INTERNAL REPORT

Integration of the digital full-Stokes spectrometer XARCOS into the control software of Sardinia & Medicina radio-telescopes

Andrea Melis[1], Carlo Migoni[1], Gianni Comoretto[2], Paola Castangia[1] , Silvia Casu[1], Andrea Tarchi[1], Andrea Orlati[3], Sergio Poppi[1] & SRT Astrophysical Validation Team*

Report N. 52, released: 17/12/2015

Reviewer: Adelaide Ladu

OAC Osservatorio Astronomico di Cagliari

Abstract

XARCOS is a spectro-polarimeter developed by the Astrophysical Observatory of Arcetri. The peculiar features of the back-end consist in the capability of processing up to 16 IFs simultaneously, thus fitting the seven-feed full polarization K-band receiver the SRT is equipped with.

A similar but limited version, just having 8 IFs, is available at the 32-m Medicina radio-telescope; no significant differences, in terms of software code, are present between the two versions.

In this report we will describe the entire infrastructure software with which the back-end is fully integrated in the control system used at SRT and Medicina radio-telescopes, and all the steps we have done to make it operational. Finally, some results that we achieved "on field" will be shown.

1 INAF – Osservatorio Astronomico di Cagliari

2 INAF – Osservatorio Astrofisico di Arcetri

3 INAF – Istituto di Radio Astronomia di Bologna

4 Max Planck Institute fur RadioAstronomy, Bonn, Germany

* *R. Ambrosini[3] M. Bartolini[3] , P. Bolli[2] , M. Burgay[1] , R. Concu[1] , A. Corongiu[1] , N. D'Amico[1] , E. Carretti[1] , E. Egron[1] , A. Fara[1] , F. Gaudiomonte[1] , F. Govoni[1] , D. Guidetti[3] , N. Iacolina[1] , F. Loi[1] , F. Massi[2] , M. Murgia[1] , A. Orfei[3] , A. Pellizzoni[1] , D. Perrodin[1] , M. Pilia[1] , T. Pisanu[1], I. Porceddu[1] , I. Prandoni[3] , R. Ricci[3] , A. Ridolfi[4] , S. Righini[3] , C. Stanghellini[3] , C. Tiburzi[1] , A. Trois[1] , V. Vacca[1] , G. Valente[1] and A. Zanichelli [3]*

1 Introduction

XARCOS [1] is a full-Stokes spectrometer made up by the Astrophysical Observatory of Arcetri. It has been installed [2] and tested [3] at the SRT exploiting all the observing modes, achieving some extremely positive outcomes.

Although not the state of the art, this correlator is at the moment the only one capable to process all the 14 IFs provided by the 7-feed K-band receiver at SRT, which made it one of the major priority for the scientific commissioning.

The SRT control software, called NURAGHE [4], is based on the framework ALMA Common Software (ACS). NURAGHE at SRT and ESCS at Medicina/Noto are the implementations of DISCOS (Development of the Italian Single-dish Control System) project.

This report describes the fully XARCOS integration in NURAGHE, also pointing out the several problems occurred and how they have been solved.

We will also discuss the C++ code used to communicate with the various XARCOS boards. Then, an overview of the ACS component will be provided.

Some astronomical observations of well known celestial sources will be also illustrated.

2 A brief history

In this section, an overview of the activities distributed over three years will be described. The work can be distinguished in three main parts:

- ***XARCOS emulator***

  The activity started in the first months of 2012. The emulator, written by Gianni Comoretto in Florence, in spite of its limitations allowed some notable advances. In particular we have been able to debug the "zoom modes". Basically, by varying the instantaneous bandwidth and the internal digital local oscillator, we have seen that the system worked properly (i. e. depending on the start frequency and bandwidth for that section, the line were resolved as expected). We made the first tests using a program called "*testBulk*", a scheduler simulator written by Andrea Orlati. Clearly, the output FITS files produced by these experiments had not most of the telescope ancillary information that, however, were not fundamental during those preliminary stages.

- ***XARCOS real machine in Florence***

  We met some initial difficulties, most of them related to the ACS component main thread. The container tended to crash because of a conflict when data of the total power readouts and those of the spectra had to be retrieved simultaneously. To overcome this, we have written a dedicated thread for the total power readout. After that, a massive number of tests were carried out: we injected the XARCOS inputs with noise mixed with a monochromatic signal at various frequencies. Even if the system showed several instabilities, the four spectra, corresponding to the four Stokes parameters, seemed to be good and quite close to expectations. After two months of intensive tests we had came to a point where it was no longer possible to make further significant progresses. Some issues, in fact, could not be resolved without all the other parts of the control system: indeed, it was impossible, for example, to figure out whether certain problems were caused by the ACS component itself or by other causes. A good example of these problems was when we noticed that the latest spectra were not written in the current FITS while, instead, they were “magically” appearing in the FITS generated in the subsequent acquisition.

- ***XARCOS installed at SRT***

At the end of 2012, XARCOS was installed at the SRT in the Elevation Equipment Room (EER). The first “moment of truth” for the correlator was the comet ISON that we tried to observe [5] in November 2013: important results were achieved during this first experiment even if XARCOS was not completely integrated yet. In particular, apart from the effort to (unsuccessfully) detect NH3 in the comet, we took the opportunity to perform a (successful) test observation of NH3 emission in the dark cloud L483. In the following months we have made a considerable effort to ensure that the FITS files produced were exactly, by content and timing, the ones expected. After we settled almost all the problems, the only remaining issue was that mentioned previously: the last dump of a sub-scan used to jump in the next FITS file. Indeed, we were not able to understand whether the responsible of this phenomenon was XARCOS (by keeping the scan stacked) or the FITS writer, called *FITSZilla*. After countless attempts to find the cause, we arrived at the result that the incorrect behavior was due to the fact that XARCOS was stoping the acquisition without waiting that the data transmission via *Bulk Data Transfer* [6] mechanism was finished. As a side effect, *FITSZilla* was keeping in memory the data that then was written in the next FITS as a first dump. Hence, apart from of the case when *FITSZilla* was launched for the first time, every FITS contained the first dump related to the previous acquisition. This phenomenon was very clear when a position switching observation was done: while the first one on-source acquisition was lacking the last dump, the sequent off-source acquisition contained the previous on-source spectra before the off-source dumps. In order to solve this issue we had to add a proper waiting time to the XARCOS component (called Xbackends) to ensure that the acquisition was not completed before the FITS file was finalized.

3 XARCOS Library

The XARCOS integration is based on the code which control the hardware at low level [7], collected up in the *XARCOS Library*. The back-end is basically made up by 16 independent spectrometers (8 in the Medicina version), each of which can process two independent streams and is capable to provide 2048x4 channels spectra (auto&cross correlations). Each stream is coming from the corresponding Analog-to-Digital Converter managed, from a software viewpoint, by the *AdcConditioner* class. Figure 1 shows a block diagram of the involved classes.

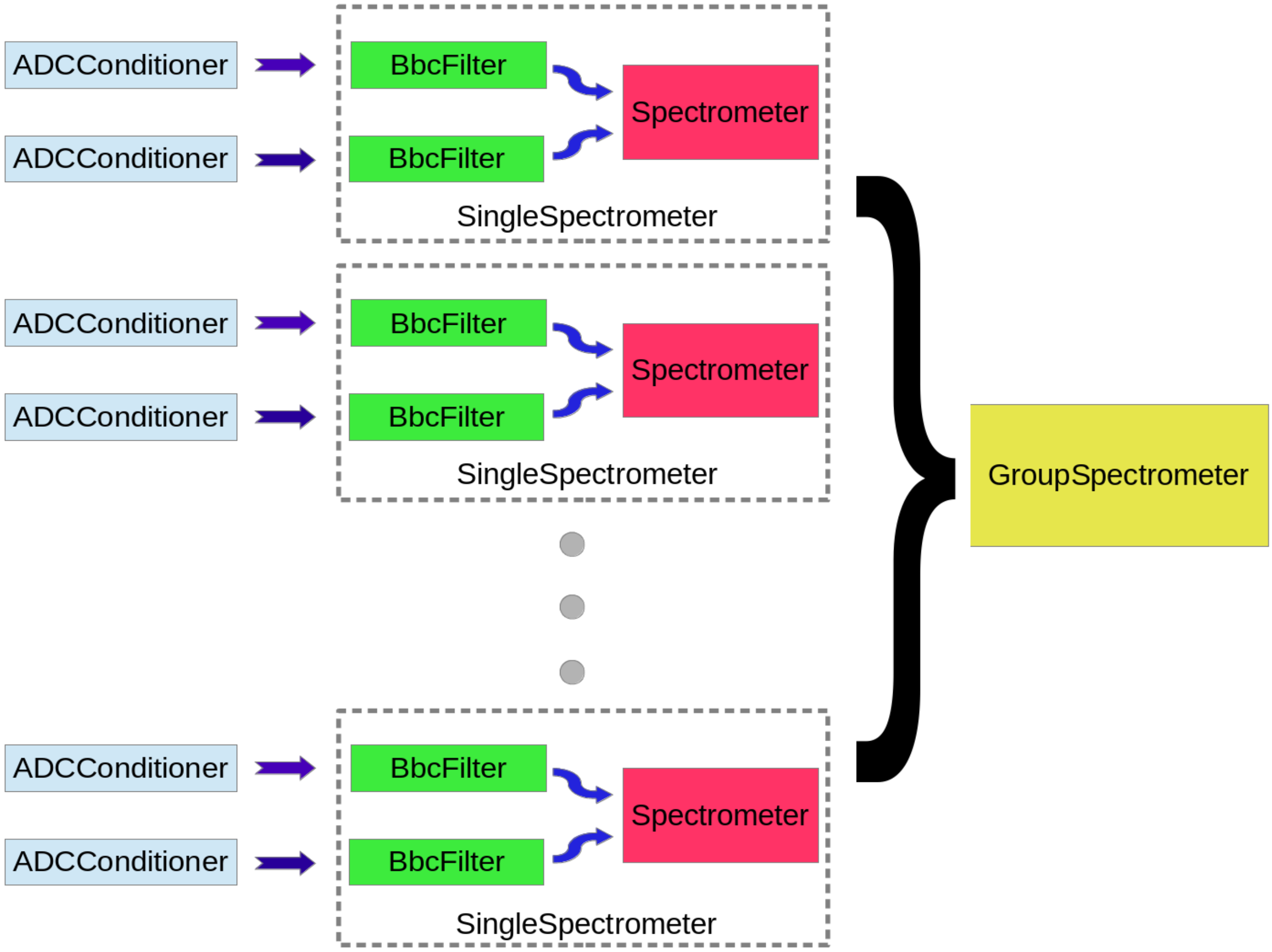

Figure 1: *Block diagram of the classes involved*

The top level class is named *GroupSpectrometer*, that represents the whole instrument. It contains 16 (or 8) spectrometers. Each spectrometer is represented by a *SingleSpectrometer* object and contains both an object called *Spectrometer* and two objects called *BbcFilter*. Each *SingleSpectrometer* manages the left & right polarization of a feed, or two arbitrary input signals, and the *BbcFilter* is responsible to select the spectrum's portion for a signal. A single object of class *Spectrometer* is used for each pair of *BbcFilter* because the FFT engine employed accepts two simultaneous digital streams at its inputs. The two instances of *BbcFilter* can receive the input from two different *AdcConditioner* objects and specify the bandwidth and central frequency of the observed signal. The bandwidth is always the same for the two instances, while the frequency may be different. Since we use only full-Stokes configurations (XC00, XK00, XK77, XK03, XK06, see next section) the two ADC will be always refer to the two polarizations of the same feed, and the frequency will be equal.

All these classes are subclassed from the *HardwareBlock* class, that manages the more abstract functionalities like hardware register definition. At the lower level the communication with the physical hardware is managed by the class named *Cpld2* (Complex Programmable Logic Device), that connects the hardware and the software using a TCP-IP socket.

The data management is managed by a set of classes that hides the physical hardware implementation. Class *Specifiche* (object Xspec) is used to specify the requirements for a spectral integration in an abstract way. The GroupSpectrometer translates a set of Specifiche to a set of *HeadResult* objects. Class *HeadResult* stores some basic informations (bandwidth, gain, central frequency of the portion selected, etc.) describing the setting of a single physical channel (*BbcFilter* object). The observed spectral data is stored in an object of the class *RisultatiIntegrazione* which is an array of *Data* objects. Class *DataIntegrazione* contains current informations for a *SingleSpectrometer*, i.e. two instances of *HeadResult* that describe the setting of the two channels involved. The class *RisultatiIntegrazione* represents an array of *DataIntegrazione* objects, in the same order specified in the Xspec object.

The *GroupSpectrometer* (GS) acts as an interface between ACS and XARCOS. It is very important to underline that, via the corresponding pointer, GS is the only interaction point between the hardware and NURAGHE/ESCS.

4 XBackends: the XARCOS ACS component

According to the ACS distributed Component-Container model, the *XBackends* component is in charge to control the XARCOS backend using both the XARCOS library and all the methods inherited from the so-called *GenericBackend* interface. It exposes all the methods required to deal with a backend and, in that way, the specific hardware dependency is bypassed. The idea is that any backend has general characteristics like, for example, the integration time, the number of bins, the bandwidth, etc.

The *GenericBackend* is based on the concept of section. A section represents a stream of data resulting from the sampling and the elaboration of an IF coming from the receiver. It is characterized by some properties like *feed*, *polarization*, *bins*, *bandwidth*, *frequency*, *sampleRate*, *inputs*, *sectionsNumber.* Usually it is possible to set all these properties but, due to the specificity of this backend, in this case the user can modify just some of them (*frequency, bandwidth and sampleRate*) while the other ones are unchangeable.

Table 1 describes the five configurations currently available [8]. The letter X indicates the backend XARCOS, the second one indicates the receiver (K-band or C-band) while the couple of numbers by identify the feeds involved.

It is worth also pointing out that the XK77 configuration works with only 6 bit instead of the 8 nominally provided by the ADCs. This happens because of a limited number of connection between the board XARCOS is equipped with; it has an negative impact on the number of bit that can be used in case of all feeds are needful, as described in [2].

	XK77	**XK00**	**XK03**	**XK06**	**XC00**
Number of Feeds involved	7	1	2	2	1
Receiver used	K	K	K	K	C
Number of different simultaneous sub-bands for a certain feed	1	4	2	2	4
Default bandwidths (MHz)	62.5	62.5 7.8125 1.953125 0.48828125	62.5 3.90625	62.5 3.90625	62.5 7.8125 1.953125 0.48828125
Full-Stokes	Yes	Yes	Yes	Yes	Yes
Spectral Channels	2048	2048	2048	2048	2048
Number of bit for representing the samples produced by the ADCs	6	8	8	8	8

Table 1: XARCOS default configurations. The central frequency is 176.25 MHz for all the sub-bands. XK03 and XK06 are present because the feeds 0, 3 and 6 are at the same elevation in the sky (when the derotator is in its “parking position”, 0 deg). Hence, they are particularly suitable to be used in “nodding” mode (see Appendix).

5 First light observations

After the ACS component for XARCOS was made fully available, a number of test observations at the SRT were performed using well known standard position-switching (see Appendix) schedules. In particular, we performed observations of the famous ultra-compact HII region W3OH, that hosts strong maser emission from several molecular species (e.g., water, methanol, and hydroxyl).

Fig. 2, obtained using the CLASS package after the conversion of the SRT FITS data into GILDAS format [9], show prototypical spectra of the 6.7 GHz (C-high band) methanol maser line transition. On-source and off-source scans were both 60 seconds; the off-position offsets in declination was two degrees from the target coordinates in order to account for the large extension of the nebula. As primary flux calibrator, we observed the strong radio galaxy 3C295 using the *XC00* configuration.

In order to properly center the methanol maser line emission (expected to peak at a V(LSR,opt) of -45 km/s [10]), within the four sub-bands, we have used the *FTrack* software package [11]. It was important especially so as to avoiding to miss the emission line in the narrowest section.

A first-order flux calibration was performed estimating the average value of counts of the continuum in the (on-off)/off spectrum of 3C295; it was done for all the four different sub-bands. This value (~0.1 for all sub-bands), used in conjunction with the expected flux density value of 3C295 at the observed frequency (4.56 Jy), was computed by using the coefficients determined by Baars et al. (1977). It allowed us to calibrate the methanol lines from arbitrary units (counts) into Jy. In this procedure, the differences in elevation and observing time when observing the target and the calibrator (that influence the atmospheric opacity and telescope gain) are not taken into account.

The main methanol maser line in W3OH was confidently detected in all four sub-bands. The flux density of the peaks are consistent, within the uncertainties and taking into account possible variability, with those reported in literature at comparable spectral resolution [10]. In particular, up to six/seven features are unveiled in the highest resolution spectra

(244 Hz ≈ 0.01 km/s at 6.7 GHz; fig. 2, bottom panels), showing the potential of XARCOS. In particular, it is able to provide, simultaneously, both a relatively broad velocity coverage around the narrow main emission (fig. 2, top panel on the left) and a detailed progressive zoom-in of the line profile (fig. 2, from top to bottom panels on the right). The former is particularly suited to provide information on emission throughout the velocity field of the source. Moreover, the latter allows us to study into detail the line profile, for example, revealing blue or red-shifted wings and/or line sub-components.

Oddly, a permanent shift in frequency of about 5 kHz has been observed in all spectra taken during our tests. This shift prevents the system to precisely center the subbands at the desired frequency. It is due an imprecise functioning of the internal quartzes that provide a slightly incorrect clock to the samplers; we are going to replace the quartzes with better ones shortly, thus solving the shift problem.

In addition, in order to make the correlator even more stable, an external reference will synchronize the entire backend; a dedicated board is under development for this purpose [12].

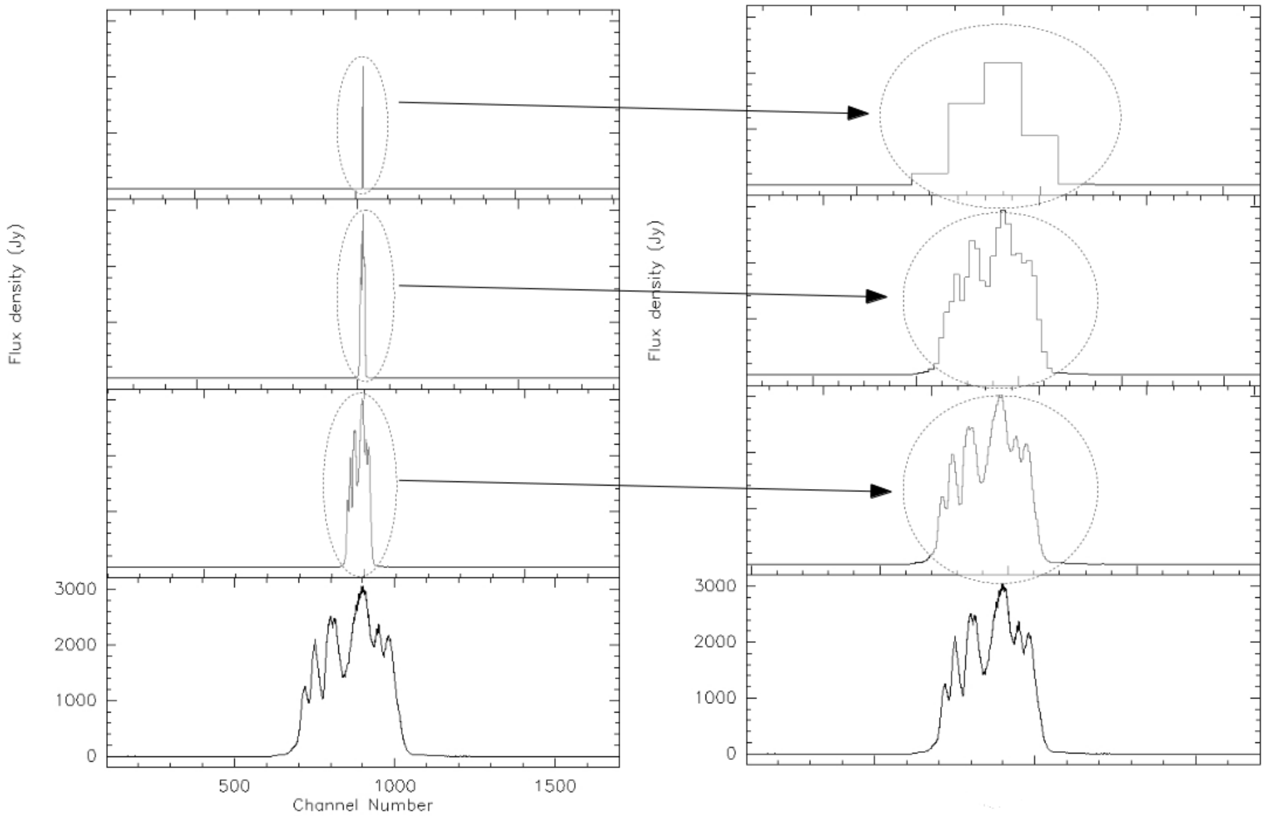

Figure 2. *Spectrum of the 6.7 GHz methanol maser emission in W3(OH) observed at SRT on November 18, 2014.*

On the left: The X and Y axis are channels and flux density (Jy) respectively; regarding the latter, and for the right panels as well, the scale is the same of the plot in the bottom. Four sub-bands are observed simultaneously in accord with the XC00 configurations, corresponding to 1.4, 0.17. 0.04, and 0.01 km/s at a frequency of 6668 MHz, respectively. Due to the frequency shift observed in the data (see Sect. 5, for details), the spectra shown are aligned to the line peak.

On the right: focus of the spectra that shows, throughout the sub-bands available, the great potential of the back-end in terms of spectral resolution. The X axis is channels; the number of channels is scaled in order to provide the same frequency range for all plots (from the bottom to the upper panel, 2048, 512, 128, and 16 channels, respectively). It is evident the increasing quality of the spectra, in terms of spectral resolution, from the top to the bottom.

6 Conclusions

In this report we describe all the steps that led to obtain the fully integrated multi-feed digital correlator XARCOS for the Sardinia and Medicina radio-telescopes.

From the point of view of its implementation in the control system, XARCOS is now ready to be made available for scientific observations with the two aforementioned antennas.

The whole work spanned a period of more than three years. Despite the successful result obtained, this is a huge time. Therefore, also due to the growth of amount of data produced by most modern digital backends, our experience may indicate that integration of the backend in the antenna control software needs a simpler and quicker approach. Since, a new technique has been recently [13] developed and new generation digital backends (ROACH2, in particular) development will indeed take profit of such alternative solution.

7 References

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Contents

Appendix

Position-switching: *This observing method consists in acquiring a spectrum pointing at the target position (ON-position) and soon after a spectrum pointing in a blank-sky position where the source is no longer within the telescope beam (OFF-position). The ON-OFF cycle time is mainly dictated by the frequency of the observation (higher frequencies require faster cycles). The final (ON-OFF)/OFF procedure, thus, produces a spectrum where the sky contribution and the bandpass shape can be considered as removed to a certain degree.*

Nodding: *This is a version of position switching for receivers with multiple beams, e.g. two beams A and B. When A is on source, B is off source (on blank sky). Then the telescope is moved so that B is on source and A is on blank sky for an equal time. This allows position switching with no lost time while performing the off-source observations.*