Astronomy in Focus
XXXIInd IAU General Assembly, August 2024
Diana M. Worrall, ed.
doi:10.1017/S174392132500033X

Real-time RFI Excision Techniques and their limitations

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Abstract. Radio Frequency Interference (RFI) poses a formidable challenge for the current and upcoming radio telescopes operating in the sub-Gigahertz and Gigahertz frequencies. Traditionally, RFI excision has been carried out offline on recorded data. While these software methods help in excising RFI, they lead to more data loss of astronomical data and do not work effectively for all types of RFI. With the advancement of semiconductor technology, signal processing hardware platforms like Field Programmable Gate Arrays (FPGA) provide a large number of resources and computational capabilities for real-time implementation of RFI excision systems. One of the major challenges in hardware implementation is the optimization required to meet the resource and timing requirements while dealing with finite precision arithmetic. A wide range of RFI excision techniques in time, frequency, and spatial domains have been implemented in the signal processing backends of various radio telescopes. We provide an overview of these techniques, including challenges in implementing, testing, and commissioning.

Keywords. radio frequence interference, radio telescopes

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https://doi.org/10.1017/S174392132500033X Published online by Cambridge University Press

1. An Overview of Real-time RFI Excision Techniques

Contemporary real-time RFI mitigation is carried out at different stages, primarily using regulatory and technical approaches. Regulatory approaches include spectrum management, radio quiet zones, and ensuring protection from self-generated RFI. The technical approaches include mitigating RFI in the analog and RF frontend systems, digital signal processing systems, and offline systems.

The signal received by a radio telescope is a combination of the contributions from the astronomical signal and a combination of system and sky background noise. RFI has an additive effect on the signal received by the radio telescope. The key distinguishing properties of RFI are that it is typically orders of magnitude stronger than the astronomical signal, and often non-Gaussian as it carries structured or modulated information. Although some sources (e.g. radar or electrical discharges) may exhibit Gaussian-like characteristics.

The capability of signal processing receiver systems has grown manifold with the advent of high-speed signal processing platforms like Field Programmable Gate Arrays (FPGA) and Graphics Processing Unit (GPU). This has enabled the development of different signal-processing techniques for real-time RFI mitigation algorithms. These are divided into the following four categories.

- Excision: This technique removes strong RFI through statistical methods and is relatively easier to implement in real-time. However, it leads to a larger data loss. The technique is widely used and can be applied to time, frequency, or spatial domains.
- Cancellation: A reference antenna samples the RFI and adaptively subtracts the RFI from the telescope data made of a combination of signal+RFI. This requires additional signal chains, typically one per source of RFI, and additional digital processing resources, but has a lower data loss than Excision.
- Nulling: This technique exploits the spatial signature of an interference source to suppress signals arriving from its direction. It can be implemented in interferometric arrays, phased arrays, and phased-array feeds by forming spatial nulls in the direction of the RFI. While effective, these techniques can impact the fidelity of the recovered astronomical signal, sometimes in non-intuitive ways, particularly when the interference is dynamic or poorly localized.
- Avoidance: Prior spatial information about sources of interference, such as location or trajectories, are exploited to avoid observations in the vicinity of a transmitter to prevent driving the telescope receiver into non-linear regimes or irreversible damages to the receiver.

The techniques that can be used depend on the type and source of RFI which also informs the best location to deploy the mitigation technique in the receiver system.

1.1. *Upgraded GMRT (uGMRT) Case Study*

Giant Metrewave Radio Telescope located 80 km north of Pune in India is an array of thirty, 45m, fully steerable parabolic dishes. The array is spread over an area of 25km. It has been recently upgraded to provide near-seamless coverage from 120 MHz to 1450 MHz, with a maximum instantaneous bandwidth of 400 MHz. uGMRT is affected by broadband and narrowband RFI from various sources like powerlines, communication transmitters, broadcast services, and navigational satellites, to name a few.

Since powerline RFI is broadband, frequency selective filtering in the receiver system cannot be used for mitigation. Hence, we use statistical threshold-based outlier detection and filtering in real-time on digitized time series from each antenna, in the pre-correlation domain.

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The algorithm uses three steps - Estimation, Detection, and Filtering. Robust estimation of the dispersion of the signal is carried out using Median Absolute Deviation (MAD) and its variant. This is followed by threshold estimation and comparison with the threshold values. Any sample outside the threshold is detected as RFI, replaced by a user-defined value, and a flag is generated corresponding to that sample. Several architectural and hardware optimization carried out are described in Buch et al. (2019).

Testing is operated wherein half the antennas pass through the filtering system and their copies without the filtering system. In the simultaneous testing mode, the imaging experiments showed about 3 dB improvement in the noise RMS, particularly on shorter baselines (<0.5 km) with an average filtering of 2-3 % data. Similarly, about 3 times improvement was seen in the SNR for time-domain experimental observation.

After rigorous testing, the system was released in April 2022 for use during the regular GMRT observations. In the last observing cycle, about 520 hours of observing was carried out, which is about 30% of the total observing time.

Current efforts focus on analyzing filtering schemes applied to visibility data, developing algorithms for narrowband RFI mitigation, and porting these methods to different platforms such as CPUs and GPUs. This includes extending the approach of Buch et al. (2023) to the Expanded GMRT and SKA-LFAA projects, as well as incorporating learning-based techniques.

2. RFI Mitigation Strategies at Murriyang, the CSIRO Parkes Radio Telescope

CSIRO Parkes telescope is a single-dish telescope with a 64m diameter parabolic dish antenna. It is the largest single-dish telescope in the Southern Hemisphere. It has been continuously upgraded and will provide frequency coverage from 0.7 to 26 GHz. The future receiver fleet consists of three main receiver systems - UWL, CryoPAF, and UWM-H. These systems are outstanding, always available, and have a continuous frequency coverage. However, due to its wide bandwidth, and in the case of phased array feeds (PAF) with wide field of view, they are susceptible to RFI.

In terms of the signal processing capabilities, Murriyang, the Parkes telescope has one backend end Medusa to take care of all the receiver systems mentioned above. Medusa is a GPU-based, highly flexible backend, with user-defined sampling rate, frequency resolution, phase binning, and support for multi-modal observing.

The current RFI mitigation strategy includes excision using the spectral kurtosis approach which is implemented in quasi real-time on GPU. The algorithm detects non-gaussianity in the data and has been shown to successfully mitigate the RFI from WiFi. This has also been demonstrated on a pulsar observation.

The cryogenically cooled PAF on the Parkes telescopes produces 72, dual-polarisation, steerable beams. This will lead to a 10-30x increase in survey speed and 2 deg^2 field-of-view. Spatial nulling (or beam nulling) using this system has been demonstrated on an observation for mitigating RFI in the L2 band at 1225 MHz (with a bandwidth of 1 MHz). The mitigation on and off plots show a large improvement due to the nulling process Hellbourg et al. (2016). Similarly, improvement is seen using beam nulling for the RFI from GPS satellites in the L5 band (1175 MHz). The technique works for moving or stationary sources of RFI.

3. On the Alleviation of the Impact of Spaceborne RFI on VLBI Results

Very Large Baseline Interferometry (VLBI) observes extragalactic sources. Their emission is much fainter than the emission from artificial satellites. Interference from satellite ranges from mild when a portion of the bandwidth has to be flagged out, to strong when

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a receiver is driven to saturation and all the data from a given source is lost, and catastrophic when satellite emission causes permanent damage to the frontend. An increase in the number of communication satellites and their transmitted power aggravates the problem. The first line of defence is to make a schedule in such a way that directions in the vicinity of those satellites that may cause interference are avoided. This is achieved by generating station- and time-dependent dynamic masks that define the zone of avoidance and using them during schedule preparation.

This approach uses a database with satellite catalogues containing information about the various orbital parameters. It includes two-line element ephemeride of each satellite, that are used for projecting the trajectories and compute the look angles. The threat level is determined based on FCC/ITU filing and look angles.

To demonstrate this, a 0.6m field antenna was deployed at the Goddard Geophysical and Astronomical Observatory (GGAO) at Greenbelt, Maryland, USA. This antenna is colocated with the 12m dish and has a wide beam and large bandwidth (2-18 GHz). The results from dynamic masking are encouraging.

The future scope of this work includes synchronizing this antenna with the 12m dish, incorporating the dynamic mask in the VLBI observing schedule, and developing a website containing information about the dynamic mask.

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