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THE DBBC PROJECT - A FLEXIBLE ENVIRONMENT FOR VLBI AND SPACE RESEARCH: DIGITAL RECEIVER AND BACK-END SYSTEMS

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Abstract

DBBC is acronym of Digital Base Band Converter and is the name of an EVN (European VLBI Network) development project. The main idea staying behind to the 'DBBC' project is to replace the existing VLBI terminal with a complete and compact system to be used with any VSI (VLBI Standard Interface) compliant recorder or data transport. Hardware programmability is a fundamental feature in order to optimize the architecture to the particular functionality the instrument is called to satisfy, because different performance involve different number of gates necessary to perform the required functionality. Under this assumptions, maximum input and output data rates are the limitation and they have to be set so to satisfy the present and reasonable future necessities. The new development is fully compatible with the existing terminals and correlators in order to require a minimum effort to be introduced in the radio-telescope stations, still maintaining the possibility to be upgraded for a new class of correlators. The possible upgrades have to be mostly in software in order to avoid and modify any hardware part, for cost savings and simplification in the operations, so that programmable hardware is the main component. Hardware upgrade is anyway still possible because a standard in the connection of the different elements is defined.

The entire project is based on a flexible architecture, composed by one or more FPGA boards as computation elements, placed in a mixed cascaded/parallel structure, so to guarantee a parallel usage of data input and a shared parallel output data flow. In a DBBC a single system unit is composed by four RF/IF Input in the ranges spanning from 0.01 up to 3.5 GHz with each of them feeding a 1.024 or 2.048 GHz sampler clock. Then four polarizations or bands are available for a single group of output channels selection. A group of 64 channels is able to handle a shared combination of channels coming from the four bands, supporting two VSI output connectors as output. Multiple architecture can be used taking the advantage to adopt fully re-configurable FPGA Core boards, where one of such board is an autonomous element populated with an appropriate number of gates, fed by any of the four IFs, and sharing the output data bus. Narrow or wide bandwidth channels per module can be assigned, maintaining the maximum number of gates provided by the Core. Modular realization for a stack processing is provided, that implies the use of one or more Core for achieving more gates number and then more processing capability. A Core can handle a maximum input bandwidth of more than 34 Gbit/s, and a maximum output bandwidth of 8.192 Gbit/s. The input bus is cascaded, with very low skew, between modules. An analog monitor, produced by DA conversion, is added for testing purposes, in order to be able and evaluate with a common spectrum analyzer the different channels content and performance. This has been proved particularly useful in order to adopt standard equipment normally in use in a radio-telescope. Field System support is used to configure the different modules and allow standard settings, and still getting total power measurements of the converted channel.

Different configurations can be supported for obtain different functionalities, as SSB down converter, wide band parallel FIR, poly-phase FIR/FFT, and still more.

Introduction

Since the VLBI introduction in the radioastronomy community it was evident a deep fusion of the interferometric methodology with the technological solution to implement it. Whether this was pertaining the receiver area with the introduction of the great deal in the phase stability of the constituting components and particularly with the frequency conversions performed with the best achievable phase lock conditions, the actual complication in the equipment area was related to the back-end instrumentation.

Indeed, still maintaining a fundamental need to keep the received signals with a great phase stability all over the process, this section presented the place where the interfacing between receivers and recording media was placed, with all the limitations and compromises this could show.

The evolution up to the present times is then bringing us to an aspect coming from the historical adaptation dictated by the best possible solutions at the time. In particular the limited width in the recorded band with respect to the entire available, and potentially usable, so as the technological limitation in the maximum working frequency in the correlation components, imposed the architecture development of the backend systems.

Any new technology now available that could improve the performance and simplify the data process was to be taken into account, and a new perspective would be envisioned to be operative in the near future.

Such process was of great importance not only for the opportunity now introduced by the fast network connections and new recording systems, but even because a further step could be considered: not only improvement and adaptation of new technology with the traditional method, a necessary step to guarantee the continuity, but even a more radical approach whose the VLBI data processing could benefit. This on the other hand could contribute to address other areas, correlators, receivers, data transfer, to converge up to solutions of excellence, to be possibly usable even in other areas such as the space technologies.

Performance of a VLBI backend

A system able to replace a VLBI terminal performing as minimum the same functionality in a fully digital fashion would immediately represent several advantages. Reproducibility and phase stability are the main elements involved in such scenario: any system would be exactly the same with respect to any other. A digital version then would represent an obvious goal.

Let's consider a list of element included in the traditional acquisition terminal and for each element consider the equivalent functionality in a digital system for each 400 MHz width IF an analog backend have: IF distributor, including total power measurement system; a number of 8-16 baseband converters, each having functionality for tuning and single side band converting with 10 KHz step in a range from 100 to 500 MHz, or 500 - 900 MHz. Side bands wide in frequency from 0.625, 0.125, 0.25, 0.5, 1, 2 , 4, 8, 16 MHz. Automatic gain control. Total power measurements in both lower and upper side band; Samplers at 1 or 2 bits; Formatter or VSI-H interface.

In the same circumstances a digital backend needs to have: No IF distributor because the first operation to perform, by definition, is the analog to digital conversion. Data distribution of the sampled signal is realized through a dedicated gigabit transmission system or through a parallel high speed bus. Total power measurement is needed; Frequency conversion can be conceived in more ways, with different architectures, whose choice is deeply affecting the final features and degree of freedom.

In particular we could divide in methods where the single converted channel is independent on the others in terms of bandwidth and methods where channels are equally spaced and wide. Channel bandwidth can be greatly improved because the lack of limitation typical of the on tape writing. Total power measurement is needed in each channel; Signals for operating in digital need to have a wider representation with respect to the 1 or 2 bits, and this appears more evident whether a control in the RFI area needs to be included. VSI-H is a standard interface between instrumentation, distribution or any other item needing a rigorous control on the timing of the data transfer. The traditional formatter is limited in the maximum data rate for future needs, because developed for feeding a tape recorder. Today can be removed.

A possible solution for giving an answer about the number of IFs a backend should support, is just to present a modular approach, where more channels could be added, considering the scientific problem to treat and a common output set of channels where data coming from more sources (frequency bands and/or polarizations) could be placed to go on the further recording media, or data transfer. Let's consider now the bandwidth for a single IF.

Numerous developments are in course in the radioastronomy community (ALMA; SKA, e-VLBI, etc.) and several analysis have been performed to choose the most proper A/D converter, considering of course the total bandwidth to process. This because different commercial options are in the field to convert with a proper number of representation bits, the received signals. Excellent low cost solutions are possible even if the major bottleneck is represented by the further processing hardware elements. So is not difficult to find solutions ranging between 1000 MS/s up to 2000 MS/s for 500/1000 MHz slices of band in different Nyquist zones.

A trade-off between bandwidth in use with the traditional VLBI receivers and hardware processing method and components capability was necessary to properly set the analog to digital conversion data rate and it appear promising to set such value not too far from 1000 MS/s, for a limitation in the cost.

Let's now evaluate what is needed as channel bandwidth coming out by the new backend. It looks useful to have available the common channel width we are used, 1-2-4-8-16 MHz, while we could ask whether the narrower bandwidth are needed. The possibility to increase the channel to 32, 64, 128, 256, or the entire 512 MHz is worth to be taken into consideration, due to the greatly improved recording data rate. So if a trend to increase channel size in frequency looks promising, the necessity to include narrow band channelization should be carefully taken in to consideration for reducing the development complexity.

The process to produce a single frequency channel, wide or narrow band, can be realized with different methods. A possibility is making use of FFT modules, dividing the frequency spectrum in more bands, equally spaced, with channel size depending on the FFT dimension. Such modules are feed by poly-phase digital filters in order to reduce data rate and perform a pre-filtering process.

A different method treats a channel as single unity giving the possibility to tune at different base frequencies choosing their bandwidth. This is reflected in a more complex implementation, but more flexible.

A crucial element that should be considered for a backend architecture to is just leaving the possibility to explore different solutions for different observing schemes, adding to the already cited modular aspect, a programmability aspect. Then it would be worth to consider in the backend a defined architecture with functionally defined modules, implementing inside different methods or technologies, well adapted to the general or particular need to satisfy.

A flexible approach can be reflected in the possibility to have tunable or fixed multi-channel modules, to have high data rate transfer modules (ex. 10G technology) or direct bus connections, and so on. A precise relation between different parts should anyway considered to guarantee an electrical and maximum data rate compatibility. Total power measurements should be included in the digital domain so as a selectable automatic gain control.

A new approach is still possible considering to add in the backend section the functionality to treat delay and fringe rotation control under a station based approach. This, while can present restrictions for astronomical usage due to the limitation in the field of view, in the geodetic data process could bring great simplification in the correlation process opening yet the possibility to easily share the process in a software approach. On the other hand a more heavy process would be left for the backend side, where a-priori calculation would be needed, with no possibility to recover for calculation errors. A deeper evaluation seems to be worth to be considered.

Functionality Distribution

Taking in consideration with a new vision, as we are trying to do, a VLBI backend functionality, it appears possible in principle to move some processes in different places, instead to maintain all together as we are at present used to see. It looks interesting to discuss about this possibility.

The conversion of the analog IF coming from the receiver is the first stage of the backend process, while being any other further activity performed in the digital domain. So it would be worth to ask whether it could be convenient to physically place the converter in the receiver area and then to transfer sampled data, using high data rate serial technology, as it could be represented by the 10G one. Indeed if data representation is 8-10 bit wide with a rate of about 1 GS/s, such standard technology could be adopted to transfer data inside an observatory or more in general inside the digital backend 'area'. Some indications could suggest useful such opportunity, because it could contribute to avoid frequency dependant performance in the traditional analog cable signal transfer, and it could represent a valid method to minimize cross-talk or interference introduction in the signal path. Still more important, signal injection for phase calibration could be much simplified, due to the single analog to digital conversion point. A great deal would still be given to the reference clock distribution. As drawback a digital front-end in the receivers area could represent a potential source of noise, so that particular care should be taken in the shielding realization. Then to talk about backend 'area' is in our intention pretty valuable, because introducing a standard method to distribute high data rate signals, implies the possibility to further process the observed data even in different places. So that it could be taken into consideration a radio interference mitigation algorithm, as it was suggested by groups working in such area, adopting a real time cancellation or a more simple digital band filtering. And such process could be realized in a different place, where interference are detected and selected, as a RFI station could represent.

The data transfer technology is quickly growing so that a possibility could also be considered to fully record a received band to process later at the correlator side for tuning or bandwidth selecting. What is traditionally performed in a station could be transferred to the correlator, reducing failure risks in the station. With an almost ideal no limitation in data transfer, it would make no sense to select portion of bands in the stations, while leaving the correlator site free to handle the data in a unique common process for all the stations. Unexpected RFI could be removed simply tuning all the station at a different band portion. This approach could appear the opposite of creating a delay and fringe rotation station based in the backend, but it is not, because simply this solution could be adopted with the backend terminal placed at the correlator side, and the delay-phase control performed in such terminal.

Today very fast A/D converters are commercially available, in excess of 20GS/s, so that it could be taken into account the possibility to sample data at sky frequency for the bands at present adopted or even for those higher if the trend will be to increase the frequency of the observed band. As soon as faster digital processing components will come to the market, able to 'fill' a VLBI network with sampled data, still a much simpler and faster process will be adopted, greatly simplifying the backend role, up to its minimization and integration with the correlator.

The DBBC Project

DBBC is acronym of Digital Base Band Converter and is the name of an EVN development project. The main idea staying behind to the 'DBBC' project is to replace the existing VLBI terminal with a complete and compact system to be used with any VSI compliant recorder or data transport.

The system is a development from Istituto di Radioastronomia-INAF (Italy) with the main collaboration of Max Planck Institute for Radiastronomy in Bonn (Germany). In a preliminary phase Shanghay Observatory (China) took part to the project with a reduced system, named mini-DBBC.

Hardware programmability is a fundamental feature in order to optimize the architecture to the particular functionality the instrument is called to satisfy, because different performance involve different number of gates necessary to perform the required functionality. Under this assumptions, maximum input and output data rates are the limitation and they have to be set so to satisfy the present and reasonable future necessities.

The new development is fully compatible with the existing terminals and correlators in order to require a minimum effort to be introduced in the stations and no modification at the correlator side, still maintaining the possibility to be upgraded for a new class of correlators. The possible upgrades have to be mostly software in order to avoid and modify any hardware part, for cost savings and simplification in the operations, so that programmable hardware is the main component. Hardware upgrade is still possible because a standard in the connection of the different elements is defined.

The entire project is based on a flexible architecture, composed by one or more FPGA boards as computation elements, placed in a mixed cascaded/parallel structure, so to guarantee a parallel usage of data input and a shared parallel output data flow.

In a DBBC a single system unit is composed by four RF/IF Input in the ranges 0.01-512, 512-1024, 1024-1536, 1536-2048 MHz, 2048-2100 MHz with each of them fed by a 1.024 GHz clock sampler.

Alternatively if 2048MHz is used as sampling clock the usable ranges are 0.01-1024, 1024 – 2048, 2048-3072 MHz. Then four polarizations or bands are available for a single group of output channels selection. A group of 64 channels is able to handle a shared combination of channels coming from the four bands, supporting two VSI output connectors as output.

Multiple architecture can be used taking the advantage to adopt fully re-configurable FPGA Core boards, where one of such modules is an autonomous board populated with an appropriate number of gates, fed by any of the four IFs, and sharing the output data bus. Narrow or wide bandwidth channels per module can be assigned, maintaining the maximum number of gates provided by the Core board. Modular realization for a stack processing is provided, that implies the use of one or more Core Modules for achieving more gates number and then more processing capability. A Core

Module can handle a maximum input bandwidth of more than 34 Gbit/s, and a maximum output bandwidth of 8.192 Gbit/s. The input bus is cascaded, with very low skew, between modules. An analog monitor, produced by DA conversion, is added for testing purposes, in order to be able and evaluate with a common spectrum analyzer the different channels content and performance. This has been proved particularly useful in order to adopt standard equipment normally in use in a radio-telescope.

Field System (NASA software) support is used to configure the different modules and allows standard settings, still getting total power measurements of the converted channel.

Different configurations can be supported for obtain different functionalities, as SSB down converter, wide band parallel FIR, poly-phase FIR/FFT, and still more. The possibility to independently tune different channels, and to have them filtered at different bandwidth, while it is an obvious feature in the analog implementation, it is not the unique so obvious solution in the digital implementation, so that different solutions could appear to be more convenient. For this reason the project allows to implement different architectures, and to change them at convenience.

A Core Board can handle a maximum input bandwidth of more than 34 Gbit/s, and a maximum output bandwidth of 8.192 Gbit/s. Two high rate bus are present, named HSI and HSO respectively, with the addition of a further Control/Configuration/Monitor bus, named CCM.

System Components

Signals coming from the receivers trough the Conditioning Module are kept at the proper level before the sampling process.

The ADBoard perform the analog to digital conversion at a rate of 1024 or 2048 MHz. Four of these units are able to feed four IFs with 8-bit representation in the processing units, the Core Module boards. The maximum number of such FPGA boards is 16 in a stack configuration. The FiLa board, whose meaning is First/Last, open and close the chain. Such board is indeed used in the initial and final part of the stack to perform more functions: 2 VSI interfaces, DA monitor, Timing synchronization and Clock Synthesizer, Communication, JTAG channel.

The FPGAs Core Configuration represent the firmware to perform the desired functionality, such as the SSB base band conversion. Different architectures can be used because of the full programmability of the module.

The Power Distributor board is generating the supply voltages for each board of the chain. The software, able to manage the entire functionality of the DBBC is run on a compact PC board with the help of two PCI commercial interfaces. System Management Software is Field System oriented, so that standard commands to set and use the instrument are Field System-like, requiring than a minimum effort to integrate the DBBC in that environment.

Configuration Firmware

Different architectures can be used in the Core boards, having different performance and behaviors. One possible configuration is the DDC digital down converter in the classical implementation meaning. In such a solution a direct SSB conversion is typically performed between high data rate sampled IF band and lower data rate base band. One or two channels are generated for each converter, as in the analog implementation. Important differences, greatly improving the performance are present: local oscillator is a Numerically Controlled Oscillator (NCO), mixer is complex as Look Up Table multiplier, low-pass band filters are Finite Impulse Response (FIR). Decimation circuitry is adopted because of the high ratio between IF and output data rate and is performed with multirate/multistage FIR.

Digital Total Power (DTP) measurement at base band level is adopted; Rescaling/Gain Control (RGC) is adopted for dynamic range control and final data representation.

The tuning step is under 1 Hz, giving the possibility to finely tune the receiver for spectroscopy or any other precise frequency settings. Narrow bandwidth typically adopted is defined for this project in the range: 16, 8, 4, 2, 1, 0.5, 0.25 MHz. Output data rate is 32 or 64 MHz at present in order to be able and fit with the standard, now adopted VSI-H data rate. A 128 MHz output clock rate is the maximum supported.

Upgrade and Digital receiver

Testing with real observation started with mini-DBBC (IRA-SHAO agreement): fringes have been detected in both analog-digital and digital-digital baselines. First digital x analog fringes have been detected on Nov 23, 2004 in the Seshan-Urumuqi (China-China) baseline, while first digital x digital fringes on Feb 2, 2005 in the Noto-Seshan (Italy-China) baseline.

Since that time numerous observations have been done with different baselines around the world. Now the system is formally adopted by the European VLBI Network and will be deployed in the stations during this 2008 and 2009. At the time of writing several radio-telescopes have already been equipped with the DBBC system.

Moreover an update program for improving performance is under way. It includes: development of a third generation processing Core board, faster AD sampler for input bandwidth increasing, AD sampler placed inside the receiver and sampled data sent through an optical fiber, RFI Mitigation Board.

An other important upgrade is the realization of an optical board that allows to transport data of the DBBC system with at a rate of 2x10Gbps.

Using the DBBC technology is possible to build entirely digital receivers, starting from the sky frequency and without any analog pre-conversion, if the frequencies are below the maximum frequency the AD converter is able to handle. At present such limit is set at 3.5GHz. With appropriate interleaved sampling is possible to achieve the maximum frequency for direct tuning up to 7 Ghz. A new development underway will take this limit up to 5 GHz in simple conversion mode and with interleaving techniques until 10 GHz, that represents for now the target value for nowadays commercial sampler devices.

A first implementation of digital receivers with the DBBC technology is underway with the collaboration with Max Planck institute for Radioastronomy (R. Keller et al.) and a L band system will be shortly realized.

Conclusion

The DBBC system is an high flexible instrument because is able to produce independent tunable channels for a full compatibility with the existing VLBI acquisition system and correlators. One Core board is replacing a base band converter module. Combination of up to 4/16 IFs in a single module is possible.

The DBBC system is able to handle also equi-spaced multichannel configuration for producing contiguous not tunable channels. One Core board is able to produce multiple channels.

More solutions are possible within the same system with software selection.

A minimal architecture is composed by 1 ADBoard, 1 Core board (multichannel configuration, or any other), 1 FiLa board (VSI interface, DA converter, etc).

A maximal architecture in one system is composed by 4 Conditioning Modules, 1 FiLa board, 4 ADBoard, 4 Core board, 1 FiLa board, PC and PCI interfaces.

Such wide range of hardware and software conditions allow to assemble a low cost system with the needed performance.

The powerful technology developed can be easily transferred to different scientific environment, where high data rate and fully digital processing is required.

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