Development of an FPGA-Based, 1024-Channel Spectrometer with Individual Channel Lock-in Amplification

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Since the mid 1930's, the concept of a lock-in amplifier has been put into practice as an efficient and mathematically simple method for extracting weak signal amplitudes and phases from noisy environments. Using a periodic reference, lock-in amplifiers (LIAs from here on out) combine homodyne detection schemes with low-pass filtering to extract signals in a defined frequency band around the reference. In effect, this allows detection systems to reject all other frequency components that do not fall within the reference band, greatly reducing integrated noise power and boosting SNR.

Given the impressive ability to pick out faint signals from noisy measurements, it is no surprise that LIAs have found a great amount of use in the astronomy community, especially in higher frequency microwave systems where avoiding environmental noise is a constant battle. At their core, LIAs need only the ability to perform quadrature multiplication with their reference signals to downmix the tone of interest to baseband then apply an adjustable low-pass filter. The relatively simple engineering of LIAs has allowed them to maintain their place as a staple in mm-wave astronomy even as more complex methods of signal extraction such as the FFT and PFB have become the standard.

The primary downside of using LIAs as readout systems for astronomical observation is the fact that each LIA typically only extracts signal information from a single band located around a single reference tone. Analog LIAs, while effective and inexpensive, are not a space or power efficient means of examining a spectrum of information unlike the FFT which is able to output thousands of spectral amplitudes in a matter of milliseconds. At this point in time, LIAs and FFT-based spectrometers are typically seen as two different approaches to reaching the objective of extracting signal power from a noisy environment. Until now there has been little research done on combining the abilities of LIAs and FFT spectrometers into a single system.

Here we present the design, justification, and preliminary results for a 1024-channel spectrometer that employs lock-in methodology to further remove systematic noise from its output readings. By creating an FPGA-generated square tone which is converted to analog output and fed into a fast-switching RF diode, incoming noisy signals can be modulated by a precisely known chopping frequency. This up-converted signal then enters the FGPA through a digitizer and is passed through an FFT or PFB which separates spectral components into bins. The act of chopping the signal at a frequency slightly slower than the FFT output frequency (in this case, the ADC sampling speed divided by the FFT length) pushes all important information into a higher frequency band that is protected from systematic noise and 1/f pink noise.

Once the data leaves the FFT, it will be in one of two states depending on the phase of the chopping signal plus a small amount of digital delay. This results in each bin of the FFT to oscillate at the chop frequency which can easily be demodulated as the original chopping clock is created internal to the FPGA. Once demodulated, the resulting product is passed through an integrator to be low-pass filtered leaving only the DC portion of the remaining spectrum for each bin. Accumulated bins are stored in BRAM and fed to an external hard drive through ethernet where they can be used for spectral analysis of the signal of interest.

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