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DESCRIPTION AND OPERATION OF THE DAGA2_HF ACQUISITION SYSTEM FOR GRAVITATIONAL WAVE DETECTORS

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Abstract

The new acquisition system for the gravitational wave detectors of the ROG group, $NAUTILUS$ operating at the $INFN$ Laboratori Nazionali di Frascati and $EXPLORER$ at $CERN$ is described.

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1 Introduction

The new DAGA2_HF data acquisition system for gravitational wave (g.w.) antennas DAGA2_HF has been conceived and realized by S. Frasca with the collaboration of M.A.Papa and P.Astone for the data filtering. In the following the final modified version, for user application is described. The new DAGA2_HF is presently operating on the two detectors of the Rome group: NAUTILUS in Frascati and EXPLORER at CERN. This new system is operating together with the old DAGA2 system, in order to do the final overall checks. The analysis software is written in FORTRAN (about $35,000$ lines), and is operating on ALFA VAX under OPEN VMS, while the front-end software is written in PASCAL. The main advantages of the new system are the following ones:

a) higher sampling frequency, 5 kHz with respect to the previous 220 Hz; this makes it possible to explore the full frequency band from 0 up to 2.5 kHz and it allows to obtain a better time resolution;

b) a simpler hardware apparatus. The lock-in amplifiers, relative synthesizers and amplifiers needed with the old system to extract the information at the main frequencies (the two resonance modes, the wide band and the calibration) are eliminated. Their functions are performed via software;

c) capability to perform real time data filtering. With the old system the on-line filtering was done using power spectra obtained at a previous time. Therefore an other off-line filtering was needed, in order to obtain the best signal to noise ratio. With the new system the power spectra are continuously updated and no off-line analysis is needed;

d) the time resolution obtained with the new system is better, for the smaller sampling time and also for a front end readout with a real time system that allows a precise timing of order $200\mu\ s$ against $10\ ms$ obtained with the old system

2 Data acquisition

The new read-out system hardware uses the VME standard for an better availability of boards with good performance. Each RUN starts with a pulse from a GPS (Global Position System) rubidium clock at the exact second, the time error on pulse second from GPS is of $100\ ns$. This is important, in particular for the continuous g.w. study and for cross-correlating the outputs of two different detectors, for the measurement of the stochastic background. A single part VME digital equipment VAX processor (KAV30-AD) gives the time of the first acquired sampling. This processor adjourns itself every two minutes using the GPS. Checks on the correct adjourns of KAV30 are performed and information about the GPS (visible satellites and time string) and about the time string of KAV30 are

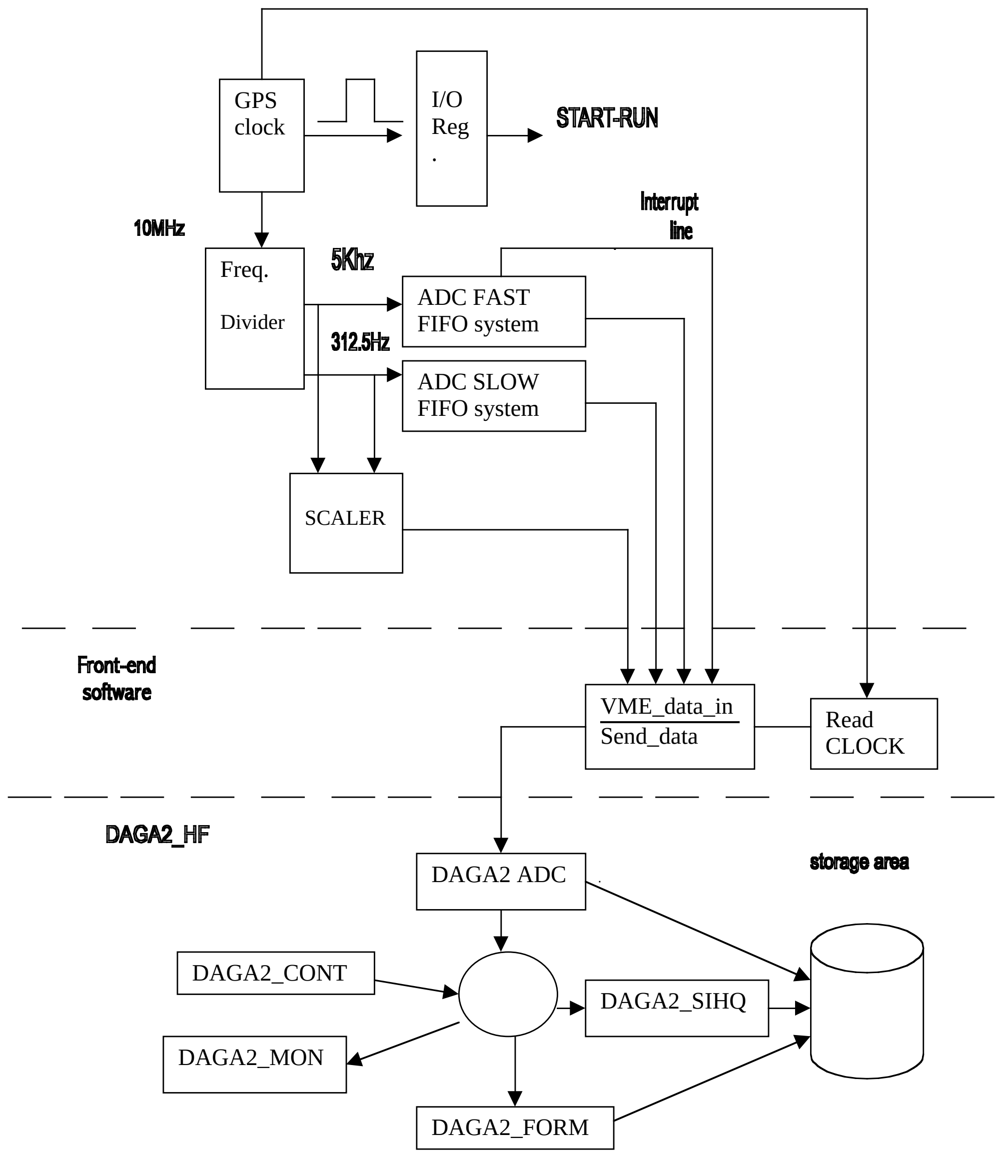

Figure 1: *Data acquisition system*

recorded in log files. Furthermore the GPS supplies the $10\ MHz$ frequency that is send to a frequency divider, programmed by front-end software at the start run, to trigger the two Pentland MPX300 ADCs (32 channels at 16 bit). One ADC acquires the $5\ kHz$ data directly from the antenna, the other one acquires at $312.5\ Hz$ the auxiliary channels which give information on the behavior of the overall experimental apparatus (seismometers, pressure gauges, cryogenic liquids indicators, etc). For this last one the acquisition frequency is $9.766\ Hz$ per channel. These trigger frequencies, $5\ kHz$ and $312.5\ Hz$, are also send to the modulo SCALER to allow the performing of a continuous check on the acquired sampled data via software. A possible loss of data samplings starts an automatic procedure which stops the RUN and starts a new RUN. The ADC converts linearly analog data into a 16 bit value (the input range is selected between $+ - 10\ V$). The converted data are written into a $512X16$ FIFO (Firs-in-First-Out) memory system, an interrupt occurs when the FIFO is half full. The buffers data are queued up to 20 and they are sent to the acquisition computer, ALPHA STATION 600, via ETHERNET in a local area network [6]. Then they are processed and archived by DAGA2_HF. Also a possible anomalous status of FIFO system, FIFO not empty or FIFO full, is checked and recorded in the log files.

3 Data processing

The DAGA2_HF system consists essentially of six current jobs. The job $DAGA2\_ADC$ runs at high priority (16), reads data coming from VME, writes the raw data and shares them with other jobs.

The job $DAGA2\_FORM$, at priority 7, processes, analyzes and stores the data while $DAGA2\_SIHQ$, at priority 5, estimates some adaptive parameters, frequency spectra, and implements the matched filter.

The $DAGA2\_CONT$ manages all acquisition RUN control and the $SUPERVISOR$, at priority 1 and checks all the data acquisition parameters. Finally the $DAGA2\_MON$ allows on-line monitor of data : raw data and already analyzed data.

The $5\ kHz$ data are collected by DAGA2_HF in sets of 262144 samplings and then transformed in the frequency domain by an FFT procedure. This is done with periodicity of 54 seconds; the frequency resolution turns out to be 19 mHz. From the 0 to 2.5 kHz frequency band, several sub-bands are extracted: the high sensitivity band of the antenna, a low frequency band to monitor the seismic noise and other intermediate bands to estimate electronic noise and disturbances. Each sub-band has its own proper sub-sampling time for the corresponding temporal series, depending on its bandwidth. The acquisition mask contains the information about the band to be extracted and all information for the data analysis. For the band which includes the two resonance modes (896.4539 Hz - 935.5068 Hz) the sub-sampling factor is 64 for a sampling time of 12.8 ms. From this band smaller bands are extracted, for each of the two resonance modes, for the calibration and for the wide-band noise, with an additional sub-sampling factor of 8, for a sampling time of 102.4 ms. To these bands software lock-ins are applied (see fig. 2). The lock-in outputs are recorded in output channels and also processed with the ZOP and Wiener filters. As far as the other ADC data, some of the channels acquired at 9.766 Hz are sub-sampled by a factor of 200 (sampling time $\Delta t = 20.48\ s$), the other channels (SQUID working status and the seismometers) remain with a sampling time $\Delta t = 102.4$ ms.

4 Linear filtering for detection of short bursts of gravitational radiation

The DAGA2_HF system includes various types of data filters that we describe in this section: the ZOP and the WIENER filters are implemented in the time domain, the MATCHED filter in the frequency domain.

4.1 The ZOP filter

This is the simplest filter for extracting signals due to delta excitations. Considering one resonant mode (say the minus mode f_0), we send the signal from the low noise amplifier to the lock-in amplifier which extracts the in phase and in quadrature components, $x(t)$ and $y(t)$, of the Fourier transform at the resonance frequency f_o. The lock-in amplifier has integration time t_o and both components are sampled with a sampling time $\triangle t = 1/t_o$. The ZOP algorithm (zero-order prediction), consists [2] in taking the difference between two successive samplings

$$z(t)^2 = [x(t) - x(t - \triangle t)]^2 + [y(t) - y(t - \triangle t)]^2 \tag{1}$$

The key idea is that a short burst will produce a jump in the data, like a hammer hit, while the fluctuations due to the noise have a long time constant depending on the decay time $\tau_v = \frac{Q}{\pi f_0}$ where Q is the merit factor. Let us now estimate the SNR for this algorithm. The noise is essentially due to the narrow-band Brownian noise (in units of $volt^2$) in the bar

$$V_{nb}^2 = \frac{\alpha^2 k T_e}{2 m \omega_o^2} \tag{2}$$

(increased by the back action from the amplifier) and to the white noise S_o from the amplifier. α is the transducer constant and the factor of two in eq.2 takes care of the fact that the energy of the signal is split between the two modes of the transducer bar system. It can be shown [2] that the the variance for the variable $z(t)$ is:

$$\sigma^2 = \frac{4V_{nb}^2}{e}\frac{\triangle t}{\tau_v} + 4\frac{e-1}{e}\frac{S_o}{\triangle t} \tag{3}$$

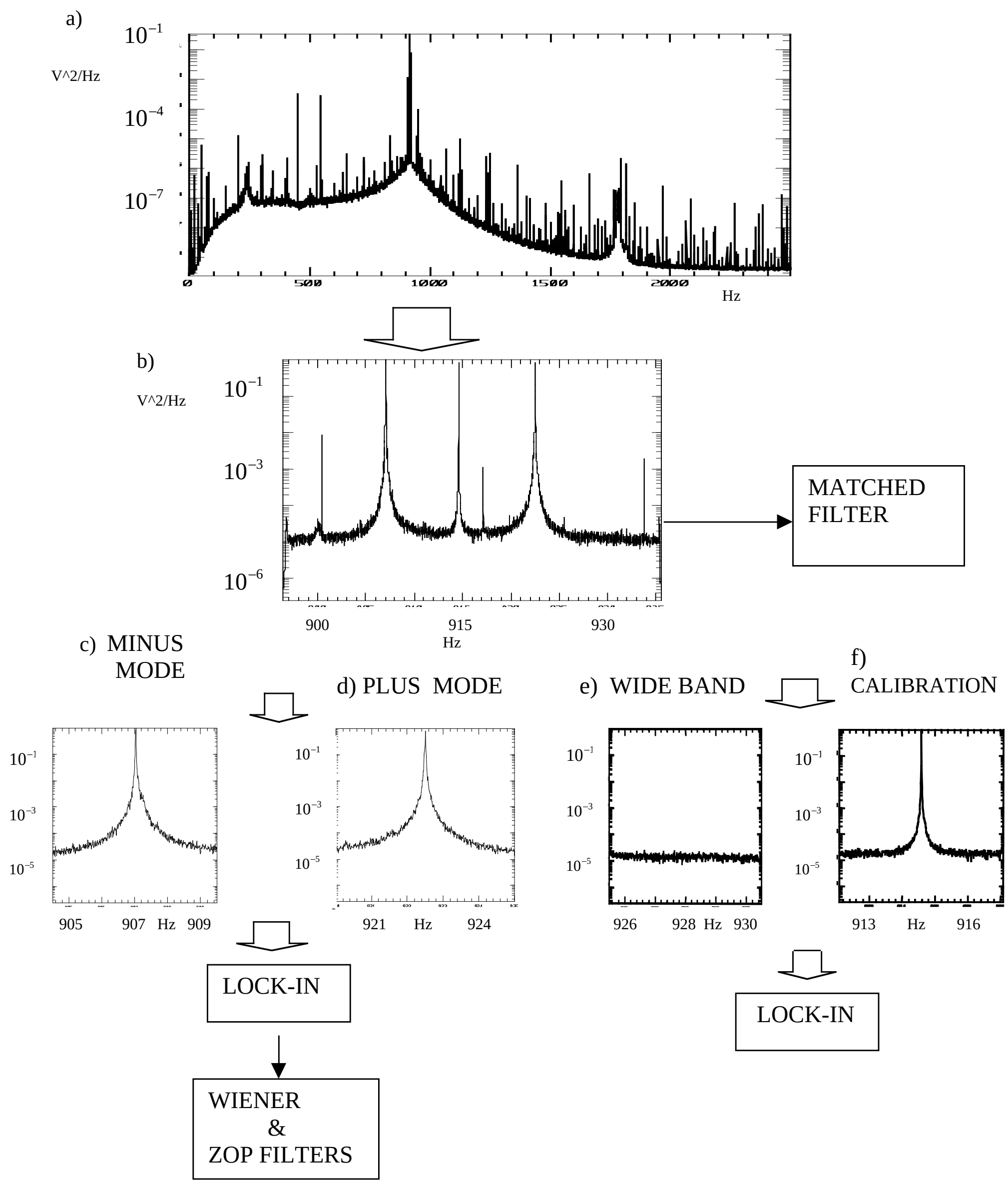

Figure 2: *Data processing: the figure a) shows the spectrum from* $0\ Hz$ *to* $2500\ Hz$*.From this spectum are extract the sensible band of antenna (fig. b), the two modes (fig. c) and fig. d)), the wide band (fig. e)) and the calibration (fig. f)).*

We notice that the two noises are in competition, one increasing linearly with $\triangle t$ and the other one with the inverse of $\triangle t$. The optimum $\triangle t$ is given by

$$\triangle t_{opt} = \tau_v \sqrt{(e-1)\Gamma} \tag{4}$$

and

$$\sigma^2_{min} = 8V^2_{nb} \frac{\sqrt{(e-1)\Gamma}}{e} \tag{5}$$

where we have made use of the quantity

$$\Gamma = \frac{S_o \tau_v}{V^2_{nb}} \tag{6}$$

This procedure is applied to both resonant modes so that the total noise is given by

$$\sigma^2_{opt} = \frac{8\alpha^2 k T_e}{m\omega^2_o} \frac{\sqrt{(e-1)\Gamma}}{e} \tag{7}$$

We calculate now the signal for this algorithm. An incoming GW short burst will produce at the low noise amplifier output a jump in the signal from the noise level to a value [2]

$$V_s = \alpha \frac{2L}{\pi^2} \omega_o h(\omega_o) \tag{8}$$

slowly decaying with the time constant τ_v. At the lock-in amplifier output (after the lock-in integration with time constant t_o) we take the difference between two next samples. If we assume that the signal arrives exactly at the time of a sampling the difference with the next sampling is $V_s(1-1/e)$. We introduce the signal energy

$$E_s = \frac{1}{2} m\omega^2_o (\frac{V_s}{\alpha})^2 \tag{9}$$

Finally we get

$$SNR = \frac{V^2_s (1-1/e)^2}{\sigma^2_{opt}} = \frac{E_s}{4kT_e\sqrt{\Gamma}} \frac{1}{1.21} \tag{10}$$

It must be remarked that this results is valid for signals arriving exactly at the sampling times. If one considers signals arriving at random times he gets a SNR that, on the average, is smaller by several per cent.

4.2 The Wiener filter

The ZOP filter can be extended by including not just two samplings but many more. This is done by using the Wiener filter [1] which is based on the idea that the data samplings are processed a few seconds after they have been recorded, in such a way to make use of past as well $future$ data. The best estimation $u(t)$ of the signal for the variable $x(t)$ at the lock-in output is

$$\tilde{u}(t) = \int x(t-\tau)W(t)d\tau \tag{11}$$

where $W(t)$ is the filter function which will be estimated with the linear mean square method. It can be demonstrated [3] that the Fourier transform $W(f)$ of $W(t)$ which minimizes the average difference $< (u(t) - (\tilde{u}(t) >^2$ is

$$W(f) = \frac{S_{ux}(f)}{S_{xx}(f)} \tag{12}$$

where $S_{xx}(f)$ is the power spectrum of $x(t)$, and $S_{ux}(f)$ is the cross spectrum of $u(t)$ and $x(t)$. From this we obtain [3]

$$W(f) = \frac{1}{W_a W_e} \frac{1}{1 + \frac{\Gamma}{W_a^2}} \tag{13}$$

where $W_a(f)$ is the bar transfer function which acts as a low-pass filter with time constant τ_v,and $W_e(f)$ is the integrating part of the lock-in which is again a low-pass filter with time t_o.

The signal reported at the antenna input has Fourier transform V_s (white spectrum because we consider a GW short burst). For simplicity, we consider the signal in phase with the lock-in reference frequency. The application of the Wiener filter gives

$$u(f) = V_s W_a(f) W_e(f) W(f) = \frac{V_s}{1 + \frac{\Gamma}{W_a}^2} \tag{14}$$

We notice that in absence of electronic noise ($\Gamma = 0$) the estimation is perfect, in the sense that its Fourier transform is equal to the Fourier transform of the GW signal. The maximum SNR occurs at time $t = 0$, when the GW burst arrives. Considering that there is an equal contribution to the noise both from the in-phase and from the in-quadrature responses of the lock-in, and using the signal energy E_s we get

$$SNR = \frac{E_s}{4kT_e\sqrt{\Gamma}} \tag{15}$$

This shows that the improvement over the optimum ZOP filter seems to be just a factor of 1.21. Actually, the advantage is that, for the Wiener filter, one can sample faster than the optimum sampling needed to optimize the ZOP filter. In this way there is no loss in SNR due to the random arrival time of the GW bursts.

4.3 The matched filter

We give in the following a brief derivation of the matched filter [3]. Let us consider a signal $s(t)$ in presence of noise $n(t)$. The available information is the sum

$$x(t) = s(t) + n(t) \tag{16}$$

$x(t)$ is the measurement at the output of the low noise amplifier and $n(t)$ is a random process with known properties. Let us start by applying to $x(t)$ a linear filter which must be such to maximize the signal to noise ratio SNR at a given time t_o (we emphasize the fact that we search the signal at a given time t_o).

Indicating with $w(t)$ the impulse response of the filter (to be determined) and with $y_s(t) = s(t) * w(t)$ and $y_n(t) = n(t) * w(t)$ respectively the convolutions of the signal and of the noise we have [3]

$$SNR = \frac{|y_s(t_o)|^2}{E[|y_n(t_o)|^2]} \tag{17}$$

It can be show that

$$SNR \leq \frac{1}{2\pi} \int_{-\infty}^{\infty} \frac{|S(\omega)|^2}{N(\omega)} df \tag{18}$$

where the equal sign holds if and only when

$$W(\omega) = constant \frac{S(\omega)^*}{N(\omega)} e^{-j\omega t_o} \tag{19}$$

Applying this optimum filter to the data we obtain the maximum SNR

$$SNR = \frac{1}{2\pi} \int_{-\infty}^{\infty} \frac{|S(\omega)|^2}{N(\omega)} d\omega \tag{20}$$

where $S(\omega)$ and $N(\omega)$ are, respectively, the Fourier transform of the signal and the power spectrum of the noise at the end of the electronic chain where the measurement $x(t)$ is taken [3,5].

Let us apply the above result to the case of measurements $x(t)$ done at the end of a chain of two filters with transfer functions W_a (representing the bar) and W_e (representing the electronics) as already considered for the $Wiener$ filter. In this case it is possible to show that the filter transfer function is given by

$$W(\omega) = \frac{S_g^* e^{-j\omega t_o}}{S_{uu}} \frac{1}{W_a W_e} \frac{1}{1 + \frac{\Gamma}{|W_a|^2}} \tag{21}$$

where S_g is the Fourier transform of the GW signal at the bar entrance.

Consequently the effective noise temperature in terms of the signal energy is [2]

$$T_{eff} = 4T_e\sqrt{\Gamma} \tag{22}$$

as for the $Wiener$ filter

4.3.1 *The* DAGA2_HF *spectral noise estimation*

We describe briefly the main features of the noise spectral estimations adopted by DAGA2_HF for various types of data filters all matched to delta signals. The differences are due to different evaluation of the noise. We remark that the basic problem with g.w. detectors planned to measure very small signals is due to the non-stationarity of the noise and to the fact that the noise itself is not Gaussian. This requires a careful study of the noise used for obtain the maximum signal to noise ratio (for delta signals). For obtaining the power spectra DAGA2_HF use a different program with a frequency resolution of 9.5 mHz. The data in the $896.4539\ Hz - 935.5068\ Hz$ band are collected in sets of 8192 samplings in the time domain, for a total time of $105\ s$. From these data periodograms are calculated. The periodograms, spanning each one $105\ s$, are exponentially and autoregressively averaged, with a varying memory time, for obtaining the adjourned spectrum needed for estimating the matched filter. Three different procedures for combining the various periodograms are used, called CLEAN, ADAPTED and WHOLE. They differ one from each other for the different time constant in the spectrum averaging procedure, and for the selection of the periodograms. All the procedures estimate the spectrum with the recursive equation:

$$S_i = P_i(1 - W) + S_{i-1}W \tag{23}$$

where

$$W = exp^{-\frac{\Delta t}{\tau s}} \tag{24}$$

P_i is the actual periodogram, S_{i-1} is the previous estimation of the spectrum and τ_s is the memory time. For the WHOLE and CLEAN algorithms the time constant τ_s is constant and equal to $3600\ s$, but the CLEAN adjourns the spectrum only if the periodogram is not disturbed. Thus CLEAN uses only clean periodograms, keeping a clean spectrum. This choice is the best one when the disturbances have small time duration and is not ignored they would degrade the spectral estimation. For long disturbances it is better to use the ADAPTED, with a time constant which depends on the goodness of the periodogram. The better the periodogram, when compared with the expected from the spectrum, the longer is the time constant of the memory. It is evident, from this discussion, that it is difficult to

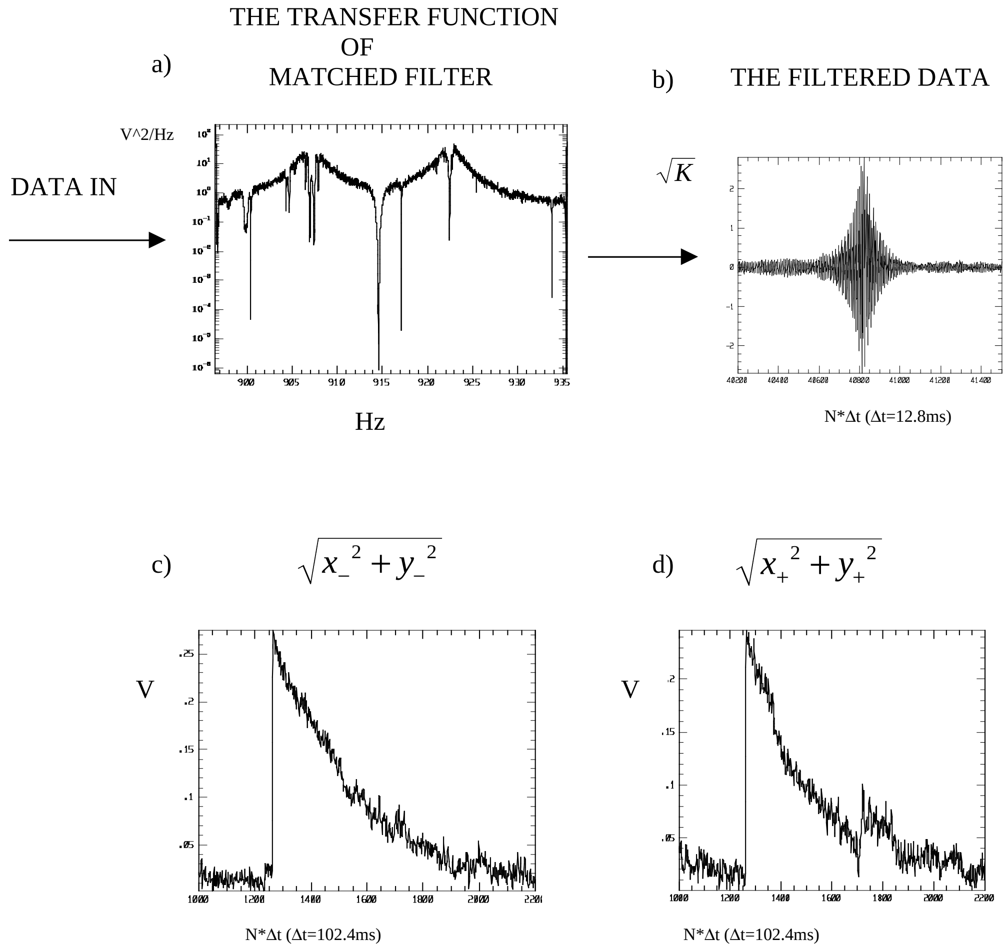

Figure 3: *The figure b) shows the filtered data by the Matched filter for a delta like signal. The figures c) and d) show the extraction of the minus and plus modes by lock-in for the same data.*

select just one algorithm, as the best estimation depends very much on the nature of the noise. Then DAGA2_HF implements all three algorithms and each time it chooses what can be considered to be the best, according to a calibration procedure by means of applied signals. Actually the data filtered by the matched filter have a sampling time of 12.8 ms but in the future we will implement the rephasing algorithm [5] for obtain the filtered data at the sampling time of $200\ \mu s$

5 Monitoring and archiving

The data acquired at $5\ kHz$, those from the auxiliary channels, the information about the sampling by the SCALER, the GPS and the KAV30 time strings are directly recorded on permanent data-base on files lasting one and a half day (about $1.4\ Gbytes$). In fig. 4 the format of these files is reported. These data are processed and every day about $50\ Mbytes$ of data are also recorded on permanent data-base. Many files are produced and recorded to allow an easier monitoring for the diagnostic of the entire system and for data analysis. Every one and a half day the files R87 are produced, about $60\ Mbytes$. In these files data are written in records. The first record contains the acquisition MASK and all parameters used for the corresponding RUN. The other records contain the time of the first data of the record and data sampled for a duration of $20.48\ s$. Each data record is divided in three parts in relation to the sampling time of the data: field 0 contains the very slow channels ($20.48\ s$), field 1 the slow channels ($104.2\ ms$) and field 3 contains the medium channels at $12.8\ ms$ (the unfiltered data in the high sensitivity band of the antenna and the corresponding filtered data). New files in ST96 format (about 1 Mbytes) are written daily on permanent data-base and contain one-minute time averages of all output channels, of the integral power spectra in the different sub-bands and of the parameters used in the implementation of the adaptive filters. These files also include the six-minute time averages of some DAGA2 output channels for a final check of the new system. Every hour one histogram of each channel is produced and recorded in the daily file HI96 (less then $500\ Kbytes$). The spectral information is recorded in the files SP96, $1.2\ Mbytes$ per day. In this file every hour the following spectra are stored: a) the low resolution spectrum ($0.1\ Hz$) of the $0-2.5\ kHz$ band; b) the high resolution spectrum ($0.01\ Hz$) of the antenna band, obtained by averaging the periodograms for one hour and finally c) the corresponding matched filter transfer function. Every day a file EV96 (about 5Mbytes per day) with candidate gravitational events, from filtered data, is written. Events from all the other output channels are also given. Information obtained about the events are recorded: the time of the event, the amplitude, the critical ratio CR, the number of zero crossing, the duration of the event (the time the data is over the threshold, usually set at $6\ \sigma$). This file also includes the time behaviour of the event for a duration of 5 seconds or less. The monitoring system allows to analyse the events, it allows to select the event from one or many channels in a given period of time, in relation to amplitude, CR, length and other characteristics of the event. It allows to search for coincidences of two series of events on-line, to plot the spectral information and to process the event with the Hilbert filter. For each run a file includes all the information on the system parameters, the mask script , the comments of the operator etc. In Appendix the users guide at DAGA2_HF is reported.

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Structure of an event record

Byte#	I*2#	I*4#	Meaning	VMS Action
---->			Start of the Event Record	
1-4		1	Length of the record (in Integer*2 words)	Overwritten
5-6	3		Data identifier = 1	-
7-8	4		Length of the user header in words = 6	-
9-12		3	Run Number	Overwritten
13-16		4	Event Number	-
17-24			Date / Time	-
25-26	13		Software Trigger Reg	ADC Channel
27-34			Hardware Trigger Reg	word
ADC status			-	
35-55			not used	
55-62			Equipment readout pattern	-
63-66			Event error code	-
error type				
70-70+2			Number of I*2 words of the first equipment	-
			Content of the first <u>equipment</u>	

Ł Same sequence for all the declared equipment

STANDARD RECORD ID'S

ID	DESCRIPTION
1	event record
10	start of run
20	end of run
30	pause
40	Resume

<u>EQUIPMENT DESCRIPTION</u>

#EQUIPMENT	DESCRIPTION
1	ADC FAST DATA
2	ADC SLOW DATA
3	KAV30 & GPS TIMES
4	TIME OF START RUN
5	SCALER :COUNTING TRIGGER AT 5KHz, 312.5Hz and 10MHz
6	GPS STRING : 2000-11-09 05:58:43 CET 445314000000200011090458518571,20,9,11,9,25,9,07,9,3*

Figure 4: *RAW data format*

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