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A Wide-Band VLBI Digital Backend System

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Abstract

Virtually all next-generation radio astronomy applications, including VLBI, will be enhanced by inexpensive new Digital Back-End (DBE) processors. Haystack Observatory is collaborating with the UC Berkeley Space Sciences Laboratory to develop a powerful and low-cost replacement for the current analog BBCs for both geodesy and astronomy VLBI applications. Based on a general-purpose FPGA-based signal-processing board developed at UC Berkeley, each board will accept two analog 500MHz BW IF signals, and process each into 2^n channels (for example, sixteen 32MHz BW channels or thirty-two 16 MHz channels) with a total aggregate output rate of 4 Gbps to two VSI output connectors. We report on the status of this DBE system and possibilities for utilizing it for both geodetic and astronomy applications.

1. Introduction

The work described in this paper couples modern high speed A/D converters and FPGA based architectures to develop a versatile new VLBI digital backend (DBE) system that will bring dramatic improvements to the practice of both geodetic and astronomical VLBI. In particular, the development of a small module based on this modern technology will:

- Replace nearly a rack full of currently used analog backend equipment
- Interface easily to the receiver system of almost any radio telescope in the world
- Extend the output data rate by a factor of four to 4Gbps; use of multiple parallel DBE's will allow data rates to easily and economically extend to 8 or 16 Gbps
- Interface directly with the new generation of high-data-rate VLBI data systems, including the Mark 5B/5B+ developed at Haystack Observatory
- Cost ~5% of that of the current backend system

From an historical perspective, this development is very timely. In 1980, the Mark III VLBI system was introduced with a maximum data recording rate of 224Mb/s [1]. This rate was achieved at great expense using a ~$200K special-purpose Mark III recorder using magnetic tapes costing nearly $1000 each and was reserved for only the most demanding scientific observations. Today, 22 years later, these tape-based systems are being rapidly replaced by disk-based systems, such as the Mark 5A and Mark 5B [2], that cost less than $20K and record at 1 Gbps with media costs less than 25% that of magnetic tape. However, just as importantly, the VLBI backend systems in use today are still based on the same basic analog technology as the Mark III system with only modest improvements. Furthermore, though each backend system originally cost on the order of $100-200K, they are irreplaceable (and almost unmaintainable) due to obsolescence of critical parts. The DBE described here will replace these old backend systems at a fraction of the cost of the original, offer much expanded capability, and become a welcome complement to the new generation of disk-based VLBI data systems.

2. Current Generation of VLBI Backend Systems

The current generation of VLBI backend systems had their origins largely in the 1970's and early 1980's, resulting in the systems that are still in use for the majority of the world's VLBI observatories. A typical current-generation VLBI backend system is shown in Figure 1. An IF signal in a fixed range of 500-1000 MHz is processed through a suite of (up to) 14 analog baseband-converter (BBC) modules; each BBC module selects a small slice, typically up to 16 MHz wide, of the IF and translates it to a pair of adjacent USB/LSB channels. Each of the output channels from up to ~14 BBC modules is then digitally sampled at the Nyquist rate, formatted and time-tagged by an accompanying 'formatter'; the formatter is typically limited to an aggregate data rate of 1024 Mbps (Mark IV). The data are then recorded onto magnetic tape or disks.

Though this backend system, or small variants, has been the mainstay of VLBI observations, it suffers from several serious drawbacks:

- Fixed IF-frequency input range: Even current Mark IV and VLBA systems use different IF ranges, while many modern RF-IF systems, particularly those at shorter wavelengths, employ IF frequencies ranges that extend as high as 10-12 GHz; this requires custom electronics at each such VLBI site in order to move the IF to the proper range for the current VLBI backends.
- High cost: Each of the BBC modules costs ~\$10K-\$25K to procure, and several parts are obsolete and nearly impossible to obtain. Similarly, the accompanying formatter module cost is ~\$10K-\$50K and also contains obsolete parts.
- Non-uniformity of channel bandpasses: Due to the analog nature of the BBC electronics, channel-to-channel differences may be significant. Analog-filter variations of up to ~2.5% can produce phase errors up to several degrees.
- Lack of expandability: Expanding data rates beyond 1024 Mbps is a practical impossibility due the high cost and non-availability of the needed components.
- Physical bulk: The current system of IF distribution, analog BBCs and formatters requires nearly a rack full of equipment, which is very expensive and fragile to ship.

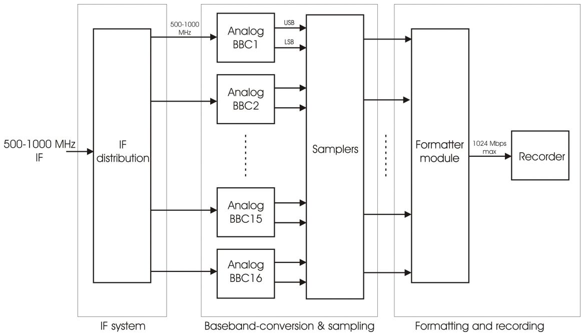

Figure 1. Simplified diagram of current VLBI backend system

2.1. Goals of the DBE

The development of the DBE system seeks to address all the aforementioned drawbacks of current systems and aims for a dramatic increase in capability. Figure 2 outlines the new backend system. The primary features of this new system are:

- Flexible IF-frequency input range: An arbitrary 500 MHz slice can be selected from each of two input IFs whose frequency range may be anywhere from 100MHz to 12GHz; this IF frequency range is designed to be compatible with both current and expected future systems. The same 500 MHz slice is selected from each of the two input IFs to support dual-polarization observations, for example.
- Uniformity of channel bandpasses: The conversion to baseband is accomplished fully digitally using a polyphase filter bank (PFB), ensuring absolute channel-to-channel uniformity.
- Dual VSI output interfaces: Dual VLBI Standard Interface [3] outputs clocked at rates to 64 MHz can support an aggregate data rate of up to 4 Gbps from 1000 MHz of aggregate bandwidth (Nyquist sampling, 2 bits/sample). Recording can be done on any VSI-compliant device.
- Low cost: The projected cost of the new sampling and baseband conversion module is ≤\$10K, at least a factor of ten lower than the current system. Furthermore, the need for a separate formatter is eliminated since the Mark 5B recording system formats all data internally.
- Easy expandability: The low-cost and small physical volume of the backend units will allow easy expansion to as much as ~16 Gbps with multiple Mark 5B+ (2 Gbps) recorders.
- Easy transportability: A full 4 Gbps backend system, including two Mark 5B+ units, will occupy ~21 inches of standard rack space. A complete 16 Gbps system with 4 IF/PFB units and 8 Mark 5B+ units will occupy two modest-size racks; this is considerably smaller than the current tape-based system with 1 Gbps capability!

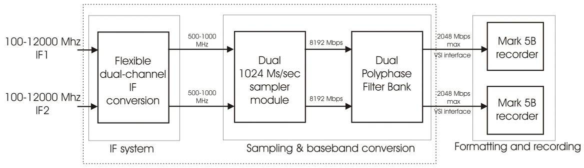

Figure 2. Simplified block diagram of new VLBI backend system including flexible IF-conversion

2.2. Flexible IF-Conversion Module

In order to convert the output from the telescope or array receiver we plan to design and build flexible IF conversion electronics that will select an arbitrary 500 MHz segment of an IF spanning the range 0.1-12 GHz and translate it to a 500 MHz wide frequency band centered at 750 MHz. The center frequency of 750 MHz is convenient since the 1024 Ms/sec sample rate for the A/D converter will be alias-sampled to cover a baseband from 8 to 508 MHz. The sample rate of 1024 MHz, rather than an even 1000 MHz, is needed for the PFB in order to provide the standard 16 MHz (32 Ms/sec) and 32 MHz (64 Ms/sec) VLBI channels. The filter sharpness will allow 14 channels of 32 MHz bandwidth with full flatness, plus two outer-edge channels with somewhat reduced flatness (i.e. a total of 2048 Mbps output from *each* PFB for each wideband input channel). Figure 3 shows a block diagram of the proposed converter module. The converter will process two IF channels which share both LO1 and LO2. Estimated replication cost for a dual channel IF converter is ~5K$.

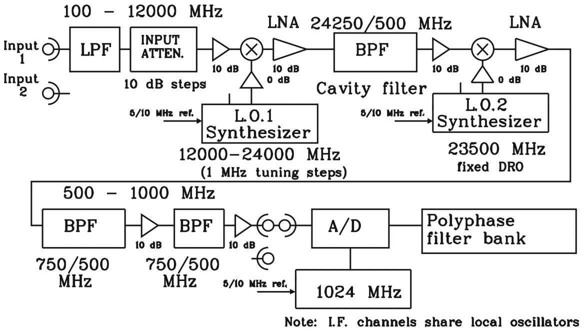

Figure 3. Block diagram of proposed IF-to-baseband converter module

2.3. Sampling and Baseband Conversion Module

The sampling and baseband-conversion modules are adapted from similar designs originally developed at the Berkeley Space Sciences Laboratory in support of the CARMA project. Figure 4 shows a simplified block diagram.

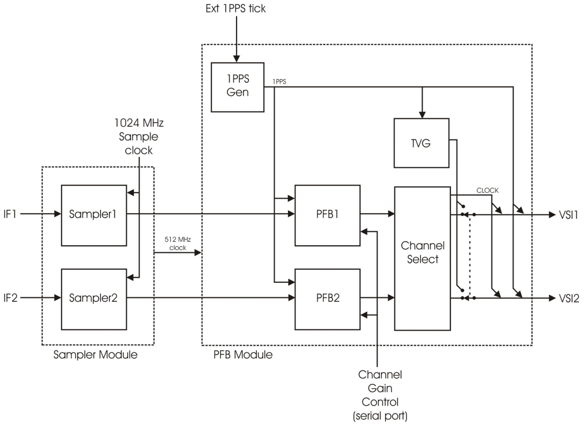

Figure 4. DBE implementation on the Berkeley prototype FPGA-based board

The data from the two IFs are sampled at 1024 Ms/sec 8 bits/sample by dual samplers in a single chip; the sample clock is supplied externally and is phase-locked to the station hydrogen-maser frequency standard. The sample data are processed by two independent FPGA-based PFBs to segment each 500 MHz IF into 2^n adjacent frequency channels spanning the 500 MHz IF bandwidth. The selection of the value of n is done by downloading the FPGA with a design particular to the value of n; depending on the requirements of the user, the value of n can be adjusted from 0 (single 512 MHz channel) to about 8 (256 channels of 2 MHz each). This flexibility in choosing baseband-channel bandwidth guarantees backward compatibility with all channel-bandwidth modes of the current backend analog equipment, as well as support for future modes requiring channel bandwidths up to a single 512 MHz channel.

Analysis carried out on the PFB algorithms [4] indicates that out-of-band response for each channel exceeds 50 dB, far better than can be done with analog filtering in the current analog BBCs. The channels to be recorded are selected in the Channel-Select sub-section of the FPGA and output to two independent VSI output buses at a maximum aggregate data rate of 4096 Mbps. An externally-generated station 1PPS signal provides a one-time reference tick to initiate a module-based 1pps generator. An on-board Test Vector Generator (TVG) provides test signals for verification of the VSI interfaces to the recording system. An externally generated channel-gain control will act to keep the channel signal gains optimal for 2-bit sampling normally used in VLBI. A photo of a prototype DBE board under test at Haystack Observatory is shown in Figure 5.

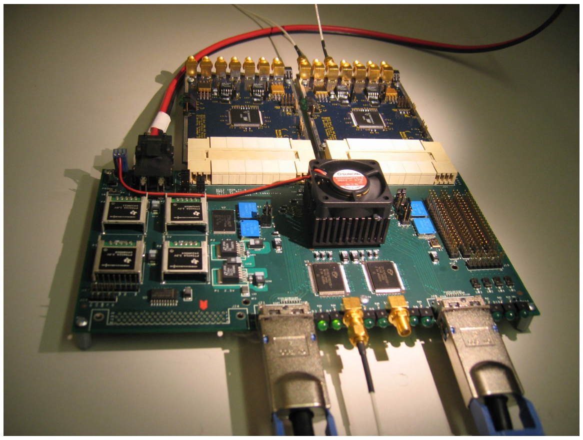

Figure 5. Prototype DBE board undergoing testing

3. Summary

Once the DBE units are commercially available, it is expected that their use will quickly become widespread. Their low cost and high performance will have a dramatic and lasting impact on the VLBI research infrastructure.

References

[1] Rogers, A.E.E. et al, *Science*, 219, 51, 1983.

[2] The Mark 5 web site at *http://web.haystack.mit.edu/mark5/Mark5.htm* contains much additional information about the Mark 5 system.

[3] “VLBI Standard Hardware Interface Specification - VSI-H”, Revision 1.0, 7 August 2000, available at *http://dopey.haystack.edu/vsi/index.html.*

[4] Rogers, A.E.E., Hinteregger, H.F., Mark 5 Memo Series, #018, *ftp://web.haystack.edu/pub/mark5/018.pdf*, 2004.