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Data Acquisition System Architecture and Capabilities at NASA GRC Plum Brook Station's Space Environment Test Facilities

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Abstract

Very large space environment test facilities present unique engineering challenges in the design of facility data systems. Data systems of this scale must be versatile enough to meet the wide range of data acquisition and measurement requirements from a diverse set of customers and test programs, but also must minimize design changes to maintain reliability and serviceability. This paper presents an overview of the common architecture and capabilities of the facility data acquisition systems available at two of the world's largest space environment test facilities located at the NASA Glenn Research Center's Plum Brook Station in Sandusky, Ohio; namely, the Space Propulsion Research Facility (commonly known as the B-2 facility) and the Space Power Facility (SPF). The common architecture of the data systems is presented along with details on system scalability and efficient measurement systems analysis and verification. The architecture highlights a modular design, which utilizes fully-remotely managed components, enabling the data systems to be highly configurable and support multiple test locations with a wide-range of measurement types and very large system channel counts.

Introduction

Three new Data Acquisition Systems (DAS) have been designed and installed at two of the world's largest Space Simulation Test Facilities both located at the Plum Brook Station in Sandusky, Ohio. The station is a 6,400 acre remote testing complex which is owned and managed by the NASA Glenn Research Center located 50 miles west of the center's main campus in Cleveland, Ohio. The two facilities referred to are the Space Power Facility (SPF) and the Spacecraft Propulsion Research Facility (B-2). The new facility data systems were part of a series of significant upgrades performed within the past 4 years by various NASA programs aimed at both restoring the facilities to their original capabilities as well as adding new capabilities to them for the purpose of preparing them for NASA's future planned space simulation work.

As part of a facility modernization and restoration project (Ref. 1), the B-2 facility was able to completely remove the original B-2 facility DAS and design and install an entirely new system. Shortly upon completion of the new B-2 DAS design, additional work began to support a project to design another new facility data system at Plum Brook which was to service the two entirely new space-simulation test facilities (a mechanical vibration test capability and a reverberant acoustic test capability) being built at SPF (Ref. 2). These new large-scale "vibroacoustic" test capabilities at SPF have been built to complement the already-existing large-scale thermal-vacuum test capability, making SPF a nearly all-in-one space environment testing location (Ref. 3). Designed to be a separate, stand-alone data system for the new "vibroacoustic" capabilities at SPF, the project also involved modernizing the data system for the thermal-vacuum system so that the both acquisition systems (the "vibroacoustic" DAS and the "thermal-vacuum chamber" DAS) would be consistent and compatible to customers and test programs. In the process of designing these three new data acquisition systems which support the primary test sites at Plum Brook Station, a common set of design goals, design approach, theory of operation and system architecture were all able to be achieved. This commonality allows the station management and facility test operations staff to share equipment and leverage common operations and maintenance support staff and station processes to provide the best value to present and future customers of the facilities.

Design Goals

Prior to providing a description of the design architecture and specifications, it is worth listing a set of design considerations that have guided many of the design choices made. The following is a list of qualities that were used as a set of evaluation criteria that the design choices were based on:

1. The data system should use Commercial-Off-The-Shelf (COTS) components whenever possible. COTS components should be proven, mature in their design lifecycle, and provided by industry leaders in that area of product design.
2. The data system design should make use of Open-Standards as often as possible. This should be considered for both hardware and software components. Components with proprietary and ad-hoc functions will be a burden to support and difficult to replace.
3. The data system should maximize the modularity of the design. A modular design has a number of benefits including; easier scalability, upgradability and system serviceability.
4. The data system should maximize software-control and minimize panel-control of the vast number of settings, set-points and configuration points. Wherever possible, avoid manual dials and knobs in favor of remotely programmable configurations. This is intended to allow for fully automated configuration SAVE and RESTORE functions and will allow the actual data system configurations to be captured as part of the test records.
5. The data system should maximize the integration and interoperability of the components. This goal is intended to ensure that the higher-level components can control the lower-level components and that, as much as possible, the components can communicate across a network. The more this goal is achieved the simpler the system will be to automate.

The intention of these design goals was to guide the design of the data systems and resulted in a technical design for a data system that is easy to operate, maintain, upgrade, and verify. It was held that these goals would result in the best quality, reliability and value in the test programs which seek to use these systems.

Design Challenges

The goals outlined above still leave a completely open design with challenges that may be unique to large space environment test facilities. While the actual facilities do tend to stay fixed in their scope and capabilities, the range of tests executed at the test sites can vary significantly. Given this quality, the facility data systems must be able to accommodate a broad range of test requirements. The following is a list of specifically identified design challenges that must be addressed for facility data systems:

1. Wide Variety of Measurement types—It would be impossible to make a complete list of the various measurement types that have been made in the facilities and will be asked to be made in the facilities tomorrow. Nonetheless, a facility data system would do well to anticipate and support as many as possible. If not carefully selected, the choice of signal conditioning platform and resulting form factor could become a limiting aspect of the design. A signal conditioning platform with a common form-factor and one that supports a wide variety of sensor-types is what is sought.
2. Distance effects and limitations—Measurements become more challenging to make the further the measurement system is from the sensor. Furthermore, the measurement system equipment is often sensitive to the challenging and dynamic environments that the sensors are in. Obviously the data system signal conditioning needs to be located away from the sensors, but how far is too far? Cable effects and electromagnetic noise almost always increase with distance. Careful attention must be given to the combinations of measurement types with signal conditioning. Failure to consider the cable length and cable type in the selection of the equipment could quickly limit the ability of the data system to meet the range and quality of the desired measurement.

3. Calibrating the system and pre-test End-To-End checks—The larger the channel count the greater the challenge of calibration and field reference check becomes. This is especially true for very large test facilities. Any data system design for a large facility like B-2 or SPF must calculate the effort required to calibrate and verify the channels. Any design choices that minimize this effort will be extremely desirable when in use.
4. Synchronization and Timing of Data—Very large data systems will unavoidably need to bring data together from multiple sources. Even if these sources are side-by-side, careful consideration must be given to the way in which the data system produces and integrates individual data points and combines them into a single data set.
5. Future System Growth—Inevitably, a request will be made to increase some quantity of the system. Usually it is the channel count that is the physical limits of the system, but sometimes it is the size of the recorded data (storage), or the number of real-time monitoring stations, etc. This can lead to bandwidth limitations due to the DAS architecture. As much as possible, every physical limit of the data system should be identified and means for scaling it up provided.
6. All-Save and All-Restore—As a system grows in size and complexity, the configuration control of the system grows significantly as well. This can be as simple as the need to pre-configure a replacement module prior to installation (jumper settings, etc.). Careful attention must be given to the net number of configuration points necessary to provide configuration control over to achieve a reliable and predictable system. Any design choices that eliminate the need for pre-configuring equipment in favor of installing it and letting the system remotely “set” a specifically designed configuration into it would be highly valuable. The converse would be equally valuable, namely, the ability to “query” the equipment and retrieve the complete status of the configuration from each element remotely. The ability to SAVE and RESTORE an entire system configuration is highly desired. Careful consideration of the over-all design must keep this in mind.
7. Metrology and Measurement Fidelity—As channel counts become very large, good metrology practices can easily become costly and challenging to perform. It is essential that the level of effort required to calibrate the system is considered in the design phase. If this is not considered in the design, there is a risk of a very large system becoming too difficult to calibrate properly.
8. Economical to operate and maintain—It is not enough to design a data system that can technically meet its performance requirements but is too costly to maintain properly or sell the use of. A universal requirement that is difficult to capture in the technical spec. is that the data system must be economically viable in all phases of its life-cycle. The cost to use it must not exceed the value of using it. In this paradigm, it is clear that an investment up front in equipment that meets the stated goals and overcomes the challenges outlined here and above will serve the facility well for today’s and tomorrow’s space simulation tests.

A Measurement Channel Topology

A first step towards a technical design was to make a generalized model of the measurement channel that will serve as a template for any specific measurement and equipment. Figure 1 shows a modular measurement model which has been used to specify the boundaries in a measurement between the physics (small signal), electronics (strong signal), and information (digital) regimes. These boundaries provide the basic framework for the modularity in our system. Our strategy was to specify and select the equipment that defines each boundary. Also detailed in the model are some of the physical limits that the data systems have been designed to.

The Measurement Channel Topology model in Figure 1 shows the signal flow of a single measurement through three distinct regimes. The first regime begins at the measurement location, with the sensor. Our goal in this regime is to keep each measurement channel separate and focus on the linear cabled path to the signal conditioning equipment. This part of the architecture is separate for each channel, however in practice we see large groups of similar channels that can be treated as sets. In this regime, every channel is configurable “per channel” and careful selection of the signal conditioning

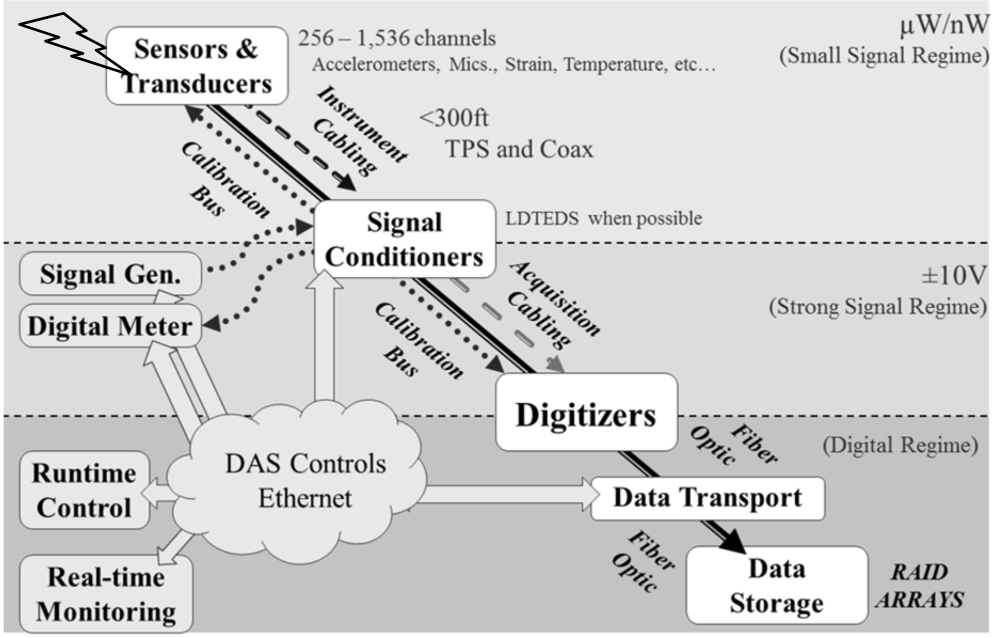

Figure 1.—The modular measurement model partitioned by signal regime.

equipment is necessary to match with the sensor type and the nature of the physics intended to be captured. Once we are at the signal conditioner, the intention is to excite, condition, amplify and filter the sensor signal so that its full-scale output is ±10 V. Once in the electronics (strong signal) regime, all of the signals have conformed to a standard format, namely the ±10 V full scale range. From here, all of the signals begin to behave the same way electrically and the only task left to do is to digitize them into electronic information that will be time-stamped, stored, and processed in a consistent way as well as distributed in real-time to equipment that will interpret the data and display it in real-time to an operator or test customer.

A Common Architecture for Data Processing Hardware

Once the signals are conditioned, filtered and amplified to the standardized ±10 V, the next regime is the information (digital) regime. Here the data must be digitized in such a way as to filter any “out-of-band” energy in the signal spectrum but yet accurately capture the portion of the spectrum that is important for the measurement. There are many quality digitizers on the market to pick from, for this design we chose a digitizer family that best suits our design goals and also provides a solution to the design challenges of a large scale space simulation test facility.

Figure 2 shows a general diagram for a Fiber-Channel Storage Area Network. This general architecture has been selected for the information regime primarily because of its distributable nature. The storage area network architecture is a topology that can be physically distributed to different locations. This feature allows the different functions (data sources, storage units, control and monitoring functions) to be installed in the most effective locations without introducing any appreciable latency in the timing and delivery of the data.

The Storage-Area-Network (SAN) architecture provides a nearly open-ended scalability with regards to the system’s total channel count. The actual limit to the number of possible channels is a function of the absolute physical limit of the number of logical channels supported by the Fiber-Channel Switch Fabric (FC-SW). The current standard uses a 4th Generation (4 Gb/s) FC-SW fabric, which supports 212 or 4,096 logical channels. Adding more channels to an architecture like this is as straight forward as connecting additional digitizer bricks to the FC-SW SAN.

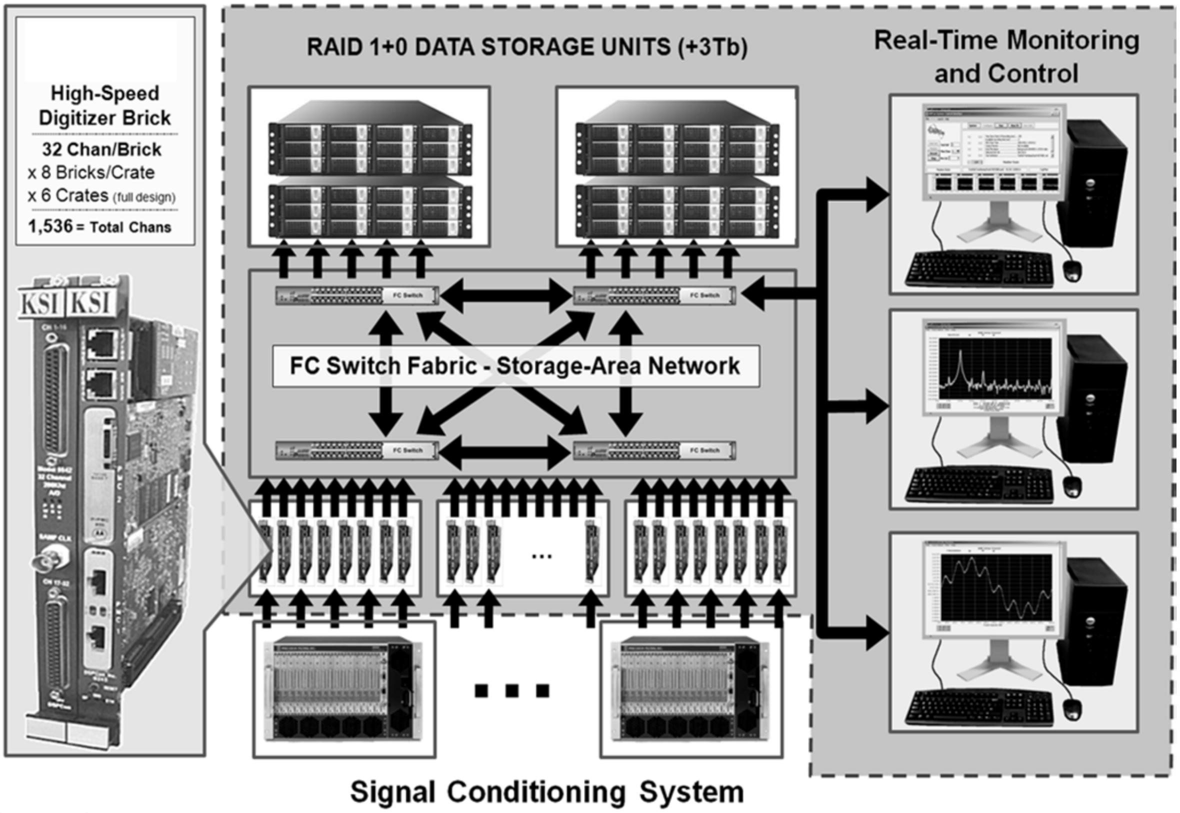

Figure 2.—The data system topology.
[A distributed, Fiber-Channel, Multi-Access, Storage Area Network (FCSAN).]

A Common Hardware Specification

By defining the design goals, identifying the main design challenges specific to large-scale test facilities, adopting a measurement model and selecting a generalized system architecture, we have produced a rather straight-forward roadmap for selecting specific hardware to use in these system. The following table (Table 1) attempts to capture the most salient aspects of the various components selected for the three data system we are describing.

This list could easily be extended, but the additional detail would be beyond the scope of this paper. The intent of the preceding discussion is to show how any COTS products would be used in the generalized design architecture. With an understanding of a common architecture for the data systems we are in a position to summarize succinctly the scale and implementation of the three new DAS system in operation at the B-2 and SPF facilities at Plum Brook.

TABLE 1.—A COMMON DAS EQUIPMENT LIST OF SPECIFICATIONS
FOR MULTIPLE DATA SYSTEMS AT PLUM BROOK

Code		
Instrument Cabling		**Specifications**
C.1	Single Pair, Twisted-Pair Shielded	3 Conductors #20 AWG per Channel Single inner twisted pair (+ & -) Individually shielded with shield drain wire
C.2	Four-Wire, Twisted-Pair Shielded	5 Conductors #20 per Channel 4 signal conductors Channel individually shielded with shield drain wire
C.3	Impedance Matched BNC Coaxial	Standard RG-58, RG59, RG-174, Micro-Dot, etc.
C.4	Alloy Thermocouple Wire	Standard High Quality Thermocouple Wire
Signal Conditioning Equipment		**Specifications**
S.1	Constant-Voltage Bridge Conditioners	Used for DC and dynamic strain measurements
	▪ 4 channels per card, 64 channels per chassis ▪ Balanced programmable constant voltage source with remote sense ▪ Up to 20 V excitation delivered to the bridge ▪ Up to 200 kHz “filtered” bandwidth or 700 kHz “wide-band” bandwidth ▪ 2- to 10-wire plus shield transducer input interface ▪ Automatic bridge balance ▪ 4096 step bipolar shunt cal; Can remotely shunt any bridge arm ▪ Switch selectable bridge configuration (1-arm, 2-arm, or 4-arm) with read back ▪ Programmable AC/DC input coupling ▪ Programmable amplifier: x1/16 to x8192 with 0.05% vernier ▪ Programmable 4-pole low-pass filters with filter bypass (wide-band) ▪ Overload detection ▪ Precise automatic calibration ▪ ±10 Single-ended Outputs on a backplane bus to support signal aggregation ▪ Auxiliary front panel output connection to support the use of custom output modules	
S.2	Constant-Current Bridge Conditioners	Used as AC Filter Amplifier or Dynamic strain measurements
	▪ 8 channels per card, 128 channels per chassis ▪ AC coupled balanced differential input ▪ Balanced differential constant current excitation ▪ Excitation disconnect for voltage/amp operation ▪ AC current test mode for verifying transducer, cabling and frequency response ▪ On-the-fly report of measured transducer excitation and resistance ▪ Transducer open/short indication ▪ Transducer leakage to ground detection ▪ 4-pole flat/pulse low-pass filter (LP4FP) with cutoff options from 100 Hz to 100 kHz ▪ Bypass filter for wideband amplifier operation (–3 dB at 190 kHz) ▪ Voltage substitution test signals ▪ Programmable amplifier: x½ to x1024 with 0.05% vernier ▪ Pre-filter overload detector to report out-of-band overloads which the filter could mask ▪ ±10 Single-ended ▪ Outputs on a backplane bus to support signal aggregation ▪ Dual buffered outputs	
S.3	ICP/IEPE Conditioners	Used for IEPE/ICP-type accelerometers and microphones
	▪ 16 channels per card; 256 channels per chassis ▪ IEPE conditioner or AC Filter/Amplifier with balanced differential input ▪ Isolated channel input allows conditioning of grounded IEPE accelerometers w/o introducing ground loops ▪ Long-Distance Transducer Electronic Datasheet compliant ▪ Gain x1 to x512 with 0.1% resolution ▪ Auto-gain setup for best ADC dynamic range ▪ Programmable 4-pole low-pass filters ▪ Current settings of 0, 2, 4, or 8 mA (programmable per channel) ▪ Sensor bias detector; in-range or out-of-range ▪ AC test current checks sensor, cable and signal conditioner health ▪ Overload detection ▪ Output monitor, selects any one of 512 outputs	

TABLE 1.—Continued.

	▪ Test input for each channel ▪ ±10 Single-ended Outputs on a backplane bus to support signal aggregation	
S.4	Charge-Type Amplifiers	Used for charge-type accelerometers and microphones
	▪ 4 channels per card; 64 channels per chassis Charge Mode ▪ Full-scale charge: 2.5 to 160,000 pC ▪ Full-scale MU: 2.5 to 160,000 pC/Transducer Sensitivity (pC/MU) ▪ Transducer Sensitivity: 0.001 pC/MU to 9999 pC/MU Voltage Mode (IEPE) ▪ Full-scale voltage: 2.5 to 10.24 V ▪ Full-scale MU: 2.5 mV to 10.24 V/Transducer Sensitivity (mV/MU) ▪ Transducer Sensitivity: 0.001 mV/MU to 9999 mV/MU Additional Features ▪ Full-scale output: ±1.0000 to 10.000 V ▪ Programmable anti-alias filters: 4-, 6-, or 8-pole ▪ Pre-filter and output overload detectors ▪ HP filter: –3.01 dB at 0.5 Hz (2-pole) ▪ Pseudo-Isolated or grounded inputs ▪ ±10 Single-ended Outputs on a backplane bus to support signal aggregation	
S.5	Filter/Amplifier Signal Conditioners	
	▪ Eight channels per card, 128 channels per chassis ▪ Balanced differential inputs with programmable AC/DC coupling ▪ Zero Suppress via a programmable DC voltage inserted at the channel input ▪ Distributed programmable gain of x1/16 to x8192 with 0.05% resolution ▪ Input MUTE mode to terminate unused channels in safe, quiet state ▪ Pre-filter overload detection ▪ 4-pole low-pass filters with programmable pulse/flat characteristics for optimized time domain performance ▪ Programmable low-pass filter cutoff frequencies: Programmable from 2 Hz to 204.6 kHz ▪ Wide-band (500 kHz) or filtered operation ▪ Precise digital calibration ▪ Single-ended outputs with ground sense ▪ Programmable test modes for calibration signal injection and input short, allowing for automated measurement system validation ▪ Output monitor bus ▪ Auxiliary front panel output connection supports the use of output buffer modules ▪ ±10 Single-ended Outputs on a backplane bus to support signal aggregation	
S.6	Frequency-to-Voltage	Used for pulse rate and frequency based sensors
	▪ 1 Hz to 50 kHz frequency range ▪ Up to 100 V input ▪ 16-bit output voltage resolution ▪ Programmable Test input ▪ Programmable Input frequency range: FL, FH ▪ Programmable Output voltage output range: VL, VH ▪ Programmable Low frequency roll-off ▪ Programmable Trigger threshold ▪ Programmable Positive or negative trigger ▪ Programmable Hold-off trigger time ▪ Programmable Pre-scaler ▪ Programmable Input range ▪ ±10 Single-ended Outputs on a backplane bus to support signal aggregation	
S.7	Direct Voltage Inputs	See Digitizer input specs for D.1, D.2, and D.3
S.8	Integrated Thermocouple Conditioners	Used for temperature measurements using Type-T thermocouples
	▪ 64 channels per chassis ▪ Accepts type E,J,K,N,R,S,T, and B ▪ Engineering Unit output, °C, °F, °R, °K and mVolts ▪ 1000 Vdc channel-to-channel isolation ▪ 600 Vdc input isolation ▪ 50 to 60 Hz noise rejection ▪ Open Thermocouple test ▪ 40 Hz maximum (samples/channel/second)	

TABLE 1.—Concluded.

	▪ Ethernet TCP/IP protocol “network ready” ▪ Accuracy ±0.25 °C (limited thermocouple types) ▪ Direct EU data out over Ethernet to data collection units	
B.1	Voltage Follower Buffered Output	Used to share conditioned signal to secondary systems
	▪ 4 and 8 channels per unit ▪ Provides fully buffered outputs derived from primary ±10 Single-ended Outputs ▪ One or two buffered outputs per channel ▪ Selectable output ground sense	
Digitizing Equipment (ADCs)		**Specifications**
D.1	High-Speed Digitizers	Used to acquire signals with measurement bandwidths <100 kHz
	▪ 6U VME form factor plug-in boards ▪ 16 bit resolution Sigma-Delta ADC ▪ Max Sample Rate of 256 kSPS ▪ Alias-free Measurement Bandwidth (MBW) up to 100 kHz ▪ Analog Gains of 1, 10, 100, and 1,000 ▪ ±10V differential voltage inputs ▪ High-impedance inputs: 100 kOhm ▪ Dynamic Range > 96dB (rel. to FS) ▪ Fiber-optic output for FC-SAN architecture ▪ IRIG-B and Master sample clock synchronization	
D.2	Low-Speed Digitizers	Used to acquire signals with measurement bandwidths < 1 kHz
	▪ 6U VME form factor plug-in boards ▪ 16 bit resolution Sigma-Delta ADC ▪ Max Sample Rate of 4 kSPS ▪ Alias-free Measurement Bandwidth (MBW) up to 1 kHz ▪ Analog Gains of 1, 10, 100, and 1,000 ▪ ±10V differential voltage inputs ▪ High-impedance inputs: 100 kOhm ▪ Dynamic Range > 96 dB (rel. to FS) ▪ Fiber-optic output for FC-SAN architecture ▪ IRIG-B and Master sample clock synchronization	
D.3	Discrete Channel Acquisition	Used to acquire on/off status signals
	▪ 6U VME form factor plug-in boards ▪ 32 channels per board ▪ Supports Open-Collector and TTL inputs ▪ Sample Rates up to 256 kHz ▪ Fiber-optic output for FC-SAN architecture ▪ IRIG-B and Master sample clock synchronization	
Data Storage		**Specifications**
R.1	RAID 1+0 redundant fail-over storage	
Control, Monitoring, and Post-Processing		
C.1	Dedicated Control Computers	▪ Run-Time Applications, ▪ Calibration Database ▪ Start/Stop Functions ▪ Test Definition/Configuration, etc. ▪ Fiber-optic connection to FC-SAN architecture
C.2	Dedicated Monitoring Computers	▪ Customer Real-time Data Display Screen ▪ Fiber-optic connection to FC-SAN architecture
C.3	Dedicated Post-Processing Computer	▪ Applications for producing customer “Quick-Plots” of: ▪ Time-Series Data ▪ Spectral Analysis ▪ Data reduction and Down-sampling ▪ Applications for Post-recording filters, etc. ▪ Fiber-optic connection to FC-SAN architecture
Other Notable System Elements		**Specifications**
X.1	IRIG-B Distribution	Common to all acquisition hardware including video
X.2	LTO-3 Tape Archival System	▪ Test data on Dedicated Reliable Long Term Media ▪ Customer Data Product Output ▪ Long-Term Data Archival

The Data Acquisition System at the Plum Brook B-2 Facility

The Space Propulsion Research Facility, designated as B-2 is one of Plum Brook Station's principal test sites. The B-2 facility is designed to hot-fire rocket engines in upper stage launch vehicles with up to 890,000 N force (200,000 Lb force), after environmental conditioning of the test article in a simulated thermal vacuum space environment. In recent years, the B-2 facility has undergone refurbishment of key subsystems to support NASA's future test needs, including controls, vacuum, propellant systems and data acquisition. Notably, the design and implementation of the facility's new data acquisition system is consistent with the common DAS architecture described above.

The B-2 DAS includes the signal conditioning electronics, data recording, storage, display, archive systems and all of the elements identified in the common architecture. The distributed nature of the common architecture is ideal for allowing the B-2 DAS to meet the unique challenges of a space environmental upper-stage engine testing facility. In addition to addressing the specific requirements of performing large-scale data acquisition for test articles in a thermal-vacuum chamber, the B-2 DAS architecture also allows the DAS to meet the corresponding DAS safety requirements for tests which involve the use of potentially explosive propellants. With this type of testing in mind, the distributed modular nature of the DAS architecture is a key aspect of the system's overall design as a facility system.

Because of the hazards of propellants, the B-2 facility has three distinctly separate locations: (1) the test building (which includes the thermal vacuum chamber containing the test article), (2) a dedicated Data Room located near the test building, and (3) a remote operations or controls building. The location of data room near the test building (Fig. 3) allows the transducer cabling impedance to be minimized, while providing protection and a safe working environment for sensitive equipment from the environments produced by the test facilities. The Data Room allows the front-end electronics of the DAS to operate safely by providing a constant positive air pressure in the room to maintain a Class-I, Div-2, Group-B compliant environment. This allows the signal conditioning and digitizing electronics to function as close to the test chamber as possible when propellants are present and the control of the DAS, monitoring and data storage functions are located in a dedicated control building over 1/2 km away.

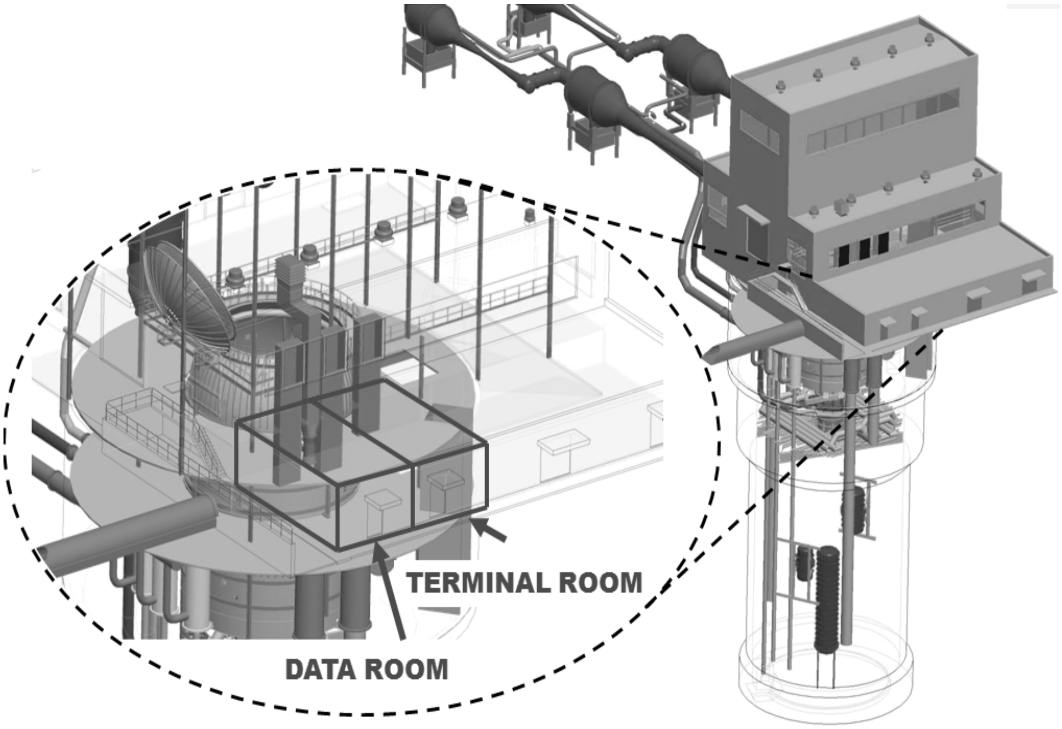

Figure 3.—A Class I Div 2 Group B compliant environment for the B-2 DAS equipment.

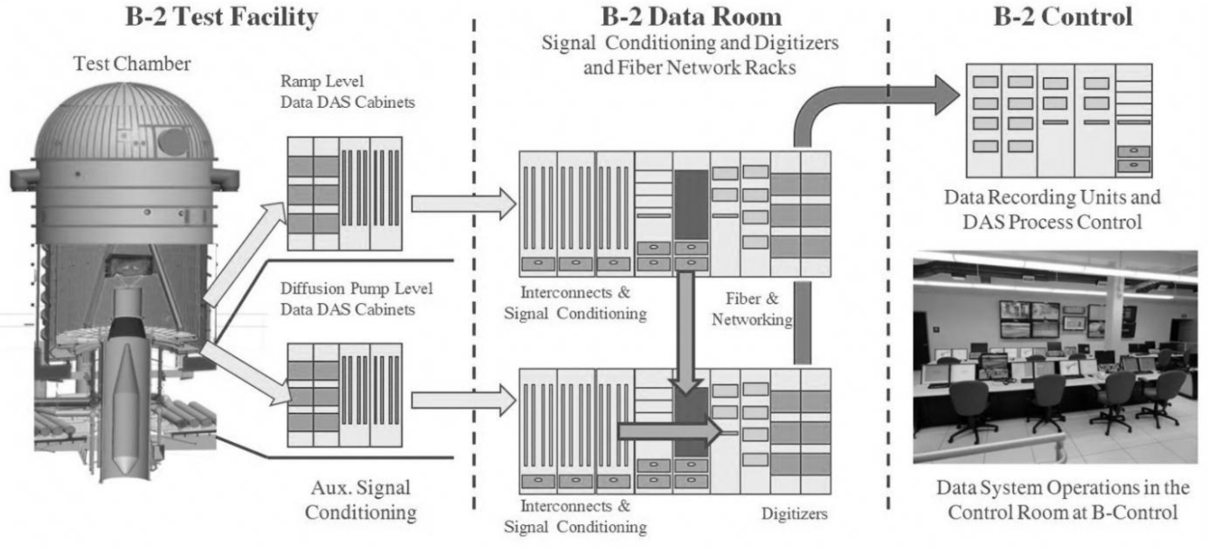

Figure 4.—The B-2 DAS distributed architecture.

Thus the distributed architecture of the DAS is used to mitigate the risk of the potential loss of data in a catastrophic scenario. Once the analog measurements are digitized in the Data Room the resulting data is streamed immediately via fiber optics to data recording units that are located at the B-Control building outside the B-2 facility exclusion zone, approximately one-half mile away from the test facility. Joined together by a 4 GBit fiber-channel switch fabric, the digitizers and the recording units form a 4th generation storage area network (SAN) for which the distance between the digitizers at the B-2 test site and the recording units at B-Control does not introduce any appreciable time delay. The data is recorded remotely with the same negligible latency it would have if the recoding units were located in Data Room with the digitizers. The three locations of the B-2 DAS are shown in Figure 4.

The B-2 DAS components have been selected to maximize commonality with the other DAS systems at Plum Brook and are based entirely on Commercial-Off-The-Shelf (COTS) hardware, and open hardware/software standards. The acquisition stations which house the A/D converters, digital signal processor (DSP) board, Fiber-Channel (FC) interfaces, and G4 Power PC embedded processors are connected to RAID storage arrays by a storage area network (SAN) over fiber channel switch fabrics. The architecture is designed to guarantee deterministic data acquisition at designed bandwidth per channel. There are currently 576 channels of A/D’s arranged in 32-channel subsystems. Data is synchronized through a clock generator which is phase-locked to an externally supplied IRIG –B signal for accurate time stamping.

A data lab in the B-Control building houses the control, monitor, and archive workstations. The control workstation runs the application to configure the hardware, define the test parameters, and control access to the test data. There are three monitor workstations that run the visualization software for near real-time data display, as well as the limit-check monitoring software. The archive server runs software to back up acquired data to mass storage and the Linear Tape-Open (LTO) magnetic tape library. The software has the capability to locate and serve archived data to other workstation clients for analysis, reduction or transmission. An on-line post processing workstation is available to define and automatically execute analyses on any number of channels once acquisition is complete.

The mass storage for the B-2 DAS consists of four 3-Terabyte RAID **(**Redundant Array of Inexpensive Disk) arrays configured as RAID 1+0. This array architecture ensures that the array can continue to execute read and write requests to all of its virtual disks in the presence of any two concurrent disk failures. Table 2 shows a summary of the facilities baseline DAS capabilities.

TABLE 2.—TABLE SHOWING CURRENT B-2 DAS BASELINE CAPABILITIES

Instrument Cabling to Test Chamber (Including chamber feed-through)			**Quantities**
1	Single Pair, Twisted-Pair Shielded	See Table 1-C.1	>1,700 Ch. 1PR TPS
2	Four-Wire, Twisted-Pair Shielded	See Table 1-C.2	312 Ch. of 4C/Ch.
3	Impedance Matched Coaxial	See Table 1-C.3	~64 Ch.
Signal Conditioning Equipment			
4	Constant-Voltage Bridge Conditioners	See Table 1-S.1	76 Ch.
5	Constant-Current Bridge Conditioners	See Table 1-S.2	32 Ch.
6	ICP/IEPE Conditioners	See Table 1-S.3	48 Ch.
7	Charge-Type Amplifiers	See Table 1-S.4	
8	Filter/Amplifier Signal Conditioners	See Table 1-S.5	160 Ch.
9	Frequency-to-Voltage	See Table 1-S.6	28 Ch.
10	Direct Voltage Inputs	See Table 1-S.7	600+ (see ADCs)
11	UTR Thermocouple Conditioners	See Table 1-S.8	<tbd>
Digitizing Equipment (ADCs)			
12	High-Speed Digitizers (110 kHz MBW/Ch.)	See Table 1-D.1	32 Ch.
13	Low-Speed Digitizers (1 kHz MBW/Ch.)	See Table 1-D.2	576 Ch.
14	Discrete Channel Acquisition	See Table 1-D.3	32 Ch.
Data Storage			
15	RAID 1+0 redundant fail-over storage	See Table 1-R.1	2.5 – 3 Terabytes
Control, Monitoring and Post-Processing			
16	Dedicated Control Computers	See Table 1-C.1	2
17	Dedicated Monitoring Computers	See Table 1-C.2	4
18	Dedicated Post-Processing Computer	See Table 1-C.3	1
Other Notable System Elements			
19	IRIG-B Distribution	See Table 1-X.1	All
20	LTO-3 Tape Archival System	See Table 1-X.2	All

The current DAS equipment counts at B-2 will likely need to be increased to support the anticipated requirements of future test programs, but the common DAS architecture provides a framework for doing so in a way that maintains consistency with the existing design of experiments and the overall operation and maintenance of the DAS systems at Plum Brook.

The Vibroacoustic Data Acquisition System at the Plum Brook Space Power Facility

The Space Power Facility (SPF) shown in Figure 5 is also located at NASA’s Plum Brook Station in Sandusky, Ohio. The SPF building houses the world’s largest space environment simulation chamber measuring 100 ft in diameter by 122 ft high. It has recently been upgraded with two new spacecraft environment test facilities which were constructed to compliment the facility’s pre-existing thermal-vacuum chamber. The new facilities provide a mechanical vibration table and a reverberant acoustic chamber. These two new facilities have been designed to simulate the mechanical and acoustic vibrations for test articles of the same scale as the thermal-vacuum chamber. The vibration table, and its related vibration control systems (VCS) taken together are designated as the Mechanical Vibration Facility (MVF) and the reverberant acoustic chamber, with its acoustic control systems (ACS) taken together is called the Reverberant Acoustic Test Facility (RATF). Because the data acquisition hardware requirements for both the MVF and RATF are nearly identical, a single data system has been included in the upgrade to serve both. This common data system for the “vibroacoustic” facilities is required to be run independently of the thermal-vacuum chamber’s data system. As a result, the two systems will be discussed separately but both conform to the common data system architecture independently. This section will focus on the data system that supports the RATF and MVF.

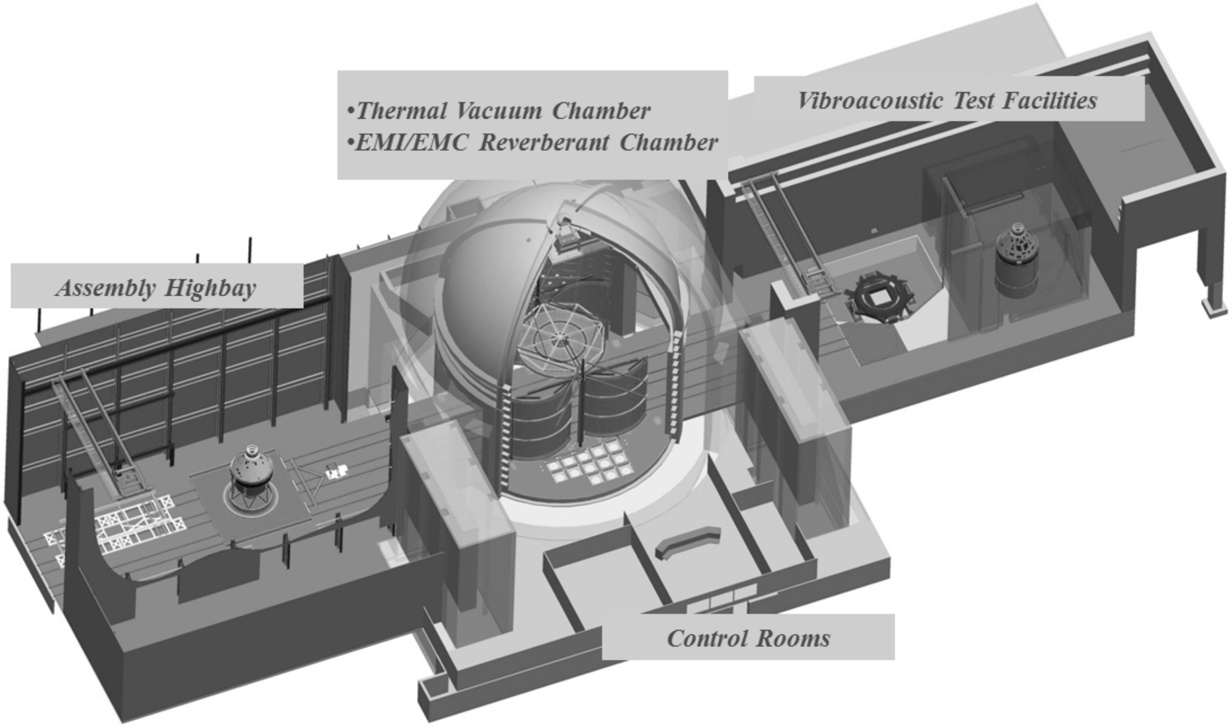

Figure 5.—The Space Power Facility with Thermal Vacuum and Vibroacoustic Test Capabilities.

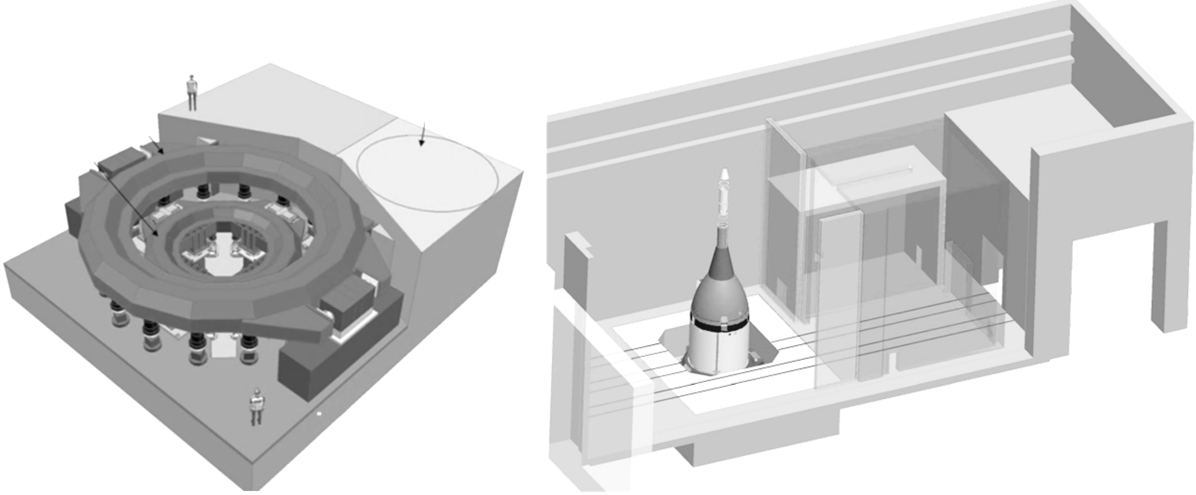

Figure 6.—The MVF Vibration Table (left) and the RATF Chamber (right) in the Disassembly Highbay.

The MVF table, Figure 6, is a three-axis vibration system. It is designed to apply a sinusoidal vibration in each of the three orthogonal axes (not simultaneously) with one direction in parallel to the Earth-launch thrust axis (X) at 5 to 150 Hz, 0 to 1.25 g-pk vertical, and 5 to 150 Hz 0 to 1.0 g-pk for the horizontal axes. In addition to the sine vibe table, a Modal floor sufficient for a 20-ft diameter test article has been built. To support this type of testing at the MVF, the vibroacoustic data system is designed to provide 800 IEPE/ICP signal conditioners for accelerometers and microphones, 184 4-arm remote bridge strain gauges and as many as 64 additional direct voltage channels for pre-conditioned signals form the ACS or VCS. To allow for consistency in quality and size across all the recorded data, all of the measurement channels are required to be acquired with a measurement bandwidth of 20 kHz.

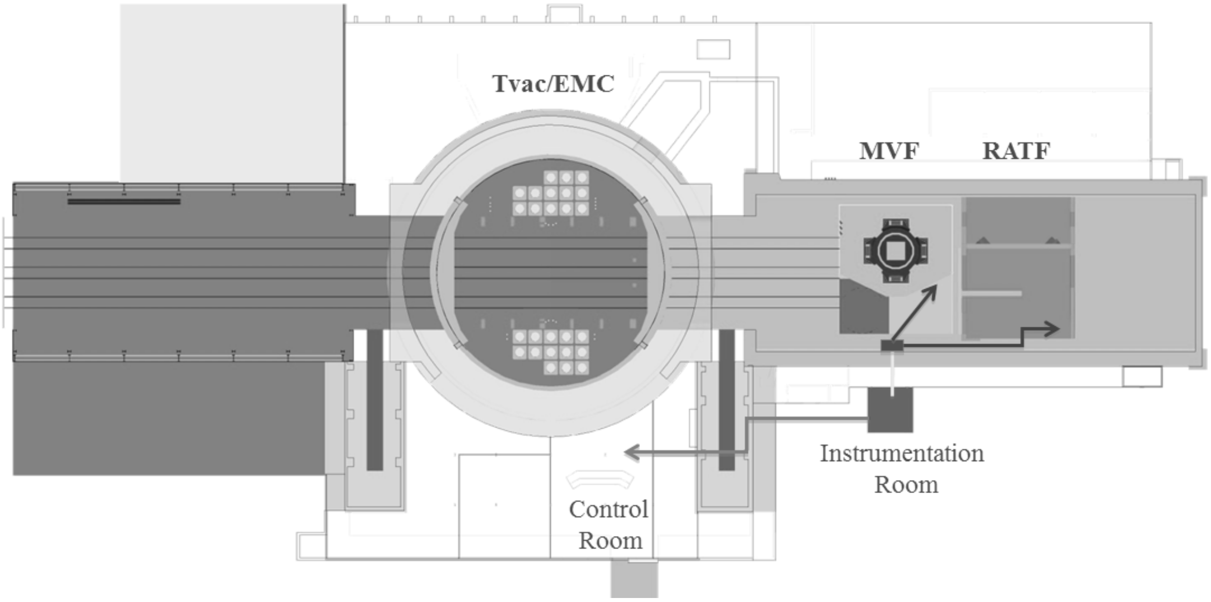

Figure 7.—The Space Power Facility with Thermal Vacuum and Vibroacoustic Test Capabilities.

The RATF is also located in the Disassembly Highbay. This test area consists of a 2,800 cubic-meter reverberant-type acoustic test chamber, which is supported on a new, independent foundation from the original building. The RATF is designed to accommodate test articles in a variety of configurations. The facility is designed to provide a 163dB Overall Sound Pressure Level (OASPL). Figure 6 also shows the relationship of the RATF chamber to the MVF table.

The vibroacoustic data system is designed to be a single system that is switchable to service both the RATF and MVF test locations (Fig. 7). This switching is done using a passive switch cabinet in the vibroacoustic Highbay to allow all of the instrumentation wiring to be manually switched between three configurations. In each configuration, all 1,024 channels of the DAS are available to the switched locations. The three locations are: inside the RATF chamber, along the sides of the MVF table pit, and direct access near the Modal floor. All instrumentation cabling from the Signal Conditioners in the Data Room make their way into a set of three Switching Cabinets using forty-four (44) 32-Channel twisted pair shielded wires. Each of these cables is terminated with a multi-pin mil-spec circular connector which is a panel mount connector accessible in the back panel of the Switching Cabinets. Switching between the test locations is accomplished by connecting the corresponding forty-four (44) 32 channel twisted-pair-shielded cables dedicated to continuing the instrumentation signal path cables for each location. In addition to utilizing the same DAS equipment for multiple test locations using all permanently installed facility cabling, the switching cabinets provide each test location with the same DAS interface. This means that a test article that is instrumented to work at one location will work at the others with no re-work of the test article sensor wiring or the DAS configuration wiring in the Data Room. This feature also eliminates the need to re-verify the entire DAS when moving from one test location to the next.

The vibroacoustic DAS components have been selected to maximize commonality with the other DAS systems at Plum Brook and are based entirely on Commercial-Off-The-Shelf (COTS) hardware, and open hardware/software standards. The acquisition stations which house the A/D converters, digital signal processor (DSP) board, Fiber-Channel (FC) interfaces, and G4 Power PC embedded processors are connected to RAID storage arrays by a storage area network (SAN) over fiber-channel switch fabrics. The architecture is designed to guarantee deterministic data acquisition at designed bandwidth per channel. There are currently 1,024 channels of A/D’s arranged in 32-channel subsystems. Data is synchronized through a clock generator which is phase-locked to an externally supplied IRIG –B signal for accurate time stamping.

A section of the SPF vibroacoustic control room is reserved for the control, monitoring, and archive workstations. The control workstation runs the application to configure the hardware, define the test parameters, and control access to the test data. There are three monitor workstations that run the visualization software for near real-time data display, as well as the limit-check monitoring software. The archive server runs software to back up acquired data to mass storage and the Linear Tape-Open (LTO) magnetic tape library. The software has the capability to locate and serve archived data to other workstation clients for analysis, reduction or transmission. A post processing workstation is available to define and automatically execute analyses on any number of channels once acquisition is complete.

The mass storage for the SPF vibroacoustic DAS consists of four 3-Terabyte RAID **(**Redundant Array of Inexpensive Disk) arrays configured as RAID 1+0. This array architecture ensures that the array can continue to execute read and write requests to all of its virtual disks in the presence of any two concurrent disk failures. Table 3 shows a summary of the SPF facilities baseline vibroacoustic DAS capabilities.

TABLE 3.—TABLE SHOWING CURRENT SPF VIBROACOUSTIC DAS BASELINE CAPABILITIES

Instrument Cabling to the MVF table and RATF chambers (common to both)			**Num. of Channels**
1	Single Pair, Twisted-Pair Shielded	See Table 1-C.1	>1,700 Ch. TPS
2	Impedance Matched Coaxial to/from ACS	See Table 1-C.3	64 Ch.
3	Impedance Matched Coaxial to/from VCS	See Table 1-C.3	64 Ch.
Signal Conditioning Equipment			
4	ICP/IEPE Conditioners	See Table 1-S.3	800 Ch.
5	Constant-Voltage Bridge Conditioners	See Table 1-S.1	160 Ch.
6	Direct Voltage Inputs from ACS/VCS	See Table 1-S.7	64 Ch.
7	Buffered Voltage Outputs to ACS/VCS	See Table 1S.7	64 Ch.
Digitizing Equipment (ADCs)			
8	High-Speed Digitizers (20 kHz MBW/50 kHz SR)	See Table 1-D.1	1024 Ch.
Data Storage			
9	RAID 1+0 redundant fail-over storage	See Table 1-R.1	3 Terabytes total
Control, Monitoring and Post-Processing			
10	Dedicated Control Computers	See Table 1-C.1	1
11	Dedicated Monitoring Computers	See Table 1-C.2	3
12	Dedicated Post-Processing Computer	See Table 1-C.3	1
Other Notable System Elements			
13	IRIG-B Distribution	See Table 1-X.1	All
14	LTO-3 Tape Archive	See Table 1-X.2	All

The ACS and VCS each have their own facility status sensors and safety shutdown systems to protect the facilities (MVF and RATF) from doing damage to themselves and the facility sensors required to do this are not considered as part of the data system. However, it is understood that at times the instrumentation on the test article is required as well to allow the system to monitor and enforce a customer requested test envelope to protect the test article from over-testing. This test envelope (or test environment limit) requires that the data system be able to provide exact buffered copies of some subset of the test article sensors. The signals provided must be already conditioned and amplified by the data system and provided to the ACS/VSC Analog Abort (AA) Redline-Computer. The AA is a 64-channel with high-speed inputs. Inputs to the abort computer will consist of selected number of table control accelerometers, facility signals (pressures, temps, strains, etc.) and test article response signals (maximum number of 32 channels). Selected test article response signals are also available as inputs to the VCS directly for response limiting inputs. All VCS control signals can also be recorded as direct voltage inputs to the DAS for correlation with the test article response signals.

The current DAS equipment list assigned to the SPF vibroacoustic data system is calculated to be completely sufficient for the majority of potential test programs that are envisioned. The one exception is the Multi-Purpose Crew Vehicle MPCV (Ref: the Orion vehicle shown as the test article in Figures 5 and 6). The additional DAS equipment needed for that program has already been calculated and designed in to the existing vibroacoustic data system such that scaling-up the data system is as straight forward as plugging-in the additional equipment in the places already designated for it. Like the B-2 DAS the common DAS architecture provides a framework for doing so in a way that maintains consistency with the existing design of experiments and the overall operation and maintenance of the DAS systems at Plum Brook.

The Thermal-Vacuum Chamber Data Acquisition System at the Space Power Facility

The SPF facility houses the world's largest space environment simulation (thermal-vacuum) chamber measuring 100 ft in diameter by 122 ft high with two 50 by 50 ft main doors for bringing test articles into the chamber as well as moving test articles through the chamber and on to testing in the Vibroacoustic Highbay. The chamber is able to sustain the high vacuum levels required for spacecraft testing on the order of 10e-6 torr. Vacuum is achieved using a 4 stage pumping system. As a thermal-vacuum chamber, the facility is able to provide simulated solar radiation to the surfaces of a test article at levels up to 4 MW using quartz lamp arrays. The chamber can also provide simulated space cold temperatures to the test article to temperatures as low as –156 °C (–250 °F) using a cryogenic shroud (included in Fig. 5). The test chamber is actually a chamber within a chamber. The inside chamber which supports hard-vacuum is made entirely of aluminum and must be protected from the mechanical forces produced by 1 atmosphere of pressure outside by a strong outer chamber that is concrete. This "chamber-within-a-chamber" design increases the complexity of providing power, instrumentation and other logistical connections to the inside of the chamber as there are two vacuum chamber walls for signals and pipes to pass through. The region between the aluminum and concrete chambers is called the annulus. When the inside chamber is pumped down to hard vacuum, the annulus region is pumped down to just a few torr. Because of the extreme vacuum and temperature environments, data acquisition equipment must be located outside the concrete chamber. Figure 8(i) shows a cutaway view of the two chamber walls and the 5 electrical feed-through flanges that are on the inside (labeled K, L, M, N, and P) for instrumentation. These instrumentation flanges are populated with dozens of multi-pin electrical feedthroughs which define the customer interface for data system instrumentation cabling from the data system outside the chamber. The instrumentation cabling connected to these feedthroughs has a corresponding feed-through on flanges on the outside of the concrete chamber in the basement of the facility. To avoid repeatedly working with hard-vacuum feedthroughs, the facility instrumentation wiring from the inside chamber flanges to the outside chamber flanges in the annulus is treated as permanent wiring. How this wiring gets used from one test to the next is customer defined, but that actual wiring is fixed as is. Figure 8(ii) shows a top view cross-section of the two chamber walls and the annulus region between. Figure 8(iii) shows a side-view of the curved path the instrumentation wiring takes as it goes from inside the chamber to the smaller flanges in the basement. Figure 8(iv) shows a top view cross-section of the basement just outside the concrete chamber. The detail at the top right of Figure 8(iv) shows a front-view arrangement of the 20 smaller instrumentation flanges arranged in 4 rows of 5. Also pictured in Figure 8(iv) is a top view of the data acquisition cabinets that are part of the thermal-vacuum DAS.

The Thermal-Vacuum DAS is a stand-alone mobile rack enclosure that includes all the components of the general FC-SAN DAS architecture. Shown in Figure 9, this mobile DAS (MDAS) system is a complete data acquisition system designed in to a two-piece, stackable rack unit. The top rack is called the Control Rack and houses a single control PC. Additionally the Control Rack contains an oscilloscope, digital function generator, digital multi-meter and an Ethernet Switch to allow all of these devices to communicate on a common network. The Control PC also has a Fiber Channel connection. The fiber, Ethernet and analog signals to and from the Control Rack are all consolidated into a custom made 1U interface panel that is installed on the bottom-rear of the Rack. From this custom interface panel, the Control Rack can be connected to the acquisition equipment below as well as other fiber and Ethernet networks that it is configured to join.

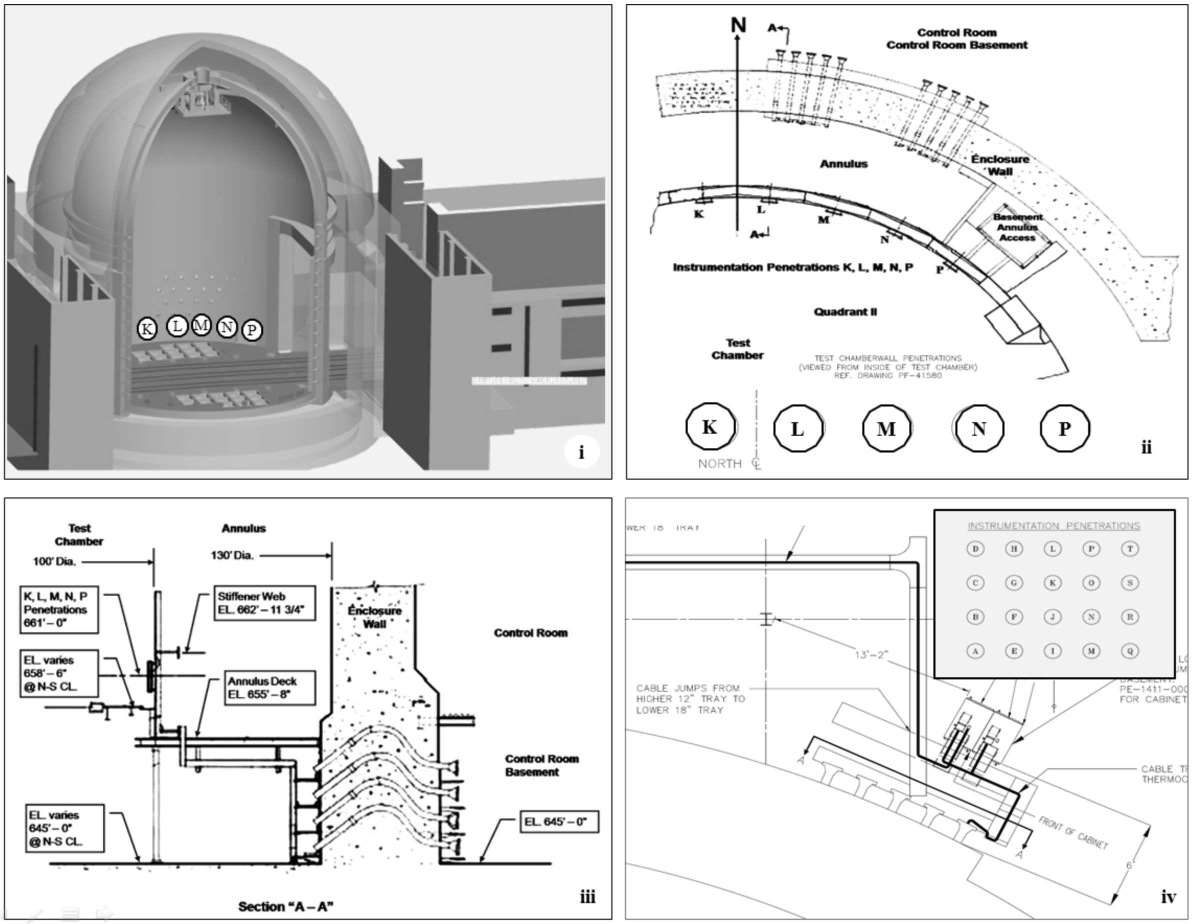

Figure 8.—The Space Power Facility's Thermal Vacuum Chamber Instrument Baseline Wiring.

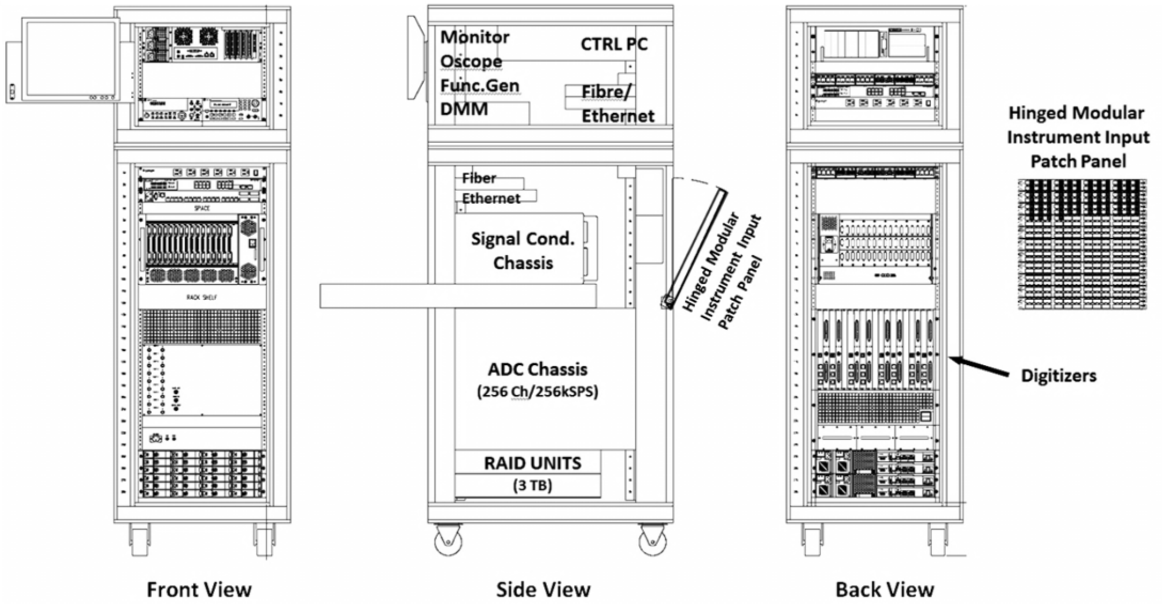

Figure 9.—The Space Power Facility's Thermal Vacuum Chamber Mobile Data System (MDAS).

TABLE 4.—TABLE SHOWING CURRENT SPF THERMAL-VACUUM CHAMBER MDAS BASELINE CAPABILITIES

Instrument Cabling in the Vacuum Chamber Annulus			**Number of Channels**
1	Single Pair, Twisted-Pair Shielded	See Table 1-C.1	324 Ch. 1PR TPS
2	Four-Wire, Twisted-Pair Shielded	See Table 1-C.2	288 Ch. 4C/Ch.
3	Impedance Matched Coaxial	See Table 1-C.3	126 Ch. BNC
4	Type-T Thermocouple Instrumentation Wire	See Table 1-C.4	512 Ch.
Signal Conditioning Equipment			
5	ICP/IEPE Conditioners	See Table 1-S.3	64 Ch.[a]
6	Constant-Voltage Bridge Conditioners	See Table 1-S.1	48 Ch.[b]
7	Charge-Type Conditioners	See Table 1-S.4	24 Ch.[b]
8	Direct Voltage Inputs	See Table 1-S.7	120 Ch.
9	Buffered Voltage Follower Outputs	See Table 1-B.1	As needed[b]
10	Thermocouple Signal Conditioning	See Table 1-S.9	
Digitizing Equipment (ADCs)			
11	High-Speed Digitizers (100 kHz MBW/256 kHz SR)	See Table 1-D.1	256 Ch.[a]
Data Storage			
12	RAID 1+0 redundant fail-over storage	See Table 1-R.1	3 Terabytes total
Control, Monitoring, and Post-Processing			
13	Dedicated Control Computers	See Table 1-C.1	1
14	Dedicated Monitoring Computers	See Table 1-C.2	[a]4
15	Dedicated Post-Processing Computer	See Table 1-C.3	[a]1
Other Notable System Elements			
16	IRIG-B Distribution	See Table 1-X.1	All
17	LTO-3 Tape Archive	See Table 1-X.2	All[a]

[a]Means that the capability is available only when the system is joined with the SPF vibroacoustic DAS

[b]Means that the capability is available only when the system is using equipment from the B-2 DAS

The bottom rack is called the ADC Rack. This rack assembles all of the components necessary to acquire high-speed data from the SPF thermal-vacuum chamber. From the instrumentation flanges outside the concrete chamber and in the SPF basement, special test cabling is used to connect the annulus wiring to the back of the MDAS ADC Rack at a re-configurable, modular patch rack. The modular patch rack is intended to be completely re-designed from test to test. It is hinged on the bottom to open to provide access to the cabling inside the ADC Rack which maps the patch panel feedthroughs to either the signal conditioning or directly to the digitizer modules. As shown in Figure 9, the ADC Rack houses two 3TB RAID units at the bottom which are written-to from the high-speed digitizer modules in the VME crate directly above the RAID units. Above the digitizer VME crate is the signal conditioning chassis which is a card frame chassis which all the signal conditioning equipment is plugged into. The signal conditioning equipment's inputs are all in the rear so the connections from the patch panel to the signal conditioning inputs is extremely short and direct-path. The ±10 V outputs of the digitizers are in the back of the signal conditioning chassis as well and also benefit from a short run straight down to the digitizer inputs directly below. The signal conditioning chassis as well as the digitizers are all connected to an FC-SAN switch and an Ethernet switch at the top of the ADC Rack in the front. All of the data and control of the unit is accessible by 1 pair of fibers and 1 Ethernet connection. These two ports are easily jumpered up to the Control Rack where they join the FC-SAN and Ethernet backbones and will even be joined will a larger network if chosen to. The stacked assembly (Control Rack and ADC Rack combined) makes a stand-alone mobile data system that can join other data systems of the same architecture and design to form arbitrarily large data systems to meet any tests requirements. The facility has only one MDAS system, but larger systems can easily be envisioned with no new design or engineering, simply by operating them side-by-side.

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Biographies

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Mr. Hill works in the Plum Brook Management Office of NASA Glenn Research Center's Plum Brook Station in Sandusky, Ohio. He is currently serving as the Space Propulsion Research Facility (B-2) Facility Manager. Prior to that appointment, Mr. Hill served as Senior Data Systems and Controls Engineer at B-2. He has over twenty years' experience as a test engineer in NASA Glenn's major Aeronautics Wind Tunnels and Space Test Facilities. In addition to managing B-2, he is also Facility Manager of the Cryogenic Components Lab (CCL), The Cryogenic Tank Facility (K-Site) and the Hypersonic Test Facility (HTF) at Plum Brook Station. He holds a BS in Electrical Engineering Technology from Cleveland State University, and MS in Electrical Engineering, also from Cleveland State University. He is a member of the ISA.

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14. ABSTRACT

Very large space environment test facilities present unique engineering challenges in the design of facility data systems. Data systems of this scale must be versatile enough to meet the wide range of data acquisition and measurement requirements from a diverse set of customers and test programs, but also must minimize design changes to maintain reliability and serviceability. This paper presents an overview of the common architecture and capabilities of the facility data acquisition systems available at two of the world's largest space environment test facilities located at the NASA Glenn Research Center's Plum Brook Station in Sandusky, Ohio; namely, the Space Propulsion Research Facility (commonly known as the B-2 facility) and the Space Power Facility (SPF). The common architecture of the data systems is presented along with details on system scalability and efficient measurement systems analysis and verification. The architecture highlights a modular design, which utilizes fully-remotely managed components, enabling the data systems to be highly configurable and support multiple test locations with a wide-range of measurement types and very large system channel counts.

15. SUBJECT TERMS
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