering only the dominant eigenvalues for each frequency channel, Figure 5.7 illustrates the approach to identifying RFI-affected channels using MAD in Figure 5.6B.

The unwanted RFI signal affects eight contiguous 1 MHz channels from 744 MHz to 751 MHz corresponding to a FIXED/MOBILE primary allocation. It only affects antenna ‘ak31’, which is one of the outer antennas in the north-east of the array and one of the closest to a road to the east. Figure 5.7 shows the dominant eigenvalues in blue, a threshold of $10 \times \text{MAD}$ is identified by the dashed grey horizontal line. For an interferer so much stronger than the noise, as is the case here, $10 \times \text{MAD}$ poses no issues. For weaker (or further) interferers, such as satellites, this threshold may have to be lower. Eigenvalues that exceed the threshold are highlighted in red; the corresponding frequency indices to the red points are the channels

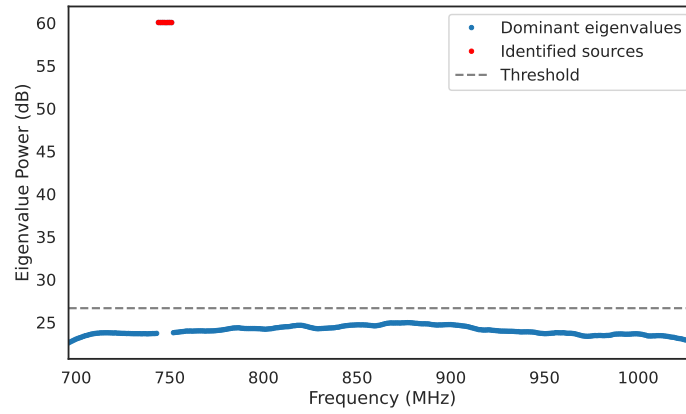


FIGURE 5.7. The Python library being developed as part of this chapter `acm-rfi-tools` (ART), in this example, uses a threshold of $10 \times \text{MAD}$ above the median to identify RFI-affected frequency channels, as an interim step to subspace estimation.

masked in Figure 5.6B. Ideally, we would like an estimate of the eigenvalues associated with the noise in those masked-out channels.

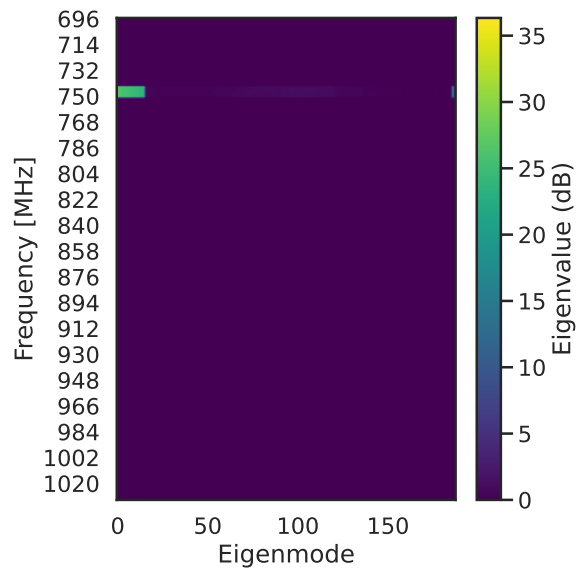


FIGURE 5.8. The ratio of an RFI-affected eigenvalue surface over a ‘clean’ noise-only reference eigenvalue surface yields the RFI subspace of the identified RFI-affected channels (in green.)

Figure 5.6C interpolates in frequency across the RFI-affected channels, yielding a ‘reference’ eigenvalue surface of the noise only. Figure 5.8 shows how by taking the ratio of an

RFI-affected eigenvalue surface (like in Figure 5.6 A) with a ‘clean’ reference eigenvalue surface (Figure 5.6 C) the RFI subspace is easily obtained.

Comparing the calculated RFI subspace, computed by the `Python` library under development as part of this chapter `acm-rfi-tools` (ART), to other methods for calculating the RFI subspace, Figure 5.9 shows we obtain a comparable result for the interferer affecting this antenna. Our method estimates the same RFI subspace length as $3 \times \text{MAD}$, suggesting we

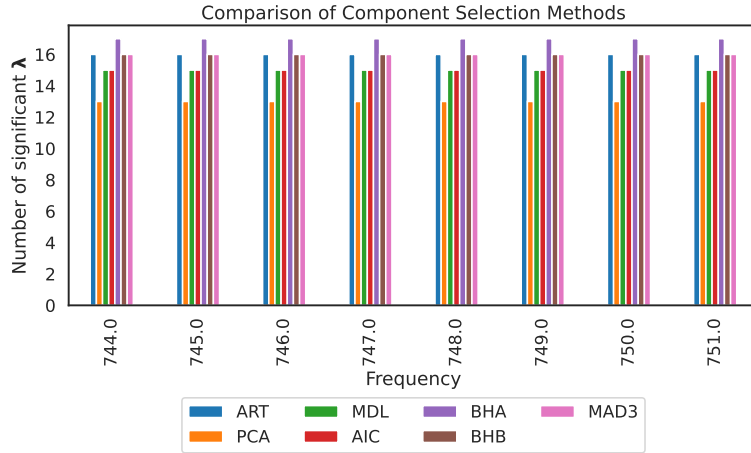


FIGURE 5.9. Comparison of different methods for estimating the RFI subspace length across eight RFI-affected 1 MHz channels, determined from their eigenvalue surface. The results from the developed `Python` library yield comparable results to other methods for subspace determination.

could make the threshold lower. It also estimates the same RFI length as BHB. The estimated RFI subspace length is 16 eigenmodes. One more than using MDL or AIC, three more than PCA, and one less than using BHB. Unlike these methods, however, we have also obtained an estimate of the noise eigenspectrum obscured by the strong RFI in the RFI-affected channels.

We will look at how varying the number of ports used affects the expected performance of the projection at the end of the next section. This is relevant for ASKAP, as the number of beams increases from 1 to 36 per polarisation, the number of PAF ports used to form each beam reduces from 188 to 60 [38]. The above estimation of the RFI subspace length was determined using the full 188 port ACM.

5.4 Predicting the performance of oblique projection

Continuing with the same example, and assuming the RFI subspace length is correct, we find that the various methods shown in Figure 5.9 are in rough agreement.

We will next assess the performance of the oblique projection. We consider the following methods:

- (1) The correlation coefficient,
- (2) the Y -Factor, and
- (3) the singular values of the projection.

The more orthogonal the RFI subspace is to the maxSNR weights, the better we may suppress the RFI without compromising beam pattern and sensitivity. This is the first time in the literature, to the authors' knowledge, that the RFI and its direction have been visualised in this way, at this scale, and using actual telescope data.

5.4.1 Forward predictions based on correlations of maxSNR weights and estimated RFI spatial signature vectors (SSVs)

According to the theory of Hellbourg et al. [6], the increase in the noise power due to oblique projection is "less trivial in a multidimensional RFI subspace scenario". In Chapter 3, we were able to accurately predict the degradation in sensitivity using Hellbourg's correlation for a 1-D RFI subspace. We need an equivalent metric for the n -D case. Ideally, in use on the telescope — and in the long run, using automation — we would like an estimate of the increase in system noise (due to the projection) as a single number (not separate correlations) per frequency, beam and antenna, which triggers the mitigation based on some pre-defined acceptable threshold.

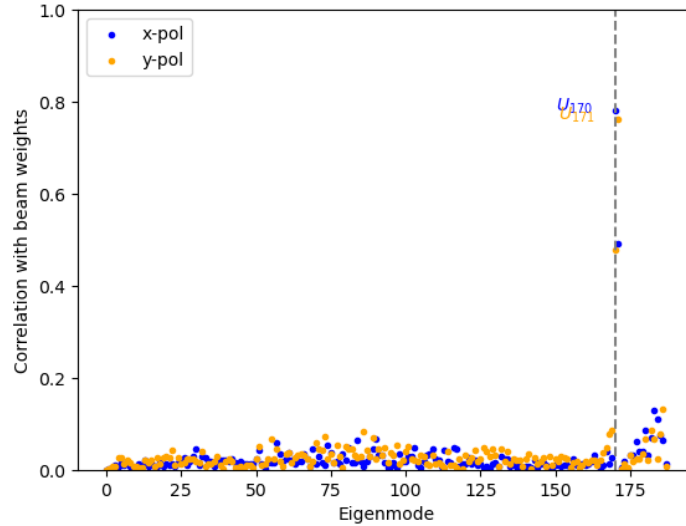


FIGURE 5.10. Correlation of on-source ACM eigenmodes and a set of max-SNR beamformer weights . Two eigenmodes are highly correlated with the beamformer weights, corresponding to the Sun, and 16 eigenmodes have more power than the Sun (to the right of the dashed vertical line) but are uncorrelated, corresponding to the identified RFI. The correlation of beamformer weights and RFI SSVs can be used to predict the degradation in sensitivity due to oblique projection [6].

Within the FoV of Figure 5.10 there are (at least) two sources, the Sun and a strong source of RFI. The correlations of a set of maxSNR weights with all the eigenvectors of an RFI-affected on-source ACM for a single frequency channel and a single dual polarised beam are shown in blue for the x-polarisation and orange for the y-polarisation. There are two eigenmodes that are more correlated with the weights, corresponding to the Sun, these are the beamforming ACMs that we are retrospectively comparing to the weights made from them, and so this is as expected (Equation 2.3). Additionally, we see 16 uncorrelated eigenmodes with a stronger power than the highly correlated modes to the right of the dashed vertical line. This is the same number of eigenmodes estimated using the off-source ACM in Figures 5.6 – 5.9, giving us more confidence that the subspace estimation is working as expected. The dominant eigenvalue of the estimated RFI subspace of the signal near 750 MHz with low beam correlation ($\rho < 0.2$) may be mitigated by 20 dB with just 1 % system noise temperature [6].

The challenge with this method is that the correlation of each of the significant eigenmodes has to be calculated for all beams and antennas. Figure 5.10 illustrates one more constraint of the subspace projection: eigenmodes related to RFI that are not strong enough to be above the noise (or the Sun) are not used as a part of the input for the mitigation and therefore not mitigated downstream. For this, ASKAP would need post-correlation spatial filtering, as shown in Figure 2.3, to mitigate weak RFI correlated between antennas.

A source, or RFI, in the FoV can have a high or low correlation (orthogonality) with a set of beamformer weights. Figure 5.11 extends Figure 5.10 to all beams and frequencies of the RFI-affected antenna. We return to the representative case of the off-source ACM in Figures 5.6, 5.7 and 5.9, i.e. there is no Sun in the FoV. This EVD was performed using the full 188 port ACM.

Correlations between the estimated RFI subspace eigenvectors and beamformer weights are divided into high and low, represented by blue and orange, respectively. Low correlations arise from the RFI subspace and the source-of-interest plus noise subspace being more orthogonal. The y-axis shows the RFI-affected frequencies and the number of estimated significant eigenmodes with x-polarisation weights on the left and the significant eigenmodes with y-polarisation on the right. The panels are organised in the same order as the footprint.

In each beam (panel) we see that the RFI-affected channels of this antenna have been identified and that the RFI subspace length across beams, and in both polarisations, is uniform. The beams (and beamformer weights) in the bottom left quadrant of the beam footprint are more correlated with the RFI eigenvectors, and the sensitivity would, therefore, be most degraded in these beams after projection. Highly correlated eigenvectors due to RFI enter the PAF through the same highly weighted ports used to create the beam, i.e. through the main beam. The remaining beams, with RFI entering the sidelobes, will experience varying degradation of the sensitivity and distortions in the outer lobes after mitigation. For RFI entering the main beam, as in the bottom left quadrant, mitigation using oblique projection is not possible, and therefore, the data will continue to be flagged.

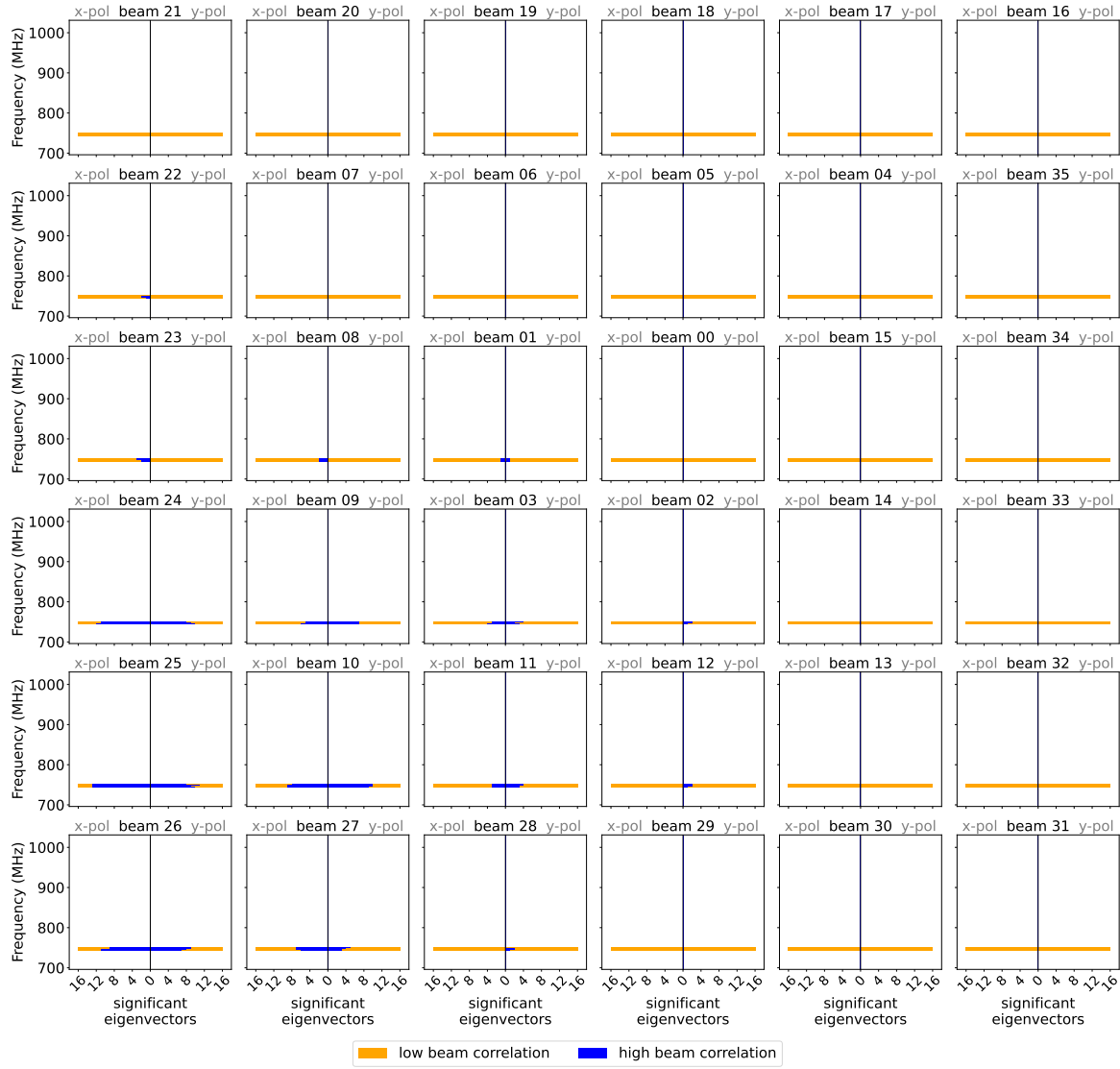
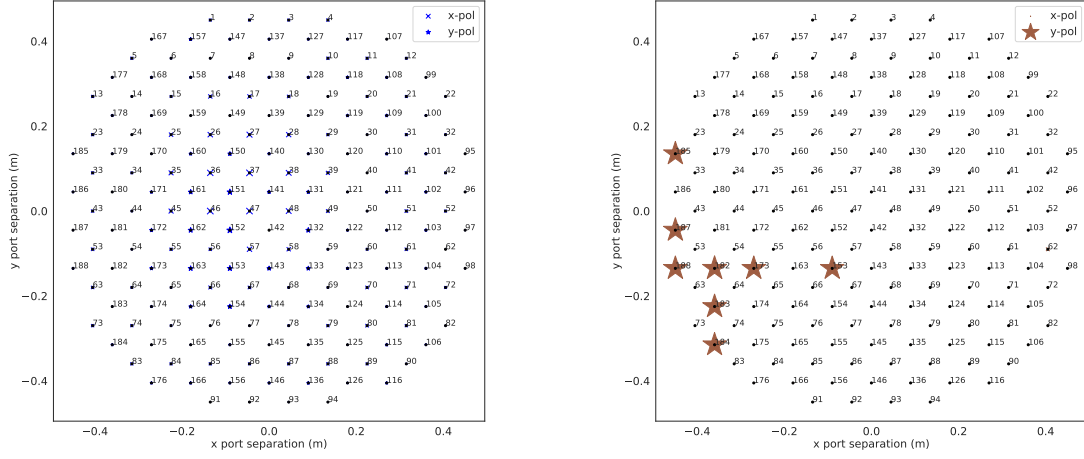


FIGURE 5.11. Correlation of beamformer weights and significant eigenvectors for the x-polarisation on the left of each panel and the y-polarisation on the right. Each panel shows the correlation with a different set of beamformer weights in the footprint. Panels are organised in the same order as the beams on the sky. High correlations are shown in blue and low correlations in orange. The lower correlation between the RFI eigenvectors and beamformer weights will yield less degradation to the sensitivity after oblique projection.

To further develop our understanding of how the RFI is affecting the telescope data, Figure 5.12 shows the set of maxSNR beamformer weights from Figure 5.11 superimposed on the PAF port positions on the left, and the RFI SSV dominant eigenvector of the off-source ACM

on the right. The RFI has a few very highly weighted ports in the y-polarisation. There will be less degradation in sensitivity when these two vectors (the weights on the left and RFI) are uncorrelated. Note that, unfortunately, the two plots are not on the same scale because the RFI is many orders of magnitude stronger than the (normalised) weights. There will be more correlation with the beams in the bottom quadrant because this is where the strong RFI is entering the PAF.



(A) maxSNR weighted ports for beam 00

(B) RFI-affected ports based on the dominant eigenvector

FIGURE 5.12. Port weighting of a maxSNR (A) beam and RFI (B), the RFI has a few very highly weighted ports in the y-polarisation. There will be less degradation in sensitivity when these two vectors are uncorrelated.

5.4.2 Forward predictions based on the Y -Factor

To reach our goal of finding a single-digit to represent the degradation of the performance, we have to do better than the correlation of the vectors and beamformer weights. Because this chapter's data uses on and off source ACMs, we can use the Y -Factor [164] to assess the performance of the oblique projection.

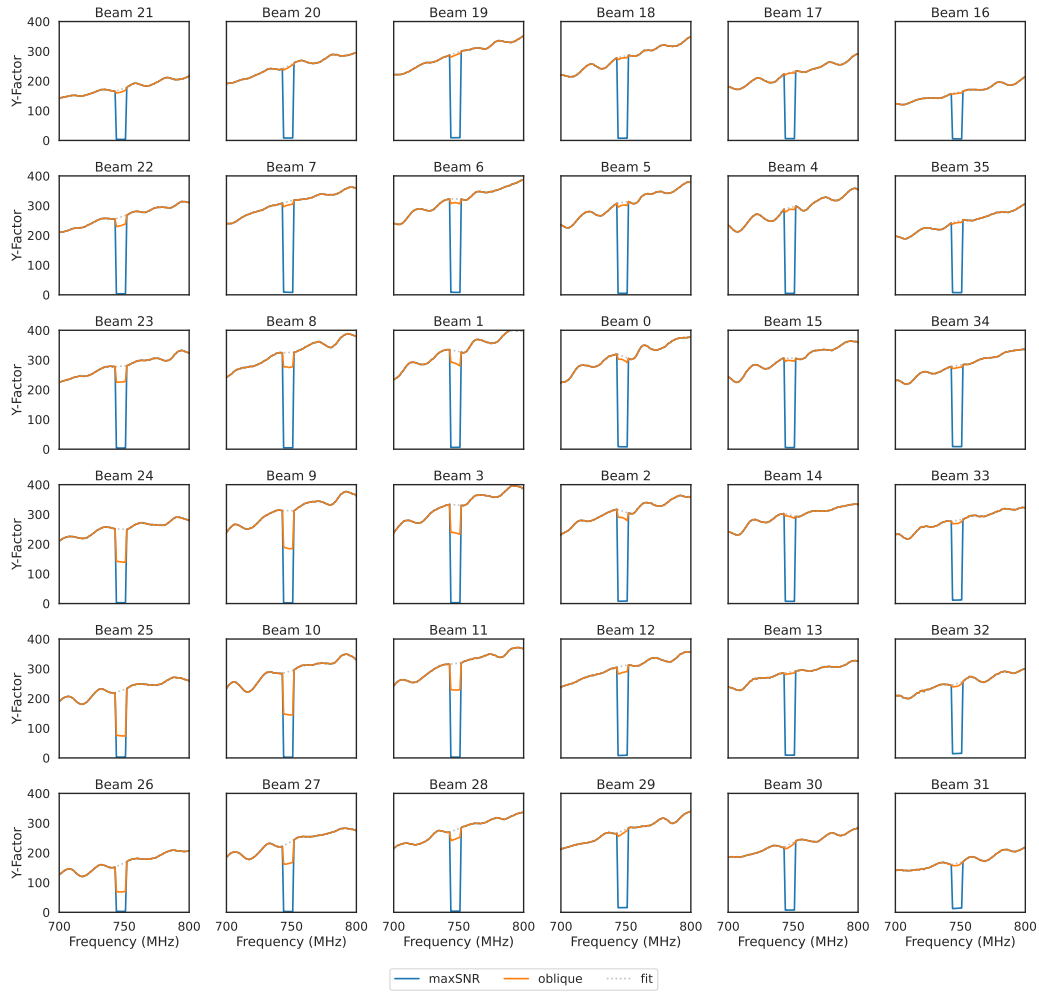


FIGURE 5.13. Comparison of Y -Factor measurements before (blue) and after projection (orange) in the 100 MHz centred at the RFI-affected channels. The grey dotted curve is an approximate of what the Y -Factor would be in the absence of RFI. The degree to which the mitigated Y -Factor (orange) approaches the approximate (grey dotted) Y -Factor indicates better performance. The bottom-left quadrant exhibits the most degradation, whereas the first two rows and last two columns predict mitigation with minimal degradation thus preserving the underlying astronomical data. Panels are again organised in the same order as the beams on the sky.

The Y -Factor is the power ratio between measurements of a known astronomical source and the nearby empty sky. It is inversely proportional to the beam sensitivity. Figure 5.13 compares the Y -Factor of beams made using x-polarisation maxSNR beamformer weights (blue) and beams made with mitigated x-polarisation weights using oblique projection (orange)

in the 100 MHz centred at the RFI-affected channels. Of interest is the difference between the unmitigated (blue) and mitigated (orange) curves at the 8×1 MHz RFI-affected channels. The RFI-subspace length and Y -factor were determined using the full 188 port ACM.

The Y -Factor of the unmitigated maxSNR x-polarisation weights is taken to zero at the corrupted RFI-affected channels. The goal of the mitigation would be to bring the Y -Factor back in line with the (approximate) values of the mitigated curve. The grey dotted curve shows this approximate Y -Factor value by masking out and interpolating over the mitigated curve in the RFI-affected channels. The closer the mitigated curve is to the interpolated (grey dotted) curve the less the degradation in sensitivity and distortion to the beam shape introduced by the projection. Similar to Figure 5.11, the bottom-left quadrant suffers the most degradation. Promisingly, most of the beams in the first two rows and last two columns predict mitigation with little degradation in performance. This highlights that mitigation works well with RFI in the sidelobes but not in the main beams. There is a median increase of 4 % in the recovered x-polarisation channels compared to the estimated value at those frequencies in the absence of RFI.

Figure 5.14 shows the y-polarisation. While not as obvious when using the correlations, we can now see that the performance of the mitigation — when using the Y -factor — is unfortunately worse in the y-polarisation. This suggests that the RFI is polarised and much stronger in the y-polarisation, which is also consistent with Figure 5.12. For beams with low correlation to the steering vector the strong RFI entering through the sidelobes would typically result in data being flagged and discarded. Those beams in Figure 5.13 can likely be mitigated and the astronomical data — projected onto a subspace oblique to the RFI subspace — preserved. There is a median increase of 6 % in the recovered channels in the y-polarisation.

The Y -factor is a great single-digit metric on which mitigation could be implemented and toggled per frequency based on an acceptable threshold, but it does require an off-source (noise only) measurement in the denominator to be calculated. That would mean before observations, an additional measurement would need to be taken. In production, an estimate

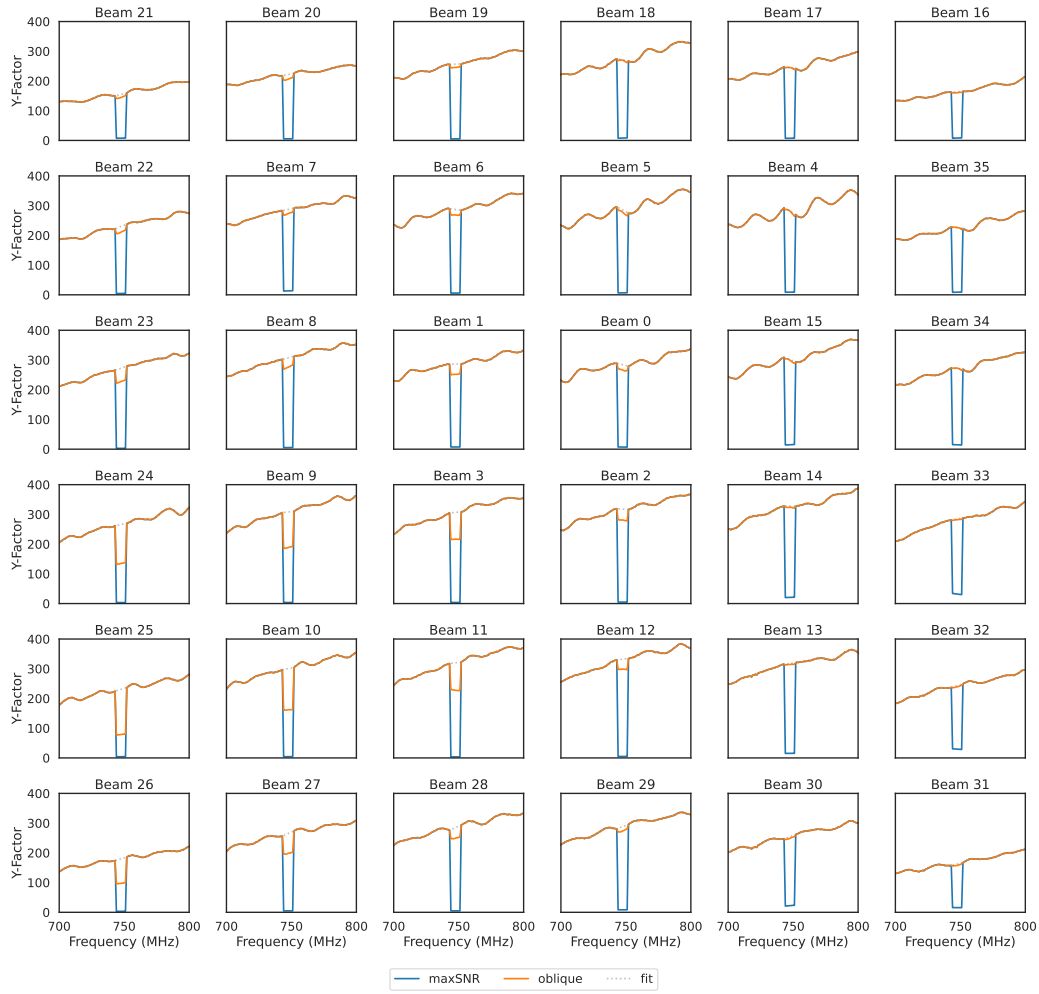


FIGURE 5.14. Comparison of Y -Factor measurement before (blue) and after projection (orange) showing the mitigation performance is worse in the y -polarisation compared to the x -polarisation Figure 5.13. There is less change in the mitigated Y -Factor (orange) from the unmitigated (blue) toward the ‘ideal’ approximate (grey dotted) Y -Factor in the RFI-affected channels. Panels are organized as beams on the sky.

of the degradation to the system performance using only the current observation would be preferable.

5.4.3 Predictions based on the singular values of the projection matrix

For frequency channels identified as RFI-affected, the RFI subspace is estimated, and the oblique projection matrix is calculated. Behrens [163] shows in Equation 5.4, that the average noise power gain can be estimated using the singular values of the SVD of the oblique projection matrix. This comes from the fact, that unlike orthogonal projection, whose projection matrix singular values are all either zero or one, the oblique projection matrix singular values can also take values greater than one [163]. Using Equation 5.4, and the full 188 port ACM as an input to the SVD, Figure 5.15 shows the calculated value of a single RFI-affected channel.

The value calculated for each beam is shown vertically for the y-polarisation and horizontally for the x-polarisation. Note that we use the maximum instead of the mean noise increase. Beams with predicted performance degradation above the median are shown in blue and beams with predicted performance degradation below the mean are shown in orange. As in the previous two subsections, we see that, again, the beams in the bottom left quadrant are predicted to perform the worst.

We plan to map the calculated average noise power gain to the Y -Factor using beamforming ACMs⁹. This requires a much larger population of ACMs though, and so we plan to routinely and automatically process all ASKAP beamforming ACMs. If we can map measurements of the Y -Factor with and without mitigation to the value calculated using Equation 5.4, we will have a value that can forward predict the performance degradation of an n -D RFI subspace using a single metric calculated from the RFI subspace and beamformer weights. Based on this value the projection can be implemented and automated (even without reference antennas or cached ACMs) given the level of increased noise a survey science

⁹We plan to also address this theoretically in the future by using eigenvalues and correlation coefficients. However, challenges arise when doing this at the 1 MHz resolution, where residual RFI power (due to imperfect nulls) could be calculated as an increase in T_{sys} . In Chapter 3 we avoided this because we had a finer frequency resolution.

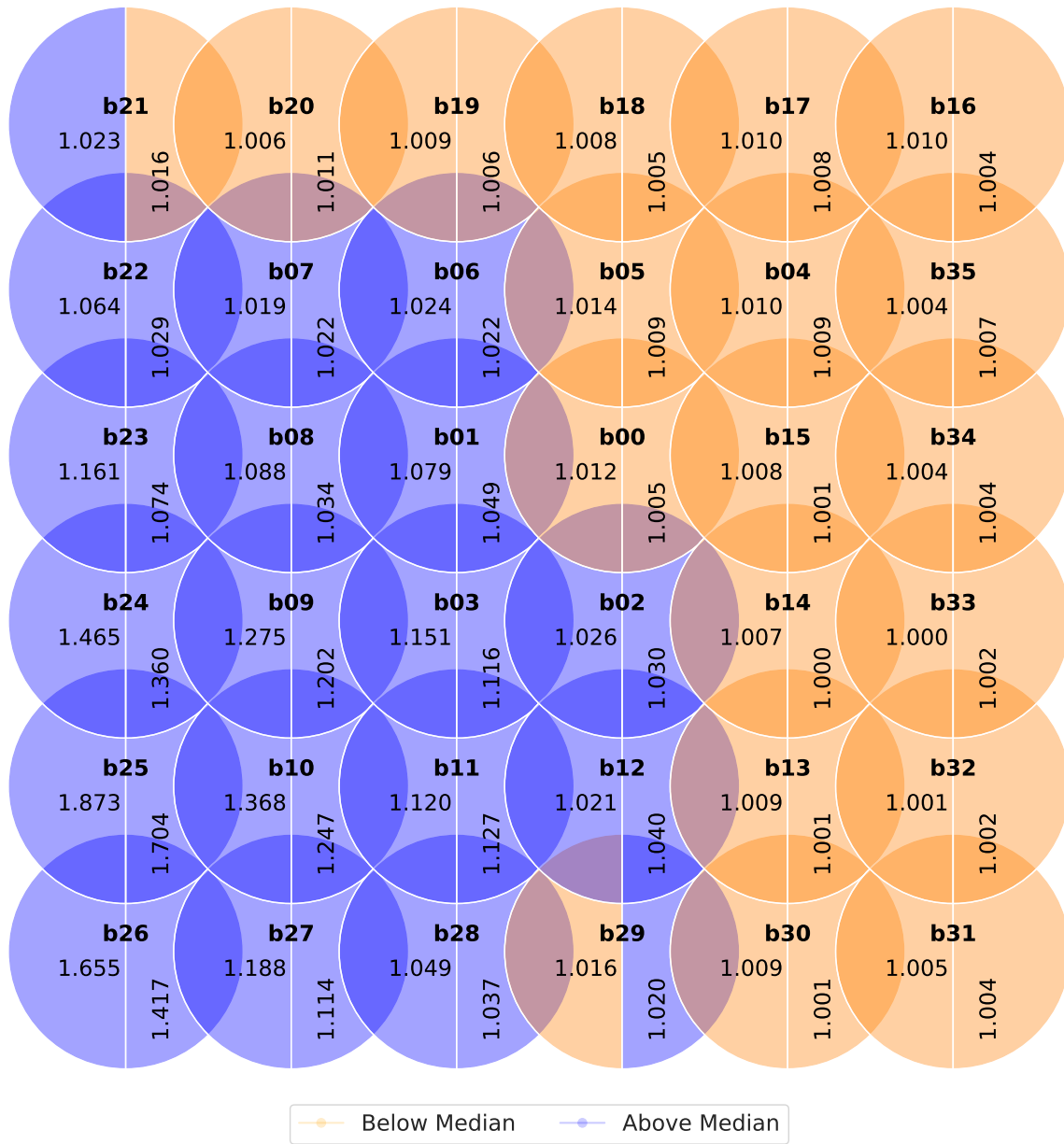


FIGURE 5.15. Estimates of the max increase in noise power gain for RFI-affected frequencies determined using a singular value decomposition (SVD) of the oblique projection matrix showing performance degradation across beams, with the most severely affected beams in the bottom left quadrant in blue.

project (SSP) is willing to accept if it means they can recover those RFI-affected channels in the RFI-affected beams and antenna.

5.4.4 Mitigation performance based on the number of ports

As the number of beams increases to 36 per polarisation, the number of PAF ports that can be used to form each beam reduces from 188 to 60. Typically 60 ports of one polarisation are used per single polarisation beam [38] on ASKAP in standard operational modes, where the polarisation of the selected ports matches the polarisation of the beam. Still continuing with the same example, we consider how the forward predictions using the Y -Factor change as the number of ports decreases. An ASKAP ACM can be separated into sub-ACMs for the x and y polarisations (Figure 2.10). In clockwise order from the top left, quadrants I and III are the 94 port sub-ACMs of the x- and y- polarisations, respectively. Figure 5.16 shows the calculated Y -Factor after identifying RFI-affected channels, estimating the RFI subspace, and calculating projection matrices per polarisation and channel using the sub-ACMs (on the left) and the strongest 60 ports (right).

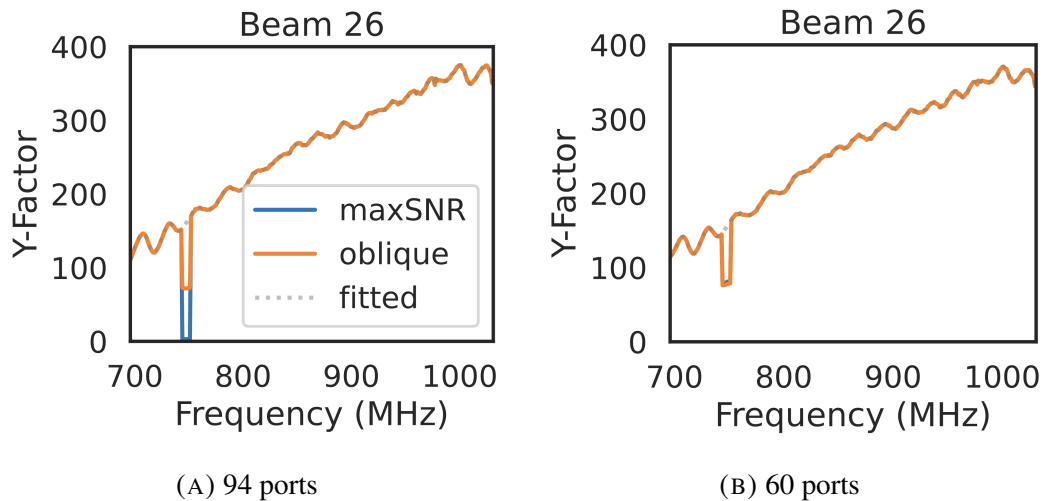


FIGURE 5.16. Comparison of Y -Factor measurement before (blue) and after projection (orange) calculated using an individual 94 port sub-ACMs of the x polarisations on the left and 60 ports on the right respectively.

Figure 5.16B, using 60 ports, is representative of ASKAP's current beamforming strategy. Recall that the aim of the projection is to bring the mitigated (orange) curve back in line with the sensitivity across the band. The estimated value of the Y -Factor at the RFI-affected

channels is represented by the grey dashed curve obtained by interpolating over the RFI-affected values. Figure 5.16 shows beams through which (we think) the RFI is entering through the main lobe, based on the correlations using all ports (Figure 5.11). The first thing we notice is that the Y -Factor evaluates to zero at the RFI affected channels using maxSNR weights when using 94 ports (and the full 188). This is the case for all beams. However, when only using 60 ports, this is not the case (Figure 5.16B); in fact, in most of the beams outside of the bottom quadrant, the RFI-affected channels are not discernible.

The difference in performance of the mitigation however, to what degree does the orange curve approach the grey dashed, is comparable across all beams. A median improvement in the Y -Factor of about 3 percent in the x polarisations across all beams using the 94 port sub-ACMs or 60 ports was calculated. Recall that most beams are affected by RFI that enters through the side-lobe so the median still works.

Although the RFI is much stronger in the y -polarisation, interestingly the mitigation seems to work better with 60 ports than 94 or 188 ports (Figure 5.14) in the beams through which the RFI enters the PAF through the sidelobes. The reason for this seems to be that those strongly RFI-affected ports (Figure 5.12) are not included in the beamforming process. This is an interesting result because, based on Chapter 4, we would expect that as the number of ports used increases, the degradation of the beam shape and added system noise would increase. In Chapter 4 the expected increase in noise power using only 60 ports 3 % and 5 % for the x - and y - polarisations, respectively compared to 0.2 % and 0.4 % using the full ACM.

Another point worth noting is that the RFI subspace length using the individual 94 port x sub-ACM is 8 eigenmodes and for the y sub-ACMs is 7 eigenmodes and remains uniform across beams as in the 188 port case. When using just the top 60 ports, the RFI subspace is more variable, ranging from 6 and 7 eigenmodes in the x - and y - polarisations, respectively, to 0 in beams with main lobes weighted from ports on the opposite side of the PAF. Furthermore, the correlations don't show any orthogonality using 60 ports using the same threshold for ρ .

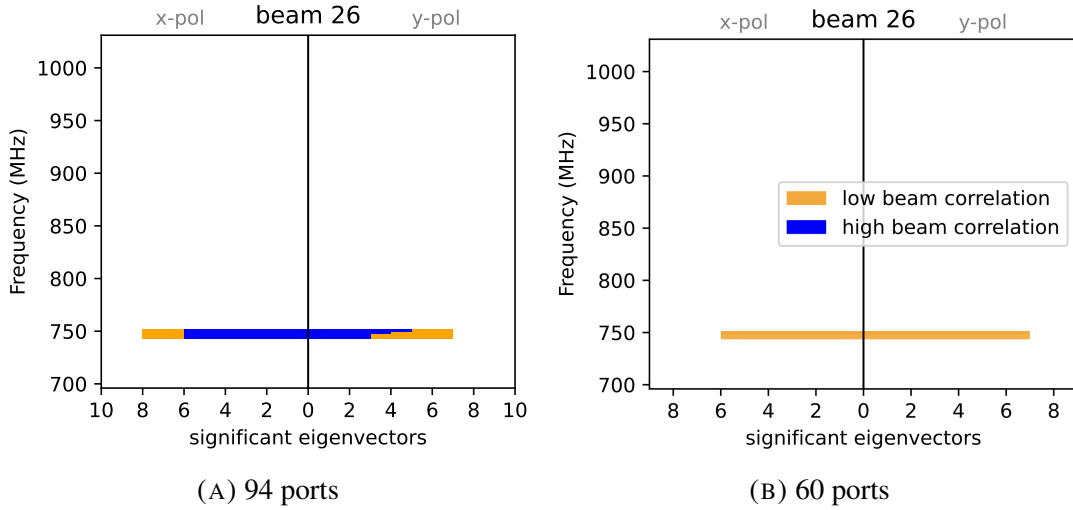


FIGURE 5.17. Comparison of correlations calculated using the 94 port sub-ACMs of the x polarisation on the left and 60 ports on the right respectively. High correlations are shown in blue and low correlations in orange. The lower correlation between the RFI eigenvectors and beamformer weights will yield less degradation to the sensitivity after oblique projection.

This section uses the same low-band example of strong (likely terrestrial) RFI affecting a single antenna as the previous sections. Forward predictions show that mitigation of some beams should be possible where the RFI enters through the sidelobe, even using 60 ports. Unlike the mid- and high- bands, ASKAP's low science band is not currently affected by satellite interference. However, this is not likely to continue to be the case; see Appendix B.

5.5 Challenges across ASKAP's frequency range

ASKAP's mid- and high- bands are known to be affected by satellite interference [38, 145]. We now need to evaluate the software performance in estimating the RFI subspace and predicting the performance degradation introduced by oblique projection for satellite interference. The experiment done by Hellbourg and Bannister using BETA showed that mitigation of satellite interference is possible [13]. We extend this work by dynamically identifying what frequencies are RFI-affected. Implementing spatial nulling on ASKAP operationally would require, even before the forward prediction of the effects of the projection, correctly identifying RFI-affected

channels and a reliable automated estimate of the RFI subspace. Identifying RFI-affected channels exactly as in Figure 5.6, but now in ASKAP’s high-band:

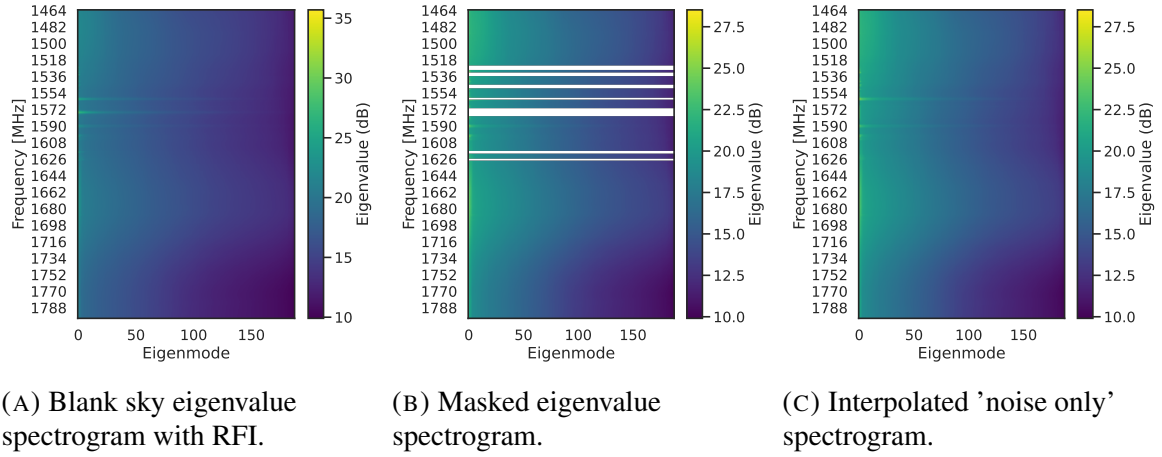


FIGURE 5.18. The bottom half of ASKAP’s high-band is severely affected by RFI from satellites. Most of the interferers are not identified using the same method as in the previous sections.

Figure 5.18 shows the process of identifying RFI-affected channels using the same method and thresholds as in Figure 5.6. Panel A is the median eigenvalue surface calculated over three time samples. Panel B masks the RFI-affected channels with power $10 \times \text{MAD}$. Panel C shows the interpolation over the masked channels to get an estimate of the noise-only eigenvalue surface. Immediately we can see that the RFI affecting this antenna is more complicated (i.e. numerous RFI sources closely spaced in frequency) and weaker than our example in the sections 5.3 and 5.4. Figure 5.18A shows at least three interferers at 1561 MHz, 1575 MHz and 1591 MHz with large estimated RFI subspaces, identified by the rows with long bright ‘tails’. These frequencies are in the RADIONAVIGATION-SATELLITE (space-to-Earth) service allocation and are likely due to a Galileo E1 signal¹⁰ [42] centred at 1575.42 MHz with a sub carrier frequency of 15.345 MHz. While there are other frequency channels that have much shorter estimated RFI subspaces¹¹, we will limit our discussion to these three for now.

¹⁰Also GPS L1 [42].

¹¹1619 MHz & 1627 MHz, Iridium UB = 1626.5 MHz, are in a MOBILE-SATELLITE allocation [42].

We can see in panel B that the first of the two interferers (1561 MHz, 1575 MHz) are identified and masked out, but the 1591 MHz signal is not. Panel C shows that although 1561 MHz was correctly identified, once it is interpolated over, the interferer is still visible in what ought to be a noise-only eigenvalue surface. In other words, the method has failed to remove two of the three interferers in the last panel. Likewise, Figure 5.19 shows an RFI subspace at 1575 MHz comparable to the interferer's eigenvalue spectra in Figure 5.18A at the same frequency. Only part of the interference around 1561 MHz has been estimated. For the strong interferer in the previous chapter, the masking and interpolation worked well — our low-band example was on the order of 60 dB — likely due to it being much closer to the antenna. For farther and weaker sources of RFI, the method for identifying RFI-affected channels and interpolating over them needs improvement.

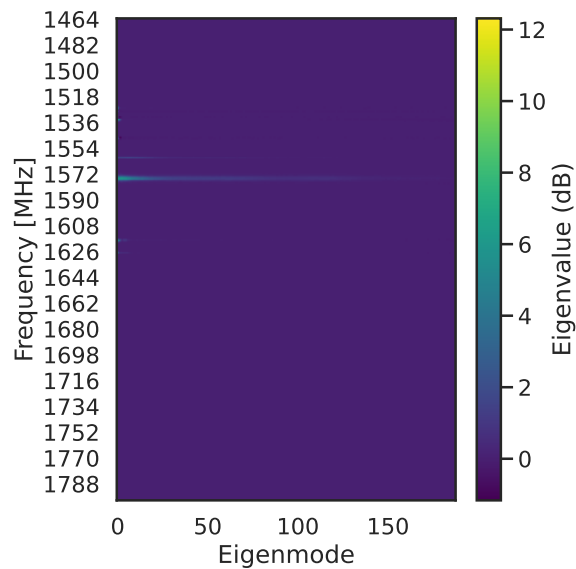


FIGURE 5.19. A viable RFI subspace of only one of the three strongest interferers has been realised, highlighting the need for improvements in the software to identify RFI-affected channels.

This example highlights the following challenges in identifying RFI-affected channels: When a channel is RFI-affected in the majority of the time samples, it will appear in the median eigensurface¹². The MAD threshold has to be set tighter because currently, the

¹²Our population of ACMs (Table 5.1) are shorter, and therefore this is more likely to be the case. Longer `ACMFiles`, with more integration cycles, might reduce RFI in the panel A

software does not correctly identify all the interferers. Finally, the interpolation may need to be improved or, at the very least, can have unexpected consequences as the RFI of a contiguous frequency block becomes more complex. The first point does raise a constraint in how oblique projection would be implemented operationally; because ACMs are not cached, the calculated eigenvalue surfaces shown in Figure 5.20A for ACM would need to be stored and the median eigenvalue surface somehow calculated iteratively throughout the observation. By contrast, we are currently calculating the median on the whole file retrospectively, which does not allow for the null to be updated as the interferer(s) move(s) through the FoV.

Again identifying RFI-affected channels exactly as in Figures 5.6 and 5.19, but now in ASKAP's mid-band, Figure 5.20 shows interference around 1176 MHz (GPS L5 [42] and Beidou B2), 1201 MHz (Glonass G3) and, 1269 MHz (Beidou B3). Of these, only a narrow set of channels at ≈ 1176 MHz have been identified in panel B and, as with the high-band, incorrectly interpolated in panel C. In fact, our method for identifying RFI-affected channels

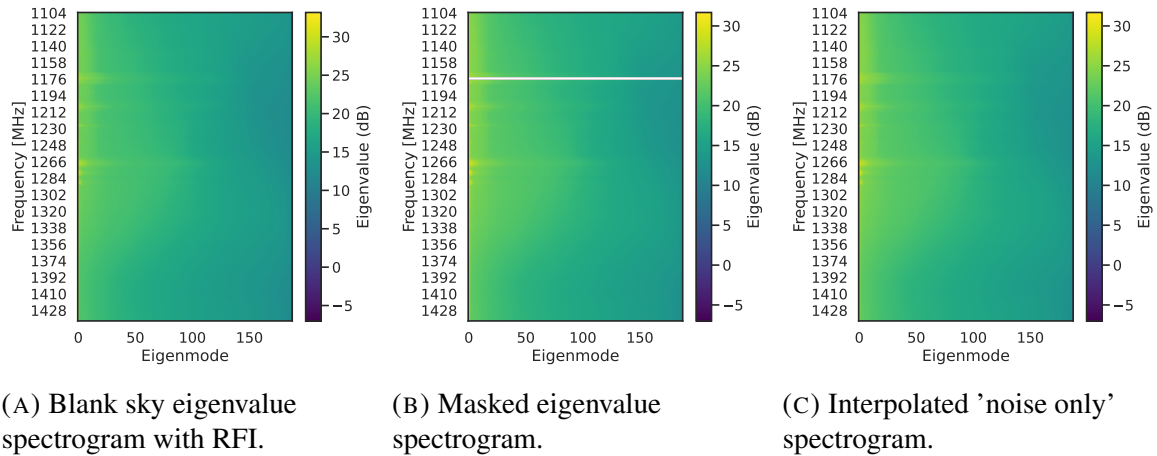


FIGURE 5.20. The bottom half of ASKAP's mid-band gets discarded to radi-onavigation satellites before processing. Like the high-band, some interferers are not identified in B, and definitely not removed in C, using the same method presented in the previous sections.

has performed even worse in ASKAP's satellite-affected mid-band, estimating no viable RFI subspaces. Figure 5.20 does, however, highlight a very important aspect of this work. Looking at ACMs in this way is likely the first time that the RFI below 1293 MHz of the ASKAP band has been looked at, including in Chapter 3. Although observed, this sub-band is discarded

before processing, resulting in a large section of bandwidth in which no flagging data has been collected [160]. As we continue to improve the method for identifying RFI-affected channels from an ACM, we can begin to provide statistics of the RFI in this band.

With regards to mitigation using subspace projection, the software has to identify RFI-affected channels and their RFI subspace better across the wider population of ACMs in Table 5.1. The degree to which the RFI subspace is accurately estimated will ultimately determine how well the projection performs. We have presented a successful proof of concept on a strong source of likely terrestrial RFI which fails to do the same in the more general case. This is ultimately where this research currently is, exploring ways to improve the RFI subspace estimation for data containing numerous weak RFI sources that are closely spaced in frequency. Useful techniques must be robust and should ultimately be automated. The remainder of this chapter looks at ways that this process might be improved: including adjusting the MAD threshold, applying a rolling median, and aggregating ACMs from different observations.

5.5.1 Changing the MAD threshold

To try to isolate the problem of where the method for identifying RFI-affected channels in Figures 5.18 – 5.20 went wrong, let us consider just the dominant eigenvector. Figure 5.21 shows the effect of reducing the threshold from $10 \times \text{MAD}$ (A), to $3 \times \text{MAD}$ (B) and $10 \times \text{MAD}$ (C) in ASKAP's high-band. The interferers at 1561 MHz, 1575 MHz, and 1591 MHz discussed are represented using the orange vertical lines.

In panel A, because the threshold is so high, it completely fails to identify the 1591 MHz signal. Furthermore, we can see why the 1575 MHz signal was able to determine a viable RFI subspace; there is enough space on either side of the interferer that the masked signals were interpolated to the noise-only levels. Lastly, because the interference to the left of the 1561 MHz signal was not masked, the interpolation did not work correctly. When the threshold is reduced to $3 \times \text{MAD}$, we can see that RFI-affected channels to the left are 1561 MHz are identified as well as the 1591 MHz signal. We have to be careful though how low we set the

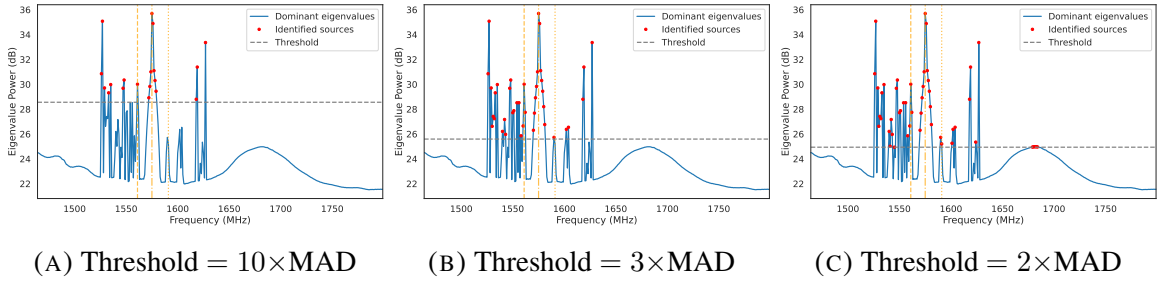


FIGURE 5.21. Lowering the MAD threshold in ASKAP's high-band improves detection of RFI-affected channels to a point but can also remove unaffected channels if it is too low.

threshold because as we can see in panel C, when set to $3 \times \text{MAD}$, the threshold is so low that channels at ≈ 1591 MHz channels that are not RFI affected will be masked out. We didn't see this effect in the original low-band example because the RFI was so strong. When we look at another low-band example, Figure 5.22, we can now see more variation around the noise.

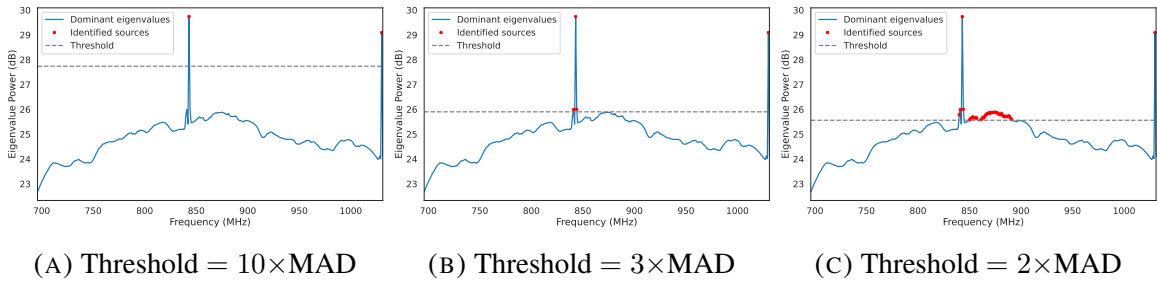


FIGURE 5.22. Lowering the MAD threshold in ASKAP's low-band improves detection of RFI-affected channels but can also remove unaffected channels if it is too low.

Similar to the mid-band, setting the threshold too high misses some of the RFI affected channels, and setting it too low incorrectly masks non-affected channels. We also see that the low-band's 'noise-only' shape is quite different to the high-band. What this plot makes clear is that there is no 'one size fits all' for the threshold and while generally $3 \times \text{MAD}$ is a more appropriate threshold than $10 \times \text{MAD}$, panel B shows there is not a lot of room for error with the threshold set to $3 \times \text{MAD}$. For completeness, I have also included the mid-band and the 1176 MHz, 1201 MHz, and 1269 MHz discussed, are again represented using the orange vertical lines.

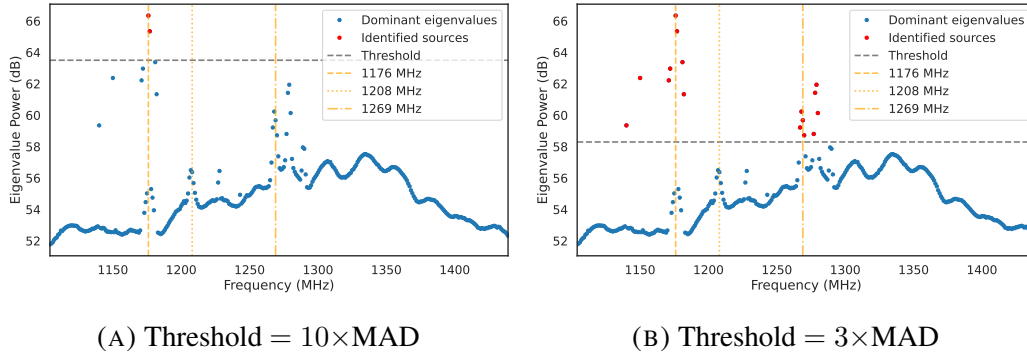


FIGURE 5.23. Lowering the MAD threshold in ASKAP's mid-band improves detection of RFI-affected channels to a point but can also remove unaffected channels if it is too low.

Figures 5.21 – 5.23 highlight a shortcoming of using a fixed threshold for identifying RFI-affected channels. For example, the interferer at 1208 MHz, is below the threshold but also below the peaks due to the noise higher up in the band. In the event that this RFI is persistent, it will not be identified using this method and, therefore, won't be interpolated to get an estimate of the noise subspace without which the RFI subspace cannot be calculated and ultimately mitigated. One way around this is to use a rolling median, which would take into account the instrument response and still allow a tighter outlier threshold.

Figure 5.24 shows the mid-band, this time with the rolling median in grey superimposed on the blue curve. The rolling median has a window of 40 MHz and is centred before extrapolating linearly to both ends of the band¹³.

The grey-shaded section of the plot indicates the frequencies affected by satellite interference, and the yellow-shaded area is the HI RAS allocation. The dotted grey line is the threshold used to identify RFI-affected channels but the thresholds are tighter in the grey-shaded area to the upper part of the band. The curve at the transition 1300 MHz is interpolated between the two thresholds over 20 MHz to avoid a discontinuity. The first thing we can see when comparing Figure 5.23 to Figure 5.23B is that more of the peaks in the bottom part of the band have been identified, including ones lower than the noise, the interferer at

¹³ASKAP collects 336 MHz bandwidth of ACM data but only 288 MHz is used in the correlator [38], so while the interpolation at the ends is not perfect it may be sufficient.

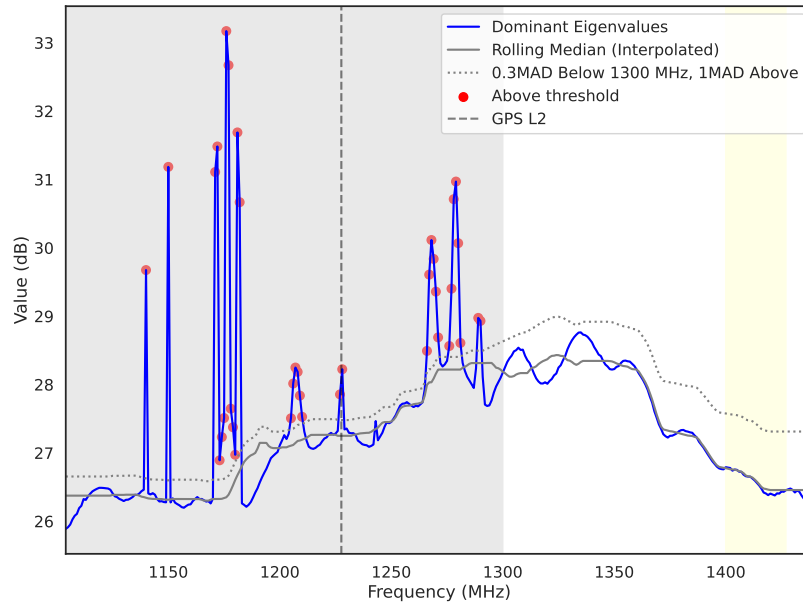


FIGURE 5.24. The mid-band with a 40 MHz rolling median filter (grey) superimposed on the blue curve. The dotted grey line indicates the threshold, the threshold is tighter in the satellite allocations (grey-shaded) than in the top half of the band around the HI RAS allocation (yellow). The threshold curve is interpolated at $1300 \text{ MHz} \pm 20 \text{ MHz}$ to avoid discontinuities.

1208 MHz which was not identified in Figure 5.23B for example. The vertical dashed line also demarcates the GPS L2 signal Bannister and Hellbourg [9] demonstrated mitigation on is also correctly identified. Figure 5.25 compares the obtained RFI subspaces using a fixed threshold versus using a rolling median with a variable threshold.

This is an example of what could be done when using a rolling median¹⁴ and incorporating our knowledge of what RFI routinely affects ASKAP as well as our knowledge about the services operating in ASKAP's band and changing the thresholds, windows etc. accordingly.

¹⁴or other filters; we are also currently considering the Sovitzky-Golay filter, which may smooth out the baseline (solid grey) curve more. Another option under review is iterative fitting, where with each iteration, the threshold is tightened and refit without the outliers.

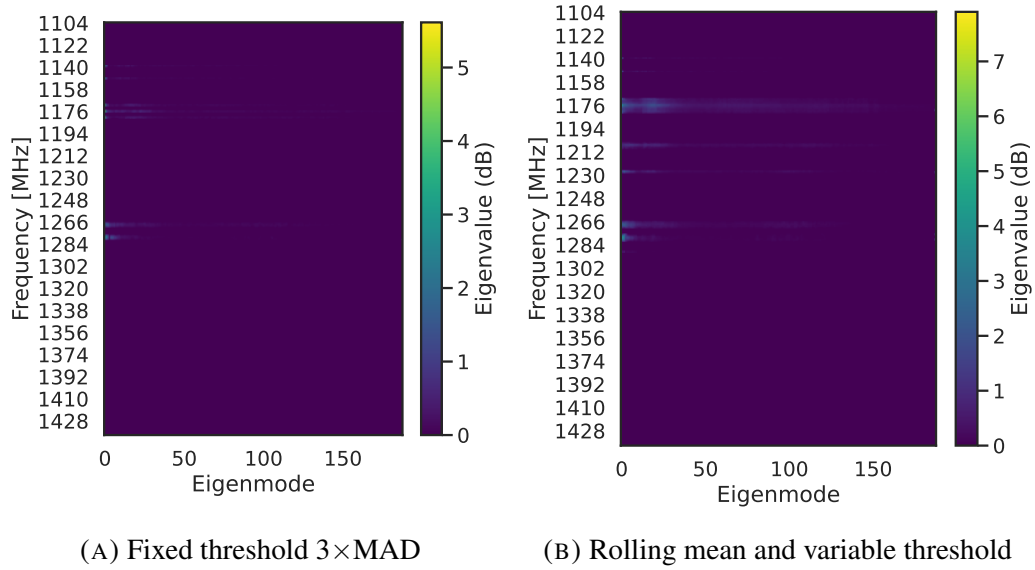


FIGURE 5.25. Where no viable RFI subspace was calculated using a fixed threshold, using a rolling mean with a variable threshold yields more believable estimates of the RFI subspaces for some of the RFI-affected channels including the GPS L2 signal.

5.5.2 Aggregating ACMs from different observations

Another method being evaluated to obtain an estimate of the ‘noise-only’ eigenvalue surface is to aggregate ACMs from different observations operating in the same frequency range. In some ways, this is analogous to ‘snapshots’ of a longer observation; as such, the idea is that any particular RFI-affected channel will be in less ACMs as the number of ACMs the median is calculated over increases. The risk is that many things are changing from observation to observation that could also account for the changes we see in the eigensurfaces.

Comparing Figure 5.26A to Figure 5.21B both use $3 \times \text{MAD}$ as the threshold but the former is aggregated over 9 off-source boresight beam observations and across all antennas.

We can see the general shape and structure in the noise are still similar, but variations in the noise shape are less. The RFI-affected channels to mask have been correctly identified. Furthermore, comparing Figure 5.19 to Figure 5.26B, Figure 5.26B shows an improvement in that a viable estimate of the RFI subspace of the interferer at 1575 MHz has also been

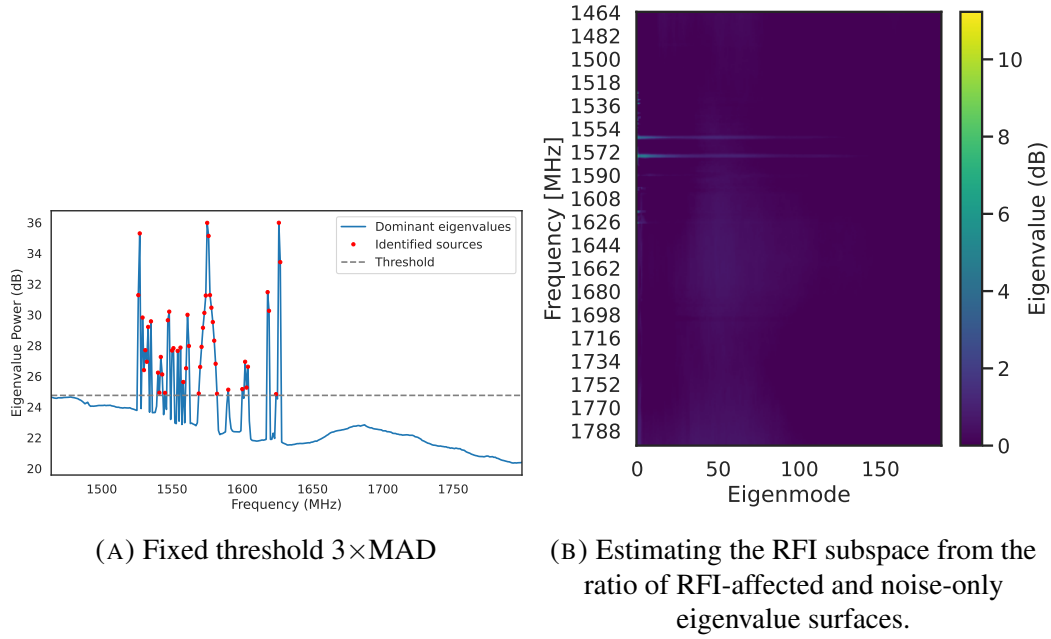


FIGURE 5.26. Aggregating scheduling blocks with the same frequency range and taking the median across all the ACMs.

obtained. In both cases (Figure 5.19 and 5.26B) the 1591 MHz interferer is missing. One of the benefits of this approach compared to using a rolling median and a variable threshold is that it is more straightforward.

The effects of aggregating only ‘clean’ (RFI free) eigensurfaces or ‘clean’ and interpolated (‘cleaned’) eigensurfaces are being examined. Ultimately a combination of the techniques presented in this subsection will probably be required to most accurately estimate the RFI subspace of a diverse population of interference affecting ASKAP.

5.6 Candidates for mitigation

Table 5.2 shows RFI-affected channels identified as initial candidates for mitigation based on the median correlation of the dominant eigenvector with maxSNR boresight beamformer weights, $\tilde{\rho} \leq 0.1$. For each identified RFI-affected channel (or contiguous range of channels), the number of significant eigenvalues and median correlation coefficient (per polarisation) are

TABLE 5.2. Candidate channels for mitigation based on the correlation of beamformer weights with the dominant eigenvalue $\tilde{\rho} \leq 0.1$

frequency [MHz]	# sig λ	$\tilde{\rho}_X$	$\tilde{\rho}_Y$	$P(\tilde{\rho}_{X \cap Y} \leq 0.1)$	allocation
977	1	0.04	0.04	0.50	(Self-generated, Chapter 3)
1000–1003	14	0.05	0.03	0.50	AERONAUTICAL MOBILE
1008–1011	14	0.04	0.03	0.50	AERONAUTICAL MOBILE
1030	1 ²	0.05 ^{0.07} _{0.04}	0.06 ^{0.07} _{0.03}	0.87	AERONAUTICAL MOBILE
1041	1	0.04 ^{0.06} _{0.03}	0.05 ^{0.07} _{0.04}	0.52	AERONAUTICAL MOBILE
1171–1172	1	0.02 ^{0.03} _{0.02}	0.02 ^{0.03} _{0.01}	1.00	AERONAUTICAL MOBILE
1176–1177	1	0.02 ^{0.03} _{0.01}	0.02 ^{0.03} _{0.02}	1.00	NAVIGATION SATELLITE
1181–1182	1	0.03 ^{0.03} _{0.02}	0.02 ^{0.02} _{0.01}	1.00	NAVIGATION SATELLITE
1202–1209	1	0.04 ^{0.06} _{0.02}	0.04 ^{0.05} _{0.02}	1.00	NAVIGATION SATELLITE
1243–1244	1	0.02 ^{0.06} _{0.01}	0.04 ^{0.06} _{0.02}	1.00	NAVIGATION SATELLITE
1247–1249	1	0.03 ^{0.07} _{0.01}	0.03 ^{0.07} _{0.02}	1.00	NAVIGATION SATELLITE
1464–1529	1 ²	0.05 ^{0.06} _{0.03}	0.00 ^{0.02} _{0.0}	0.75–1.00	FIXED MOBILE
1530–1535	2	0.05 ^{0.08} _{0.03}	0.01 ^{0.07} _{0.0}	0.58–0.89	MOBILE SATELLITE
1541–1559	1	0.05 ^{0.07} _{0.01}	0.04 ^{0.07} _{0.01}	0.88	NAVIGATION SATELLITE
1560	3 ⁴ ₂	0.03 ^{0.06} _{0.02}	0.03 ^{0.06} _{0.02}	0.84	NAVIGATION SATELLITE
1561	10 ¹¹ ₉	0.04 ^{0.06} _{0.02}	0.04 ^{0.06} _{0.02}	0.74	NAVIGATION SATELLITE
1562	4 ⁵ ₃	0.04 ^{0.06} _{0.02}	0.04 ^{0.06} _{0.02}	0.77	NAVIGATION SATELLITE
1563–1574	1 ²	0.05 ^{0.06} _{0.03}	0.00 ^{0.06} _{0.0}	0.69–1.00	NAVIGATION SATELLITE
1575–1576	15 ¹⁶ ₁₃	0.04 ^{0.06} _{0.02}	0.04 ^{0.06} _{0.02}	0.84–0.87	NAVIGATION SATELLITE
1599–1605	1 ²	0.04 ^{0.06} _{0.02}	0.00 ^{0.02} _{0.0}	0.78–0.97	RADIONAVIGATION SATELLITE
1618–1627	1	0.04 ^{0.07} _{0.03}	0.04 ^{0.05} _{0.00}	0.75–0.91	MOBILE SATELLITE

given. Where the upper and lower IQR are the same as the median they have been omitted otherwise the upper and lower quartiles are given as a superscript and subscript, respectively. The probability that the median correlation is less than 0.1 is also given; that is $\tilde{\rho} \leq 0.1$ over the number of occurrences of that RFI-affected channel. The primary allocations are also given.

Candidates were selected using beamforming off-source ACMs from boresight beams. In ASKAP's low-band four scheduling blocks (with 36 antennas) in the frequency range 752 MHz to 1087 MHz were used, in the mid-band five scheduling blocks from 1104 MHz to 1439 MHz and, in the high-band using nine scheduling blocks from 1464 MHz to 1799 MHz. Note that contiguous channels with similar values have been grouped together. A $\rho \leq 0.1$ using the dominant eigenvector maps to a $g_{\max} = 0.005$ calculated from the singular values of the projection matrix. The Y -Factor has not been calculated because in this population we

did not collect on source ACMs. As the determination of RFI-affected channels and their RFI subspace improves so will the estimates (and predictions) presented above.

The way to interpret this table is as follows, consider the 1575 MHz to 1576 MHz affected channels, these 1 MHz channels are currently discarded; In this example we predict (using the correlation of the dominant eigenvector) that between 84 % to 89 % of the time we can recover these channels with, at best, the same beam performance as presented in Chapter 4, based on this population of ACMs.

5.7 Ongoing work

This chapter builds on the static case discussed in Chapter 4, extending the analysis to the more typical and significantly more challenging scenario of multiple, weaker and moving RFI sources that are closely spaced in frequency. It also dynamically identifies RFI-affected channels building on the work of Hellbourg and Bannister. A set of tools under development has been introduced to estimate the RFI subspace and assess the expected performance of oblique projection. Subspace estimation using MAD has been extended to include information about the eigenvalues of neighbouring frequency channels. It is also the first time, to the author's knowledge, that the RFI's orthogonality to the beamformer weights has been analysed in this way, at this scale, and using actual telescope data across all beams and antennas.

To implement the mitigation based on a forward prediction, our immediate next step is to map the effects of oblique projection on beam sensitivity using the Y -Factor to the calculated value from the singular values of the projection matrix. We aim to do this using a larger population of ASKAP ACMs by automatically analysing the temporarily stored beamforming ACMs. In addition, we plan to automatically collect statistics of the identified interference (particularly in the discarded bottom half of ASKAP's mid-band) to supplement the flagging statistics presented in Chapter 3. In the future, applying the same analysis presented in this chapter with longer ACMs is required to assess the temporal stability of the RFI subspace

and associated eigenmodes is also needed. We also want to look at the relationship between the RFI subspace length as a function of antenna pointing—in particular elevation.

Several other aspects of the `acm-rfi-tools` library require further refinement. We need to understand how the mitigation performs as the number of ports varies. This is likely to inform decisions in the design of new PAFs under development and upgrades to existing PAFs. Efforts to improve the identification process of RFI-affected channels and obtaining better estimates of the source-of-interest plus noise subspaces are already underway, for interferers with short RFI subspaces and of different strengths to ensure robustness across a diverse set of RFI scenarios affecting ASKAP. The threshold for detecting RFI-affected channels, using MAD — how low it can be set without over-masking unaffected channels — must continue to be refined. If a rolling median is used to determine the channels, further investigation is required to identify a suitable window length and to determine the best approach for extrapolating the edge values.

Generalising the code so that methods other than MAD can easily be used to identify RFI-affected channels needs to be implemented; this is currently only possible manually and on a per-frequency basis. Moreover, further research is needed to understand how variations in subspace length affect mitigation performance, as different methods can yield slightly different results. For instance, PCA generates a subspace that is four eigenmodes shorter than our method in the first example, and it's important we quantify the impact of these subtle variations in techniques. The power method for estimating the RFI subspace as it evolves throughout an observation should also be assessed.

Not touched on in this chapter but requiring more analysis is the need to match ACM integration time to the motion rate of the source. Longer integration leads to more sensitivity but increases subspace smearing errors in the RFI subspace estimates. On the other hand, shorter integration will have less subspace smearing but be less sensitive and have more measurement error. Different RFI integration times may work better for different RFI sources; for example, faster-moving sources will likely work better with shorter integration times.

Finally, there are plans to extend the analysis of ACMs from the new Murriyang CryoPAF, which operates in a more complex RFI environment, has more beams and finer frequency channels compared to ASKAP. In this case, methods for subspace estimation using a reference antenna and cached ACMs will need to be investigated, as well as implementing broad nulls. The `acm-rfi-tools` code has been designed with modularity in mind, comprising an ingest component followed by the downstream analysis, making it adaptable to other instruments but not yet put into practice.

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Conclusion and future work

Non-destructive RFI mitigation techniques offer significant advantages over flagging as they preserve the underlying astronomical data. With over 20 years of research, spatial filtering is especially promising as it introduces deep nulls into the beam pattern, preventing RFI from entering science-ready data products. Understanding, predicting, and communicating the effects of these techniques on astronomical observations is crucial for effective implementation and adoption across the community. The use of spatial filters via subspace projection in radio astronomy for phased array systems has largely been for research purposes so far, and although significant work remains to integrate these techniques into routine large-scale telescope operations (alongside traditional RFI mitigation techniques), this thesis begins to address this gap. It also aims to bring together what are often practically treated as individual problems, monitoring and mitigation, as part of a holistic RFI strategy. With a new generation of high-sensitivity aperture arrays and PAFs coming online and the unprecedented threat of increased satellite RFI just on the horizon, advancing subspace projection has never been more imperative.

Chapter 3 of this thesis has realised a baseline of discarded RFI-affected data against which future trends of ASKAP's RFI environment can be measured, including mitigation. The average amount of flagging due to RFI across the routinely-used continuum science bands is 3 % and the percentage of discarded data has increased year-on-year for some services. Two 'self-generated' clock signals in ASKAP's backend were identified as the most persistent sources of RFI, affecting ASKAP continuum science data in the 'clean' low-band.

Chapter 4 describes the downstream effects of oblique projection on ASKAP's sensitivity and beam pattern after mitigating the 976.6 MHz interfering clock signal. Oblique projection for this signal has been implemented in the ASKAP weights codebase. In this case, the interfering signal is stationary, meaning the mitigation only needs to be applied once (by updating the beamformer weights) at the beginning of the observation. The unwanted narrowband signal was suppressed by 31 dB (to the noise floor) in line with previous work. Chapter 4 is the first measurement of the degradation of sensitivity across the array via interferometric assessment of SEFD. It is also the first measurement of beamshape distortions due to oblique projection using holography on a large aperture synthesis array telescope. The beam sensitivity in the 1 MHz affected channel was degraded by 3.1 % on average and, distortions to the beamshape were within ± 0.4 % on average at the half-power point of the main beam. Measurements of the changes to the beamshape were consistent with the modelled effects, and the noise increase is in line with theoretical calculations using the correlation of the beam weights and RFI spatial signature vector. The static case has applications for stationary terrestrial interferers affecting aperture arrays without relative motion.

Chapter 5 extends the investigation of the effects of oblique projection (and implementation) to the more difficult case of RFI moving with respect to the PAF, based on a small population of ASKAP beamforming ACMs. Our approach has been to estimate the source-of-interest plus noise subspace by identifying RFI affected channels, interpolating over their eigenvalues in frequency and then estimate the RFI subspace from the source-of-interest plus noise subspace. Forward predictions of the degradation in beam sensitivity are made based on the correlation of maxSNR beamformer weights with individual RFI SSVs, the Y-Factor, and the singular values of the projection matrix. This is the first time the RFI and its orthogonality have been looked at in this way, at this scale and using actual telescope data. Good subspace identification and forward predictions of beam performance were achieved for a strong moving interferer that was isolated in frequency (isolated mobile handset?). The biggest challenge appears to be accurately detecting and identifying the RFI subspace of multiple weak and moving interferes that are closely spaced in frequency, as is the case for satellite navigation related interference in ASKAP's mid-band.

An initial test epoch of the SMART RFI survey has been completed. This comprehensive and dedicated RFI survey covers ASKAP’s full 700 MHz to 1800 MHz frequency range, including bands not typically used due to severe RFI and is the first survey of its type using ASKAP since 2016 and it is also the first using the full ASKAP array. The `flagstats` library is being modified to be compatible with observations in ASKAP’s nominal full-band spectral-line resolution of 18.5 kHz (i.e. excepting zoom modes), which will allow us to, more accurately, identify interferers and plan a mitigation strategy around them.

Estimating a viable subspace for satellite interference, in particular, remains challenging. Additional research using longer ACMs is planned to see how the RFI subspace evolves over longer time frames. As the software continues to develop, we aim to broaden the analysis to a larger population of ACMs, enabling us to make statistical claims about which RFI can most reliably be mitigated using oblique projection. A larger population of ACMs will allow us to map the Y-Factor to the average gain increase based on the singular values of the projection matrix. The singular values of the projection matrix are a promising metric with which the projection of dynamic RFI could be implemented in the ASKAP code base. Additionally, we plan to extend our analysis to ACMs from the new Murriyang CryoPAF receiver and other instruments.

Subspace projection may have applications for improvements to ASKAP other than suppressing RFI:

- It may be able to reduce the negative effects of strong solar interference on ASKAP data and,
- reduce unwanted downstream effects on imaging of bright sources outside of ASKAP’s FoVs.

There is also scope to do a second round of subspace projection to remove weak correlated RFI from the visibilities. There is an open question about what the effects of the changes to the beamshape’s sidelobes will have on downstream processing, in particular for widefield imaging, which requires a stable and well-characterised beam pattern for deconvolution.

Finally, this thesis could inform future upgrades to the ASKAP PAF or make recommendations, including the use of integer flags for discerning the cause of the data being flagged and the benefits for RFI mitigation of cached ACMs and using all ports for beamforming. Furthermore, which bands of the spectrum are expected to be lost due to LEO mega-constellations and which should be able to be recovered using the methods and tools outlined in Chapter 5.

The developments made here, in implementing oblique projection using ASKAP's PAF for dynamic RFI, will ensure that we are more prepared to meet the challenges ahead in an increasingly more difficult RFI environment. It is exciting and timely to see spatial nulling slowly moving from the literature into telescope operations, ultimately reducing the amount of discarded data and improving the quality of ASKAP's scientific conclusions.

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Appendices

A The radio regulations revisited

The predecessor of the International Telecommunication Union (ITU) (the International Telegraph Union) was founded in 1865 to facilitate international connectivity in communications networks. Between November 1947 and January 1949 the ITU entered into an agreement and entered the United Nations as a specialised agency tasked with allocating the global radio spectrum and orbits (both geostationary and non-geostationary satellites), developing the technical standards, ensuring communication networks and technologies interconnect, and aim to “strive to improve access to ICTs to underserved communities worldwide” [64]. Now based in Geneva, the ITU is comprised of three sectors of which the ITU-R specifically regulates the radio spectrum. The International Consultative Committee on Radio (CCIR) (established in 1927) became the ITU-R in 1993 [43].

Frequency allocations in the Radio Regulations (RRs)

The frequency allocations themselves are contained in Volume 1, Chapter II, Article 5 of the RRs [55].

Article 5 can most easily be understood as a series of sequential tables. An excerpt from Article 5 that defines a radio astronomy service (RAS) protected band is shown in Figure 6.1. Each table, in turn, describes a sub-band of the spectrum. Rows correspond to further frequency divisions in that sub-band and columns show the three geographical regions’ allocations are divided [55]:

- Region I - Europe, Africa and northern Asia;
- Region II - North America and South America;
- Region III - southern Asia and Australasia.

The RRs include varying levels of allocation with decreasing levels of protection:

- **PRIMARY** allocations provide legal protection from interference, but the allocation may not be exclusive;
- **Secondary** allocations have no legal protection from interference caused by services with a PRIMARY allocation in the same band. Given the passive nature of radio astronomy, secondary allocations to RAS provide limited practical protection;
- **Footnotes** provide additional information and often provide protection to particular services on a primary or secondary basis [56]. Footnotes do not provide the same legal protection as table allocations but have proven valuable in coordination with other services [43].

1 610-1 660 MHz

Allocation to services		
Region 1	Region 2	Region 3
1 610-1 610.6 MOBILE-SATELLITE (Earth-to-space) 5.351A AERONAUTICAL RADIONAVIGATION 5.341 5.355 5.359 5.364 5.366 5.367 5.368 5.369 5.371 5.372	1 610-1 610.6 MOBILE-SATELLITE (Earth-to-space) 5.351A AERONAUTICAL RADIONAVIGATION RADIODETERMINATION- SATELLITE (Earth-to-space) 5.341 5.364 5.366 5.367 5.368 5.370 5.372	1 610-1 610.6 MOBILE-SATELLITE (Earth-to-space) 5.351A AERONAUTICAL RADIONAVIGATION Radiodetermination-satellite (Earth-to-space) 5.341 5.355 5.359 5.364 5.366 5.367 5.368 5.369 5.372
1 610.6-1 613.8 MOBILE-SATELLITE (Earth-to-space) 5.351A RADIO ASTRONOMY AERONAUTICAL RADIONAVIGATION 5.149 5.341 5.355 5.359 5.364 5.366 5.367 5.368 5.369 5.371 5.372	1 610.6-1 613.8 MOBILE-SATELLITE (Earth-to-space) 5.351A RADIO ASTRONOMY AERONAUTICAL RADIONAVIGATION RADIODETERMINATION- SATELLITE (Earth-to-space) 5.149 5.341 5.364 5.366 5.367 5.368 5.370 5.372	1 610.6-1 613.8 MOBILE-SATELLITE (Earth-to-space) 5.351A RADIO ASTRONOMY AERONAUTICAL RADIONAVIGATION Radiodetermination-satellite (Earth-to-space) 5.149 5.341 5.355 5.359 5.364 5.366 5.367 5.368 5.369 5.372

FIGURE 6.1. Radio Regulations Article 5 defines the frequency allocation (per region) as a series of tables like the one above. PRIMARY ALLOCATIONS are identified using uppercase and secondary allocations in lowercase letters. Following a table defining a sub-band of the radio spectrum is a series of footnotes that provide additional information. [16]

Within each cell, the PRIMARY SERVICE ALLOCATIONS are identified in uppercase and the secondary allocations in lowercase [16]. Following a table that defines a subband of the radio spectrum is a series of footnotes that provide additional information. In the example shown in Figure 6.1 footnote 5.149, for example, states “... *administrations are urged to take all practicable steps to protect the radio astronomy service from harmful interference. Emissions from spaceborne or airborne stations can be particularly serious sources of interference to the radio astronomy service...*” [16, 56].

World Radio Conferences (WRCs) and radio astronomy interest groups

RRs are the result of World Radio Conferences (WRCs), formerly World Administrative Radio Conferences (WARCs). WRCs are held every three to four years to review, and, if necessary, revise the RRs. Revisions are made on the basis of an agenda determined by the ITU Council [56]. Only member state administrations have voting rights and may present proposals, however other stakeholders try to influence the outcome of the various agenda items [56]. Co-ordinating the case for radio astronomy (and Space Science) is done internationally by the Scientific Committee on Frequency Allocations for Radio Astronomy and Space Science (IUCAF)¹. IUCAF participates in WRCs as a recognized international sector member, but has no voting rights [55]. IUCAF under the auspices of the International Science Council that operates under the aegis of the United Nations (UN) Educational, Scientific, and Cultural Organization (UNESCO) [56]. IUCAF was formed by the following scientific unions in 1960 to represent scientific usage of the radio spectrum [55]:

- The International Astronomical Union (IAU)²,
- the International Union of Radio Science (URSI)³
 - in particular *Commission J*: radio astronomy,
- the Committee on Space Research (COSPAR)⁴

¹<http://www.iucaf.org/index.htm>

²<https://www.iau.org>

³<https://ursi.org/homepage.php>

⁴<https://cosparhq.cnes.fr>

Regionally, IUCAF regional committees, advocate for the spectrum management concerns of the radio astronomy community [43]:

- Committee on Radio Frequencies (CORF)⁵ founded in 1961 (Region II) [56] and,
- Committee on Radio Astronomy Frequencies of the European Science Foundation (CRAF)⁶ founded in 1988 (Region I) [43],
- Radio Astronomy Frequency Committee in the Asia-Pacific region (RAFCAP)⁷ founded in 2001 (Region III).

Figure 1.1 of [55] has an excellent diagram of the inter-relationships between international agencies involved in frequency coordination for the RAS. The ITU *Handbook on Radio Astronomy* [55] also recommends *World Radiocommunication Conferences* by T. Gergely in [177] for a complete description of how astronomers participate in WRCs.

Study groups are set up by a ITU-R Assembly to examine questions and prepare draft recommendations on the technical, operational, and regulatory/procedural aspects of radiocommunications [177]. Working party WP7D is the section within ITU-R Study Group 7 that is responsible for radio astronomy [55] (and the search for extraterrestrial intelligence (SETI)). [56] describes an extensive system of formal documents created by the ITU-R by study groups and working parties in the following categories:

- *Questions*—which specify the subjects to be studied within the study groups,
 - Questions are organised into categories of priority and earmarked as a priority for either a WRC or study group
- *Recommendations* and reports—which record the conclusions from these studies,
- *Regulations*—which are adopted by adhering administrations and have treaty status.
 - and footnotes.

⁵<https://www.nationalacademies.org/our-work/committee-on-radio-frequencies>

⁶<https://www.craf.eu>

⁷<https://www.atnf.csiro.au/rafcap/>

Recommendations may be approved between WRCs or at an ITU-R Assembly, which is held just before a WRC. Relevant recommendations from the ITU-R Recommendations series are discussed in the following sub section. New observatories must also be registered with the ITU-R.

Noteworthy outcomes of WRCs for radio astronomy

The recognition of RAS at WRC-59 is a historic milestone, establishing a legal foundation for seeking protection against radio frequency interference (RFI) [43]. Thompson [68] highlights particular ITU-R recommendations that are important to radio astronomy, of which I have selected a limited number of the most relevant ITU-R recommendations in the two following categories upon which this subsection elaborates:

- (1) protection for frequencies used by radio astronomy and protection criteria,
- (2) unwanted emissions.

1) Protection criteria

Recommendation ITU-R RA.769-2 (2003), first published in 1992, *Protection criteria used for radio astronomical measurements* estimate interference threshold levels [40]. Threshold levels are in terms of power flux density and spectral power flux density that are detrimental to radio astronomy. Thresholds consider the instrument sensitivity, long integration times, propagation distance due to ducting and satellite transmissions [68]. ITU-R RA.769 is used to define the upper limit of interference by planes and satellites given specified heights and integration times, as well as terrestrial transmitters, determining the size of (radio-quiet) coordination zones [55]. A thorough overview of how the detrimental thresholds are calculated is given in [68]. Annex 1 of RA.769 which outlines the method of determining threshold levels of interference originate from CCIR Report 224-1 (1966) [55].

Recommendation ITU-R RA.1513-2 (2015), first published in 2001, *Levels of data loss to radio astronomy observations and percentage-of-time criteria resulting from degradation by interference for frequency bands allocated to the radio astronomy service on a primary basis*. [178] states the maximum percentage of data loss as a fraction of time during which transmissions from any one service into a RAS exceeding the thresholds in RA.769 should not exceed 2 %. Furthermore the aggregate emission from all services within the radio astronomy band should not exceed 5 % [56]. This particular recommendation is important for Chapter 3 of this thesis.

2) Unwanted emission

Unwanted emissions of three types are discussed in [68]; from transmitters in RAS adjacent bands, spurious emissions and resulting from wideband digital modulation.

Recommendation ITU-R RA.517-4 (2006), first published in 1978, *Protection of the radio astronomy service from transmitters operating in adjacent bands* [179]. Specifically relating to emissions from bands immediately adjacent to a RAS band, in particular where the adjacent is satellite or airborne transmission, pose a significant threat to RAS. RA.517 recommends that filters by existing transmitters and by radio astronomy receivers should be used at the edge of the band. Furthermore, that future allocations adjacent to radio astronomy should be carefully considered to limit interference from adjacent bands because the likelihood of any service causing such interference depends strongly upon the nature of the transmissions [56]. High power transmitters may cause inter-modulation products in the adjacent band. The annex in the recommendation contains a list of services adjacent to RAS bands that could cause RFI [68].

Recommendation ITU-R RA.611-4 (2006), first published in 1986, *Protection of the radio astronomy service from spurious emissions* [180]. [68] defines *spurious* as “unwanted emissions that fall outside of a bandwidth of ± 2.5 times the necessary bandwidth for the system concerned”. In short, this RFI is due to modulation techniques with inadequate

filtering, which appear in RAS with the transmission frequency/allocation ‘far’ in frequency from the spurious emission. Appendix 8 of the RR gives the maximum permitted loss of spurious emission relating to thresholds in RA.769. To minimize this RFI, radio-quiet zones are encouraged and reduce the gain of sidelobes. With regards to geostationary satellites, RA.611 states that interference should be low enough within 5° of the geostationary orbit. Note that radio-quiet zones and geostationary satellites are discussed in further detail in forthcoming subsections.

Finally, Recommendation ITU-R RA.1237-2 (2010), first published in 1997, *Protection of the radio astronomy service from unwanted emissions resulting from applications of wideband digital modulation* [181]. [68] points out that the distinction between out-of-band and spurious emission, as defined in Article 1 of the RRs is unclear and that practically this unwanted emission is no different from spurious emission. RA.1237 recommends that efforts to reduce the sidebands, which are a product of wideband digital modulation should be taken. The annex shows that for at least two decades, a significant source of RFI is due to emissions from satellites, with thresholds given in the case of a GLONASS satellite [68]. [55] points out the difficulty of distinguishing this type of RFI from cosmic sources of interest.

B The problem of RFI from satellites

Satellites present a unique challenge for radio astronomy because, as highlighted in the previous section, they fall outside the jurisdiction of radio-quiet legislation, which is radio astronomy's primary defence from active radio transmission. The recent development of satellite mega constellations, is of increasing concern. The scale of these constellations will exasperate an already — unresolved — significant risk to radio astronomy. Of course, these satellites must exist on the radio, and radio waves easily penetrate the atmosphere. Satellites are a particular problem because of line-of-sight propagation, and the need to minimize weight in satellites can make filters expensive [56]. In general terms, satellites receive (downlink) and transmit (uplink) signals many orders of magnitude more powerful than the noise floor of radio telescopes, but it is particularly the downlink that affects radio astronomy.

RFI from satellites ($[.]_S$) to radio telescopes ($[.]_T$) can therefore follow the following permutations of main-beam (M) and side-lobe (s):

- | | |
|-------------------------|-------------------------|
| • $M_S \rightarrow M_T$ | • $s_S \rightarrow M_T$ |
| • $M_S \rightarrow s_T$ | • $s_S \rightarrow s_T$ |

Powerful RFI, for example, in the M-M case, can destroy telescope receivers or cause the receiver to respond non-linearly (i.e. distortion) [56]. Note the mitigation technique proposed in this thesis (§4 and 5), in practice is best suited to RFI entering the telescopes side lobes.

There are various types of satellites categories worth describing in this section.

1) Geo-stationary satellites ($\approx 35\,000$ km),

- each nation gets an allocation in their country's field of view.
- Examples of geo-stationary satellites are:
 - meteorology satellites;

- satellite navigation systems augmentation⁸ and;
 - satellite communication satellites, including the service provider
 - * Thuraya.
 - These satellites will always be in the same position in the sky from the telescopes point of view.
- 2) Non-geo-stationary can be divided in to two categories:
- Medium Earth Orbit (MEO) satellites (5000 km to 10 000 km)⁹ [43],
 - examples of which are,
 - * satellite communications systems and
 - * satellite navigation systems including;
 - Global Positioning Satellite (GPS), USA;
 - GLObalnaya NAvigatsionnaya Sputnikovaya Sistema (GLONASS), Russia;
 - Galileo, Europe and;
 - Beidou, China ¹⁰.
 - Low Earth Orbit (LEO) constellations (150 km to 1500 km) [43]
 - require a high density of satellites because they have a small field of view.
 - They are close to Earth to because of the low latency and less energy needed to get the units into orbit.
 - Examples of LEO satellites are,
 - * satellite internet mega-constellations;
 - * Earth observation satellites.
 - * satellite communication systems including;
 - Iridium and
 - GlobalStar.

The explicitly listed examples in the list above have been included because they operate globally and in Australian SKA Pathfinder (ASKAP)'s frequency range.

⁸The Indian and Japanese regional navigation services are entirely geo-stationary.

⁹Other references have this going up to 20 000 km [182].

¹⁰Beidou also has geo-stationary components.

Large and mega Satellite constellations

Mega constellations as systems with more than 1000 satellites and large constellations as systems with between 50 – 1000 satellites [183]. In addition to the LEO constellations already mentioned in the list above, the following are examples of large constellations;

- Keplar,
- Bluewalker,
- Lynk,

and mega-constellations;

- OneWeb,
- Starlink (SpaceX),
- Kuiper.

See [183] for an up to date complete list and statistics of the various large and mega Satellite constellations services.

Satellite constellations, particularly at the scale of mega-constellations, pose a significant risk to both optical and radio astronomy [184–186]. An excellent resource on the topic is the United States Government Accountability Office 2022 Report to Congressional Addressees on “*Large Constellations of Satellites*” [187]. As a result of the problem of satellite constellations the SKA Observatory (SKAO) and NOIRLab ¹¹ on behalf of the radio and optical astronomy community, respectively, as well as the International Astronomical Union (IAU), have formed the IAU Centre for the Protection of the Dark and Quiet Sky from Satellite Constellation Interference (CPS) “*to help mitigate the negative impact of satellite constellations on ground-based optical and radio astronomy observations as well as on humanity’s enjoyment of the night sky.*”

¹¹the United States’s NSF’s centre for ground-based optical astronomy

The last part of the previous sentence relates to astronomy's economic impact and cultural significance, discussed at the beginning of the chapter. I want to highlight two papers that deal specifically with the economic and cultural impact and risk of large constellations. [188] discusses the dollar cost constellations will have on (optical) surveys due to integrating for longer to get to the required sensitivities after discarding more data due to large-scale constellations. [189] has coined the term *Noctalgia* or 'sky-grief' to describe all we stand to lose as a result of changes to the sky due to large satellite constellations.

For L-Band telescopes like ASKAP, 'direct-to-cell' is a concern. Currently, certain allocations (FIXED/MOBILE) of the frequency spectrum in L-Band are limited to ground-based transmission for our mobile phones. As discussed, transmissions from base stations can be mitigated through the use of radio-quiet zones. This new 'direct-to-cell' technology will use LEO satellites — which radio quiet zones do not currently provide any protection from — in the FIXED/MOBILE bands. Bluewalker, Lynk and SpaceX are all testing 'direct-to-cell'. The latter two have had experiments in Australia in ASKAP's frequency band [190, 191].

In addition to the interference from the transmitter of these satellites, there are two other considerations with regard to large satellite constellations. 1) unintended electromagnetic radiation (UEMR), which is emission outside the service allocation of the intended transmission [47, 48]. 2) If enough of the field of view is blocked by satellites continually passing through, there will also be negative impacts on the flux.

Different legislation is required for transmitters in space as current legislation does not extend to space. The primary legislation pertaining to satellites is the 1967 Outer Space Treaty coordinated by Committee on the Peaceful Uses of Outer Space (COPUOS) [43]. [43] lists Articles I, VI, VII, VIII, IX as being relevant for the protection of radio astronomy, as well as the 1971 Liability Convention and the 1974 Registration Convention. Of these it cites Articles VI, VII of the Outer Space Treaty as being the most relevant. Article VI requires that non-governmental entities (private companies) obtain authorization and ongoing supervision from the state(s) for their space activities. Article VII is the counterpart of Article VI on

the matter of liability. Finally, CRAF points out that whilst the Outer Space Treaty is more fundamental than the RRs the Outer Space Treaty is also far more general. The generic use of terms like “exploration” and “damage” could be extended to protect radio astronomy from RFI. Committee on Space Research (COSPAR) could advocate on behalf of the passive services.

Most recently at the WRC 2024 The following agenda item has been included for WRC 2027 *Technical and regulatory provisions necessary to protect radio astronomy operating in specific Radio Quiet Zones from radio-frequency interference caused by systems in the non-geostationary-satellite orbit* [192–194]. The inclusion of this agenda item means that in the years leading up to WRC 2027 ITU-R WP7D will investigate the issue and make recommendations. Similarly COPUOS’ Scientific and Technical Subcommittee has also added an agenda item for their next meeting in five years *Dark and Quiet Skies, astronomy and large constellations: addressing emerging issues and challenges* [195, 196].

C Development of phased array feeds for radio astronomy

There are different arrays used in radio astronomy. Interferometric arrays are multiple radio telescopes that work together as one. Synthesis imaging arrays measure correlations between sparse, typically single-dish parabolic telescopes with single-pixel feed horns at the focus of each reflector. Phased arrays use beamforming (often digital) to steer multiple beams on the sky.

We have also already seen that, while pivotal in early radio astronomy, by 1960, phased arrays became less popular than parabolic dish telescopes with feed horns, which proved more reliable at the time [34, 84, 197]. However, the cost and advances in network throughput, storage, and compute have made phased arrays at scale more realistic for radio astronomy, especially for low-frequency astronomy (hundreds of megahertz or less) [34, 84]. Phased arrays have also seen more development in other radio communication applications because of their multibeam flexibility [39].

Since the 2000s — primarily due to the SKA [198] — this new generation of dense phased arrays, which point directly up at the sky, are called aperture arrays [34, 84]. As the size of the individual antenna elements and the distance between them is reduced, the frequency of electromagnetic (EM) waves that they can detect increases. At approximately mid-Ultra-High Frequency (UHF) and L-Band frequencies, the element’s spacing and array size start to make it feasible to put the densely packed phased array at the focus of a reflector, which we call a PAF¹².

Because a phased array feed (PAF) is in the focal plane of the reflector, it is also a focal plane array (FPA). PAFs can be used on a single-dish telescope or as part of an interferometer. Early PAF designs included work by Fisher at the U.S. National Radio Astronomy Observatory (NRAO) as early as 1996 [199, 200]. In 2007, ASKAP was proposed¹³, construction started in 2012, and the commissioning began with 6 antennas in 2013 [201]. The last of the PAFs

¹²This terminology starts to be used from about 2005 [197]

¹³https://www.atnf.csiro.au/news/ASKAP_ATNF.pdf

was installed in 2016, pilot surveys commenced in 2019, and since 2022 ASKAP has been fully operational [202].

From 2007 through 2011 NRAO and Bringham Young University (BYU) proposed and realised an experimental 19 element PAF [5, 139], and in 2010 APERTure Tile in Focus (APERTIF) a PAF to replace the horn feeds of the Westerbork Synthesis Radio Telescope (WSRT) was already under development [203]. Table 6.1 provides a summary of past and currently operational PAFs, as well as aperture arrays at higher frequencies.

I recommend Warnick’s 2016 [84] and Ekers 2022 [197] for historical developments in aperture arrays, PAFs and FPAs. For a comprehensive source on PAFs see Warnick 2018 [39] or Jeffs 2008 [5] for a summary.

At the same time PAFs were being developed complimentary techniques in RFI mitigation have also continued to be developed (§2.4). A significant driver in the increased prevalence, significant research and development of PAFs in radio astronomy has been due to their potential RFI mitigation capabilities. This, along with their other benefits (survey speed and wide field-of-view (FoV)) and the challenges identified by Jeffs et al. in 2008 [5] largely worked out mean the next generation of PAFs are already under in development, and presented in Table 6.2. These next generation PAFs, will mostly retro fit existing single dishes, many are cryogenically cooled and feature graphical processing unit (GPU) backends. One example of these recievers is the Parkes cryoPAF [14] which the research in this thesis could be extended to. This will be a crogenically cooled 196 ‘rocket’ element PAF with 40 dual-polarized beams and a frequency range of 1.3 - 1.72 GHz and a 305 GHz instantaneous bandwidth, currently being developed by the CSIRO [14].

Potential PAFs not included in Tables 6.1 & 6.2 at various stages of development include a PAF for Five-hundred-meter Aperture Spherical radio Telescope (FAST) [84, 204, 205], for the Giant Metrewave Radio Telescope an array of 30×40 m dishes in Pune, India and finally a PAF demonstrator for the Thai National Radio Telescope [144].

TABLE 6.1. Past and Current High Frequency PAFs and phased arrays.

Name and Description	Research Group(s)	Telescope (site)	Frequency (MHz)	RFI Mitigation	Approximate Dates	References
19 Sinuous antennas	NRAO	PAF - Single dish, Green Bank 43 m WV, USA	1400	-	2000	[200]
FARADAY 2 beam 112 Vivaldi element demonstrator	ASTRON	PAF - array, WSRT14×25 m dishes Westerborg, NL	2000 – 5000	-	2002	[206]
THEA 256 Vivaldi element demonstrator	ASTRON	aperture array, Dwingeloo, NL	600 – 1700	-	2002	[84]
PHAROS 4 beam 144 Vivaldi element demonstrator	ASTRON, JBO, INAF, MECSA, TCfA & CSIRO	PAF - Single dish, Jodrell Bank Observatory, Cheshire, UK	4000 – 8000	-	2007	[84]
APERTIF 40 beam, 121 single polarised Vivaldi element 300 MHz instantaneous bandwidth, 37 Beams FPGA backend, SKA pathfinder	ASTRON	PAF - array, WSRT 14×25 m dishes Westerborg, NL	1130 – 1750	-	2008 2019 Operational	[203]
PHased-Array feed Demonstrator (PHAD) Engineering proof-of-concept with modular design, 180 Element Vivaldi elements FPGA backend, superseded by AFAD	DRAO	PAF - Single dish, Penticton 10 m, BC, CA	1000 – 2000	-	2009	[207, 208]
FLAG dipole elements, 11 beams cryogenic, FPGA backend	BYU & NRAO	PAF - Single Dish, Green Bank 20 m, WV, USA	1200 – 1600	-	2011	[5, 84, 139]
EMBRACE 256 element demonstrator	ASTRON	aperture array, Westerborg, NL & Nançay, FR	500 – 1500	-	2012	[84]
AO40 cryogenic 92 dual polarization dipole elements 300 MHz instantaneous bandwidth	Cornell & BYU	PAF - Fixed Single dish, Arecibo 305 m, PR, USA	1280 – 1680	-	2013	[84, 209]
MKII PAF 36 dual polarized beams, 188 element chequerboard, 300 MHz instantaneous bandwidth FPGA backend	CSIRO	PAF - array, ASKAP 36×12 m dishes WA, AU	700 – 1800	[7, 142, 210]	2012 [131] – 2021 [38] - 2012 BETA [201] - 2016 Murriyang 64 m [142] - 2017 Effelsberg 100 m [211] 2022 Operational	[38]

TABLE 6.2. High Frequency PAFs in development

Name and Description	Research Group(s)	Telescope
Advanced L-band Phased Array Camera for Astronomy (ALPACA) cryogenically cooled 69-element dual-polarized broadband dipole array 40 dual polarised, 1.3 - 1.72 GHz, 305 GHz instantaneous bandwidth GPU Backend	BYU & Cornell	Single Dish 100 m Green Bank Telescope (GBT)
Parkes cryoPAF [14] cryogenically cooled 196-element rocket antenna 72 dual polarised beams, 0.7 - 1.9 GHz, 307.2 MHz instantaneous bandwidth FPGA and GPU Backend	CSIRO	Single Dish 64 m Parkes Radio Telescope
Pharos2: C-band cryoPAF 220-element Vivaldi array 40 full-Stokes beams, 4.75 - 6 GHz, 1.25 GHz instantaneous bandwidth GPU Backend	Jodrell Bank Observatory (UK) INAF (IT) Chalmers University of Technology (SE) ASTRON (NL)	Single Dish 64 m Sardinia Radio Telescope
First generation Cryo-PAF for Effelsberg cryogenically cooled 256-element dual-polarised broadband dipole array 40 full-Stokes beams, 1.3 - 2 GHz, 305 MHz instantaneous bandwidth FPGA and GPU Backend	MPIfR	Single Dish Effelsberg 100 m telescope

For more information, see Abstracts and Presentations from the Phased Array Feed & Advanced Receiver Workshop 2022 [144] and 2024 [212].

D Effects of changes in phase on spatial nulling

In the process of constructing the model, we considered two instances of self-generated RFI; a uniform amplitude arriving at all ports with and without a random phase, i.e. randomised and aligned phase, respectively. Figure 6.2 shows an X polarisation beam centred in the direction -2.4° , before and after mitigation. Figure 6.2 shows an X polarisation beam centred in the direction -2.4° , before and after mitigation.

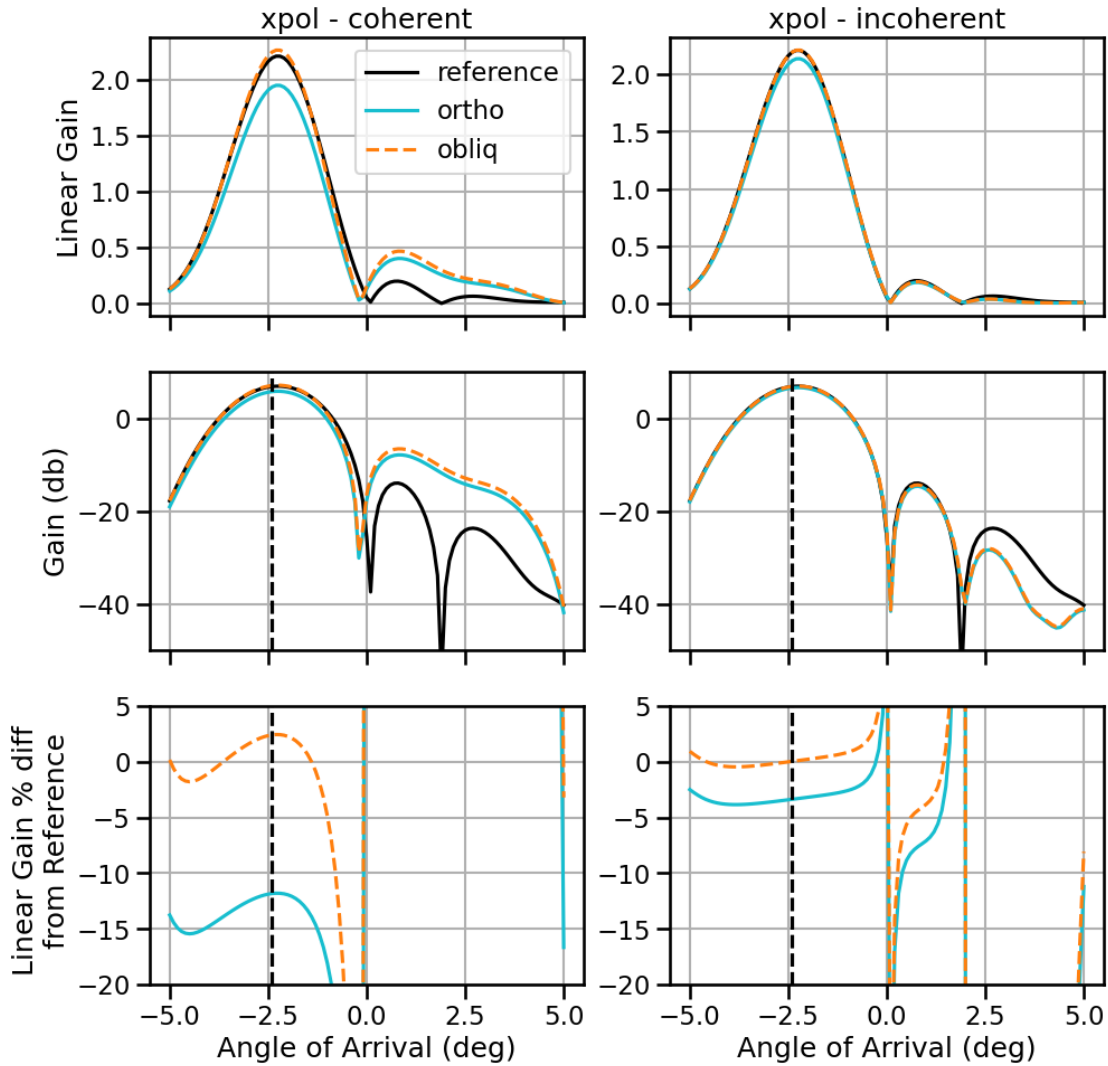


FIGURE 6.2. X polarisation beamformed response in the direction -2.4° , before and after mitigation, showing that variations to the beampatterns are reduced when the phase of the generated signal is randomised. The rows show the linear gain, gain in decibels and the percentage difference in linear gain compared to the unmitigated beam.

Changes to the beam based on an RFI spatial signature with aligned phase on the left and randomised phase on the right are shown using both the orthogonal and oblique projections. The rows show the linear gain, gain in decibels and the percentage difference in linear gain to the unmitigated beam respectively. After mitigation, more significant variations to the beam patterns were observed in both the main lobe and the outer lobes without a uniform phase compared to a random phase, where variations were most pronounced starting at the second null and an almost complete agreement between the reference and projected beamformed patterns in the main lobe and first side lobe. Although, the top left panel of Figure 6.2 shows that the oblique projection corrects for the error in the main beam experienced by the orthogonal projection when the RFI subspace is randomised in phase. Variations to the beam patterns are reduced when the phase of the generated signal is randomised. The measured RFI spatial signature in Figure 4.4 is consistent with a clock signal arriving at the PAF ports with differing delays along the signal path of each port. The delay differences are dominated by random digital delays that are introduced each time ASKAP's digital receivers are reset.