A Possible Back-end Solution for the ALFA Recombination-line Survey: *alias* the WAPPs

Avinash A. Deshpande\(^1\),\(^2\) and Mayra Lebron\(^1\)

\(^1\) Arecibo Observatory, NAIC, HC 3 Box 53995, Arecibo, PR 00612, USA
e-mail: desh@naic.edu, mlebron@naic.edu
\(^2\) Raman Research Institute, Bangalore 560 080 INDIA
e-mail: desh@rri.res.in

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Abstract. This note briefly discusses the back-end requirement for the ALFA Galactic recombination-line survey. It then explores an unconventional method that employs an appropriate combination of filtering and sampling techniques, to assess possible use of the existing WAPP correlator as an attractive back-end for the proposed RRL surveys. A few illustrative examples of the set of transitions that can be covered are also presented.

Key words. Radio recombination lines, signal processing, down-conversion, harmonic sampling, aliasing, filtering

1. Introduction

The bank-end requirements for the Galactic radio recombination line survey with the Arecibo L-band Feed Array (ALFA) are significantly different from those for other ALFA surveys. Within the 300 MHz band of ALFA (1225 to 1525 MHz), there are about 12 alpha transitions of H, He & C, as well as a comparable number of higher-order transitions (i.e. beta, gamma, etc.) associated with the correspondingly higher levels. The bands corresponding to successive alpha transitions have an average separation of about 25 MHz. Only in some cases are the higher-order transitions located close to the alpha bands. Many of the bands are likely to be affected by strong RFI, particularly at the lower-end of the ALFA band. While one would like to observe as many transitions as possible, we believe that a survey of a selected subset of the observable transitions within the ALFA band would be valuable and adequate for the relevant studies. The spectral resolution requirement here is less demanding than that for the Galactic HI surveys, and a 4-5 kHz (i.e. 1 km/s in velocity at L-band) resolution would suffice. With these specifications, we proceed to explore possible ways in which several well separated bands, each of width ranging from 3 to 7 MHz in width, can be observed simultaneously with each of the ALFA beams. We also consider some of the OH bands for possible inclusion, in the later part of our exploration.

2. Spectral spread Vs. resolution

The band from 1400 to 1500 MHz is relatively free of RFI and contains 4 alpha transitions, along with a few bands containing higher-order transitions. Therefore, let us assume that these bands adequately provide the main spectral focus for the proposed survey. Below we list some obvious and some non-obvious possibilities.

a) If one is to observe the entire 100 MHz band, a suitable spectrometer with at least about 20000 spectral channels is needed. The WAPPs can offer about 8k channels if only one polarization channel is processed. Processing both the polarization channels, the possible velocity resolution would be about 5 km/s. The GALFA spectrometer can also process a 100-MHz bandwidth, but has too coarse a resolution in its wide-band mode to be useful for RRL studies. However, it would be worth exploring with Jeff Mock whether the GALFA spectrometer can be programmed to select (i.e. digital filter) the desired set of narrow bands from the digitized 100-MHz BW and obtain a set of spectra with adequate spectral resolution. A disadvantage in sampling a wider band such as 100 MHz, and then digitally filtering the narrow bands, is that any RFI within the wider band would be sampled and could leave its imprint in the desired bands, unless adequately fine quantization and filtering is achieved.

b) Request NAIC to provide a dedicated FPGA-based back-end for the RRL work.

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c) Investigate how the present capabilities of the WAPPs can be utilized fruitfully, where the several desired narrow bands within the 100 MHz can be filtered and packed to form a band much narrower than 100 MHz.

In the next section, we pursue possibility c) further.

3. Enter the WAPPs: to alias or not to alias

There are several ways in which one can filter/select the desired narrow bands and pack them together to form a band that is narrower than the original span over which they were spread. A brute-force filtering using one filter per band and combining the outputs to pack these compactly would required a large number of filters and mixers, as well as local-oscillators and power combiners, per ALFA pipeline, even when the number (n) of sub-bands is not very large.

However, if the desired bands are appropriately filtered (defined) by using a single filter with multiple (closely harmonic) responses, the compact packing may be achieved by exploiting (the otherwise undesirable) “aliasing”. This method (Deshpande, 2004) is based on the fact that the sampling/digitization of a signal is equivalent to a formal ‘mixing’ operation wherein all (i.e. a comb) of harmonics of the sampling frequency beat with the signal band, producing a (convolved) repetitive spectrum which, over each of its sections of width equal to half of the sampling frequency, contains a shifted and/or folded copy of the signal input to the sampler. Any resultant “aliasing” is generally undesirable, and is overcome by limiting the band of the signal to be sampled appropriate to the sampling frequency or by using a sampling frequency based on the Nyquist criterion. However, in this method the apparent folding of the input bands with respect to the harmonics of the sampling frequency is exploited to compactly pack together otherwise well-separated bands. It is worth noting that in doing so, one is not necessarily violating the Nyquist criterion. In fact, we will be strictly following the Nyquist criterion in its basic spirit, such that the ‘total’ signal bandwidth we wish to sample, and which is input to the digitizer, does not exceed half of the sampling frequency. The method is based on the technique of harmonic-sampling wherein the down-conversions of different bands of the signals effecting different amount of shifts is implicit. It is clear that meeting the Nyquist criterion as above is a necessary condition, and by no means sufficient to avoid aliasing. This aspect is elaborated on later in the discussion.

Noting the existing ALFA IF/LO system, we assume that only one formal analog down-conversion will be effected. The LO used in this conversion will account for any Doppler-shifts, if they need to be corrected for. The RF band input to this mixer stage is assumed to be nominally limited to the 350 MHz width (1188-1530 MHz), and may include an additional 120-MHz wide section (1605-1725 MHz) when OH lines are also to be considered.

Following the signal path further, we assume that the IF is filtered through a suitable multi-band response filter whose detailed response function we wish to determine. However, the overall extent of the response is specified based on the back-end input requirement. The existing IF/LO system for the ALFA (or for any single-pixel receiver) presents signals to the WAPP at an IF frequency of 250 or 275 MHz, depending on whether the BW is 100 MHz or ≤50 MHz, respectively. Noting this, we define the allowed IF extent to be within the “window” 200-300 MHz for using the presently available WAPP-input paths. However, we also explore the possibility in which WAPP-input has no bandwidth restriction. The sampling frequencies of the WAPP are normally fixed; however we assume that these can be varied if needed.

Adopting a generalized approach from Deshpande (2004), we specify a complete list of radio frequency (RF) bands that we wish to analyze and employ the adaptive search algorithm to seek suitable values of the first LO frequency and the sampling frequency that we should use such that we can sample as many RRL-transition bands as possible given the above front-end and back-end constraints. The supplied list covers all the RRL bands of interest (i.e. around the respective rest-frequencies) in the 1225-1525 MHz band of ALFA, and may include in some cases the OH frequencies.

Certain bands can be specified to be in a “must-include” category. The suitable values of LO frequency and sampling frequency are sought through a simple grid search. For each combination of these two parameters, the adaptive part of the search iteratively includes/excludes a subset of the listed bands in/from the final selection, based on following considerations. This applies only to all of the “optional” (i.e. non-“must-include”) bands, and any of them can be excluded, if

a) the LO frequency falls within that RF band, or
b) any harmonic of the sampling frequency falls within the corresponding IF band, or
c) the corresponding IF band is outside the allowed IF range,
d) any part of its baseband version suggests a possible alias with the baseband version of any of the “must-include” bands or already included other “optional” bands. Self aliasing (or band folding) is also penalized, since real sampling (as against complex/quadrature sampling) is assumed.

On the other hand, any combination of the LO and sampling frequencies is ruled out if it results in folding/aliasing of any of the “must-include” bands.

Various possible solutions are noted and the ones offering compact baseband-packing are considered. If appropriate, the list of “must-include” bands (or even the basic list) is revised, and the entire search procedure repeated.

4. Results & conclusions

We present some sample results of the search.
Fig. 1. The selected RF bands associated with the indicated RRL transitions. The y-axis scale is somewhat arbitrary, and the higher-rise edge in each band corresponds to the its lower RF frequency end. The LO and sampling clock frequencies found most appropriate are indicated in the top text.

In first of the three cases discussed here, 4 key bands of varying bandwidths, and in the range 1400-1480 MHz, were specified as the “must-include” bands. The IF band was restricted to 200 – 300 MHz and the sampling clock frequency was limited to 100 MHz or below, consistent with the WAPP specifications. Figures 1, 2, & 3 show the selected bands as a function of RF, IF and baseband frequencies respectively.

It is clear that the six RRL-bands of interest in the 1397-1485 MHz range can be sampled together within a baseband span of 34 MHz, using a sampling frequency of 68 MHz. The harmonic-sampling induced folding of the bands has resulted in efficient packing. The 80% usage should be considered as near optimum considering the variety in the widths and the non-uniformity in the locations of the bands. We note that only 4 of the six bands packed here were specified as “must-include’ (the others are the optional bands, indicated in the figures by the tag ‘OPT:’). Using the WAPP in its “3-level, 2-channel auto-correlation” mode, we estimate the spectral resolution to be 4.15 kHz (or slightly finer than 1 km/s resolution in velocity). Based on this exploration,

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1 The picture at IF (e.g. in figure 2) is a result of a straight-forward translation (with a possible common flip about the LO frequency, if a higher side LO is used) of the set of RF bands (e.g. as shown in Figure 1). In order to help visualize the possibly complex translation of the IF picture (e.g. in figure 2) in to the corresponding packed version at the base-band (e.g. in figure 3) as a consequence of the so-called harmonic sampling, please note, in the IF picture, the sets of “tall” and “short” markers placed at frequencies corresponding to integral multiples and half-integral multiples of the sampling frequency, respectively. The start and end frequencies (and hence the spectral extent) in the IF display(s) are chosen deliberately to be suitable integral multiples of the sampling frequency. Given this, the translation to the base-band locations would become apparent when the higher IF end of the plot/paper is folded alternately to the left and to the right with folds at the “short” and the “tall” markers, respectively. All the “tall” markers would then overlap with the right-edge of the plot window (corresponding to the “zero” frequency at the base-band), and the “short” marks at the left-edge of the reduced span. In reality, a replica of the limited span at the base-band (for example, as in Fig. 3), would exist at the right side of each harmonic of the sampling frequency, and a mirrored replica on its left. However, the limited span displayed in the base-band plot (e.g. Fig. 3) includes all of the non-redundant signal information we need to consider.
Fig. 2. The selected bands associated with the indicated RRL transitions after the first down-conversion, i.e. their respective locations at IF. The start and end frequencies (at the left and the right edges) are harmonics of the sampling frequency and the tall vertical lines mark the locations of the harmonics within the plotted range. The other harmonics of half of the sampling frequency are marked by the ‘short’ vertical line. The individual bands are not flipped relative to each other at IF, but the flips about the ‘short’ and ‘tall’ markers would be apparent at baseband (figure 3).

It appears possible to use WAPPs (through its 100 MHz BW path) as the ALFA-RRL back-end if suitable IF filters (e.g. with band-pass windows as shown in figure 2) can be obtained, and if WAPPs sampling clocks can be adjusted suitably (e.g. to 68 MHz).

In the other two cases (case 2 & 3), 6 key bands of varying bandwidths, including one OH band, were specified as the “must-include” bands. All the known RFI-prone bands were excluded from the list of bands to be considered. The IF bandwidth was left unrestricted (corresponding to a possibility of by-passing the WAPP filters), and the range of sampling clock frequency was limited to 95-105 MHz, to ensure ready compatibility with existing WAPP usage.

Figures 4 and 5 show the selected bands (case 2) as a function of IF and baseband frequencies, respectively. Figures 6 and 7 show similar plots for another combination of bands selected (case 3). In both of these cases, 8 bands (which include 2 OH-bands) could be packed in a bandwidth slightly under 50 MHz. The packing efficiency (65 to 68%) is somewhat lower here, as a consequence of the limits on the sampling frequency, than in the first example. Noting that two of the selected 8 bands can be treated as one (i.e. 1417-1427), only seven distinct band-pass windows need to be considered. Use of the same WAPP-mode as discussed above (i.e., 3-level, 2 channel), would provide a spectral resolution of 6 kHz (a little over 1 km/s in velocity). Although this resolution may be a bit coarse for OH-maser studies, it would be adequate for the survey purpose. Inclusion of some of the OH bands, along with the RRL bands, would open up a rewarding survey prospect without any significant additional “cost”. Implementation of any of these two cases (shown in figures 4-5 and 6-7) does not require any significant change in the WAPP sampling setup, and so the existing boards would not need any fine tuning. According to Bill Sisk, it would be easier to provide a direct IF path to the WAPP digitizers (by-passing the existing 50/100 MHz filters), than to change the WAPP clock frequencies by a large factor. So, a setup with a by-pass IF-path would enable use of the WAPPs as an attractive back-end for ALFA surveys.
Fig. 3. The resultant packing in the baseband, i.e. over the range 0 to half of the sampling frequency. Note the flips and the shifts apparent in individual band version associated with baseband. The efficiency of packing is indicated at end of the top label, and is be considered as near optimum, given the variety in spacing and the widths of the RF bands.

A formal request may be made to NAIC to explore and pursue one (or more) of the possibilities illustrated here. The above suggested technique uses existing WAPPs (with a minor or no modification) to offer a relatively inexpensive and speedy solution to the RRL back-end requirements in the ALFA context (as well as in the context of single-pixel receivers). In any case, the packing method elaborated above, if used, would simplify RRL back-end design considerably, even for a new RRL-specific back-end that NAIC may offer to build.

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References
Deshpande A. A. 2004, in preparation
Fig. 4. Similar to figure 2, but for the case 2 (please refer to the text for details).
Fig. 5. Similar to figure 3, but for the case 2 (please refer to the text for details).
Fig. 6. Similar to figure 2, but for the case 3 (please refer to the text for details).
Fig. 7. Similar to figure 3, but for the case 3 (please refer to the text for details).