RFI excision without a reference signal

T.J. Cornwell, R.A. Perley, K. Golap, S. Bhatnagar, NRAO[1]

Draft: 6/17/04 4:49 PM

Abstract: *The excision of interfering signals is crucial to the continuation of radio astronomical observations into the future. Many algorithms for RFI excision require an estimate of the interference found by observations with a reference system. However, often the best measurements of the interference come from the scientific observations themselves – the sensitivity and sampling are guaranteed to be appropriate. This is similar to the logic of self-calibration whereby the best way to calibrate the telescope is to use the scientific observations. We develop and test an algorithm in which the interference is estimated by a least squares fit to the observations and removed by simple subtraction. Differentiation of interference from signal is crucially dependent on the natural fringe rotation of celestial sources, and the lack of fringe rotation for ground-based interference. Our test is on VLA 333MHz observations of the closely circumpolar radio source NGC6251. The interference source is a radar transmitter at Albuquerque airport, some 200km from the VLA.*

1. Introduction

2. A model

Consider a collection of sources of narrow band RFI from stationary emitters. After fringe stopping, the visibility function measured will be:

$$V_{ij}^{\mathrm{obs}}(\upsilon,t) = g_i(\upsilon,t)\,g_j^*(\upsilon,t)\,V^{\mathrm{source}}\left(\underline{r}_i(t)-\underline{r}_j(t),\upsilon\right) + a_i\left(\underline{s}_i(t),\upsilon\right)a_j^*\left(\underline{s}_i(t),\upsilon\right)k_i\left(\underline{s}_i(t),\upsilon\right)k_j^*\left(\underline{s}_i(t),\upsilon\right)P(t,\upsilon)$$

Equation 1

From now on, we will drop the dependence on time and frequency:

$$V_{ij}^{\mathrm{obs}} = g_i g_j^* V^{\mathrm{source}} + a_i a_j^* k_i k_j^* P$$

Equation 2

Given a model of the source, we may solve for the on and off axis gains in the least squares sense:

---

[1] *The National Radio Astronomy Observatory is operated by Associated Universities, Inc., under cooperative agreement with the National Science Foundation.*

$$S = \sum_{ij} w_{ij} \left| V_{ij}^{\text{obs}} - g_i g_j^* V^{\text{model}} - a_i a_j^* k_i k_j^* \right|^2$$

Equation 3

Calibration of the observed data and removal of the estimated RFI can be performed thus:

$$V_{ij}^{\text{cal}} = \left(g_i g_j^* \right)^{-1} \left(V_{ij}^{\text{obs}} - a_i a_j^* k_i k_j^* P \right)$$

Equation 4

Under what circumstances is it possible to disentangle the source visibility and interference? In table 1, we show the characteristics we have assumed for the various effects.

Term	Definition	Time variation	Frequency variation
V_{ij}^{obs}	Visibility measured between antennas *i* and *j*	–	
V^{source}	Source visibility function	*~ antenna crossing time*	*~ antenna crossing bandwidth*
g_i	On axis gain for antenna *i*	*~ atmospheric coherence time*	*~ constant*
a_i	Off axis gain for antenna *i*	*~ antenna beam crossing time*	*~ antenna beam crossing bandwidth*
k_i	Propagation of interference to antenna *i*	*~ 1/(fringe frequency)*	*~ low order polynomial*
P	Power of interfering source	*Intermittent or constant*	*Narrowband*

Table 1 Characteristics of various terms in the measured visibilities

The strength of the interfering source can in principle be determined from observations with a wide-beam antenna or a narrow-beam antenna pointing at the source of interference (if known). Alternatively, we can treat the power as an unknown to be determined from the corrupted observations themselves. In fact, since we are mostly uninterested in the absolute value of the off axis gain, we can absorb the power into the gains:

$$V_{ij}^{\text{obs}} = g_i g_j^* V^{\text{source}} + a_i a_j^* k_i k_j^*$$

Equation 5

If the interference is broadband then it may help to search over a range of channels. For example, consider an interfering source over the horizon. A search in direction and range could be performed. In the more usual case, the interference will be narrowband and the propagation terms may be simplified to a fringe frequency[2].

$$V_{ij}^{\text{obs}} = g_i g_j^* V^{\text{source}} + a_i a_j^* e^{j\omega_e t}$$

Equation 6

It is the fringe frequency that enables solution for the on and off axis terms separately. By averaging over many cycles of the fringe frequency, the two terms will be split. In practice, we find the gains by a least squares fit for a given model.

$$S = \sum_{\upsilon t} \sum_{ij} w_{ij} \left| V_{ij}^{\text{obs}} - g_i g_j^* V^{\text{model}} - a_i a_j^* e^{j\omega_e t} \right|^2$$

Equation 7

Note that if the model is omitted, then the some part of the structure can be absorbed by the off-axis gains (Lesham and van der Veen, 2000). While this could be addressed in the deconvolution by suitable adjustments to the Fourier sampling, our approach is more straightforward and direct.

Once the on and off axis gains are estimated, calibration and excision requires the following straightforward calculation[3]:

$$V_{ij}^{\text{cal}} = \left(g_i g_j^* \right)^{-1} \left(V^{\text{obs}} - a_i a_j^* e^{j\omega_e t} \right)$$

Equation 8

3. An algorithm

Our algorithm (Figure 1) solves for the various terms in Equation 8 in a round robin pattern similar to self-calibration, but with the addition of steps for interference estimation and removal.

To test this algorithm without an undue amount of software development, we wrote an AIPS++ Glish script (see Figure 2). All the necessary work can be done using existing AIPS++ tools such the imager and calibrater supplemented with Glish operations. Cross

---

[2] To derive this relationship, remember that in an interferometer, the fringes are stopped by some means, thus conferring a fringe rotation on the naturally constant interference.

[3] This calculation is different from that proposed in Perley and Cornwell (2003) in which the data themselves are corrected by the estimated gains.

subtraction is performed using the AIPS++ table tool and Glish math. The antenna gains must be inverted before application; this too is done using the table tool and Glish math.

For production work, one would want to implement this algorithm in a more streamlined way. However for a test, this approach is adequate.

Figure 1 Algorithm for imaging, selfcalibration, and interference estimation and removal

1. Initialize on and off axis gains $\begin{aligned} g_i &= 1 \\ a_i &= 0 \end{aligned}$
2. Calibrate using current estimates of on and off axis gains

$$V_{ij}^{\mathrm{cal}} = \left(g_i g_j^*\right)^{-1} \left(V^{\mathrm{obs}} - a_i a_j^* e^{j\omega_e t}\right)$$

3. Make Clean model from V_{ij}^{cal}
4. Stop if Clean image is satisfactory
5. Predict model visibilities V_{ij}^{model}
6. Solve for gains g_i, a_i by minimizing

$$S = \sum_{\nu t} \sum_{ij} w_{ij} \left| V_{ij}^{\mathrm{obs}} - g_i g_j^* V^{\mathrm{model}} - a_i a_j^* e^{j\omega_e t} \right|^2$$

7. Return to step 2

Figure 2 AIPS++ implementation of the algorithm in Figure 1

a. Make two copies of MeasurementSet, one for the target *(Mt)* and one for the interference *(Mi).*
b. Initialize interference source model to point source at the pole.
c. Predict model visibilities for *Mt* and *Mi* :
d. Mt:
    i. Solve for off-axis gains using antenna bandpass solution, B, in calibrater.
    ii. Apply off-axis gains to model visibility (contains Fourier transform of the target) to obtain predicted observed target visibility
e. Mi:
    i. Solve for on-axis gains using antenna gain solution, G, in calibrater.
    ii. Apply on-axis gains to model visibility (contains Fourier transform of the interference) to obtain predicted observed interference
f. Cross subtract:
    i. *Mt:* Subtract predicted observed interference visibilities to obtain estimate of observed visibilities in absence of interference
    ii. *Mi:* Subtract predicted observed target visibilities to obtain estimate of observed interference visibilities in absence of target
g. Update estimates of on axis gains and correct *Mt*.
h. Update model of target by clean deconvolution (or similar)
i. Stop if converged, else repeat from step c onwards.

4. A test

We tested this algorithm on VLA observations at 333MHz. The VLA sees strong, constant interference from the Albuquerque airport radar at ~333MHz. Our target source, NGC6251, at declination 86 degrees, was chosen carefully to keep the fringe rate relatively low so that the sampling time and data rate would be manageable with the current VLA correlator and computers.

Table 2 Details of observation

Configuration	D (up to 700m) with North arm in C (up to 2km)
Source	NGC6251 (declination ~ +86deg)
Observing date and time	2004May21, 00:44UT-05:46UT
Integration time	3.3s
Channelization	3.1MHz total bandwidth, 127 channels for channel width of 24.4kHz
Polarization	RR and LL

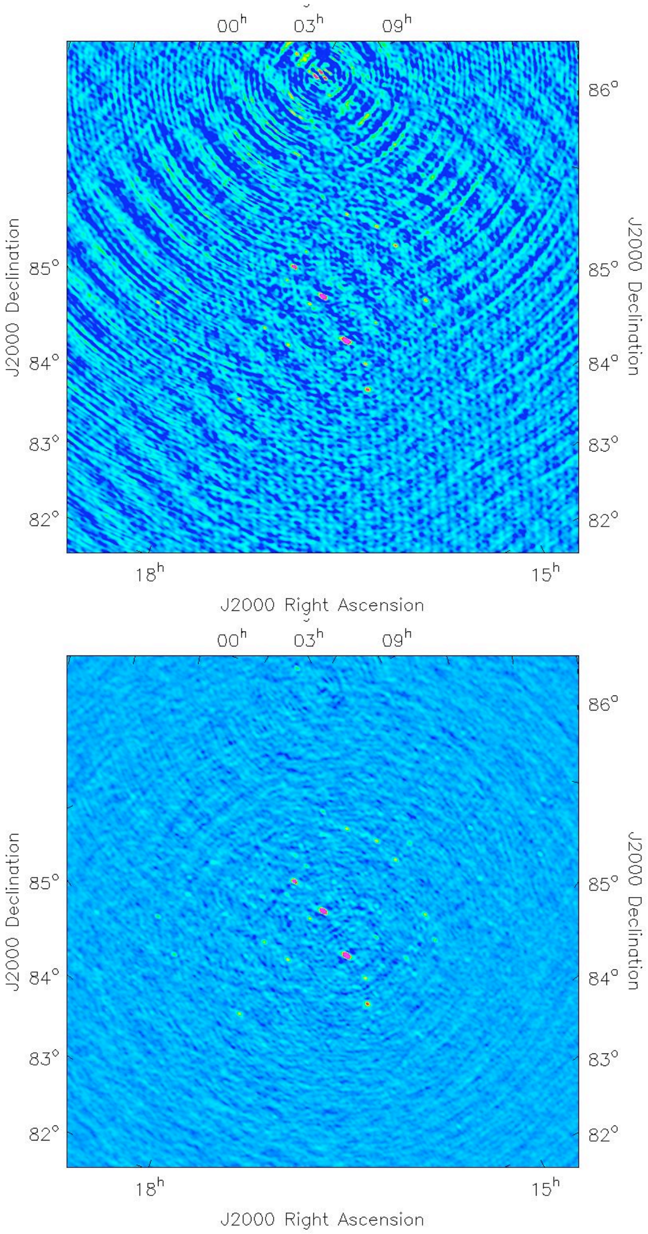

Figure 2 Image of NGC6251 (top) without RFI excision or self-calibration, and (bottom) with.

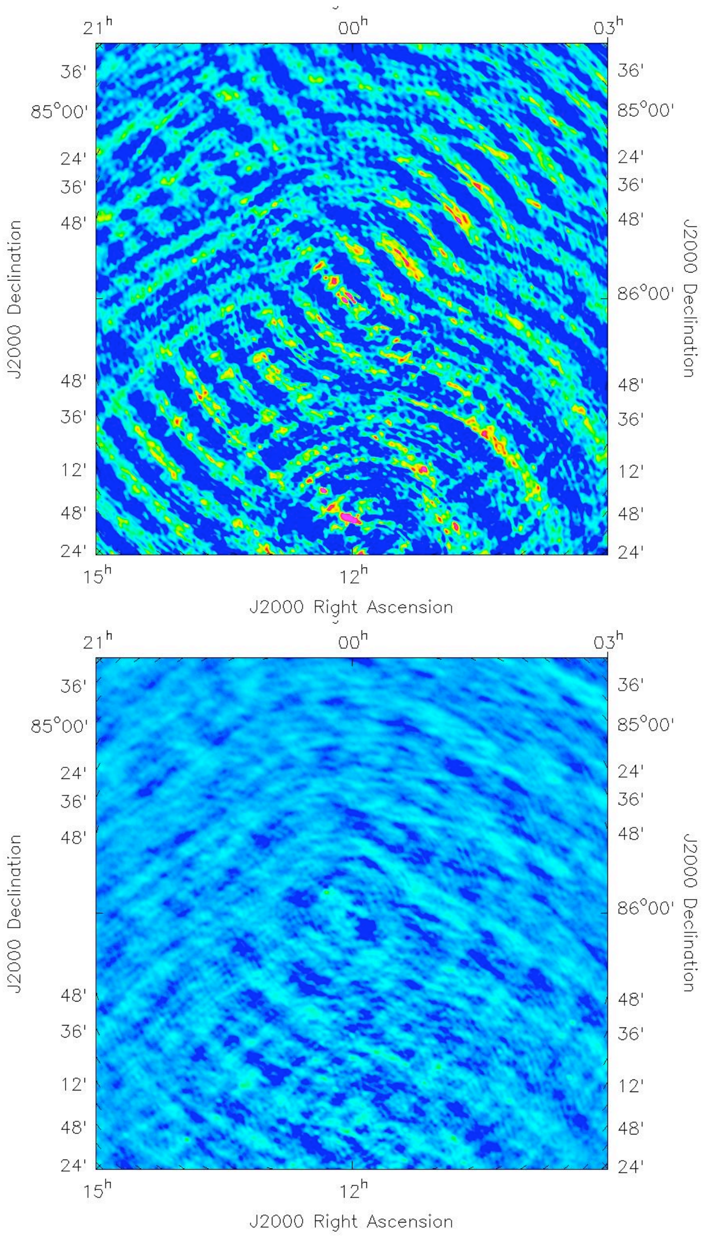

Figure 3 Image of North Pole (top) without RFI exicision, and (bottom) with RFI excision and removal of NGC6251.

5. Implications for EVLA and SKA

As discussed by Perley and Cornwell (2003), observing to allow RFI excision must be performed with little time and frequency averaging. Our test was carefully arranged so that the interference fringe rate was low and could be accommodated with the current VLA correlator. In the general case of a source anywhere on the sky, the fringe rate will be much higher, and the maximum allowed averaging time much smaller. Post excision, the data may be averaged to a rate commensurate with the source size rather than the entire sky. Thus excision must be performed in real time. We see two ways to do this.

First, the role of the model in our algorithm may be simply ignored. In that case, the deconvolution algorithm must be modified to account for the excised spatial frequencies (Lesham and van der Veen, 2000). Second, a model may be specified *a priori*, or built up over the course of observing, requiring rapid real time calibration and imaging that is challenging but feasible. The array would auto-calibrate and auto-edit in real time.

Our algorithm is adaptive and late, working on the correlation of the electric field measurements rather than the electric field measurements themselves. This requires that the system be linear throughout the signal path. The advantage of late methods is that the interference is estimated and removed where it is most easily detected and where it does the most damage – in the imaging step. Following this logic, we believe that if stations of antennas were to be used instead of single antennas then instead of adaptively steering the station beams to null out interference, the station beams should be held as constant as possible and our technique used at the back end. This would largely avoid the nasty problem of wide-field imaging with unstable station beams.

[What is the noise behavior? Do we actually gain over just excising the interference laden channels?]

[Connection to adaptive spatial nulling]

References