Spectral Domain Algorithms For RFI Excision In Real Time

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Abstract

We describe algorithms for real-time radio frequency interference (RFI) excision based on data from a prototype instrument for the Frequency Agile Solar Radiotelescope (FASR), called the FASR Subsystem Testbed (FST). The FST instrument records data over a 500 MHz bandwidth at full time resolution [1], allowing off-line application of various RFI excision algorithms for head-to-head comparison. We describe algorithms operating in the spectral domain [2, 3] that are possible to implement in FPGAs in real time.

1. Introduction

The Frequency Agile Solar Radiotelescope (FASR) is a solar-dedicated radio facility that is now in the design phase. FASR represents a major advance over existing solar radio telescopes and is expected to remain the world's premier solar radio instrument for 2 decades or more after completion. It will use hundreds of antennas to perform broadband imaging spectroscopy over a frequency range of 0.05–20 GHz, with spatial, spectral, and temporal resolutions that are designed to exploit radio diagnostics of the wide variety of physical processes that occur in the solar atmosphere [4]. To construct a prototype and characterize the broadband radio frequency (RF) transmission system and digital signal processing to be used for FASR, we have developed the FASR Subsystem Testbed (FST) [1]. Three antennas of the Owens Valley Solar Array have been modified so that each sends a 1–9 GHz band of radio frequency to a central location using a broadband analog optical fiber link. A dynamically selected 500 MHz subset of this frequency range is digitized at 1 GSps (gigasample per second) and recorded to disk. The full-resolution time-domain data thus recorded are then correlated through offline software to provide interferometric phase and amplitude spectra on three baselines. An important feature of this approach is that the data can be reanalyzed multiple times with different digital signal-processing techniques (e.g., different bit-sampling, windowing, and radio frequency interference [RFI] excision methods) to test the effect of different designs.

We have used the FST data to explore and develop some spectral domain algorithms for detection and excision of RFI, with the aim of implementing the system in real time. In this paper we summarize our previous work and describe new efforts at a real-time implementation on a new system, the Korean Solar Radio Burst Locator (KSRBL) now under development.

2. Summary of Algorithms

The first radio frequency interference (RFI) excision algorithm that we developed [2] was based on spectral kurtosis, a spectral variant of time-domain kurtosis. Kurtosis is based on the 4th moment of the voltage probability distribution function (PDF), which in the spectral domain becomes the square of the power. The algorithm works by providing a robust estimator for Gaussian noise that, when violated, indicates the presence of non-Gaussian RFI. In [2], we developed a theoretical formalism that unifies the well-known time-domain kurtosis estimator with past work related to spectral kurtosis, and leads naturally to a single expression encompassing both. The theoretical analysis is general and should be directly adaptable for many applications in addition to RFI mitigation in radio astronomy.

The main findings in [2] are as follows:

1. There exists a discriminator that we refer to as the spectral kurtosis, which for the special case of Gaussian noise has the value $V_k^2 = 1 + |W_{2k}|^2$, where W is a generally small correction that depends on the windowing function used in the spectral analysis.

2. Using sums S_1 and S_2, which are sums of the first two powers of M PSD estimates, we define a discriminator for Gaussian noise—the spectral kurtosis estimator, $\hat{V}_k^2 = M(MS_2/S_1^2 - 1)/(M-1)$.
3. The value of this SK estimator is unity in most spectral bins, with a variance given approximately (see [2] for an exact expression) by

$$\mathrm{Var}(\hat{V}_k^2) \approx \begin{cases} 24/M, k = 0, N/2, \\ 4/M, k = 1, (N/2-1). \end{cases}$$

where N is the frequency bin (the upper expression refers to the DC and Nyquist frequency bins).

We find that frequency bins containing RFI can be identified if their spectral kurtosis estimator exceeds 3σ, where $\sigma = \sqrt{\mathrm{Var}(\hat{V}_k^2)}$. One problem with the estimator, however, concerns its behavior under intermittent RFI. The estimator is most effective at small duty cycles (i.e. when RFI is present in a small, but not zero, number of PSD estimates), but is blind to RFI with a duty cycle around 50% (i.e. when RFI is present for around 50% of the PSD estimates, and absent for the rest.) To address this issue, we consider in [3] a second RFI discriminator that can be used in concert with the spectral kurtosis estimator.

The second algorithm [3] is based on a generalized likelihood ratio test, and uses the spectral power P equivalent to the sum S_1 above. In our application, a fast Fourier transform (FFT) filter bank is utilized to allow the statistics to be tested at different FFT bins. The ratio considered (see [3] for motivation) is

$$L_G(x) = \left(\frac{\hat{\sigma}_0^2}{\hat{\sigma}_1^2}\right)^{N/2}$$

where $\hat{\sigma}_0^2$ is the expected variance under the hypothesis that there is no RFI, and $\hat{\sigma}_1^2$ is the expected variance under the hypothesis that RFI is present. Because of the Gaussian noise hypothesis, in the spectral domain the mean and variance are expected to be equal. Thus, we replace the variance $\hat{\sigma}_0^2$ with the instantaneous power, $P(\mathrm{x}; f_k)$, on the frequency bin f_k under test, and replace the reference variance $\hat{\sigma}_1^2$ with the instantaneous power, $[P(\mathrm{x}; f_{k-1}) + P(\mathrm{x}; f_{k+1})]/2$, on the adjacent frequency bins f_{k-1} and f_{k+1}. Whether or note the above ratio exceeds an adjustable threshold determines which hypothesis (Gaussian noise or presence of RFI) is true for a given frequency bin f_k. The threshold is settable based on the theoretically determined variance for this problem, given by

$$Var\{T(x; f_k)\} = \frac{3M^2 - M}{2M^3 - 4M^2 + 2M} \approx \frac{3}{2M} \quad \text{(for large } M\text{).}$$

where T is the power ratio discussed above.

This second algorithm has the advantage of giving reasonable sensitivity to RFI with a 50% duty cycle, so that using both algorithms together should provide better performance than either alone.

3. Discussion

We have demonstrated the performance of each algorithm [2,3] using FST data, but did not yet investigate the combined performance. We are currently working on such an investigation using FST data, and plan to implement the combined algorithm in an FPGA-based hardware system for the above-mentioned KSRBL. Although FST records the full-resolution data, making it ideal for investigating RFI algorithms, it has the limitation that sustained recording of data is only possible at a low duty cycle of around 1%. This low duty cycle results in rather long elapsed times (of order 1 s) in order to accumulate sufficient data to develop the statistics needed for reliable RFI detection. The KSRBL system, with instantaneous bandwidth of 2 GHz, will feed the digitized data to an FPGA-based digital signal processor for accumulation and implementation of the RFI excision algorithms in real time, at a rate sufficient to keep up with the incoming data rate. The resulting 100% duty cycle allows the needed statistics to be accumulated in a small fraction of a second (a 25 ms dump time will be used).

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5. References

1. Liu, Z.; Gary, D. E.; Nita, G. M.; White, S. M.; Hurford, G. J., "A Subsystem Test Bed for the Frequency-Agile Solar Radiotelescope," *Publ. Astron. Soc. Pacific*, **119**, 2007, 303.

2. Nita, G. M., Gary, D. E., Liu, Z., Hurford, G. J., White, S. M., "Radio Frequency Interference Excision Using Spectral Domain Statistics," *Publ. Astron. Soc. Pacific*, **119**, 2007, 805.

3. Wang, X., Ge, H., Nita, G. M., Gary, D. E., "Statistical Signal Processing for Radio Frequency Interference Identification in Mixed-Spectrum Solar Data,", 2008, submitted.

4. Gary, D. E., & Keller, C. U., ed., "Solar and Space Weather Radiophysics: Current Status and Future Developments" (Kluwer: Dordrecht), 2004.