

Cancellation of GLONASS signals from Radio Astronomy Data

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ABSTRACT

Astronomers use the 1612 MHz OH spectral line emission as a unique window on properties of evolved stars, galactic dynamics, and putative proto-planetary disk systems around young stars. In recent years, experiments using this OH line have become more difficult because radio telescopes are very sensitive to transmissions from the GLONASS satellite system. The weak astronomical signals are often undetectable in the presence of these unwanted human generated signals. In this paper we demonstrate that GLONASS narrow band signals may be removed using digital signal processing in a manner that is robust and non-toxic to the weak astronomy signals, without using a reference antenna. We present results using real astronomy data and outline the steps required to implement useful systems on radio telescopes.

Keywords: GLONASS, interference, cancellation, radio astronomy

1. INTRODUCTION

Many papers in the astronomical literature cite problems with interference from the Russian *Global'naya Navigatsionnaya Sputnikovaya Sistema* (GLONASS) system of navigational satellites when trying to observe 1612 MHz OH spectral line emission. Galt (1991)⁷ and Combrinck et al. (1994)⁴ both present data demonstrating the damaging effect of GLONASS signals on astronomy data. Some reports have stated that up to 50% of all observations have had to be discarded.⁷ The scientific merits of OH spectral line observations are discussed in detail elsewhere^{3,8}; however, there is no question that this is extremely valuable spectrum whose continued use is essential to radio astronomy.

One possible solution to the problem is regulation; this is being addressed within international organisations such as the ITU and URSI. However, regulation cannot be expected to recover the spectrum into which the GLONASS system already transmits. The solution most often employed by radio astronomers in dealing with unwanted signals is to put their telescopes in remote locations. However, when dealing with signals that emanate from Earth-orbiting satellites, that method obviously fails. The next most obvious solution is not to observe when interfering signals are present, or simply throw away affected data.⁷ Some “GLONASS aware” tools have been developed that allow dynamic scheduling observations in order to minimise interference.⁴ However, the strategy of avoidance results in the loss of valuable telescope time, which often amounts thousands of dollars per day, a better solution is desired.

Here we present a direct, technical solution to the problem. We have developed and demonstrated a parametric signal processing algorithm which identifies GLONASS signals present in the pre-detection, complex baseband telescope output, and removes them. This algorithm results in a high degree of suppression with negligible distortion of radio astronomical signals. We believe this approach can be applied to interference from the U.S. Global Positioning System (GPS) and possibly other sources as well. This technique is presented in Section 3 of this paper. First (Section 2), we describe the properties of GLONASS that are relevant to the operation of the canceller. In Sections 4–5, we present experimental results demonstrating the effectiveness of this approach. Section 4 describes the procedure used to collect GLONASS-corrupted data; whereas Section 5 shows the results before and after application of the canceller. In section 6 we consider how this approach may be implemented on existing telescope systems.

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2. PROPERTIES OF GLONASS SIGNALS

GLONASS satellites transmit at frequencies between 1602–1616 MHz and have shared primary user status with radio astronomy for the 1610.6–1613.8 MHz band.⁴ There are 24 carriers spread over the 14 MHz band at intervals of 0.5625 MHz. The carrier is modulated by a pair of noise like, equal power, pseudo noise (PN) codes of 0.511 and 5.11 MHz. Figure 1. of Combrinck et al. (1994)⁴ shows time averaged spectra of these signals. The unfiltered sinc² side lobes of these signals have relative power levels as high as -25 dB extending out to 20 MHz either side of the main carrier in some cases.⁷ GLONASS satellites launched more recently do have some band-limiting filters.

GLONASS, despite its wide band spectrum, actually has a very simple structure.⁹ Consider the narrow band (0.511 MHz) GLONASS modulation. This signal is simply a sinusoidal carrier which experiences a phase shift of 0° or 180° every $(0.511 \text{ MHz})^{-1}$. Each phase shift represents a modulation symbol, or *chip*. Each group of 511 chips represents a PN code, which is public knowledge, never changes, and is the same for every GLONASS satellite. GLONASS data bits are represented by changing the sign of a block of 10 PN codes, with 10 ms period. Parameters of the signal which are unknown when received are (1) the Doppler shift due to satellite motion, (2) the *code phase*, that is, the relative position within the 1 ms PN code period, and (3) the carrier phase, which rotates because the satellite is moving and the transmitter's LO is not perfectly stable. However the carrier phase, the current value of the data bit, and the complex gain due to the antenna pattern can all be combined into a single unknown complex magnitude parameter. Thus three parameters are sufficient to describe the GLONASS signal with high accuracy.

Finally, we note that the modulation used by the course/acquisition (C/A) mode of the U.S. Global Positioning System (GPS) is very similar to modulation used in the GLONASS 0.511 MHz transmission. The main differences are longer code (1023 chips) and higher chip rate (1.023 MHz); also, all GPS satellites transmit on the same centre frequency, but with different (but known) PN codes. Thus, techniques which are effective against 0.511 MHz GLONASS modulation may be effective against GPS C/A transmissions as well.

3. CANCELLATION ALGORITHM

3.1. Theory

Our technique for suppressing GLONASS signals in radio astronomy data is based on *parametric signal modelling*. Recall that the GLONASS signal can be described using a model consisting of just three parameters: Doppler, code phase, and complex magnitude. Given a block of data containing a GLONASS signal, one can then estimate the parameters. Given the parameters, it is possible to synthesise a noise-free copy of the GLONASS signal. This copy is then subtracted from the telescope output to achieve the suppression. This procedure is illustrated in Figure 1.

The parametric solution proceeds on two time scales. Doppler frequency and code phase are difficult to estimate, but change slowly. Complex magnitude, on the other hand, is simple to estimate, and changes quickly. Our approach is to first *acquire* the GLONASS signal. This involves a joint search over the possible Doppler frequencies and the code phases. For each Doppler/code phase pair, a complex baseband (zero-IF) version of the signal is cross-correlated with the PN sequence. The correct Doppler/code phase pair is the one which maximises the magnitude of the cross-correlation. Although tedious, this is a simple procedure, and is essentially the same acquisition procedure used by hand held GPS receivers. Once acquired, the Doppler and code phase can be tracked simply by sensing the drift in the correlation peak and adjusting the Doppler and code phase parameters accordingly. It appears that the Doppler and code phase estimates can be frozen for at least 0.1s between updates without any significant effect on the results.

Once the signal is acquired, we estimate the complex magnitude by cross-correlating the time- and frequency-aligned PN code with the complex zero-IF representation of the GLONASS signal. The magnitude and phase of the cross-correlation then represents the desired complex gain. The complex gain is expected to change quickly, so this procedure must be updated often. In the example presented below, the complex gain update rate is $128 \mu\text{s}$, using 1024 samples at 8 Msamples per second (conversion to a complex baseband signal has halved the sample rate).

Given the Doppler frequency, code phase, and complex magnitude, one can then synthesise a noise-free estimate of the GLONASS signal. However, it has been found by experience that better cancellation is achieved by low-pass filtering the zero-IF version of the synthesised GLONASS signal before subtraction from the telescope output. This models the real-world low-pass effect which smoothes discontinuities in band limited signals. This also has the desirable effect of suppressing the high-order side lobes of the synthesised signal, which may not be accurately represented by the proposed signal model. A suitable filter was found to be a 32-tap finite impulse response (FIR) filter based on the Hamming window, with cutoff frequency equal to $0.05F_S$ at $F_S = 8 \text{ MSPS}$. Such a filter can be obtained using the MATLAB command `fir1(32,0.1)`.

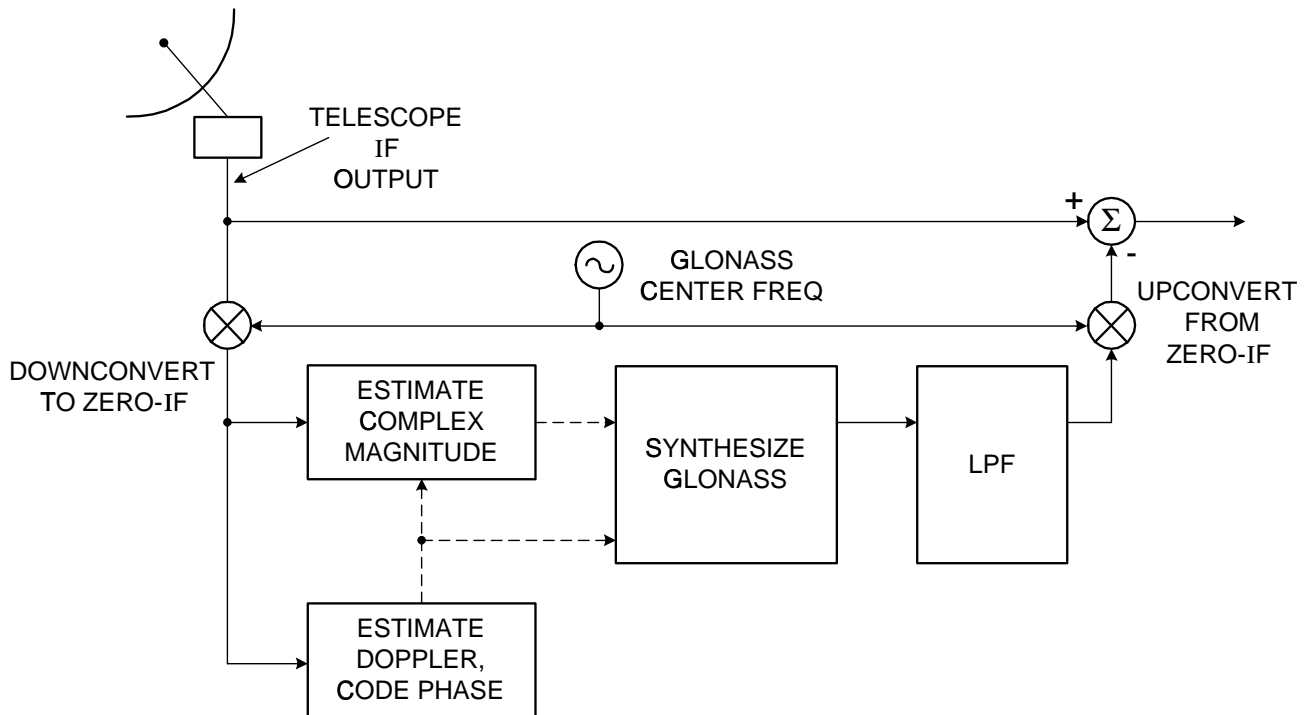


Figure 1. Parametric cancelling technique. The ESTIMATE DOPPLER, CODE PHASE block uses the down converted telescope signal to generate an estimate of the time aligned PN code and the offset in frequency between the GLONASS CENTER FREQ oscillator and the down converted GLONASS signal. These two estimates and the down converted signals are used by the ESTIMATE COMPLEX MAGNITUDE block to calculate a magnitude and phase correction. These estimates of time aligned PN code, frequency, magnitude and phase are then used to synthesise a zero-IF GLONASS signal.

3.2. Implementation

The results presented below were obtained using non-real-time post-processing software, written in MATLAB. On a 400MHz pentium the processing presently runs at 1000 times real time. The MATLAB source code is freely available from the authors. Any practical system would, of course, require real time implementation. The maturity of GPS technology means that the techniques and hardware for the acquisition of GLONASS and GPS signal parameters are well developed. The design of the signal modulators in the satellites is also known. With the knowledge of these two areas a practical real time implementation is within reach and is discussed in Section 6.

4. DATA COLLECTION

The astronomy data used in testing these algorithms is a single linear polarisation, 4-bit data stream from each antenna of the 6x22m antenna, CSIRO Australia Telescope Compact Array at Narrabri in Australia. The data was 4-bit sampled at 16MHz and recorded on an S2 recorder.¹⁴ The resulting 8MHz bandpass centred on 1610 MHz was wide enough to include signals from GLONASS-69 at ~1609 MHz, an OH maser source (IRAS 1731-33) at ~1612 MHz and some flat spectrum. The data were then extracted using the S2TCI system¹⁴ and demultiplexed. More details on this dataset and others that are freely available for conducting these kind of experiments are in reports by Smegal et al.¹³ and Bell et al..¹ The algorithm works on a single polarisation data stream from one antenna only. However, data from a second antenna were also used in cross correlations as a test of how well the GLONASS signals were removed.

5. RESULTS TO DATE

The results so far are encouraging, with GLONASS narrow band signals being effectively removed in a way that is non toxic to astronomy signals. Figure 2 (left plot, top curve) shows a spectrum of the raw data, with test tones added in software. The bottom curve shows the same 0.1s (1.6×10^6 samples) of data with cancellation technique applied, with no apparent GLONASS signals left. There is an OH maser source at ~ 1612 MHz. The top two curves in the right plot of Figure 2 show a blow up of this region. The bottom curve in the same plot shows the difference multiplied by a factor of 1000, indicating that no damage has been done in the spectral region of the OH source.

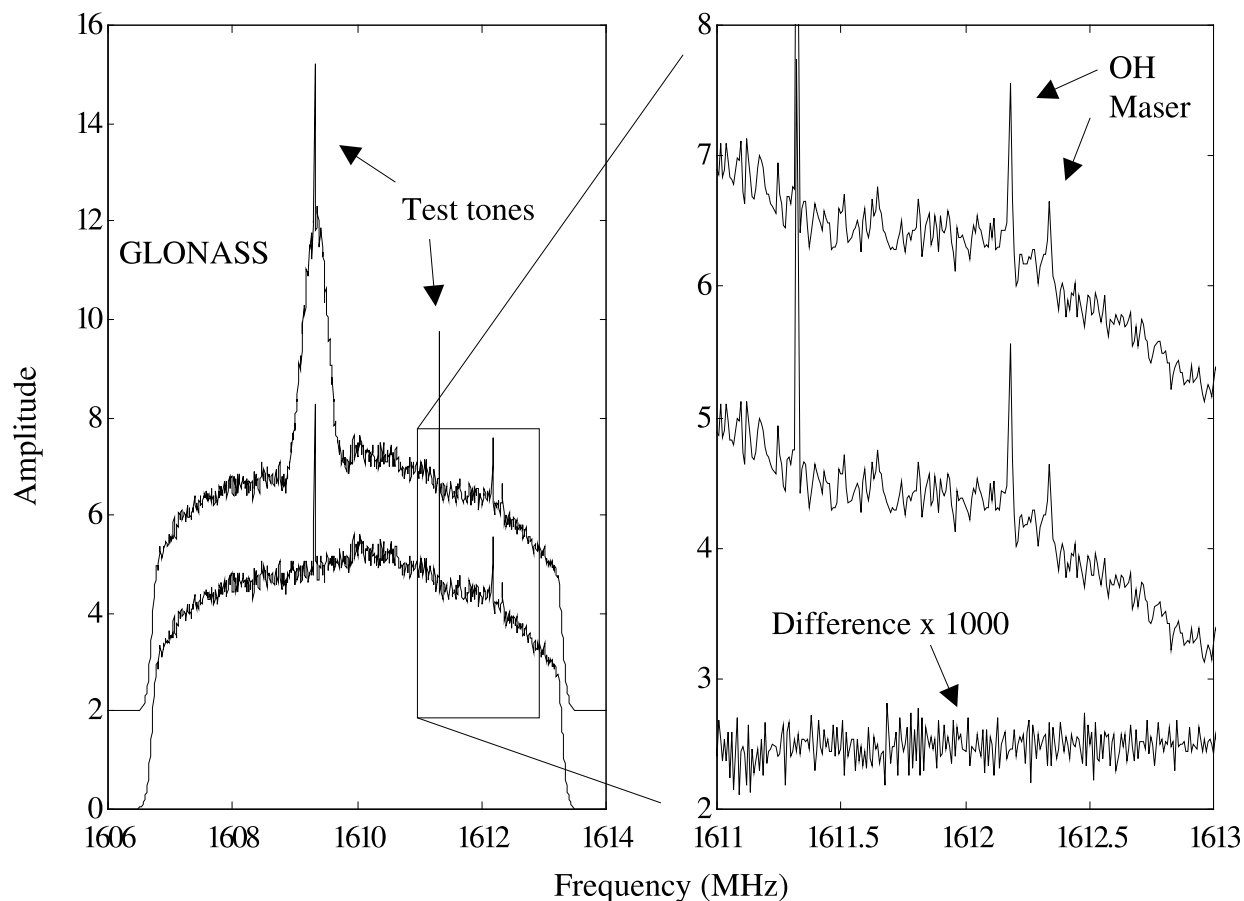


Figure 2. Left plot: top curve: raw data, OH maser source at 1612 MHz, test tones inserted (in software) at 1609.3 and 1611.3 MHz. Left plot: lower curve: data with GLONASS removed. Right plot: blow up of region around OH source. The bottom curve shows the difference of the pre and post cancellation spectra multiplied by 1000. This indicates that this region of the spectrum is not changed by more than a few parts in 1000. (curves offset for clarity)

In order to examine the toxicity of this algorithm in the same frequency range as the GLONASS signal we added a test tone to the data before the cancellation was applied and examined how it was affected by the processing. The left plot of Figure 3 shows the result of subtracting the test tone again, after the cancellation. There is no evidence that the test tone has been affected by the cancellation. However, there is a small spike left right under the middle of the GLONASS signal, that is unrelated to the test tones. This seems to be a result of some break through, or leakage of the GLONASS carrier signal from the GLONASS imbalance in the GLONASS phase modulator. It should be possible to model and remove this as well, but we have not addressed that yet.

A more sensitive test of the suppression is to cross correlate with signals from another antenna. The Right plot of Figure 3 show some cross correlations. The top curve is the cross correlation of raw data from two antennas. The bottom curve is the cross correlation of raw data from one antenna and data with GLONASS cancelled from data from another antenna. There are some extra ripples here that are not apparent in the other spectra, suggesting that there are some inaccuracies in the algorithm that need further investigation. The majority of the signal seen in this cross correlation is probably due to the GLONASS wide band signal, which we have not tried to suppress yet.

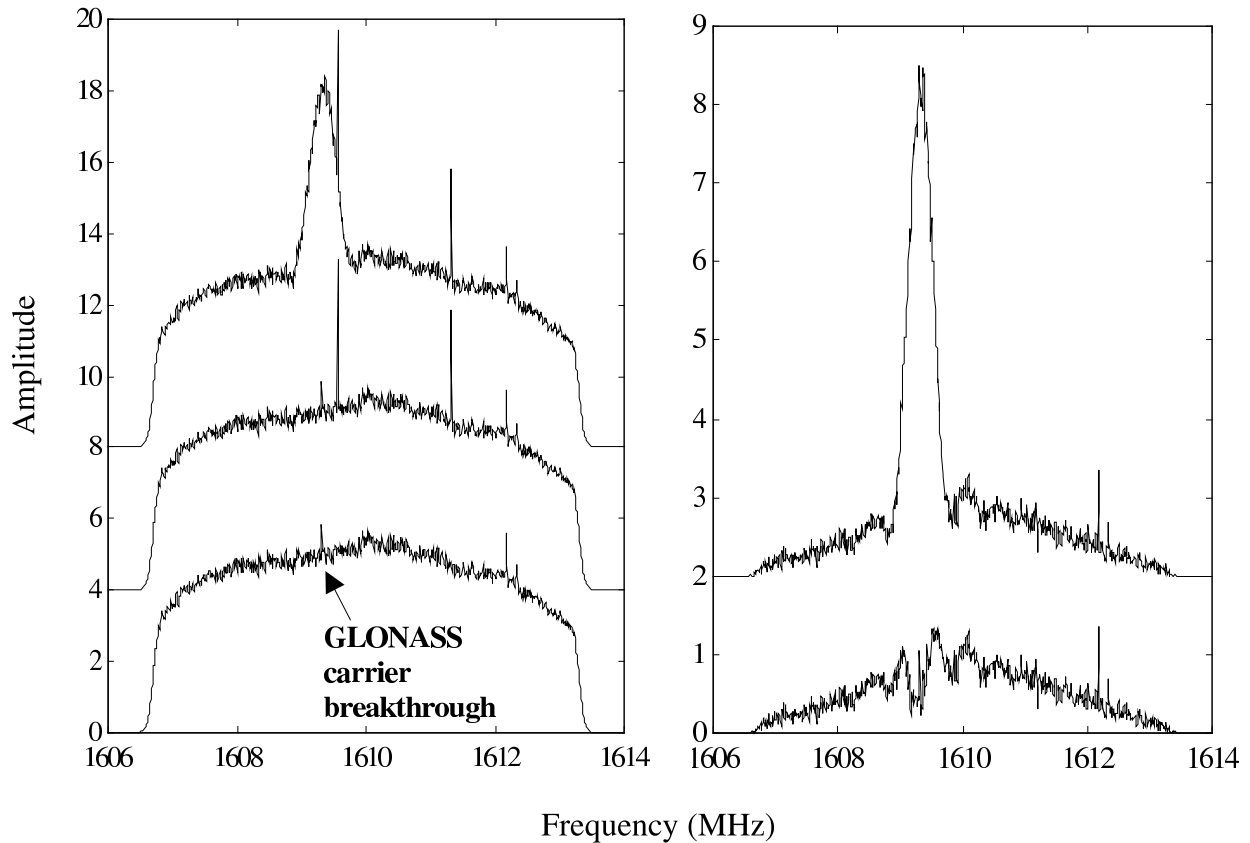


Figure 3. Left plot: Top: Offset test tone added before cancellation. Middle: Carrier signal break through apparent after GLONASS signal has been cancelled. Bottom: Offset test tone subtracted after cancellation shows the test tone is unaffected. Right plot: top curve: Cross correlation of raw data from 2 antennas. Bottom curve: Cross correlation of data with GLONASS removed and raw data from another antenna. (Curves offset for clarity).

The addition and subtraction of test tones give us some indication of how toxic the algorithm is to astronomy signals. However, astronomy signals are not coherent sine waves, but are more like band limited noise in the case of spectral lines and wide band noise in the case of continuum sources. We replaced the test tones with some synthetic band limited noise, added it before the cancellation and subtracted it again after. As shown in Figure 4 the band limited noise is not affected by the cancellation algorithm, down to a part in 1000, in other words, we have achieved 30 dBs of dynamic range in the suppression. Processing with and without the presence of an astronomy sources make very little difference to the effectiveness of the cancellation.

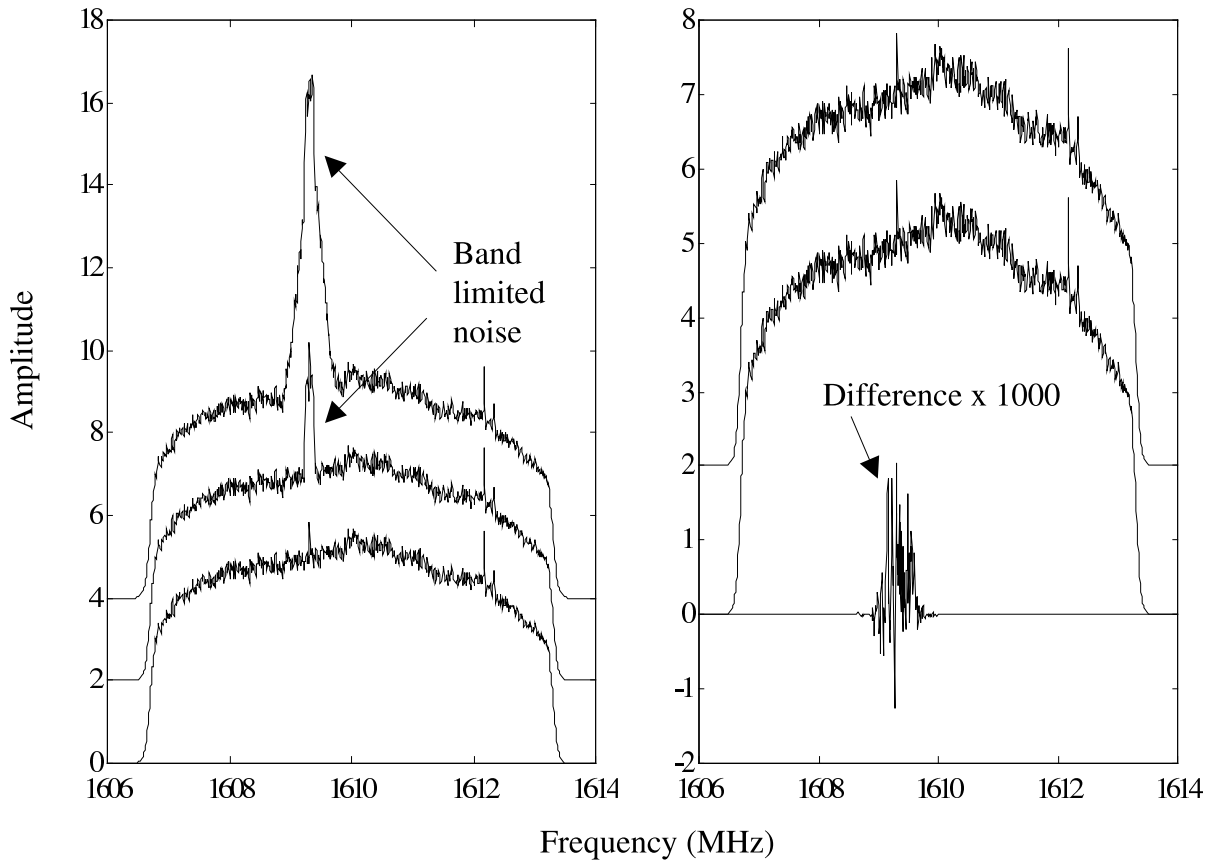


Figure 4. Left plot: Left plot: Top: Band limited noise added before cancellation. Middle: GLONASS signal has been cancelled. Bottom: Band limited noise subtracted after cancellation shows the band limited noise is unaffected by the cancellation (the carrier break through is still present). Right plot: Top: Result of cancellation with no test tone or noise added. Middle: Result of cancellation with band limited noise added before and subtracted after cancellation. Bottom: Difference of top 2 curves multiplied by 1000 shows that the band limited noise was not affected by more than 1 part in 1000. (Curves offset vertically for clarity in several cases).

6. LIMITATIONS AND FUTURE IMPROVEMENTS

The carrier break through described earlier needs to be modelled and cancelled. While we have not investigated this carefully yet, we believe this should be possible. We do not know the cause of the ripples in the cross correlation spectra and some more investigation there may lead to an improvement in the algorithm. At present we have modelled the band limiting filters of the GLONASS transmission system by a low-pass filter when the signal is centered on zero-IF. This is limiting the accuracy with which we estimate the GLONASS spectrum and therefore possibly limiting the cancellation. We aim to either obtain details of the band limiting filters used on the GLONASS transmission system, or use the existing data to estimate them.

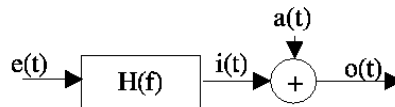
Note that both GPS and GLONASS have in-band secondary channels that are spread 10 times wider, and therefore have power spectral density about 10 times weaker. This secondary channel for GPS and GLONASS is much harder to deal with, because the PN codes are more complex and may not be completely known. We do need to find a way to mitigate against these signals, because they do still cause substantial problems for radio astronomy.

In addition to GLONASS and GPS, many other satellite systems have well-specified modulation and coding schemes. This opens up the possibility of removing these other classes of signals using digital signal processing. The techniques described here will be useful for some others, but not all. At a recent meeting⁶ a wide range of interference mitigation techniques applicable to many different undesired signals were presented and discussed.

The usefulness of the method presented in this paper must ultimately be shown by conducting astronomy in the presence of GLONASS or GPS. Ideally the astronomy results with and without interference present would be indistinguishable. The use of recorded data and post processing is useful for demonstrating the method. But with processing currently running at one 1/1000 real time the amount of astronomy that can be demonstrated is very limited. It is therefore desirable to explore the use of dedicated hardware to achieve real time processing of the signal.

The most comprehensive approach is to build a complete receiver that incorporates the interference cancellation method described in this paper. This is the approach that must be taken in designing new interference resistant receivers but currently the best option is to build an 'add on' to existing receivers. The problem with this method is that the quantiser in current receivers is designed for adequate performance when processing noise like signals. Typically a 1 or 2 bit quantiser is used. Techniques like adaptive noise cancellation will cause the number of bits needed to represent the signal to grow when the interference is suppressed. For example, consider an interferer whose peak amplitude is equivalent to one eighth of the least significant bit in the quantiser and assume that 2 bits can accurately represent the interference. To generate an interference free estimate of the signal it is necessary to subtract the estimate of the interferer from the signal. In doing this, the number of bits needed to represent the signal grows by 4 lower order bits. The signal now has too many bits to be processed by receivers normally used for radioastronomy. The solution to this problem is to form auto and cross correlations of the measured signal and the estimate of the interference. If the estimate $e(t)$ and the interference $i(t)$ are related to each other by a linear transfer function then in frequency domain this can be written as $I(f) = H(f)E(f)$ where $H(f)$ is the frequency domain transfer function.

In this context the astronomy signal can be considered to noise. The system can be redrawn as



where $o(t)$ is the wanted astronomy signal plus interference. The cross-spectrum method can now be used to estimate the transfer function $H(f)$. If the astronomy signal $a(t)$ is uncorrelated with $i(t)$ then $H(f)$ ^{2,12} equal to the ratio of the cross-spectrum $S_{oe}(f)$ between $o(t)$ and $e(t)$ and the power spectrum $S_{ee}(f)$ of $e(t)$.

$$H(f) = S_{oe}(f)/S_{ee}(f)$$

The power spectrum $S_{aa}(f)$ of $a(t)$ is now equal to:

$$S_{aa}(f) = S_{oo}(f) - |H(f)|^2 \cdot S_{ee}(f)$$

Thus measurement of the power spectrum of $a(t)$ and $e(t)$ plus the cross spectrum of the two gives enough information to derive the power spectrum of the uncorrupted astronomical signal. These spectra can be obtained from the auto and cross correlations of the two signal. Correlators used for astronomy normally process at most 2-bit data. Straight 2-bit sampling may not be sufficient to accurately represent the estimated GLONASS/GPS signal. The addition of dither and the use of noise shaped oversampling should solve this problem. The hardware itself will internally generate a multi-bit accurate representation of the interferer.

The hardware used to synthesise the baseband GLONASS or GPS is comparatively simple and easy to emulate in an FPGA. The main difficulty is the estimation of and tracking of signal phase and amplitude. This task is best left to software. Data needed to perform this task are correlations between the input and the current estimate of the interferer. If a reasonable initial estimate of the interferer has been found then very few correlations are needed to maintain tracking of carrier phase, carrier Doppler and code phase. The hardware could also be used to generate these correlations. The operations performed by the hardware are:

1. Generate the carrier digitally with adjustable carrier phase and Doppler.
2. Generate the GLONASS/GPS modulation with adjustable code phase
3. Modulate the carrier with the GLONASS code. This gives an unscaled 'noise free' estimate of the interference.
4. Generate the zero delay and $\pm 1/2$ chip correlations between the input signal and the 'noise free' estimate.
5. Scale the magnitude of the 'noise free' estimate to match the interference.
6. Optionally delay data and estimate. This allows the magnitude and phase corrections to be applied to the estimate used in generating the corrections. This extra item is needed to fully emulate the current software. In practice it may be unnecessary.

This hardware removes most of the intensive tasks from software and leaves the software to monitor the correlations. From this monitoring the software then needs to generate updates for the carrier phase, carrier Doppler, code phase and amplitude. With these updates the output of the hardware is a 'noise free' estimate of the interference.

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