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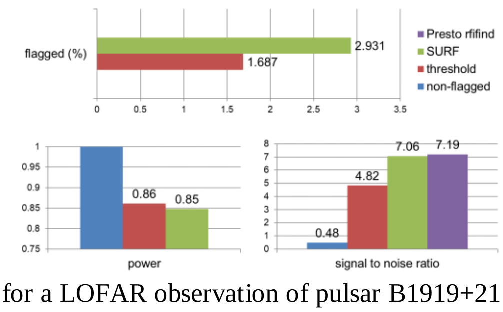
Real-time RFI mitigation for LOFAR, Apertif and SKA

R. van Nieuwpoort*[(1)], J. van Leeuwen[(2)], A. Sclocco[(3)], H. Spreeuw[(4)], and C. Williams[(5)]
(1) Netherlands eScience center & Univ. of Amsterdam; e-mail: R.vanNieuwpoort@esciencecenter.nl
(2) ASTRON & Anton Pannekoek Institute for Astronomy; e-mail: leeuwen@astron.nl
(3) Netherlands eScience center, Amsterdam, The Netherlands; e-mail: A.Sclocco@esciencecenter.nl
(4) Netherlands eScience center, Amsterdam, The Netherlands; e-mail: H.Spreeuw@esciencecenter.nl
(5) University of Oxford, United Kingdom; e-mail: Christopher.Williams@physics.ox.ac.uk

Radio Frequency Interference (RFI) mitigation is extremely important to take advantage of the vastly improved bandwidth, sensitivity, and field-of-view of modern radio telescopes like LOFAR, Apertif (WSRT) and SKA. Due to the high bandwidth requirements, RFI mitigation must be done automatically, and in real-time. In previous work [1], we introduced novel real-time RFI mitigation algorithms that are based on earlier offline methods by Offringa and others [2]. Our approach has the following key design and implementation features.

1) **Real-time**. Our algorithms were designed specifically for real-time mitigation, and fit in different places of real-time processing pipelines. For instance, our LOFAR prototype can perform mitigation before and after the correlator, and before or after the beam former. In the current SKA time domain prototype, a part of the Central Signal Processor (CSP), we only perform post-beam forming RFI mitigation in software. Because of real-time computational and memory restrictions, our algorithms are designed to work with only very little data. This typically means time windows of only one second or less, and only few frequency channels. The latter is because frequency channels are often distributed over different compute nodes. Therefore, our algorithms keep statistics about past signal properties to improve mitigation performance.
2) **High-performance.** Our algorithms are extremely fast, and all methods were chosen or designed such that the computational requirements scale linearly in the number of samples and frequency channels. This is a requirement to meet real-time deadlines, but equally important for power budget considerations. We have versions of the code for CPUs and GPUs. The latter are an order of magnitude faster and more power efficient.
3) **Scale-invariant.** The algorithms are scale-invariant, and work on microsecond to second time scales, and on widely different frequency scales as well. This property is important to make sure the algorithms work in various places in the signal processing pipelines, and on different telescopes.
4) **Generic.** We aim to make the mitigation algorithms as generic as possible, both in terms of software engineering, making it easier to integrate in an existing pipeline codebase, but also for portability to multiple telescopes and multiple science cases (both in the imaging and time domain). Because of this, the implementation works on visibility data, but also on raw voltages, and beam formed data.



We will illustrate these properties by presenting results for LOFAR, initial results for Apertif (WSRT), and our experiences with the SKA central signal processing (CSP) time domain pipeline prototype. RFI is usually intrinsically variable, making it especially detrimental while searching for transient astrophysical signals in time domain data. We thus evaluate the quality of the algorithms with pulsar observations. Using the signal-to-noise ratios of the folded pulse profiles, we can qualitatively and quantitatively compare the impact of different real-time RFI mitigation algorithms. In the figure on the right, we show results for a LOFAR observation of pulsar B1919+21 at 138.0 – 145.2 MHz. Our real-time approach, called SURF for "Scalable Universal Real-time Flagger", performs almost as well as the *offline* Presto `rfifind` method, the de-facto standard in pulsar RFI mitigation.

1. R. van Nieuwpoort, "Towards exascale real-time RFI mitigation.". Proc. of 2016 Radio Frequency Interference, Socorro, New Mexico, USA, Pages 69-74, October 2016, DOI: 10.1109/RFINT.2016.7833534.

2. A.R. Offringa, A.G. de Bruyn, and S. Zaroubi, "Post-correlation filtering techniques for off-axis source and RFI removal". MNRAS, **1**, 422, pp. 563-580, 2012, DOI: 10.1111/j.1365-2966.2012.20633.