Suppression of Strong Quasi–stationary Narrow–band Signals in Radio Interferometry

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***Abstract*—A discussion is given of the effects of strong, quasi–stationary narrow band interfering signals on radio interferometry data. Some techniques for dealing with such signals are described and examples given.**

***Index Terms*—Radio Interferometry, RFI flagging**

I. Introduction

IMPROVEMENTS in sensitivity resulting from the very wide bandwidths of radio interferometers such as the EVLA come at the cost of being sensitive to the many terrestrial radio signals which are many orders of magnitude stronger that the celestial signals of interest. These signals appear in a variety of forms; signals from low earth orbit satellites appear only for limited periods of time while those from fixed transmitters such as microwave links are persistent. These signals may be continuous or impulsive in either time or frequency

Many of these signals are sufficiently strong that they can serious corrupt calibration of the data as well as any images derived from them. This memo describes some of the effects of strong, quasi–stationary narrow band signals in the interferometer passband and details some techniques for dealing with them. An example is given using EVLA C band data. In the following, these strong signals will be referred to as "interference" or "RFI" in spite of the fact that most are completely legitimate transmissions. The techniques discussed are implemented in the Obit package ([1], http://www.cv.nrao.edu/∼bcotton/Obit.html).

II. RFI and Radio Interferometers

Modern wide-band interferometers record data in multiple sub-bands of the total bandpass and each of these sub-bands is divided into multiple channels. The spectral resolution within a sub-band is usually provided by some variation on a Fourier transform spectrometer with a limited range of lags (AKA delays) measured. Strong, narrow band signals will have significant power at lags not measured. The truncation of the lag spectrum may result in ringing of the response in frequency. An example of this is shown in Figure 1. This figure illustrates the effects of strong signals appearing in several sub-bands of data on a strong calibrator. The ringing appears as oscillations in both amplitude and phase as is strongly seen in the fifth sub-band. Uncorrected, this ringing can render all data for a given sub-band useless.

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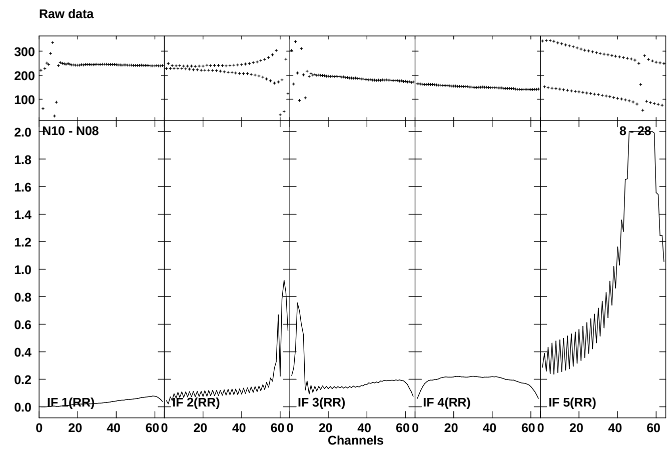

Fig. 1. Raw data on 3C286 on one baseline from 6.00 to 6.64 GHz. The strong interference causes ringing over wide frequency ranges. The upper plots are the phases in degrees and the lower plots are amplitudes clipped at 2.0.

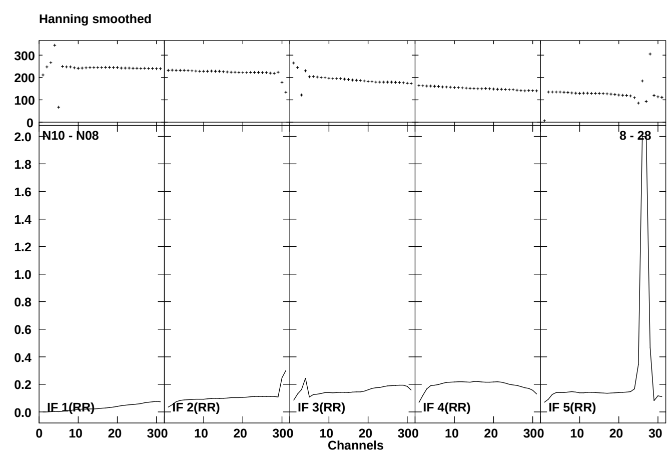

Fig. 2. Like Figure 1 but after applying Hanning smoothing.

A. Hanning Smoothing

The traditional solution to this ringing is Hanning smoothing of the spectrum. This is a simple convolution of the spectrum with a triangle function of weights 0.25, 0.5 and 0.25 which effectively cuts the spectral resolution in half. Only every other channel is kept after Hanning smoothing. The data shown in Figure 1 was Hanning smoothed using Obit task Hann and the results are given in Figure 2. The Hanning has very effectively suppressed the ringing leaving only the channels directly affected by the signals corrupted.

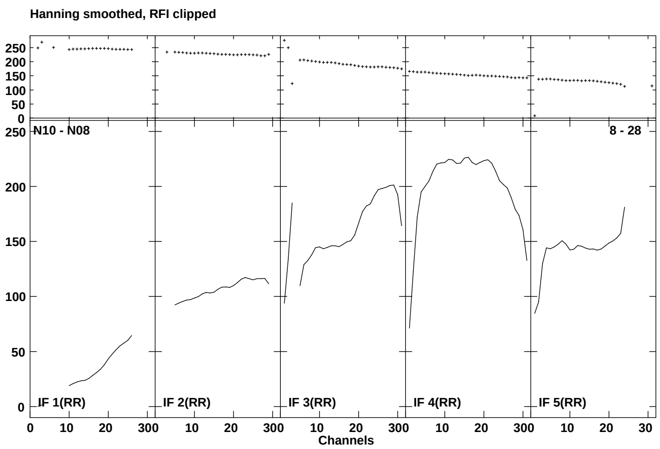

Fig. 3. Like Figure 2 but after flagging channels differing from a median. Note change of scale.

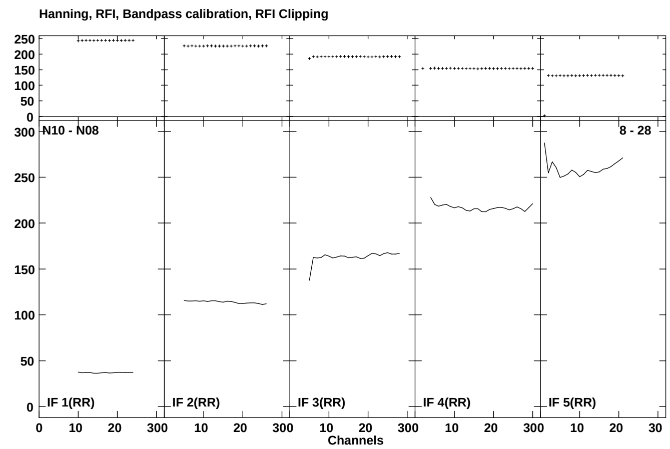

Fig. 5. Like Figure 4 but after another RFI flagging.

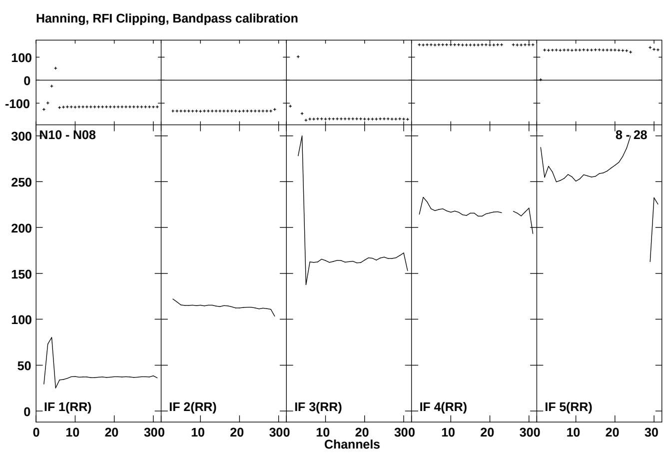

Fig. 4. Like Figure 3 but after bandpass calibration.

B. RFI Removal Strategy

If the interfering signal is sufficiently strong that either the gain of the amplifier is depressed or there are insufficient bits in the A/D conversion to represent the celestial signals in the presence of RFI, the data are irreparably corrupted and should be discarded While Hanning limits the effects of strong but less damaging signals to the channels corresponding to the frequencies of the emission, these channels should be ignored in subsequent processing, an action referred to as "flagging".

Assuming the data not to be completely and irreparably corrupted, the following procedure appears to result in limiting the effects of strong narrow band interference and eliminating the directly affected channels; details are given below,

1) **Hanning Smooth** As shown above, Hanning very effectively removes the ringing resulting from the truncated lag spectrum. The effects of Hanning are the differences between Figures 1 and 2.
2) **Frequency Domain Flagging** As can be seen in Figure 2, Hanning smoothed data may contain RFI contaminated channels which stick out from the unaffected channels. These channels can be identified by their contrast with a running median, assumed to be free of the effects of RFI. Note, there is a significant channel to channel variation simply due to the spectral response of the electronics. This will mask weaker interfering signals. The results of frequency domain flagging is illustrated in Figure 3.
3) **Bandpass Calibration** The variation of the gain of the electronics is corrected by a process known as bandpass calibration in which the instrumental response to a bright calibrator source is used to determine corrections. As the interfering signals may be transient, the channels containing stronger interfering signals should be flagged prior to this calibration.
4) **Deeper Frequency Domain Flagging** Once the instrumental spectral response has been corrected, a subsequent frequency domain search for interference can detect and remove weaker interfering signals.

This procedure should at least be adequate to allow calibration of the data. Weaker interfering signals may still be present which adversely affect the derived images; these interferences must be dealt with by other means.

C. Frequency Domain RFI Flagging

Narrow band signals are by definition impulsive in frequency hence relatively easy to identify in a frequency domain analysis if sufficiently strong to appear above the noise. The technique applied here is to do limited time averaging of the data and compare each channel with a running median in frequency. If the channel amplitude deviates from the median by more than a specified multiple of the estimate of the noise, that channel and polarization is flagged. The noise estimate is the root mean square of the least 80% deviant of the samples in the median window. This estimator is relative insensitive to a small number of RFI affected channels but underestimates the true noise in the absence of interference.

This process does not depend on prior calibration of the data but before bandpass calibration, any variation in the channel–to–channel instrumental gain will be included in the estimate of the noise. The data shown in Figures 3 and 5 were flagged using Obit task AutoFlag using a 31 channel median (all channels after Hanning), 2 minute averaging and clipping at 5 times the estimated noise. Each sub-band (labeled "IF" in the figures) was processed independently.

Two passes of frequency domain flagging were used, before and after bandpass calibration. The flagging prior to bandpass calibration removed the most discrepant interference to minimize the corruption of the bandpass calibration. After bandpass calibration it is easier to distinguish interference as the variations in instrumental gain have been removed.

D. Bandpass Calibration

The purpose of bandpass calibration is to remove the channel–to-channel instrumental variations in gain and phase using measurements of a strong calibrator. These are dominated by the sub-band filter response and the phase slope resulting from residual group delay errors from the correlation. The spectral index of the calibrator source is included in the calibration so that variations in calibrator brightness with frequency are accounted for.

The data shown in Figure 4 were calibrated using Obit task BPass. BPass first removes temporal variations in phase using a limited set of channels in a self calibration. The data are then time averaged and a subsequent self calibration on a running block of channels is used to derive the bandpass function. Multiple scans on the bandpass calibrator may be used for either an average bandpass function or a time variable bandpass correction.

III. DISCUSSION

The technique presented of Hanning visibility data affected by strong narrow band interference greatly suppresses the ringing resulting from truncation of the visibility lag function. The remaining interference can be greatly reduced using a combination of frequency domain flagging and bandpass calibration. This process will result in data that can be used for an accurate calibration although lower level interference may still adversely affect images produced.

Sample EVLA data seriously affected by RFI was shown to be largely corrected and the RFI affected channel data removed by the suggested procedure. Note, data with interference which is impulsive in time can be identified and flagged using a time domain analysis similar to the frequency domain analysis described above. This process was not beneficial to the data presented here but is available in Obit task MednFlag.

REFERENCES

[1] W. D. Cotton, “Obit: A Development Environment for Astronomical Algorithms,” *PASP*, vol. 120, pp. 439–448, 2008.