# Hardware Recommendations for the UK Met Office EXSCALABAR Instrument

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The purpose of this document is to detail the recommendations for the EXSCALABAR data acquisition (DAQ) hardware. This document outlines some of the important factors concerning the recommendation and uses the proceeding discussion to provide recommendations. Hard recommendations drawn from the details are highlighted within the text. These points will be laid out periodically within the relevant portion of the text.

It is important to note that this document is just providing recommendations on my experience developing similar systems. It is entirely possible to conceive of many different configurations using other products such as microcontrollers from Arduino or Tern or a MicroZed from Avnet. We can even develop a data acquisition system on low cost single board RIOs coupled with custom electronics for high speed acquisition. We can also build into the EXSCALABAR data acquisition system functionality to launch a small space vehicle. All that is required is time. And money. Lots of it most likely.

# Overview

As with many instruments, EXSCALABAR is an instrument consisting of several distinct subsystems. EXSCALABAR consists of two main subsystems – a five channel photoacoustic spectometer (PAS) and a six channel cavity ringdown spectrometer (CRDS) – which make up the bulk of the measurement capability of the instrument. While EXSCALABAR is intended to be run as a single instrument, it is desirable to maintain the integrity of these two subsystems which provide very distinct functionality: these two subsystems measure different properties of particles, occupy different physical spaces, and the sampling environment for the two subsystems are controlled independently.

Maintaining the integrity of the different subsystems in hardware has the side effect of simplifying the software. Since the two subsystems operate asynchronously on a macro scale (i.e. the timing of one subsystem is not reliant on the other), the software for the two systems can be maintained separately, thus allowing us to remove one subsystem if there are issues with that subsystem or if that subsystem is not being used or for testing. If one of the children misbehaves, we can simply put him in a timeout until he is ready to play nice again. In addition to these two main subsystems, we can further divide the hardware and software into yet another system that crosses these boundaries (i.e. is required by both the PAS and CRDS for proper operation). This subsystem might include the filter and the flow controllers.

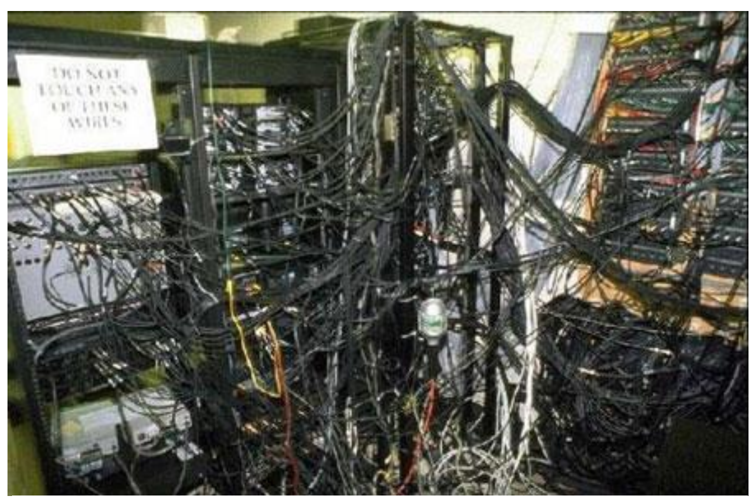

*Figure 1. You don't want to end up like this (I believe the engineer responsible for this was consumed by his own creation).*

The theme of subsystems will carry through to most of the design decisions made with respect to the instrument as a whole. It can be found in the recommended layout of the DAQ as well as the file structures (both the data files and within the configuration file). Within the context of the hardware, maintaining the distinction between the subsystems as defined above simplifies signal routing thus decreasing confusion in the cabling. In addition, as with the software, maintaining these organic distinctions will allow us to more readily excise and offending subsystem when necessary.

## Signal Requirements

The list of signals expected to be probed or generated by EXSCALABAR are given in Table 1. These signals were provided by scientists at the UK Met Office and represent the most current knowledge of the instrument at the time of writing this document. Table 1 is the list from which we will build recommendations for a data acquisition system. The data acquisition hardware should fulfill the needs of the signals as outlined in Table 1. Simply put, with the exception of DIO (of which most multifunction DAQ cards have copious amounts of), if the signal ain't in there, it ain't gonna be considered. The table provides a brief description of the different signals, the IO type associated with that signal, the number of signals associated with each descriptor and the rate of acquisition or generation in Hz.

*Table 1. EXSCALABAR signal list as provide by the UK Met Office.*

| Instrument | Signal | Qty | IO | Rate (Hz) |
|---|---|---|---|---|
| PAS | Thermistor Temperature | 10 | AI | 10 |
| | RH | 5 | AI | 10 |
| | Hygrometer temperature | 5 | AI | 10 |
| | Laser RMS | 5 | AI | 10 |
| | Speaker | 1 | AO | > 10k |
| | Microphone | 5 | AI | > 10k |
| | Speaker Power | 5 | DIO | On demand |
| | Laser Modulation | 5 | AO | 10k |
| | Laser Power | 5 | DIO | On demand |
| | Temperature control | 5 | AO | On demand |
| | Laser Power Detector | 5 | AI | >10k |
| CRDS | Laser Modulation | 3 | DIO | 5k |
| | PMT Output | 6 | AI | >2M |
| | Relative Humidity | 4 | AI | 10 |
| | Hygrometer temperature | 4 | AI | 10 |
| | Pressure | 3 | AI | 10 |
| | Temperature Control | 2 | AO | On Demand |
| General | Flow controllers | 10 | RS232 | 1 |
| | Pressure controller | 1 | RS232 | 1 |
| | Filter | 1 | DIO | On demand |
| | Chiller | 1 | RS232/485 | 1 |
| | Ozone relay | 1 | DIO | On demand |

Table 2 provides a summary of the signals described in the Table 1. Here, the signal list is condensed into the number of signals for each subsystem associated with a type of IO. This information provides us with a crude manner in which to determine whether the recommended system is sufficient to handle the signals generated and required by EXSCALABAR. As stated above, most multifunction DAQ cards have plenty of available DIO ports, so it is unlikely that any conceivable configuration for operation will overwhelm any DIO requirement. Hence, it is sufficient to say that EXSCALABAR needs *at least* 15 available DIO lines. The understanding here is that there will be available DIO lines for further expansion (adding valves, servos or other signals that require a DIO line) regardless of the subsystem.

*Table 2. Break down of signals for each system as specified by scientists at the UK Met Office.*

| Subsystem | AI | AO | DIO | RS232 |
|---|---|---|---|---|
| PAS | 35 | 11 | 10 | 0 |
| CRDS | 17 | 2 | 3 | 0 |
| General | 0 | 0 | $\geq 2$ | 3 |
| Total | 52 | 13 | $\geq 15$ | 3 |

# Timing Requirements

Following the actual list of signals described above, the timing requirements have the largest impact on the choice of DAQ hardware. These requirements affect the controller chosen (due to computational loads imposed by strict timing requirements) as well as the actual cards chosen. These requirements are dominated by the two main subsystems: the PAS and the CRDS. While most measurements and controls do not require rigorous timing, the main signals from the PAS and CRDS (the microphone signal and the photodiode signal respectively) require higher acquisition rates for proper signal analysis. Most other signals can be generated or acquired at frequencies considerably less than 1 kHz. These sampling frequencies are readily handled by most multifunction DAQ cards.

## PAS

The PAS has several signals that need careful consideration (I guess, technically, all signals need careful consideration, but for the sake of argument, we will ignore those not listed below). These signals are:

- The laser and speaker signal generation.
- The microphone signal that measures the acoustic signal from the interaction of the particle with light in the cell.
- The signal from the photodiode at the back of the cell.

### Acquiring the Signals

The acquisition rates necessary to resolve the signal of interest is dependent on the resonant frequency $f_0$ of the cell. It is important to note that when attempting to attain an accurate representation of a signal for a given frequency, sampling well above the Nyquist frequency, provides no additional information of interest. This frequency is given by

$$f_{nyquist} = \frac{1}{2 \times f_s}$$

where $f_S$ is the frequency of interest in Hz. This means that if the signal of interest is 2 kHz, then the Nyquist-Shannon theorem suggests that a sampling rate of 4 kHz will be sufficient to resolve this without aliasing. Since cell resonant frequencies will likely be between 1 and 2 kHz, **a 10 kHz sampling rate should be sufficient to resolve this band and prevent aliasing of higher frequency signals into the region of interest** (however, if a bandpass filter is not used to reject signals at higher frequencies, this rate might not be sufficient to prevent significant amounts of leakage into the signal of interest from higher order signals). Many DAQ cards provide sufficient bandwidth to sample well above this frequency.

Here it is important to note that, based on our understanding of Fourier transforms, increasing the sampling frequency **will not increase the frequency resolution!** The frequency resolution will go as the inverse of the integration time (the period over which the data is acquired for the transform). This means that if the integration time is 2 s, the frequency resolution is 0.5 Hz; if the integration time is 10 s, the frequency resolution is 0.1 Hz. This implies that higher resolution in the frequency domain will be attained at the expense of resolution in the time domain. Increasing the sampling rate well beyond the Nyquist frequency defined above only has the effect of increasing the computational load.

### Driving the Lasers

While the 10 kHz limit imposes no major obstacle for acquiring data (most multifunction data acquisition cards can handle these acquisition rates readily), the generation of the laser signal poses a more significant problem. Although the rates are not particularly high, we need to operate the lasers at slightly different frequencies. Since the lasers are driven at different frequencies, the lasers must either utilize different cards for the signal generation or have a way of generating or storing the signal on board.

Storing the signals on board is not a reasonable solution as this would divide the laser signals in an inorganic manner and possibly unnecessarily increase the size of the chassis to accommodate more cards. Likewise, no data acquisition card is available with the amount of memory to store the data in a circular buffer for five lasers attempting to drive a cavity with a 1 to 2 kHz resonant frequency. This is attributable to the fact that the largest on-board buffer (where the signal may be stored) is usually ≫ 10 kS; considerably less than the *at least* 50 kS required for storing the signal for five lasers. If the signals driving the lasers are something other than a square wave, the best possible solution is one in which these relatively simple signals are generated within the hardware.

**Recommendation:** The requirement to drive five lasers using a function other than a square wave necessitates a card that can drive them without having to utilize the controller processor to serve the input buffer. Currently, the only solution is a card that utilizes reconfigurable IO. I recommend using one of the R-series multifunction cards to drive these lasers. These cards can generate simultaneous analog outputs that can run can be driven at different rates.

## CRDS

CRDS timing requirements are more complex. To acquire a proper signal, we need enough points to fit the data to an exponential. In its basic form, as with a line, we can define an exponential with two points. However, we know that this would be woefully inadequate for ringdown analysis. The literature suggests that the sampling rate, $1/\Delta t$, should be defined such that[1]

$$\frac{\Delta t}{\tau} \ll 1$$

where $\tau$ is the ringdown decay time. However, there is little improvement as this value falls below 0.1, or ten points per decay constant. So, the rate at which we digitize will be determined by 1) the error in the signal that we can live with and 2) the minimum time constant we expect to be able to resolve (i.e. the highest extinction we can measure at a given wavelength). Ideally, if we wish to resolve a signal with a $\tau = 2\ \mu$s, then we would like to acquire data at 5 MHz. This is the *ideal* solution and ideal solutions often provide answers with more resolution than the situation requires. As stated at the outset, an exponential can be fit to two points – it is up to the user to determine what an acceptable amount of uncertainty is.

In addition to this requirement, we have to consider the amount of data that we will require to obtain a good fit. This will be dependent on the dominant source of noise in the system, shot noise or detector noise. According to the literature (see footnote), if the dominant source is detector noise, then we should fit up to 3 time constants while if it is shot noise that number increases to 6. Beyond this, there is little gain. In fact, fitting too much of the tail could result in a distortion of the fit due to the influence of noise within the tail.

[1] Berden, G. and R. Engeln, eds. *Cavity Ring-Down Spectroscopy: Techniques and Applications*: Wiley-Blackwell, 2009.

In a real system, we may run into a limit simply based on the laser rep rate and the requirements for cavity ring up. These requirements place an upper limit on the rate at which the lasers operate for some channels and a minimum limit on the digitizing rate for other channels. While the upper limit on the laser repetition rate poses few issues, the sampling frequency limit may have considerable impact on the choice of hardware selected for the data acquisition system. If taken as a whole, the minimum rate at which the photodiodes should be sampled is 2.5 MHz. This will allow us to resolve ringdown times to greater than or equal to 2 $\mu$s while minimizing errors associate with fewer points.

One issue to consider when attempting to determine the proper DAQ configuration for sampling CRDS signals is the potential disparity in ringdown time constants between cavities. When sampling with a single card, we generally gate the signal using the duty cycle of the output laser signal. This makes it unnecessary to perform large amounts of parsing of the data on the controller to determine where the signal of interest is thus decreasing the computational load. We can draw an analogy with your common fire hose – attempting to drink from this would result in either a) a lot of water wasted, or b) death. If we could put a valve on this stream (probably a pretty big one) then we can more readily handle the water coming out. Similarly the gate decreases the flow of information thus allowing the CPU to not collapse under the burden of too much information. But, I guess the analogy breaks down when the one ingesting all that water becomes saturated and eventually dies anyway. You won't find a CPU that behaves quite like this. Hopefully.

Given potential disparities in ring down times, there is the possibility of acquiring samples via multiple A/D cards. This option has the benefit of not only allowing us to resolve smaller ringdown times on channels where the zero ringdown times are quite small, but it also allows us to take advantage of smaller ringdown times and potentially operate the laser associated with those smaller times at higher repetition rates than the other laser. A tradeoff is that there will be additional computational burden associated with higher repetition rates.

Unlike the PAS, there is no issue with driving the lasers to generate the CRD signals. These lasers may be driven using a standard TTL or counter output found on most cards.

**Recommendation:** There is a considerable amount of computation required for servicing the signal photodiodes. On the NOAA AOP instrument, we perform 1000 exponential fits on 8 channels every second. On a quad-core controller, these fits consume over 50% of the CPU time on all four cores. While co-adding may reduce the computational load, maximizing the computational power will provide more options as to how computations are performed. I recommend here we use a controller containing a quad-core (or larger) processor. The base code is designed to use the parallel capabilities of a multi-core system and has been proven to run effectively on a similar controller.

## The Run-time Environment

When referring to run-time environment (RTE), we are referencing the operating system on which the DAQ software runs. The run-time environment boils down to two choices – Windows OS, a traditional environment and a real-time operating system (RTOS). The decision of a RTE is heavily impacted by the run-time requirements. These requirements have a significant impact on the choice of a controller used by the data acquisition system.

As indicated by initial instrument specification provided, the ultimate goal is to have a system that is prepared for headless, autonomous operation. Technically, any OS will do. LabVIEW and the RTE run with their full capabilities under both the Windows OS and the various RTOSs available on National Instruments real-time controllers (Phar Lap, RTLinux, vxWorks, etc.). While LabVIEW does technically "run" on Mac's, the distribution is severely crippled on this platform and is therefore not considered here.

While the computational capabilities are going to be primarily determined by the hardware (processors, memory, etc), there are some fundamental differences between the two environments that favor the RTOS over the Windows OS as the preferred RTE for this application. Unlike a traditional operating system which must service requests from a variety of system users, an RTOS will provide deterministic and precise timing. In this application, there is little need to respond to inputs on such small scales that would warrant a decision to utilize an RTOS based on this advantage. However, an RTOS provides a reliability in performance that is necessary in a high performance system that is intended to run for extended periods under potentially harsh conditions (such as in an aircraft). The RTOS provides a minimal environment which boots rapidly and is does not have to interrupt threads to service applications that are not being used by the main application (such as user interface).

The down side of an RTOS is that there is potentially more effort required to develop and maintain data acquisition systems that are intended to run on them. While the development on an RTOS is not significantly different in the LabVIEW environment, the engineer must have a firm understanding of how to connect to the real-time target, how to run applications down on the target and how to deploy an application to the target for startup operation. Despite this, EXSCALABAR is an excellent instrument for utilizing an RTOS: the system will run in more difficult conditions for potentially longer periods and there is the possibility of operating without a user.

**Recommendation:** With regards to operating systems, go with a controller that runs an RTOS. While the base libraries for the system are designed to be run time environment agnostic, for embedded systems that are intended to be run in demanding environments, require fast, deterministic response times, or will be operating for extended periods, the natural choice is RTOS. Aircraft platforms can be challenging and qualify as demanding environments.

# The Hardware Platform

When we refer to the hardware platform, we refer to how the different cards and controllers are collected within the system. There are a wide variety of platforms available – PCI, PXI, cRIO, cDAQ, sbRIO etc. However, the previous sections lay some foundation for the recommended choice of platform. Because of the potential deployment platform, we seek a moderately compact system. In addition, we desire an embedded system that can run with little or no user interaction.

## PCI

Traditional PCI systems require either a large motherboard that can accommodate multiple PCI cards or a chassis that will connect to a PC via a cable connected to the chassis and an expansion card located on the computer. The latter have limited bandwidth for moving data to and from the chassis while the former require a more expansive physical setup (such as a tower). In addition, if we wish to run an embedded system using a real-time operating system, we must carefully consider the hardware for this setup.

## cDAQ and cRIO

The two compact platforms, compact DAQ (cDAQ) and compact RIO (cRIO) provide an intriguing alternative to the PCI (and PXI) platforms. Hot swappable modules are interchangeable between the two systems and both systems have an embedded chassis/controller that is capable of running a real time OS. The fundamental difference lies in the chassis backplane – the cRIO chassis houses a user programmable FPGA while the cDAQ chassis does not.

The major issue with these hardware platforms is the selection of IO modules available. For the most part, the available C series modules would fit the needs of EXSCALABAR with several exceptions. First, the selection of IO modules for this hardware platform are limited. The card with the highest sampling rate is the

9223 – a four channel analog input module that can sample all four channels simultaneously at 1 MHz/ch. Based on the above discussion of the acquisition of ringdown times, this means that the best *ideal* time constant that we could resolve would be 10 $\mu$s.

The second major issue that these platforms pose is the processing power. Both are fairly small (hence the compact) platforms that are intended for industrial IO. As such, the most powerful controllers for both of these systems (the cRIO 9082 and the cDAQ 9139) consist of a dual-core, 1.33 GHz Intel i7 processor. While this processor is quite powerful, this is likely not sufficient for the computational requirements of EXSCALABAR.

Finally, due to the compact nature of these platforms, a data acquisition system built off of this platform would require considerably more IO modules than one based off of the PCI or PXI platform. C series modules do not have as much general functionality – such as additional counters and digital IO – and often have lower channel counts. Were we to go with a system utilizing either cDAQ or cRIO, we would have to be more creative about assembling the system and the cost is likely to be higher than that built off of the PCI or PXI platform.

### PXI

PXI is a PC-based platform that has an electrical bus similar to that of the PCI bus with some added synchronization buses. The platform is an industry standard developed by National Instruments for which over 70 different companies have developed over 1500 different modules for the platform. As with the PCI platform, these modules include high speed digitizers as well as multifunction DAQ cards. While not as compact as a C series system, the PXI platform is considerably more compact that the PCI system and comes in an integrated package that allows inter-module synchronization via buses on the backplane of the PXI chassis. The NOAA AOP instrument uses an 8 channel PXI chassis for data acquisition.

**Recommendation:** The variety of modules available, the multifunction nature of those modules and the availability of high performance controllers make this platform a natural choice for the EXSCALABAR data acquisition system.

## Recommended System Configurations

The sections below detail specific recommendations regarding the EXSCALABAR data acquisition system. These recommendations are based off information provided by the UK Met Office concerning the operation of EXSCALABAR. If the specifications are incorrect or incomplete, these recommendations may not be sufficient to cover the expected needs of the system.

### Data Acquisition Cards

Table 3 and Table 4 contain two lists of possible cards for EXSCALABAR DAQ hardware. These two tables are similar in all respects accept for the specification of the cards used to acquire the CRDS ringdown signals from the photodiodes. Both tables list the recommended cards for the EXSCALABAR system and group the capabilities of each card in terms of analog input (AI), analog output (AO), digital input/output (DIO; here no distinction is made between input and output as most DIO are accessible as programmable functional inputs or PFIs) and counters. For each capability, the characteristics of each card are listed; these are, where applicable:

- The number of channels available (#). In the case of analog input, if different numbers of channels are available based on whether the signal is single ended or differential, the number of available single ended channels is shown first with the number of differential following in parenthesis.
- The maximum rate of the signal acquisition or generation (Res). In the case of some analog inputs and outputs, such as with the 6341, the signals may be multiplexed across all channels and therefore

the rate is an aggregate rate for all channels. In other cases, such as with the S series cards (the 6133 and the 6124), each channel has its own multiplexer and therefore the maximum rate is per channel.

- The resolution of the signal in bits. The resolution in volts can be calculated from the resolution in the table by the following equation

$$\Delta V = \frac{FS}{2^R}$$

  where *FS* is the full scale of the measurement and *R* is the resolution given in the table. Although not given in the table, the full scale is generally programmable to a variety of levels. An example of the range is given for the analog inputs on the 6133: ± 10, ± 5, ± 2.5 and ± 1.25. The corresponding resolutions in mV for these ranges based on the 14 bit resolution given in the tables below are 1.22, 0.61, 0.3 and 0.15 respectively.

  No resolution is provided for the digital IO as these signals generally consist of fixed voltages at the two different logic levels. For counters, the resolution indicates the maximum count before the counter roles over. So, the two counters on the 6133 may count to $2^{24} = 16777216$ before rolling over. For the most part, this functionality of the counters is not used in instruments such as EXSCALABAR so the resolution is of little importance when specifying counter capabilities.

Table 3 specifies a single card for the acquisition of this signal. The card, a 6133 with a 32 Mb buffer, can sample 8 channels simultaneously at 2.5 MS/s (3 if set to warp mode). This is the card that is currently used in the NOAA AOP instrument and has been sufficient for acquiring 1000 ringdowns on the 8 channels every second.

Table 4 specifies two cards to acquire the signals from the six photodiodes. The first card, the 6132, has the same sampling characteristics as the 6133. The difference between the two is that where the 6133 acquires data on 8 channels, the 6132 acquires data on only 4 channels. The second card is the 6124. This card has higher resolution (16 bits as opposed to 14 bits) and can acquire data on 4 channels simultaneously at 4 MS/s.

The specification in Table 4 has two benefits for the EXSCALABAR data acquisition system. First, dividing the photodiode data acquisition between two cards provides the potential ability to operate the cavities at different laser repetition rates thus taking advantage of any discrepancies between the ringdown times of the two wavelengths. Following on the first benefit, with two cards we can also increase the temporal resolution to maximize the level of quantification for wavelengths associated with shorter ringdown times.

Finally, not listed in either table is the card required for serial communication. As discussed, we have multiple options for communicating with various devices. NOAA AOP communicates with different devices via 232. These devices have included a bank of Alicat flow controllers, a thermoelectric cooler and various other auxiliary instruments that have made measurements that have complimented the measurements in the rack (such as two different instruments that have measured a filter based absorption).

*Table 3. This table shows components for retrieving ringdown data from a single card (6133). The available IO are grouped in column sets with analog inputs (AI), analog outputs (AO), digital input/output (DIO) and Counters. Under each heading are the number of channels (#), the rate (in Hz) and the resolution (Res) in bits. For the AI channels, the numbers represent the number of single ended inputs available and the number of differential inputs available in parentheses. The cost of the card in dollars is given in the final column.*

| System | Card | AI | | | AO | | | DIO | | Counters | | | Price |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | # | Rate | Res | # | Rate | Res | Number | Rate | Number | Rate | Res | |
| PAS | 6224 | 32(16) | 250k | 16 | 0 | | | 48 | 1M | 2 | 80M | 32 | 876 |
| | 7842R | 8 | 200k | 16 | 8 | 1 M | 16 | 96 | 40M | 96 | 40M | 64 | 3996 |
| | 6704 | | | | 32 | Static | 16 | 8 | | | | | 1761 |
| CRDS | 6341 | 16 (8) | 500k | 16 | 2 | 900k | 16 | 24 | 1M | 4 | 100M | 32 | 1029 |
| | 6133/32 | 8 | 2.5M | 14 | | | | 8 | 10M | 2 | 20M | 24 | 3413 |

*Table 4. Similar to Table 4 but this provides an alternative to the single card (6133) for obtaining cavity ringdown. In its place is are two four channel, high speed simultaneously sampling cards – the 6132 and the 6132.*

| System | Card | AI | | | AO | | | DIO | | Counters | | | Price |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | # | Rate | Res | # | Rate | Res | # | Rate | Number | Rate | Res | |
| PAS | 6224 | 32(16) | 250k | 16 | 0 | | | 48 | 1M | 2 | 80M | 32 | 876 |
| | 7842R | 8 | 200k | 16 | 8 | 1 M | 16 | 96 | 40M | 96 | 40M | 64 | 3996 |
| | 6704 | | | | 32 | Static | 16 | 8 | Software | | | | 1761 |
| CRDS | 6341 | 16 (8) | 500k | 16 | 2 | 900k | 16 | 24 | 1M | 4 | 100M | 32 | 1029 |
| | 6132 | 4 | 3M | 14 | | | | 8 | 10M | 2 | 20M | 24 | 2121 |
| | 6124 | 4 | 4M | 16 | | | | 24 | 10M | 2 | 80M | 32 | 3837 |

In regards to serial communication, I have discussed with the scientists at the UK Met Office the possibility of using a multidrop RS-485 measurement for some measurements which the AOP instrument currently captures via analog lines. This can reduce cabling and provide more extensive measurements from these devices. However, it is clear now given the decisions being made concerning vendors that it will be simpler to use analog inputs rather than digital measurements for these existing signals (such as pressure and hygrometer based temperature and relative humidity). With this in mind we may want to retain the 232 communication and expand beyond the controller provided 232 port. Given that EXSCALABAR currently contains only two digital meters/controllers (a bank of flow controllers and a thermoelectric cooler), we can obtain that control by adding a single 2 channel card (PXI-8430/2; $322). However, for ~$150 more, the PXI-8430/4 provides two extra ports. This will allow the instrument to expand if necessary in the future.

**Recommendation:** Use the 4 port PXI-8430 to provide additional ports for serial communication. This will allow the system to expand as necessary in the future for little additional cost.

## Controller

To handle signals acquired by the data acquisition system (and particularly the CRD subsystem), EXSCALABAR requires a controller that can make optimal use of those portions of the software which might benefit from parallelization. Single core controllers will not provide the computational horse-power required to fit a minimum 6000 exponential decays a second. A very limited evaluation of a dual core controller suggests that we will be pushing the limits of the computational power of that controller without significant co-adding. The dual core would provide the most basic handling thus precluding the addition of more advanced features such as more calculations of fit uncertainties, online Allan variance calculations or handling multiple PAS integration periods. With this in mind, I recommend a high performance controller that will not impede the online analysis capabilities of the DAQ software.

**Recommendation:** For a high performance controller, go with the PXIe-8135RT rated for extended temperatures. The cost of this controller is $6,549.

## Chassis

In addition to the cards listed in the preceding tables, the EXSCALABAR requires several other pieces. The first is the easiest – for at least 6 cards, the most appropriate chassis for the systems described above is the PXIe-1078. This chassis provides 8 slots (plus one for the controller) – 5 hybrid slots and 3 express slots (both the 6124 and the 6341 are PXI express cards). The cost of the 1078 ($2,300) is similar to the PXI-1042Q ($2,599; currently used by the NOAA AOP instrument) which contains 7 slots for cards and can not incorporate PXI express cards. If we decided to go with 1042Q, we will not be able to incorporate the 6124 for higher sampling rates and we will have to change the choice of multifunction DAQ cards for the PAS (6224). The main issue with using an express chassis is that only five slots are designated as hybrid. This means that the remaining 3 require an express card. The primary need for an express controller and chassis is the possible integration of the 6124 for sampling at higher rates. The functionality of the 6341 is duplicated by other cards such as the PXI-6221.

## Cabling

In addition to the components above, the DAQ system requires cabling particular to the hardware. Below is a list of the recommended cables for use with the systems described above. The cables listed below are sufficient for simply communicating with the different cards; the list does not allow for backups. All cables are specified at 1 m, but we may want to consider some 2 m cables to get to those hard to reach places.

*Table 5. List of cables for recommendation hardware configurations.*

| Cable | Use with Card(s) | Qty | Cost per Unit |
|---|---|---|---|
| SHC68-68-RMIO Cable (2m) | 7842R | 1 | $144 |
| SHC68-68-RDIO Cable (1m) | 7842R | 2 | $116 |
| SH68-68-D1 Cable (1m) | 6704 | 1 | $144 |
| SHC68-68-EPM Cable (2m) | 6341,6224,6124 | 4 | $187 |
| RS232 Null Modem Cable | Controller COM | 1 | $28 |
| SH68-68-EP Cable (1m) | 6132 | 1 | $114 |

### Providing Access to Signals for Testing

None of the following is required for acquiring data, but will aid in the actual development of the system. First, it is recommended to have at least two, if not more break out boxes. These would take the cables to or from the chassis and allow us to easily break them out into their individual lines to probe or inject signals. Most cables will connect to NI's SCB-68A ($322). This is a simple screw terminal block for available for all signals on the card and two general purpose bread board areas. Along similar lines, the TB-2709 ($229) is specific to the S-series and provides direct SMB connectivity to the card. This is very convenient given that photodiodes on the CRDS are likely to use similar connections. If it is more straightforward to connect signals via BNC for the multifunction DAQ cards, then the BNC-2110 ($373) breaks out signals on the M, X, and S series cards into BNC connections. However, the available connections are limited due to the nature of the board itself and its intended use (it provides only 8 analog inputs regardless of the card it connects to).

## Final Recommended Configuration

Images of the two final systems discussed above are show in Figure 2 and Figure 3. Note the card placement here – this is expected. The first three card slots are express cards only. In the first configuration (a single card for sampling the CRDS), two express slots are available. In the second configuration, two cards are used to sample the photodiodes on the CRDS. The 6124 is an express card and now occupies one of the express slots previously unoccupied. The final costs of the two systems are as follows:

- $21,840 for the single card system (configuration ID: PX4120357).
- $24,780 for the two card system (configuration ID: PX4120361).

Both prices include the cables mentioned above as well as several break out boxes. Each of these configurations are saved as lists with National Instruments and should be retrievable using the configuration IDs above by going to the PXI advisor site and clicking Retrieve at the top. From there, anyone should be able to provide the configuration ID or by clicking the links above.


*Figure 2. Single card DAQ Hardware Configuration for EXSCALABAR.*


*Figure 3. Two card configuration for EXSCALABAR DAQ hardware. This configuration includes two four channel S-series cards - the 6132 which is similar to the 6133 that can sample at 2.5 MHz/ch and the 6124 which can acquire data at 4 MHz/ch. The 6124 is an express card and therefore occupies one of the first three slots along with the 6341.*

## One Final Consideration

Both systems recommended above are based off of the PXI Express standard. The AOP instrument at NOAA uses a DAQ platform based off of the PXI standard. The primary benefit of the PXI Express standard is that it increases the bandwidth of the backplane from a maximum of 132 Mb/s (PXI-1042Q) to 1 Gb/s for the systems specified above. It is not expected that EXSCALABAR will be able to take advantage of the extra bandwidth available (we will not be streaming enough data to the controller or other cards to justify the increase in bandwidth). However, the PXI Express standard as specified in the systems above enables some functionality not available with the PXI standard; namely, the two card option as specified above is not available in the traditional PXI standard. Also, for the money, the PXI Express systems should be a better fit for the EXSCALABAR DAQ. Both systems above utilize the PXIe-1078 which is an 8 slot chassis. The PXI-1042Q is a 7 slot chassis. With the PXIe-1078, we will have 1 (2 card option) or 2 (1 card option) slots available – both compatible only with PXIe cards.

Although I will not give this a strong recommendation, I have provided one final configuration for the EXSCALABAR DAQ hardware. This system is based solely off of the traditional PXI standard and is most similar to the NOAA AOP DAQ configuration. The primary difference between the configurations specified above and the one described in the following is that the chassis is replaced by the 1042Q, the controller is replaced by PXI-8119RT and the PAS multifunction DAQ card is replaced by the PXI-6229. The final cost for the traditional PXI system is:

- $24,681 (configuration ID: PX41344446)

This price includes all cables required for the system and an extended temperature range, 24/7 controller with an 80 Gb solid-state hard drive.

## Conclusion

The recommended configurations cover the signals outlined in the initial section covering the system requirements. The express PXI system is well suited to the requirements for EXSCALABAR. However, it is important to note that *all* hybrid spaces are occupied in both configurations. This means that if there is any intention to expand measurement capacity of the system, this limitation must be considered (that is, if it is currently believed that there is potential for expansion, this information should be provided now to determine if there will be an acceptable card to fit the current configuration or whether we need to reconsider the choices above). Also, the choice of multifunction DAQ cards, the 6341 and the 6224, assumes that many of the basic housekeeping signals will be single ended as opposed to differential. If this is not the case, then we may want to consider swapping the current multifunction DAQ cards for higher channel count DAQ cards. This in turn will have implications for the choice of controller and chassis as well as cabling. However, if most are single ended, then the number of signals available is more than sufficient to fit the needs of the instrument.