The Data Acquisition and Control Systems of the Jet Noise Laboratory at the NASA Langley Research Center

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ABSTRACT

The features of the data acquisition and control systems of the NASA Langley Research Center's Jet Noise Laboratory are presented. The Jet Noise Laboratory is a facility that simulates realistic mixed flow turbofan jet engine nozzle exhaust systems in simulated flight. The system is capable of acquiring data for a complete take-off assessment of noise and nozzle performance. This paper describes the development of an integrated system to control and measure the behavior of model jet nozzles featuring dual independent high pressure combusting air streams with wind tunnel flow. The acquisition and control system is capable of simultaneous measurement of forces, moments, static and dynamic model pressures and temperatures, and jet noise. The design concepts for the coordination of the control computers and multiple data acquisition computers and instruments are discussed. The control system design and implementation are explained, describing the features, equipment, and the experiences of using a primarily Personal Computer based system. Areas for future development are examined.

INTRODUCTION

The problem of jet noise has been studied for many years. Since sound from jets is generated by a variety of fluid mechanical mechanisms including turbulence, reducing jet noise is challenging. The particular part of jet noise studied in the Jet Noise Laboratory (JNL) of the NASA Langley Research Center (LaRC) is the noise generated by the jet exhaust, or plume. Fluid mechanic phenomenon that generate plume noise are turbulent mixing, supersonic eddy Mach wave radiation, noise generated by turbulent eddies passing through shocks denoted as broadband shock noise, and resonant shock oscillation known as screech.

In order to make progress in the field of jet noise reduction, scientific research has been required to try to understand the physics behind the different noise generation mechanisms. The simulation of jet flows in model scale has been a cost effective way of achieving results. An important feature of real jet exhausts is the high temperatures of the combustion process and the affect of temperature on the noise generation mechanisms. Solutions that lead to the reduction of jet noise sources in an unheated jet do not always lead to noise reduction in a hot jet. Reducing noise from jet aircraft requires a research facility that can simulate realistic temperatures, pressures, and air flow paths.

Another important concern of jet simulation is to correctly model a mixed flow turbofan engine instead of just a single averaged condition at the nozzle exit. A normal turbofan engine, typical of those in service on subsonic transports or jet fighters, have a hot combusting flow (core stream) surrounded by a cooler compressed flow (bypass or fan stream). The ratio of bypass mass flow/core mass flow is termed the bypass ratio (BPR). Engines for subsonic airliners have BPR values on the order of 5 to 14 and supersonic engines rarely exceed a BPR of 1.

Descriptions will follow of the JNL facility, the control system, and the data acquisition systems. A discussion of how the different parts were integrated together to form the complete system is presented. The evolution of the systems will be briefly recounted. A discussion of the various improvements under consideration completes this paper.

DESCRIPTION OF THE FACILITY

The JNL apparatus designed to simulate turbofan flows is called the Dual Stream Propulsion Model (DSPM). By providing dual independent air streams, each with combustion, virtually any bypass ratio and exhaust temperature can be simulated. The configuration can also be used to simulate novel engine designs in which the central stream is a lower temperature than the outer stream. This concept was investigated in the 1970's, known as a duct burning engine and favorable noise reduction was observed due to the inverted exhaust velocity profile. The DSPM is housed in an indraft style subsonic wind tunnel called the Low Speed Aeroacoustic Wind Tunnel (LSAWT) which has a maximum speed of Mach 0.32 (240 MPH). Figure 1 displays an overview of the LSAWT installation.

The compressor stage of a turbofan engine is simulated by high pressure air that is stored in a centrally located bottle field. Supplied through a twelve inch diameter pipe, this service can be
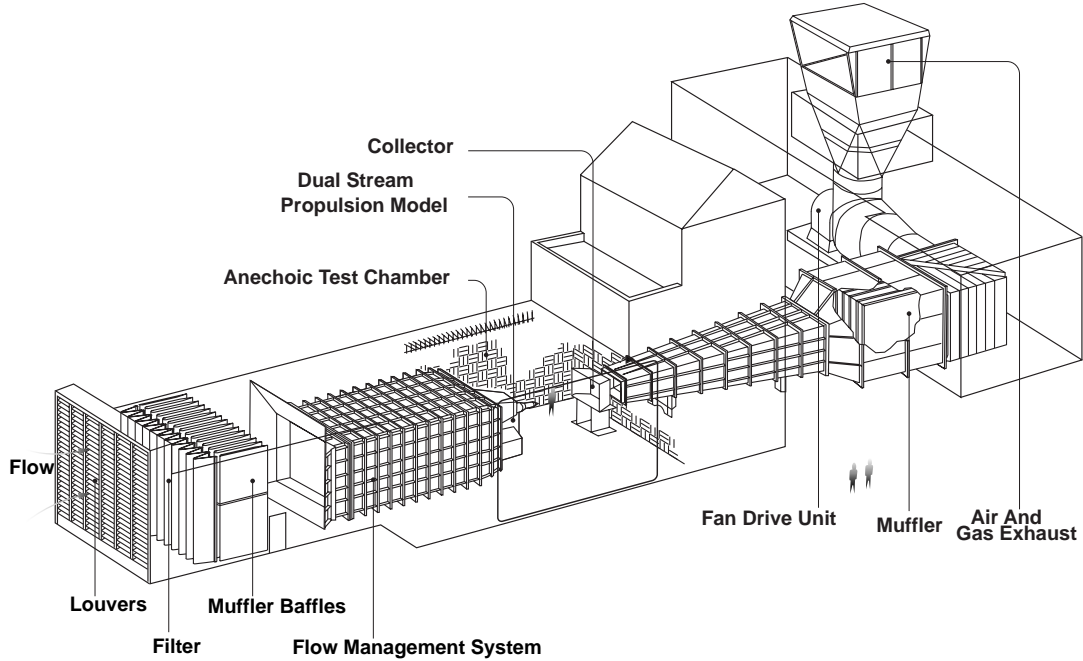
Figure 1: Low Speed Aeroacoustic Wind Tunnel

adjusted up to 600 pounds per square inch gauge pressure (psig). The air is dried and can be heated to about 100 degrees Fahrenheit before distribution. At the JNL, the 12" line is split into two streams termed the core and fan legs. Each of these streams is split into two inch and eight inch lines (loop and main respectively). The air flow rates are adjusted by pneumatically positioned Fisher control valves (loop leg 2 pounds per second, main leg 23 pounds per second). The loop and main legs are recombined and pass through a venturi meter, a muffler (to remove valve noise), and a two stage electric heater. Each heater stage is rated at 250 Kilowatts. At the output of the heaters the pipe is reduced to four inch diameter.

The air lines lead to the combustion chamber (burner) inlets. The burner design is an axisymmetric dump combustor called "SUE", for SUdden Expansion, with an inlet of four inches diameter that expands to eight inches diameter. The Marquardt Company [1] produces the burners as a standard product. There are eight 1/4" diameter fuel injector tubes spaced around the step. The injectors have slots to create a fan shaped spray pattern. Depending on the fuel flow rate and burner pressure range required for a nozzle model, the injector set may have slots anywhere from 0.003 inches to 0.010 inches wide. The slot depth into the side of the 1/4" tube is usually 1/4 to 1/3 of the circumference. The combustion chambers are fueled with liquid propane pressurized by gaseous nitrogen at up to 600 psig. The burner is water cooled and rated to 3000 degrees Fahrenheit. The air mass flow rate through each burner is from about i 1 lb/sec for ignition, up to about 14 lb/sec.

The DSPM control and data acquisition systems described here have been in operation since September, 1996. Figure 2 shows the complete setup of the burners, piping, and nozzle mounting area and a detail of a burner (not to scale). The facility can operate virtually continuously due to water cooling of the heated components. The limiting factor for run time is the size of the propane run tank which currently holds 200 gallons and is being replaced by a 500 gallon tank. For
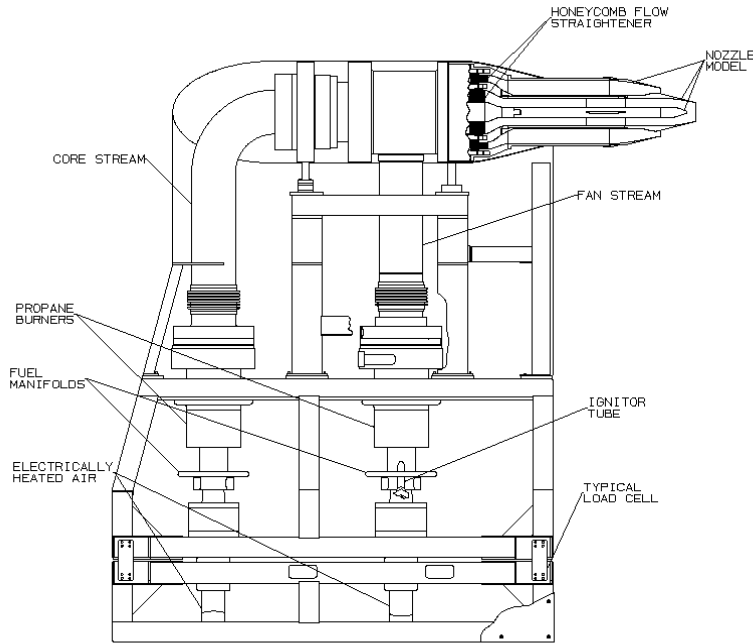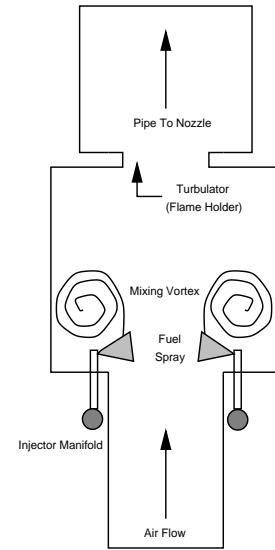
A) Overview of DSPM   B) Detail of SUE Burner

Figure 2: Dual Stream Propulsion Model

large nozzle models operating at 2000 degrees Fahrenheit, up to 20 gallons a minute of propane would be consumed. Most nozzle models require less fuel so the 500 gallon tank is expected to last about 4 hours in normal use. Approximately 40 minutes are required to vent the run tank down to atmospheric pressure and refill it from a 6000 gallon storage tank.

CONTROL SYSTEM DESCRIPTION

The system is designed to control all air, fuel, cooling, and ignition services required to operate the dual stream propulsion model. The control system for the DSPM is the Commercial Off The Shelf (COTS) package Paragon TNT by Nemasoft Corporation (formally Intec Controls). This package was chosen as a way of performing all normal functions of a control system with a single software product: control, operator interface, alarming and events, and data logging. Paragon TNT works on the operating systems IBM OS/2 Warp, Microsoft Windows 95, and Microsoft Windows NT. The JNL installation currently uses OS/2 Warp. The input and output (I/O) hardware is a version of the industry standard Optomux optically isolated modular product introduced by the Opto22 Corporation. For the DSPM controls, the control system functions are split among several IBM compatible PC's. Two PC's are used for operator interface stations and a third PC is used for the I/O and control logic. One of the operator PC's also runs the data logging task and handles the interface to the Dynamic Data Acquisition System.

The I/O system consists of controllers with RS-485 serial communications that connect to mounting racks of 16 digital I/O modules and 16 analog I/O modules. The control PC has a 4-port communication card and there are three I/O controllers daisy-chained per port at 38,400 Baud. As the RS-485 supports a fairly large distance (>2500 ft), the I/O controllers are split into two groups with 6 being mounted in the control room (with 6x16 analog and 6x16 digital modules) and 6 are mounted on top of the wind tunnel inlet duct (with 6x16 analog modules only). The total I/O point count is 192 analog and 96 digital.

The optically isolated modules provide the sufficient protection for the explosive limits of propane in this application so additional intrinsically safe barriers are not required. The modules also allow for a wide variety of sensors and actuators to be connected to the system without changing jumpers or switches on the I/O system.

This particular software package was found to be relatively easy to use and was capable of creating a usable system that met most of the project requirements. The application is developed by using a set of master programs call "Builders". There are builders for process I/O, control strategy, operator interface screens, data management, and networking.

The operator interface development program allows multiple screens to be built with sliders, push buttons, data displays, and indicators. It was determined that displaying real-time graphics trends loaded the PC too much and so that feature is not used. The operator PC's are set up with video cards that provide two 17" monitors per PC in a lower/upper configuration. The operating system saw the two monitors as a single display with a resolution of 800 pixels wide by 1200 pixels tall (800x600 over 800x600). A screen with data is usually positioned on the upper monitor for easier viewing by other people and screens with input objects are usually placed on the lower monitor for the operator's convenience. Some of the problems of the operator interface screens were the quality of the available fonts, inability of using the same screen on computers with different video resolution, and the entire package used the screen height to set the aspect ratio of most of its windows. In the case of a nonstandard 800x1200 pixel screen Paragon drew most windows to fit a 1600x1200 screen, without controls to resize the window. The builder windows then had to be moved from side to side by the title bar to configure objects, greatly increasing the time required to edit screens.

The process I/O builder enables the definition of the hardware connected to the controlling computers. The sample rates, engineering units conversion, alarming, and filtering are specified with this tool. There are a number of different types of I/O supported and many can be used simultaneously. The Optomux compatible style I/O was chosen primarily because virtually every control software package on the market provides a driver. However serially connected I/O does not offer the throughput that PC cards or newer bus I/O provides.

Control logic is programmed with the Continuous Strategy Builder. This style of programming is object oriented with each item being displayed as a box. Editing the box allows selection of object type (input, calculation, logic, sequence, etc.), the object name, the execution rate, alarming, and other features. The various input and outputs of each object are then connected to other objects to control the data flow through the strategy to create the users program. Complicated sequences are possible; for the JNL programming extensive trial and error configuration was performed to determine how the software would actually execute.

A feature of this graphical program environment compared to a procedural language like FORTRAN is how the flow of information must be organized to perform a function. For instance, if a decision affects a valve position, that decision must interact with all other logic to determine the

valve position. A FORTRAN compiler automatically gathers up all of the references to the valve position so that the valve will open and close per the program instructions. In the graphical editor, the user is responsible for connecting all logic through and gates, or gates, truth tables, etc. in order to change the valve position. The author found this more time consuming and in cases difficult to implement. Programmers more familiar with ladder style programming might be more successful.

The operator interface screens also contain quite a bit of executable elements. When an operator pushes an on-screen button, values can be set in the control strategy or directly in the I/O system. Documentation of the control logic was not as usable as desired. The only way to print the block diagrams of the logic was by using the print screen function of the operating system. The documentation feature of Paragon TNT produced a 500 page text file to describe the JNL control program.

DATA ACQUISITION SYSTEMS

The Dynamic Data Acquisition System (DDAS) is designed to record time data with frequencies up to 100 KHz. The JNL DDAS is based on a SUN SPARC10 VME bus computer with a recording capacity of 30 dynamic channels. A VME array processing card is included for performing data analysis (primarily fast Fourier transforms) in conjunction with data acquisition. The JNL has a 28 microphone linear array for recording the far field jet acoustics. Brüel & Kjær (B&K) Instruments Type 4136 1/4" free field response microphones and Type 2811 Multiplexer Power Supplies are used. The microphone bandwidth extends to about 100 KHz. Depending on the nozzle model, dynamic pressure sensors may be flush mounted to an internal part of the nozzle to measure the surface pressure fluctuations. The usual sensor is Kulite Semiconductor Products Model XCE-093, with a 3/32" diameter and a custom designed water cooling jacket is used to protect the sensor.

The direct output of the B&K 2811 are buffered, filtered, and amplified by Precision Filters, Inc. System 6000 components. These GPIB programmable bandpass filter amplifiers provide low and high pass corner frequency selection up to 102.3 KHz, pre-filter gain of up to 40 dB in 10 dB steps, and post-filter gain from -9.9 to 30.0 dB by steps of 0.1 dB. Each microphone signal is then split into three paths: two different analog to digital (A/D) converter types and a custom 32 channel voltmeter.

Typically one data set is acquired at a 250 KHz sample rate using 12 bit resolution Transient Data Recorders (TDR) from Pacific Instruments Incorporated. The TDR system is capable of sampling at up to 1 MHz simultaneously on all channels in the system, with 512 K samples of storage per channel. After data is recorded into the TDR memory, the host computer downloads the information over a GPIB IEEE-488 bus interface or over the TDR 16 bit parallel bus through a custom interface circuit into the host computer. The parallel bus transfer rate is about 170 KB/sec versus about 30 KB/sec for the GPIB interface. Another data set is acquired at a lower sample rate, usually 62.5 KHz with a 16 bit ICS-110A VME card from Integrated Circuits and Systems Limited. The microphone signals recorded by the ICS-110A card are low-passed through a 32 channel VME amplifier card with 25 KHz fixed corner frequency from Frequency Devices Incorporated. The VME array processing card (a SKY Computers Inc. SKYBoltMP with Shamrock i860 daughter

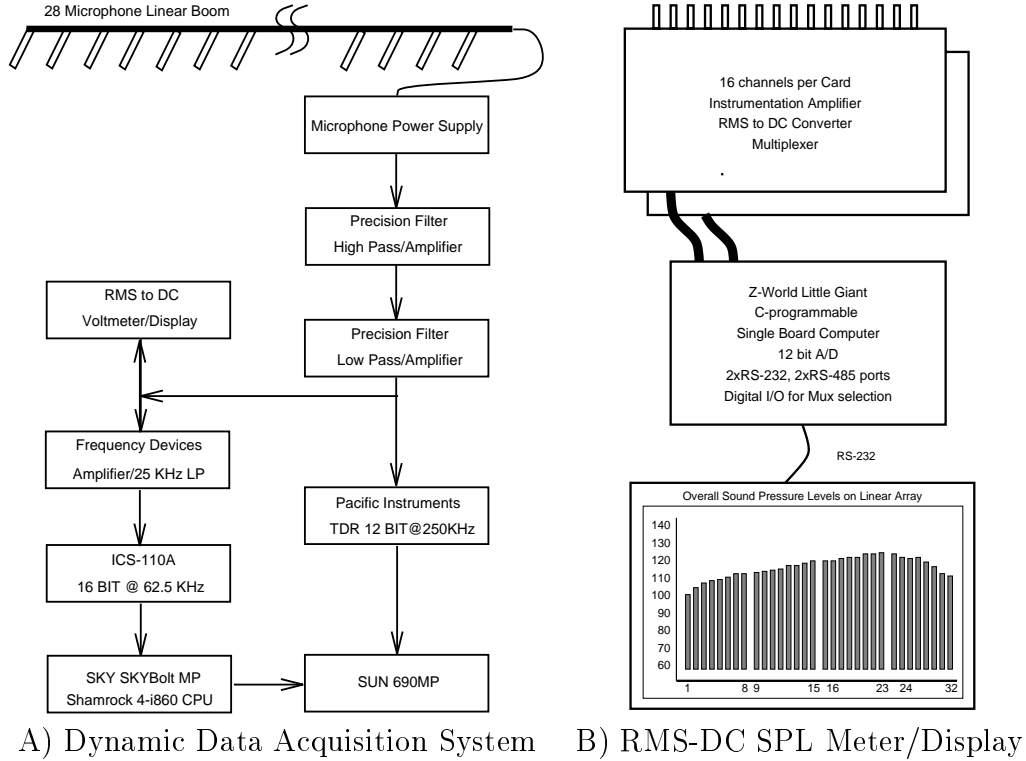A) Dynamic Data Acquisition System   B) RMS-DC SPL Meter/Display

Figure 3: Jet Noise Dynamic Data Acquisition System

card) controls the ICS A/D card over the VSB bus the writes the data to the SUN hard disks. Figure 3A shows a block diagram of the complete dynamic data system.

Another important part of the DDAS is a custom 32 channel Root-Mean-Square (RMS) voltmeter with a Liquid Crystal Display (LCD) display. The RMS voltmeter uses an embedded Z80 based single board computer by Z-World that has a 12 bit A/D converter to measure the output of the multiplexed RMS to DC converter circuits. The Z80 computer displays the overall Sound Pressure Level (SPL) of the microphone array on a 7"x4" LCD screen in a bar graph format (Figure 3B). The DDAS reads the voltages on the RMS voltmeter to select amplifier gains of the microphone signals before digitization by the TDR.

The DDAS computer, while the central controller, is not the only computer in the system. The Static Data Acquisition System (SDAS) is designed to record slowly varying signals and compute the average values of these signals over some time span. The JNL SDAS is a Modcomp Open Architecture computer. The Modcomp is a 6-U VME bus system using dual Motorola 88K CPU's and the REAL/IX real-time UNIX operating system. The data acquisition software used on the Modcomp was developed by Wyle Laboratories under contract to NASA. It features a graphical user interface (GUI), real time graphics displays, user programmable equations and calibrations for channels, and adjustable data point duration and sampling rate. Both individual samples and the average values over the point duration can be saved to disk.

The analog input system is a Neff Instrument Corporation System 620 Series 600 which has a 100 KHz sample rate 16 bit A/D converter and can scan up to 512 channels per system. The JNL Neff has 64 channels in one 7" rack mount unit. The Neff 620 also supplies amplification and low

pass filters. The force balance load cells are powered through a Neff System 620 Series 300 signal conditioner. The load cells are full bridge with built-in temperature compensation. Software on the Modcomp derives the final loads from the voltages of the load cells using an interaction matrix based on the results of a static calibration of the DSPM.

Thermocouples are connected to the Neff Series 600 through a Kaye Instruments Uniform Temperature Reference plate (UTR). This isothermal terminal strip has a 100 Ohm platinum resistance temperature detector (RTD) to measure the cold junction temperature of the plate where the specific thermocouple wire changes to twisted pair copper wiring. The Modcomp software is programmed to correct for the cold junction temperature and performs a multi-zone polynomial fit of the thermocouple voltage to derive temperature.

Another major part of the SDAS is the measurement of static pressures. Critical to setting the jet operating conditions are the total pressures just upstream of the nozzle exit (termed the charging station). The nozzle models might also have pressure taps along the wall so that internal velocity can be calculated for comparison to computational fluid mechanics solutions. Other pressures are measured using probes remotely positioned in the actual jet exhaust plume.

The JNL uses the Electronically Scanned Pressure (ESP) System from Pressure Systems Incorporated (PSI). This product consists of sensor modules of 16, 32, 48, or 64 individual strain gauge pressure sensors (overall size of a module is about 2.5"x1.5"x1.5"). The sensors are multiplexed in each module and at other external junctions before being measured by a 16 bit A/D converter capable of sampling at 50 KHz. Each module has a built in valve so that calibration pressures may be applied to the process side of the sensors. The system includes working standard pressure sources and software for performing fourth order polynomial calibrations of each port.

INTEGRATION OF SYSTEMS

The entire JNL DDAS is comprised of a variety of different instruments and computers. The main computer originally was a DEC Micro-VAX computer but has been changed to a SUN UNIX system. Instrumentation connects to this host through the General Purpose Interface Bus (GPIB) or RS-232 serial communications. Most of the original data acquisition software was coded in FORTRAN. The main effect of switching from DEC to UNIX was that the software for accessing RS-232 serial ports and GPIB adapter were now through the C language. Most of the engineers supporting the JNL had only FORTRAN programming experience, so a set of C functions were created to simplify access to the C serial and GPIB features from the FORTRAN language. Almost every program for the JNL uses a combination of C and FORTRAN routines. The newest instrument additions to the system are VME bus cards which are accessed through C language based operating system functions and drivers.

An operating system feature that improves the data acquisition programs is shared memory. Shared memory allows multiple independent programs to communicate with each other very rapidly. On UNIX computers, the shared memory region is created by C functions. The address of the region is passed as an argument to a FORTRAN subroutine and the FORTRAN code uses a structure definition to define variables relative to memory locations. This sharing feature was also available under the DEC VMS operating system.

Another important mechanism for connecting computers is by using the Ethernet network. The SDAS developed by Wyle Labs included a server program that was based on Berkeley Standard Distribution (BSD) Sockets. The server can send out real time or averaged data, be triggered to take a data point, accept values into the system in real time, and provide SDAS status information.

Two programs developed for the DDAS combine all of these features and serve as the foundation for testing with the DSPM. A real time program called 'Background' is designed to provide information for monitoring the conditions of the facility and model. Background establishes the shared memory region, initializes communication with various instruments, connects to the SDAS by sockets and the control system by RS-232. It then enters an endless loop in which it reads the instruments, SDAS, and control system values, calculates derived values such as average pressure and temperature at the charging station, then sends values to the SDAS and the control system.

The other main program of the DDAS that acquires the microphone signals is named 'lsawt' after the facility. This is the program that coordinates the data acquisition processes of the SDAS (for performance and model aerodynamic data), the control system, and the DDAS (dynamic microphone and pressure data). A series of menus provide the user the opportunity to change default settings for such things as number of sensors to record, sample rate, size of the data set, and filter cutoff frequencies. Once the operators have adjusted the DSPM to the required test conditions, the data acquisition operator proceeds to the section of the program that communicates with the RMS-DC meter and adjusts the Precision Filter gains to reach the target RMS value. When the data acquisition operator is satisfied that the DSPM is at the correct conditions and that the gains are acceptable, the lsawt program triggers the SDAS (which is set to average from 10 to 30 seconds), the ICS-110A card which samples at 62.5 KHz for 8 seconds, and the Pacific TDR's which sample at 250 KHz for 2 seconds. The current values in the background program are written to a log file at both the start and the end of the averaging period.

FUTURE IMPROVEMENTS

As research requirements change, so do the tools necessary to meet those requirements. Every aspect of the JNL data acquisition and control systems have been modified in some way after entering service. The control system is currently inadequate for closed loop control of both burners simultaneously. Replacing some of the Optomux I/O with a higher speed type is being examined as a way of improving the system for closed loop control. Installing PC I/O cards that would still be controlled by the Paragon TNT software is one option. Adding a Programmable Logic Controller (PLC) or other brand of control system/software package that can be interfaced to Paragon TNT is being considered as well. The Optomux analog input is a 12 bit A/D converter and for certain parameters more resolution is desired.

The DDAS is limited currently by the 12 bit resolution and the data download speed of the Pacific Instruments TDR's. Because of the 12 bit resolution the gains must be set carefully to prevent clipping but achieve the highest signal to noise ratio (SNR) and dynamic range. Future plans include the purchase of 16 bit A/D converters, providing a finer resolution which in turn gives a greater dynamic range for a given gain setting. The gains must be set just high enough to get above the filter noise floor for good recording. The gains are currently set by reading the RMS-DC

meter for all channels, computing the gain required to get about 1 volt RMS, setting those gains, then rechecking the RMS values before taking data. Jet noise tends to have crest factors near 3 (non-sinusoidal) and therefore using RMS is not a reliable way to prevent clipping. The gain setting process can take from 2 to 5 minutes.

The other limitation of the TDR system is the slow download speed. It takes approximately 4.5 minutes to read out the data and write it to disk on the DDAS computer. The goal for setting the gains and having the data written out to the DDAS disks is a total of 2 minutes. One type of product that is being examined to meet this requirement is a VME bus based A/D card with 16 bit A/D converters that can sample at 250 KHz, with a high speed data port connected to an auxiliary processor (AP) like the SKYBolt currently used. For 32 channels, the aggregate data rate would be 8 million samples/second or about 15.26 MB/second. As these types of A/D cards have no on board storage (other than a FIFO buffer), an AP is required to control and absorb the data into its memory. The AP can perform gain setting while previewing the actual data from the FIFO. The plan is that the AP continually monitors the A/D voltages, adjusting the gains and saving the data only when commanded by the DDAS computer program. The AP could also derive the RMS of the signals and create a real time display on the computer screen similar the the RMS-DC display.

References

[1] Marquardt Company Burner Manual, 1994