Radio Frequency Interference Mitigation

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Report

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Abstract.

The next generation of radio telescopes will achieve unprecedented sensitivity, frequency coverage and resolution. As a consequence of their design goals and the increasing use of the radio spectrum, however, they face unprecedented challenges from radio frequency interference. New techniques for RFI mitigation are essential to the success of these projects. These techniques must be diverse and must be incorporated into all elements of telescope design to accomodate the wide range of interferers and science goals.

Current research has identified a number of promising directions. Simulations, software analysis and prototype hardware have demonstrated significant mitigation of RFI in a few specific circumstances. Few techniques, however, have been tested at a level indicating that they can be implemented in routine observations. Moreover, all methods of mitigation involve compromises in the quality of observations, some of which are substantial.

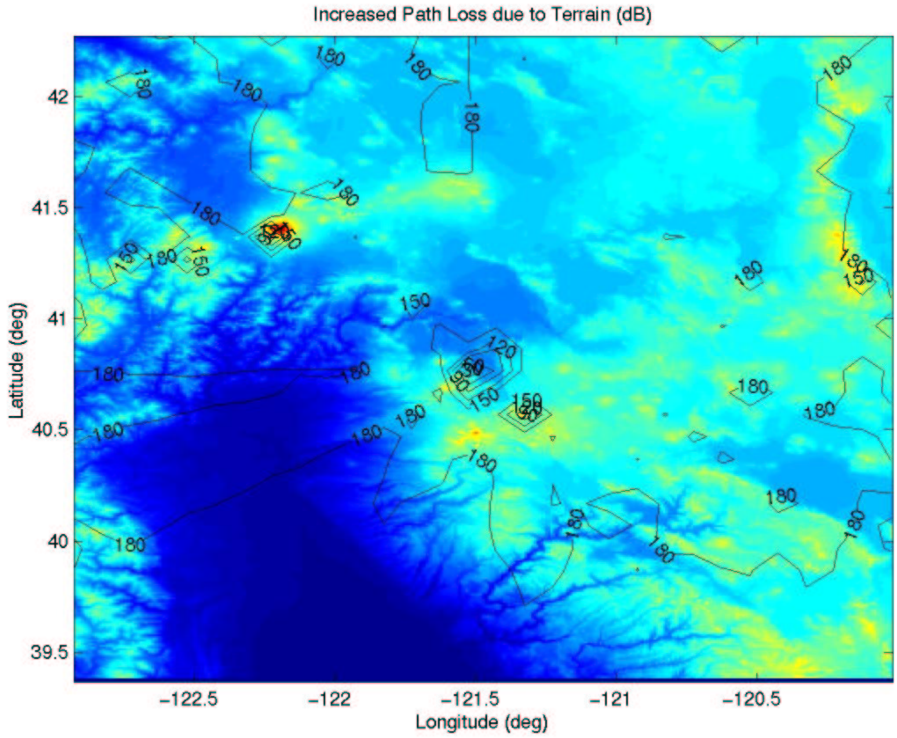
1. The Next Generation of Radio Telescopes and Radio Frequency Interference

Planning is currently under way for a wide range of new radio telescopes that cover frequencies from 100 MHz to 1 THz. These new instruments, principally interferometers, will achieve unprecedented sensitivity and frequency coverage and resolution in their respective bands. They include the Low Frequency Array (LOFAR), the Allen Telescope Array (ATA), the Very Large Array Expansion (EVLA), the Square Kilometer Array (SKA), the Combined Array for Research in Millimeter Astronomy (CARMA) and the Atacama Large Millimeter Array (ALMA). The Green Bank 100m Telescope (GBT) and the upgraded Arecibo dish are also pushing into new parameter space in frequency and sensitivity.

At the same time, active use of the radio frequency spectrum is dramatically increasing, leading to increased interferer power, a higher spectral density of interferers, and a higher temporal density of interferers.

The desire to observe outside of the protected radio astronomy bands as well as to achieve sensitivity beyond protected limits inside the radio astronomy bands drives us to consider radio frequency interference (RFI) mitigation. For instance, Ransom (2003) reports that typically 10-20% and occasionally all of pulsar data obtained in a given day at Arecibo and the GBT are corrupted by RFI. We discuss several RFI problems and the solutions currently under development for the next generation of radio telescopes. There are no "magic bullets" to the problem of RFI. We emphasize a tool box approach to RFI mitigation: different tools for different interferers and different science goals, implemented at all stages of telescope design and operation. The more

Figure 1. Contours of constant attenuation (in dB) due solely to terrain effects for the region surrounding the Hat Creek Radio Observatory. The r^{-2} distance propagation effect has been removed. Terrain effects are calculated according to ITU-526.



we know about a particular interferer and about our cosmic target signal, the more we can mitigate the interference.

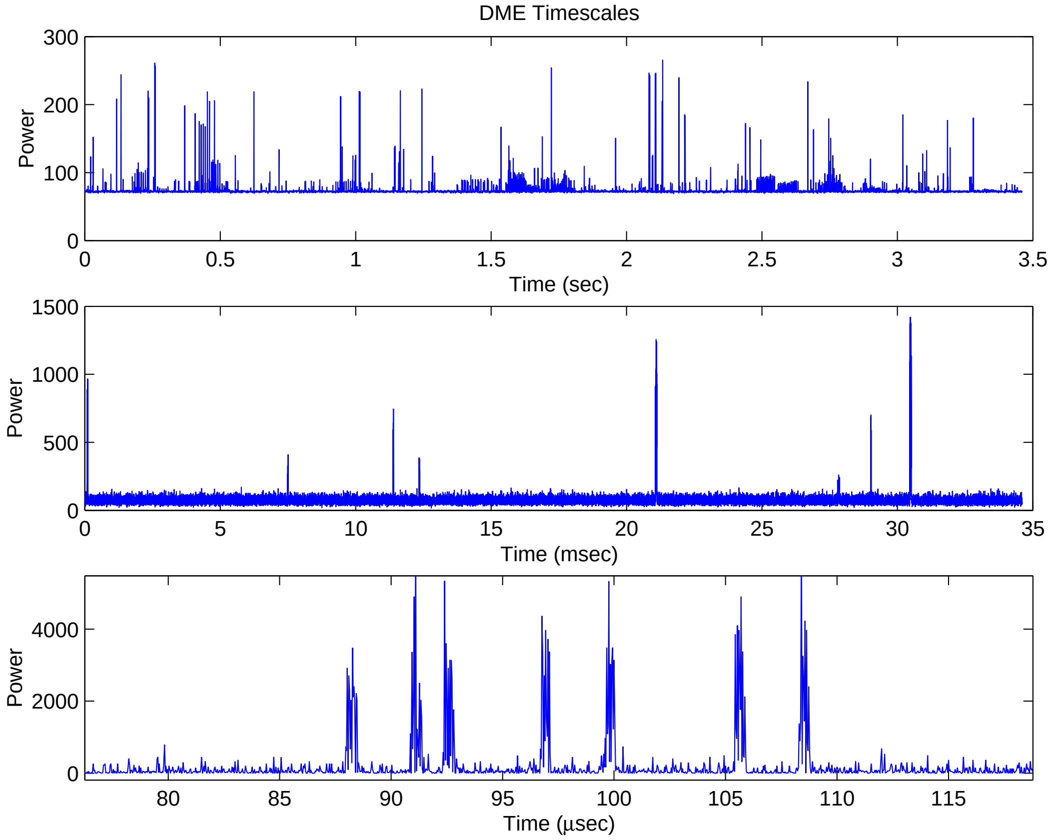
It is not possible to create a comprehensive review of this subject in a few pages without some omissions and simplifications. This paper is intended to give a broad overview of the problems, techniques and goals of interference mitigation research. We recommend that the reader seek out items in the bibliography, as well as consult the general review of Fridman & Baan (2001).

2. The Interference Environment

Site selection is the most important RFI mitigation technique available. Isolation by distance and terrain from population centers can provide substantial reduction of interference. Modeling indicates that terrain suppresses interference by ~ 100 dB above simple propagation loss for both the Hat Creek Radio Observatory and the Green Bank Telescope (Figure 1). Nevertheless, interference from a variety of sources is still present at the site.

RFI monitoring equipment is critical for characterizing the local environment. Typical systems employ a low-gain or isotropic antenna such as a discone

Figure 2. Plot of the time averaged power in one channel of a single DME channel on second, millisecond and microsecond timescales. These results suggest a strategy of time-blanking that could be executed with very high efficiency.



and require monitoring over long periods of time to fully characterize the site. There is a role for both peak power detection as a function of frequency and high-time resolution total power monitoring. The ability to capture samples at microsecond timescales is critical for characterizing interferer types. Among the interferers readily detected are radar, aircraft distance measuring equipment (DME), cellular phone and pager signals, television and radio broadcasts, orbiting satellites such as GPS, GLONASS, DARS and Iridium, geostationary satellites, and local interference from household and office appliances, computers, oscillators and digital electronics. We show as an example the time occupancy from microsecond to day timescales of DME signals (Figure 2). Detailed knowledge of this kind allows us to tailor mitigation strategies to the specific problem.

3. Engineered RFI Mitigation

Low antenna sidelobes are an important line of defense against interference. For instance, the unblocked aperture of the ATA offset Gregorian antenna provides $\sim$ 40 dB rejection of interference signals which are outside of the primary beam.

Receivers must be designed to prevent very strong RFI from saturating amplifiers or other components. Receivers of this type are often called robust receivers (e.g., Tan 1998, Woestenburg, 2001). Since many new receiver designs are instantaneously sensitive over wide frequency ranges, frequencies that are dominated by strong interferers such as FM radio and Iridium cannot be simply avoided. Receivers and downstream electronics must be designed with sufficient headroom, that is, they must be capable of detecting signals much more powerful than the system noise without saturation. To achieve this, digital systems must sample the analog signal with a large number of bits: the ATA will sample 8 bits and LOFAR will sample 14 bits.

Electronic devices including computers, local oscillators and digital electronics must be carefully shielded in laboratories (e.g., Landecker *et al.* 2003) and in antennas. The EVLA project has achieved 110 dB of shielding for samplers located in the vertex room of the antennas (Durand *et al.* 2003).

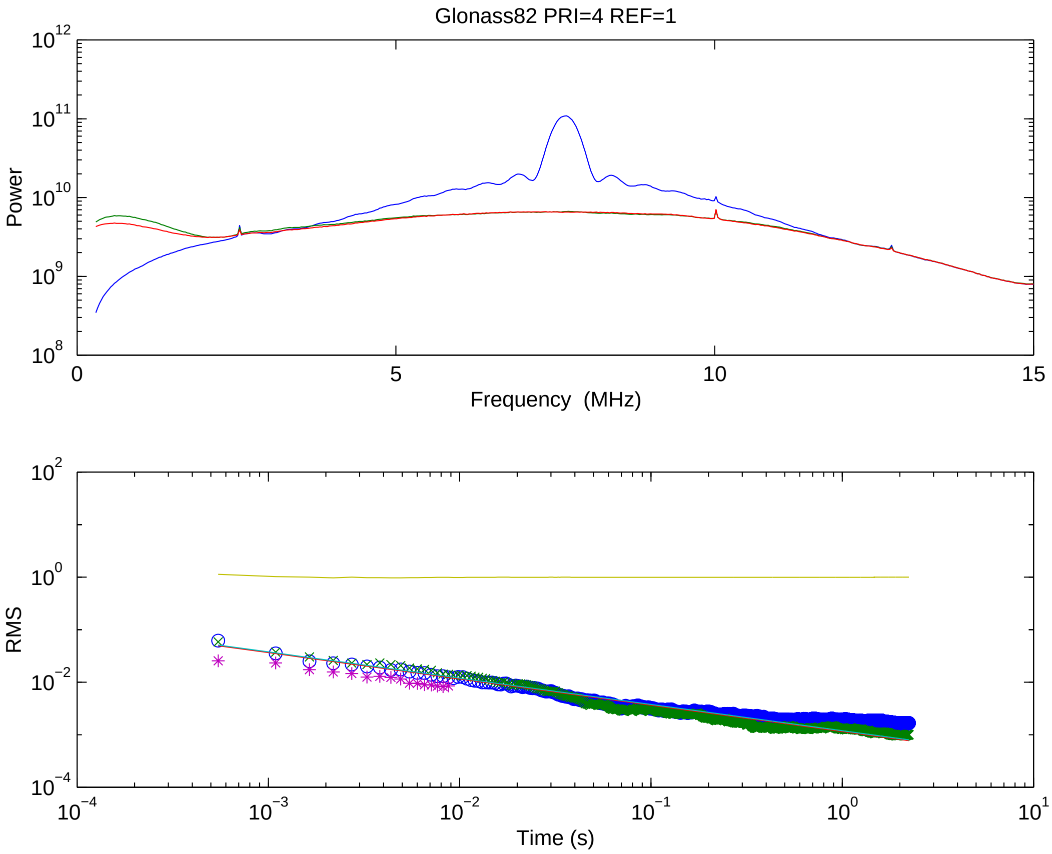
4. Real Time RFI Mitigation

Scheduling is the first layer of defense against interferers in the real time system. To prevent saturation of the ATA front end, for example, artificial horizons will be placed around the most powerful interferers in the sky. Additionally, the use of an RFI monitor permits the scheduling of experiments when particular interferers are quiet. Monitoring has shown that aircraft DME frequencies are typically quiet in the early morning hours.

Active techniques for RFI mitigation can be placed in four categories: time blanking, frequency blanking, adaptive canceling, interferometric nulling, and post-correlation analysis. All of these have a multiplicity of implementations and can be achieved through a variety of algorithms. Many algorithms for these methods can be shown to be analytically identical although the implementation may differ substantially. The development of mathematical formalisms is important for understanding the relationship among these techniques and conventional radio astronomical techniques (e.g., Hamaker, Bregman & Sault 1996, Leshem *et al.* 2000). It is essential to the performance of these algorithms that these techniques be integrated into the analog and digital design of new telescopes.

These methods can be divided into adaptive and *a priori* classes. In general, all adaptive methods achieve better results with stronger RFI. This is a consequence of the fact that the RFI must be independently identified, detected or modeled in order to be removed. RFI with an interference to noise ratio INR < 1 (defined over a time interval appropriate to the method) are difficult to detect and will rapidly accumulate. An important example of an *a priori* method is interferometric nulling of an interferer with a known position and frequency spectrum.

Figure 3. In the top panel, spectrum before (blue line) and after cancellation of a GLONASS signal with a Wiener filter method. We show the residual power spectrum for single (green) and dual (red) polarization cancellation methods. In the bottom panel, blue circles and green crosses indicate the rms residual in the power spectrum from the single and dual polarization modes, respectively. These follow $t^{-1/2}$ laws (red and aqua lines).



4.1. Time Blanking

Radar and aircraft DME occur in the frequency range from 960 - 1400 MHz. Without mitigation, it will be very difficult to observe extragalactic HI at redshifts between 0 and 0.5. While these signals overlap in frequency space with desired astronomy signals, they actually have a very small time occupancy (Figure 2). Ellingson & Hampson (2003) have tested pulse-detection and blanking of radar at Arecibo and achieved 16 dB of suppression but find that undetected pulses limit performance. Multi-path propagation and side-lobe emission from the radar are the principal sources of weak pulses not easily detected or removed. Fridman (2001) has also explored power detection algorithms with WSRT observations of Galactic sources in the presence of a CW interferer. Research by Fisher (2002) at the GBT has demonstrated that a predictive time blanker can observe 90% of the time without corruption by radar signals. This requires sophisticated time-dependent modeling of the radar and local environment including aircraft and rain clouds. Time blanking is not adequate for all science, however. SETI requires a continous time series in order to measure low frequency signals.

4.2. Frequency Blanking

Signals may also be blanked in frequency space either through the use of notch filters or through post-processing algorithms. For example, Ransom *et al.* (2003) and Nice *et al.* (2003) have described methodologies for joint time-frequency blanking in pulsar processing. In general, bad channels are identified through a detection method or through *a priori* knowledge of a known interferer and then removed from a data set. These techniques exploit the dispersion relation that exists for pulsars in order to separate terrestrial interferers.

4.3. Adaptive Canceling

Reference antennas can also be used to implement adaptive canceling (Barnbaum & Bradley 1998, Ellingson et al. 2001). In this technique, a reference signal with a high interference-to-noise ratio is obtained and used to estimate the weaker interference present in the astronomy signal. The estimate is subtracted from the astronomy signal leaving the signal interference free. The estimate can be determined through a Wiener solution, an adaptive LMS method, or parametric estimation as in the case of GPS or Glonass where the interference signal is well-known. These techniques are inherently wideband and are insensitive to multi-path problems. They are ideal for interferers that can be tracked with an antenna: fixed transmitters and satellites with known trajectories. Poulsen *et al.* (2003) have recently tested an LMS canceller with the GBT that employs a 3-m reference antenna. For interferometers, the reference antenna can also be a phased array beam of the main array rather than a separate antenna.

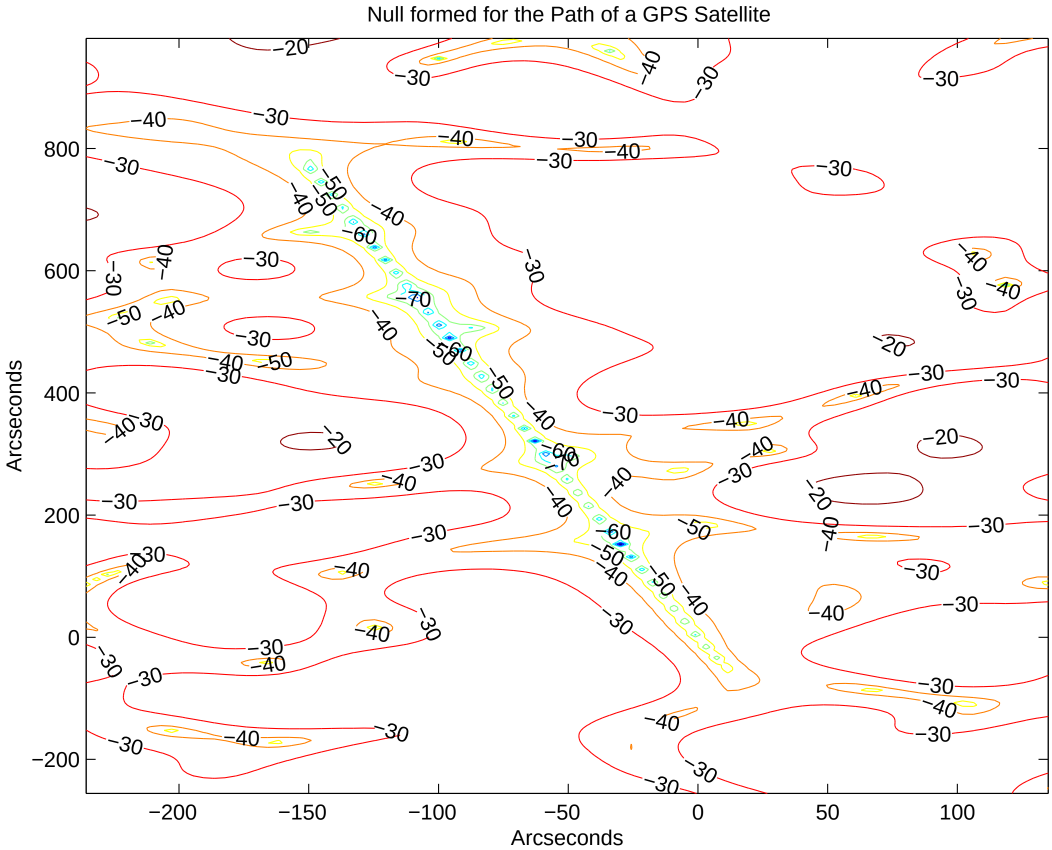
We have tested both the time and frequency-domain Wiener solutions and LMS methods with data obtained at the Rapid Prototyping Array (Bower 2001a, Mitchell & Bower 2001). We can achieve > 30 dB suppression of GPS and GLONASS signals (Figure 3), where the limiting factor in these result is the amount of data that we have obtained, not the algorithm.

This method works best on phased array beams from interferometers and on single dish feeds. Application to an interferometer is possible but requires a cancellation network for each input to the correlator.

4.4. Interferometric Nulling

We can exploit the full power of large$-N$ arrays through the use of interferometric nulling. For interferers in known positions, we can manipulate the complex gains of the array to place a null in the location of the interferer while maintaining most of the gain of the array in the direction of the astronomical source (Bower 2001b, Harp 2002). Since these gains must be updated rapidly for fast moving interferers, the IF processor requires the capability to update the gains every 10 msec in the case of the ATA. Higher rates are necessary for

Figure 4. Null formed for the path of a GPS satellite. Fifty individual nulls were placed along the 1.5 second path of the GPS satellite. Contours are sensitivity of the array relative to the main beam peak in dB

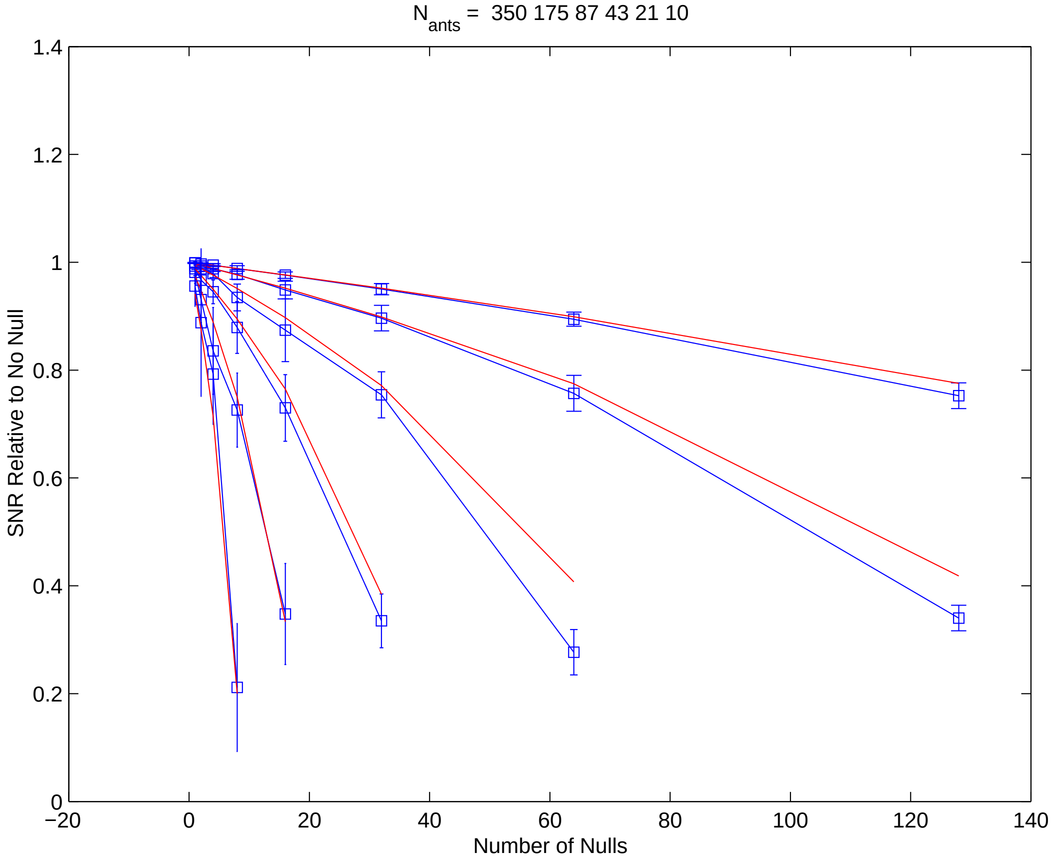


arrays more extended than the 1-km ATA. In cases of multiple interferers or in cases of interferers with poorly determined positions, it is desirable to place a large number of nulls on the sky (Figure 4). The number of nulls which can be placed on the sky is limited by the number of antennas in the array (Figure 5). Finally, while a phase implementation of this technique is intrinsically narrow-band, we have shown that just as one can place multiple nulls in the spatial domain, one can place multiple nulls in frequence space. On the other hand, a delay implementation of nulling is intrinsically broadband. For the ATA 100 nulls can be placed to null out a region that is 45 arcmin^2 in solid angle or 10 MHz in frequency space, while maintaining greater than 80% efficiency.

4.5. Post-Correlation Analysis

A number of mitigation techniques exist which operate on a measured correlation matrix (Leshem et al. 2000, Briggs et al. 2000). Many of these are adaptive counterparts to the *a priori* technique of interferometric nulling described above. These techniques can benefit from rapid dump times from the correlator but require prodigious processing power for large$-N$ arrays. For

Figure 5. SNR at the phase center as a function of number of nulls and number of antennas. The blue curves indicate the results of simulations for arrays of 350, 175, 87, 43, 21 and 10 antennas. The red curves are the theoretical values expected. As an example, the ATA with 350 antennas can place more than 100 nulls while maintaining > 80% sensitivity.



the ATA, the maximum dump rate of the correlator necessary for some RFI mitigation is 400 Gb/s! Even a large ($\sim$ 100 unit) Beowulf-type cluster cannot handle the full data rate.

Image processing is an important subset of post-processing algorithms (Thompson, Moran & Swenson 1991, ch. 14; Leshem & van der Veen 2000). Differential fringe rotation for a stationary interferer and the celestial source will lead to decorrelation of the interferer on sufficiently long baselines and time intervals. It will also lead to the appearance that all stationary interferers are at the North celestial pole. For sufficiently short integration times, the interference can then be removed through simultaneous self-calibration and deconvolution of the celestial source and of the interferer (Perley 2003).

5. Summary

We have described a variety of techniques for RFI mitigation. Not all techniques are applicable to each instrument, interferer or science goal. Further, we emphasize that these are experimental techniques. There are undoubtedly hidden technical issues lurking in many if not all of them. In order to support the next generation of radio telescopes, they require demonstration at a level beyond current experiments. Future generations of hardware will include substantially more sophisticated implementations.

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