VLBA Sensitivity Memo 28

Some Thoughts on Gain Control in the DBE Era

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Abstract Here is described at a conceptual level the gain control capabilities of the upcoming ROACH Digital Back End (DBE) for VLBI systems. Some requirements are set and a strategy for its use is presented. With some care the ability to track system temperature can be greatly enhanced over current practice. Some recommendations regarding implementation of the hardware, control software and scheduling software are made.

1 RDBE gain control

This memo addresses gain control in the ROACH DBE (RDBE) being developed by NRAO and Haystack Observatory, but the concepts discussed could be extended to any analogous system. The relationships between power in the analog input signals and digital output data streams produced by the RDBE for a fixed configuration is determined by two gain settings; one before digitization and one afterward (see Figure 1). To first order these control knobs act in the same way, however some subtle but important differences suggest a specific strategy for their usage. For more information about the VLBA sensitivity upgrade see the memo series at `http://www.vlba.nrao.edu/memos/sensi/`.

1.1 External gain control

External gain control, also referred to as analog gain control, is implemented as a series of switchable attenuators. Five such attenuators with gains of -1, -2, -4, -8 and -16 dB (power) can be independently switched into or out of the data path. An additional -20 dB gain "solar" attenuator may also be switched into the signal path; an IF amplifier sits between this solar attenuator and the others. Note the negative signs; this document treats gains as multipliers of signal strength. The use of this system for gain control is essential to ensure that power entering the digitizers is within range. Two properties of these analog devices must be considered in planning for their usage:

- There is no guarantee of path-length equality when changing gain. Therefore changing this gain could incur an unknown, but calibratable, delay.
- There is no guarantee of bandpass equality. It is possible that changing this gain could affect the bandpass of the analog signal.

For these reasons, adjustments of these gains within a calibration domain of an experiment may be detrimental. Calibration of these affects is certainly possible, but could be cumbersome. Lab tests of the RDBE attenuator unit have shown worst delay changes up to 25 ps and 1.5 dB gain slope changes across the band (K. Morris, private communication).

1.2 Internal gain control

Internal gain control is performed digitally inside the FPGA. The implementation inside the FPGA of this "gain" may not be done through multiplication but rather by appropriate setting of quantization thresholds in the quantizer block, notably in the case of 2-bit quantization. This internal gain has no effect for 1-bit quantization. This memo aims not to address the implementation, but rather the generic properties of this internal "gain".

Unlike for the external gain, the internal gain is implemented digitally and is equivalent to multiplication of the digital voltage stream by a gain factor which could be greater than or less than unity, and can, in principle, allow arbitrary small step sizes, although step sizes smaller than about half a dB in power come without substantial performance improvements. This process is completely repeatable and deterministic and the gain can be changed without delay or bandpass change.

The total and switched power detectors should precede the internal gain, if possible, to maximize the utility of these data products and the independence of their calculation from gain control.

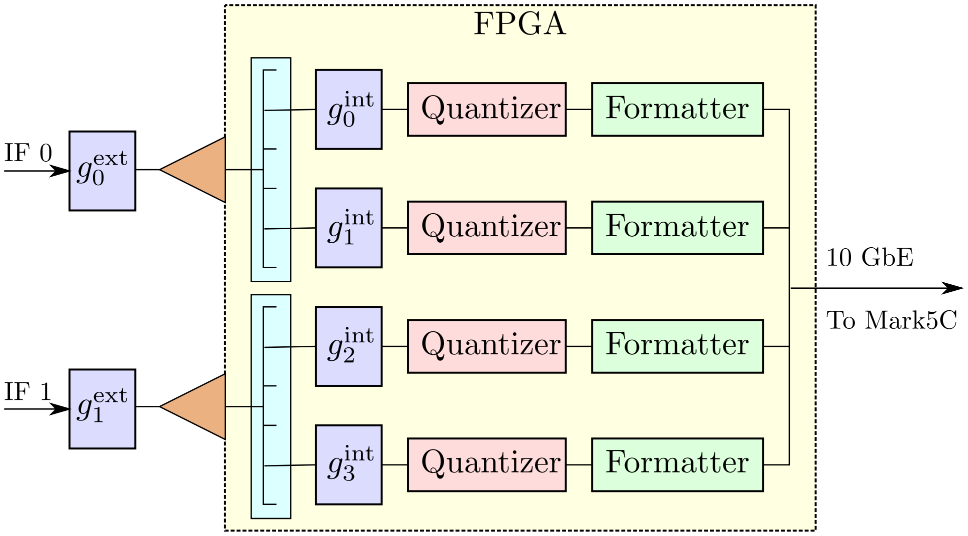

Figure 1: *ROACH Digital Back End conceptual block diagram emphasizing gain control.* Analog signals from the antenna enter from the left. External (analog) switchable attenuators impart the first stage gain, g^{ext} separately for each input (IF) signal. These signals are then digitized (within tan-colored left-pointing triangles) and sent into the FPGA. A channelization process is then performed (light blue box) either via a polyphase filterbank or through digital down-converters. Before final quantization (usually to 1 or 2 bits) a final gain, g_{int} is applied on a per sub-band basis. The quantized data is then formatted and sent out to a data recorder.

2 Discussion of requirements

2.1 Expected total power range and variation timescales

Any effective gain control mechanism must act over the full range of conditions and on timescales that significant change is to occur. Here the requirements of the gain control system are motivated.

During the course of an observation, the total power entering the digitization pass-band can change considerably. At frequencies and temperatures relevant to centimeter-wave radio telescopes, system temperature (T_{sys}) and received power can be used interchangably, within a constant factor. Except for the cases of the sun and extreme radio frequency interference (RFI), external contributions to T_{sys} over the 330 MHz to 100 GHz range, averaged over a typical digitized bandwidth of a many tens to some hundreds of MHz, are bounded by about 3 K from below (assuming no spill-over and contribution only from the cosmic microwave background) and 300 K from above (assuming complete spill-over, an opaque warm atmosphere, and/or at low frequencies the Galactic synchrotron background). This contribution is added to the receiver temperature, which itself is bounded from below at about 7 K and is assumed to remain constant during an observation, to form T_{sys}. Thus excepting severe RFI, the extreme range in T_{sys} that one would experience during an observation within one frequency setting covers a range of 15 dB (a factor of 30) in power, or a range of 7.5 dB (factor of 5.5 in RMS voltage). More typically this range will be far smaller.

In good observing conditions, especially at frequencies below 20 GHz, the majority of the gain change will be correlated with observation elevation. At low elevation, the spilled-over beam has more contact with the warm (300 K) ground and the column density of the atmosphere is greater, both leading to higher $T_{\rm sys}$. The total power change will occur on timescales of many minutes at low elevations and hours at high elevations when tracking a source.

In partially cloudy conditions, especially near the 22 GHz water line, significant changes can occur on the cloud-crossing timescale, $\max(D_{\rm antenna}, D_{\rm cloud})/v_{\rm wind}$. This equates to 2 seconds for a 45 km/hour wind over a 25 m antenna with tiny clouds. Usually $D_{\rm cloud} > D_{\rm antenna}$, increasing this timescale proportionally. Note that this timescale is just an approximation, it does not attempt to determine exactly the proper interval for gain control, but this likely yields a relevant gain control that is accurate within a factor of a few. Given that observations at high frequencies in winds much stronger than this will likely be limited by pointing performance, a gain control interval of 1 s is reasonable in most circumstances, but it might be required on timescales a few times smaller in the case of small, stiff antennas, with ALMA being the extreme example of such a system.

2.2 Required gain precision

Dynamic gain adjustment is critical to maintain optimum quantization efficiency, η_Q. This efficiency factor is directly related to the final sensitivity of the interferometer and is thus as important as any other efficiency factor. With levels properly set, 2-bit quantization yields $\eta_Q = 88\%$. However, if gains are either too high or too low, the quantization scenario ultimately reduces to 1-bit sampling with $\eta_Q = 64\%$ (see Figure 2). In order to remain within 2% of peak efficiency, the gain must be kept within 1 dB of optimal RMS voltage (2 dB in power). Efficiency drops rather quickly outside this range. A detailed treatment of quantization efficiency can be found in EVLA memo 88, `http://www.aoc.nrao.edu/evla/geninfo/memoseries/evlamemo88.pdf`.

3 Suggested gain control strategy

The RDBE makes use of 8-bit samplers. The signals they ultimately produce for most VLBI applications will be requantized to 2 or even 1 bit before recording to minimize the data transport problem. As long as no quantization with fewer than about 4 effective bits occurs before the final quantization, there is little incremental loss to the final system efficiency. Thus there is headroom of 4 bits (a factor of 16 in RMS voltage or 256 in power) within the digital processing, assuming that digital processing of the digitized signal does not itself limit the headroom. This range is greater than the factor of 30 needed to span extremes of $T_{\rm sys}$ range even if the digitized signal has power variations of several dB. Note that more typically $T_{\rm sys}$ at a station ranges over a factor of at most a few during an observation. Given this, it is quite reasonable to hold the external gain fixed for a particular frequency tuning over the course of an entire experiment. The numerous choices for how to cross-calibrate settings used for different frequency setups or lock external gains for small frequency shifts should be exposed to the user of the instrument. A suitable gain could be set during a setup scan at the beginning of the observation. Such a system should be careful to make use of the current $T_{\rm sys}$ in order to set the external gain to allow for maximum reasonable increases and decreases in total power. On stable, well calibrated systems it should be possible to use a look-up table to drive the gain control, independent of any setup scan. In cases where frequency switching is used, even for different IF tunings within the same receiver band, the external gain for each tuning will need to be set somehow, either through look-up table with a different value for each possible IF configuration or through auto setting on the first scan making use of that frequency/IF configuration.

Once the external gain is fixed, control of the internal gain can then be used to independently set levels on short timescales on each sub-band based on frequent power measurements. If the internal gain values are logged when changed they can be used to reconstruct accurately the digitized power on a fixed scale over the course of an experiment. Periodic switched power measurements, which can be averaged over many tens of seconds (usually 120 s on the VLBA currently), can be used to periodically calibrate the gain of the analog electronics to convert this digital power into a calibrated $T_{\rm sys}$. Since total power measurements are

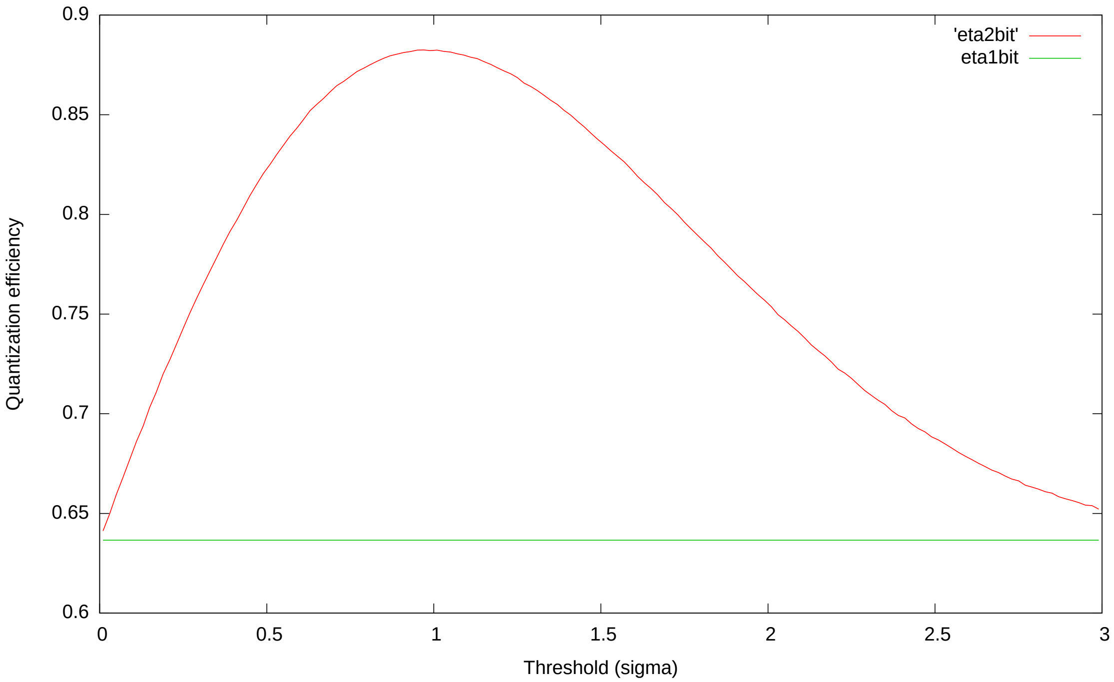

Figure 2: *4-level quantization efficiency as function of sampler threshold.* In the gain interpretation of the sampler level used in this document, the threshold is inversely proportional to the gain. This efficiency is derived assuming the canonical reconstituted levels of -3.3359, -1, 1, 3.3359, as is used by both the VLBA hardware correlator and DiFX and assumes uniform power across the digitized spectrum (see VLBA scientific memo 9, `http://www.vlba.nrao.edu/memos/sci/sci09memo.pdf`). Use of an adaptive reconstituted level set can marginally improve the situation but has not been implemented. The threshold value is relative to σ, the RMS voltage. For reference, 1-bit efficiency (64%) is shown in green.

many times more accurate than switched-power measurement (by roughly the ratio of T_{sys} to calibration noise source temperature), T_{sys} could be measured much more accurately and on much shorter timescales than are typically done today, assuming receivers have stable gain on the timescale that switched-power measurements are made. Accurate total power measurements on the timescale of any attenuator changes are desired to minimize amplitude closure errors in phase referenced (i.e., non-self-calibrated) observations. The recorded information would make it trivial to revert to the present technique of determining the flux scale based solely on switched power if desired.

4 Recommendations

Below are some suggestions to the implementors of the hardware and software related to gain control:

1. Changing of the external gain should be minimized. When changed, its previous and new values should be logged. It should be the purview of the astronomer and/or scheduling software to make intelligent decisions about such changes.
2. The external and internal gains are conceptually very similar. Any VSI commands or queries for the two should be made analogous.

3. The point in the signal chain at which the total/switched power detectors tap the voltage streams inside the FPGA should precede internal gain control.

4. Any changes to either internal or external gain should be made effective at a one-second tick, if possible, and logged.

5. Unless gain control is desired on timescales considerably shorter than one second, it is highly recommended to keep the gain control loop outside the RDBE FPGA and internal control software and kept wholly within software external to the RDBE control program that runs on the ROACH PowerPC processor. This does not rule out the option of an addition program that runs on that PowerPC processor that has the sole job of adjusting in real time the gains.

6. Ideally, the following flexibility should be exposed to the final user for setting the external gain on a per-scan basis: 1. option to set the gain now, either using an autolevel routine or a specified value, 2. option to keep existing gain setting, 3. option to return to previous setting used for the given frequency setup, 4. option to change gain on receiver change, 5. option to change gain on any change of frequency settings, and 6. default option to allow the software to decide what it thinks is best.

7. Ideally, the following flexibility should be exposed to the final user for setting the internal gain on a per-scan basis: 1. option to set and hold the gain now, based either on an autolevel routine or a specified value, 2. option to automatically update the settings at a specified interval, and 3. option to hold the gain.

5 Acknowledgements

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