

Portland, Maine
NOISE-CON 2001
2001 October 29-31

**LOW-COMPLEXITY CONTINUOUS NOISE MONITORING SYSTEM FOR
COMMUNITIES, SMALL AIRPORTS AND REMOTE AREAS**

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INTRODUCTION

Background. There is a demonstrable need for low cost, low complexity noise monitoring systems that can provide continuous, unattended measurements meeting ANSI standards and FAA requirements. Small and medium sized communities, including relatively small regional airports cannot afford high-end complex noise monitoring systems and the attendant need for skilled personnel and consulting support. Available low-cost handheld sound level meters do not meet either continuous measurement needs nor the accuracy standards required to support noise ordinances and regulations.

The Thayer School of Engineering was originally motivated to undertake student noise monitoring projects as part of senior design courses by the need of the nearby Lebanon Municipal Airport for quantifiable continuous noise data and a user-friendly measurement and analysis system. Two prior projects provided initial design specifications, component studies and a preliminary marketing study performed under the guidance of HMMH, Inc.

Objectives. The overall goals of the current noise monitoring system project are to formalize system and component specifications, complete the engineering development and construct a functional prototype, and demonstrate its capabilities in full-scale, in-situ testing at the Lebanon Municipal Airport and other venues. The specific objectives are:

- Design and build the analog and digital portions and validate performance specifications.
- Address the issue of short and long-term data storage
- Design and implement an appropriate hardware and software user-interface
- Fabricate the prototype and perform calibration and laboratory benchtop tests
- Conduct field tests at the Airport and other selected locations
- Prepare a final report with recommendations for product development

NOISE MONITORING SYSTEM

System Specifications. To address the needs identified above, we have developed a sound monitoring system that is simple to use, inexpensive, and able to remotely monitor sound levels for at least one week. To keep the monitoring system flexible, our philosophy has been to keep

the hardware as simple as possible, while creating powerful PC-based software to process the data. In this way, the cost for manufacturing the meter is relatively small, and a diversity of software can be written to apply the meter in different types of analytical environments. A summary of the specifications is shown in Table 1.

SPECIFICATION	JUSTIFICATION
Meet or exceed ANSI/IEC Type II standards	FAA requirements
Fast and slow response	ANSI requirement
Record 1 sec Leq's in memory	Needed for statistical analyses and identification of events
1 week of storage	Required for remote operation
Record hourly L _{min} , L _{max} , and percentiles	Useful for environmental monitoring
Operate over 30 to 120 dB range	Typical for community and airport use
Record simultaneous A and C	Helpful for identification of events
Download data to PC for further processing	Keeps hardware simple and lowers overall cost
Software that creates summary statistics, graphs events and specified time periods, and screens events	Required to display results and conduct further processing and analysis
Self-contained power with solar backup	Needed for remote operation
Simple front end that can be run by airport employee or non-technical person	Airport requirement
Weatherproof	Required for outdoor operation
Temperature range of 0° to 70° C	Required for outdoor operation

Table 1: Basic meter specifications

The monitoring system is design to collect simultaneous measurements of C- and A-weighted 1-second Leq's. In addition, the system has an exponential time averaging circuit that records hourly L_{min}, L_{max}, L₁₀, L₅₀, and L₉₀. The system is supplied with 32 megabytes of non-volatile RAM which is more than sufficient for one week of continuous monitoring. Since the monitor is intended for remote operation, it is supplied with gell-cell batteries supplemented by a solar panel. It has an optional cellular modem hookup for remote downloads, and an analog output of the linear signal. The system has four analog input channels to collect additional analog information, such as that from meteorological instruments. *EventMonitor* analysis and graphical software has been developed to meet the specifications listed in Table 1. The system can also use software such as HMMH's proprietary *NoiseManager* and other commercially available analysis software

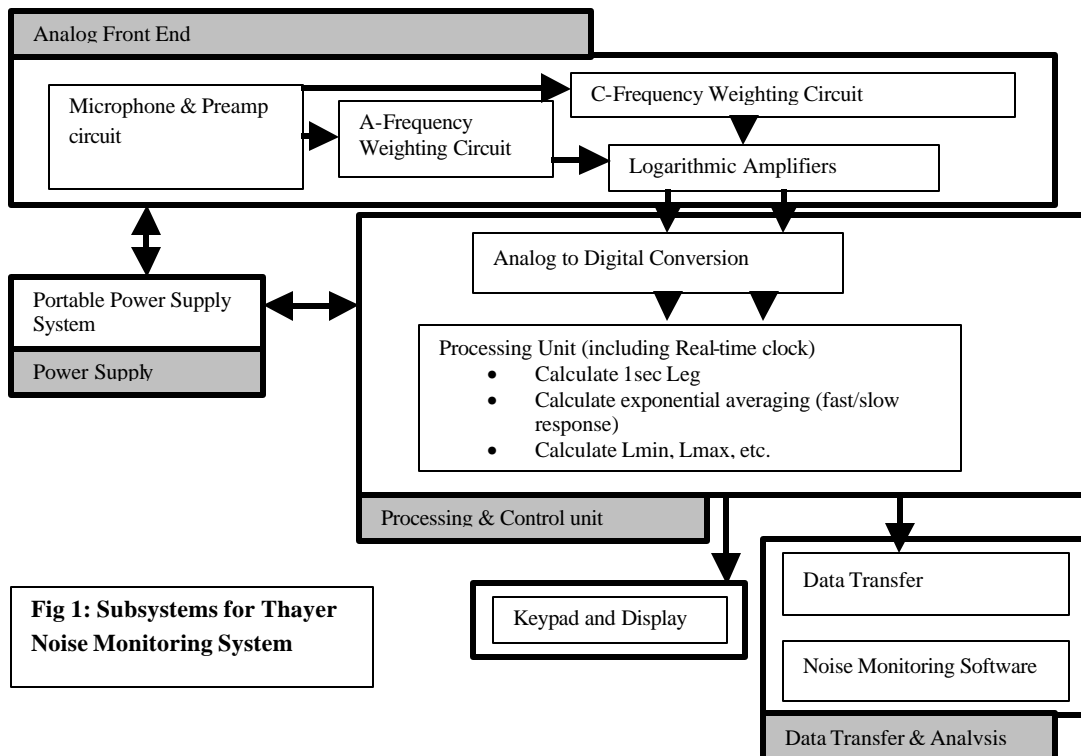
Interface - The system is designed to be able to be used by airport administrators, local police, community groups, park personnel, etc. who do not have formal training in the collection and analysis of sound levels. In that regard, the hardware is designed with a small keypad and a full alpha-numeric LCD display. In setting up the system, the user is asked simple questions in more-or-less full sentences. For each question, a default answer is supplied that would be applicable for general environmental noise monitoring. For example, after entering site information, the following questions are asked:

- Do you want slow or fast weighting? (Default is SLOW):_____
- Do you want to record both A and C weights? (Default is YES):_____

The software is similarly simple to use and employs a graphical user interface. The downloading of data is simplified by having the software automatically set the communications parameters based on whether the download is hardwired or cellular. The software also automatically detects the format of the file, since other meters, such as the Bruel and Kjaer Type 2236 and 2238 can be used with the software as well.

PROTOTYPE DESCRIPTION AND PERFORMANCE

Figure 1 shows the basic configuration of the noise monitoring system. The key parts are described below.



A and C- Weighting Filters. The basic design of the analog front end is similar to other devices on the market. The microphone input is first connected to a user-selectable gain, depending on the desired decibel range. The signal is then directed to both an analog output and the C and A weight filters. The meter, however, uses an original design of C and A weight filters that has 4 poles that correspond to the C-weighting filter; two are situated on the real axis at 20.6Hz and the other two are again on the real axis at 12,200Hz. Two additional poles, again on the real axis at frequencies 107.7Hz and 737.9Hz, constitute the A-weighting filter. The performance of the resulting passive filter is shown in Figure 2. The filter was both simulated and tested on a circuit board and meets ANSI and IEC Type 0 specifications for laboratory instruments.

The signal then passes to a logarithmic amplifier to compresses the range of the signal so that it can be read by an analog to digital converter (ADC) with required accuracy. The input to the ADC is in the form of a DC voltage that indicates the logarithm of the envelope of the signal.

Exponential Response. The initial approach was to design the circuits for both slow and fast response as part of the analog front end. Due to the complexities of the design and its implementation, the time weighting functions were implemented in firmware using digital processing, thus simplifying circuit and power requirements.

Logarithmic Amplifiers. The log amplifier test results show a specified 70 dB dynamic range with three user-selectable ranges and gains between 30 and 120 dB.

Other Analog Inputs. The analog front end also provides for four analog inputs for meteorological and other collateral measurements.

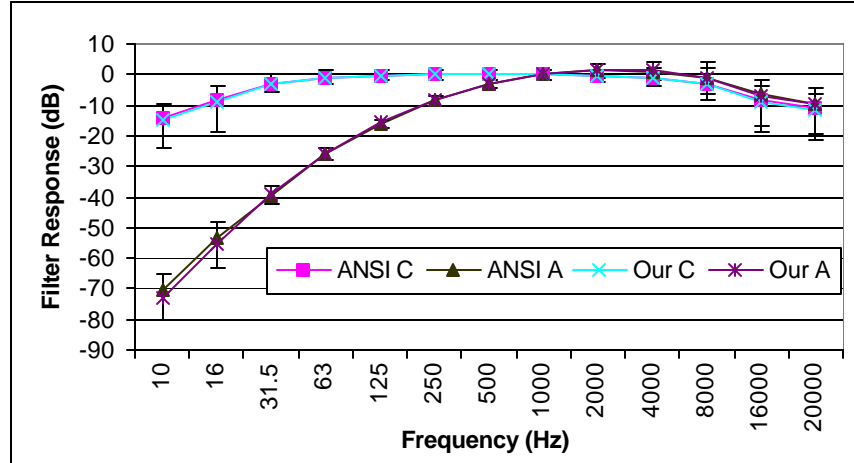


Figure 2: Performance of Thayer A- and C-Weight Filters Compared with ANSI Standard

Processor and Computations. The functions of the processor firmware are as follows:

- Sample the output of the A and C channels of the analog circuit using an analog-to-digital (A/D) converter
- Based on the signals from the A and C weight channels, calculate 1-second Leq (Equivalent Sound Level) measurements
- Calculate the exponential time response sound levels, and based on these, determine hourly L_{max} , L_{min} , L_{10} , L_{50} and L_{90} sound levels (maximum, minimum, 10th, 50th and 90th percentile sound levels respectively.)
- Control the storage of data in RAM
- Control the operation of the noise monitoring system, including responding to remote download requests
- In conjunction with a keypad and LCD display, provide an interface for calibrating and setting up the noise monitoring system
- Provide an interface for viewing current sound level measurements.

After investigating alternative processors, the JK MicroSystems Flashlite 386SX system was selected and interfaced with a M-Systems DiskOnChip, which provides for 16 MB of non-volatile data storage in human-readable text files.

Algorithms. The Equivalent Sound Level, or Leq, is defined by the following:

$$Leq = 10 \log \left(\frac{1}{T} \int_0^T P_A^2(t) dt \right) - 10 \log(P_0^2)$$

where $P_A(t)$ is the sound pressure at a point in time, P_0 is the reference pressure of 20 μ Pa (defined by ANSI standards), and T is the averaging period, which in our case is 1 second. All logarithms are taken to base 10. In order to calculate the Leq in firmware, we converted the continuous integral to the following discrete sum:

$$Leq = 10 \log \left(\frac{\Delta t}{T} \sum_{n=0}^N P_A^2(n) \right) - 10 \log(P_0^2)$$

where N is the total number of samples taken in the time T , and Δt is the time between samples. With $T = 1$ second, N is the sample frequency, and Δt is the sample period.

Exponential Time Averaging - The exponential time-averaged sound level is calculated from the following formula:

$$L = 10 \log \left(\frac{1}{t} \int_{ts}^t P_A^2(\mathbf{x}) \left(e^{-\xi(t-x)/\tau} \right) d\mathbf{x} \right) - 10 \log(P_0^2)$$

where $P_A(t)$ and P_0 have the same meaning as for the Leq, τ is the time-constant of the exponential time-averaging (defined as 1s for “slow” response, and 0.125s for “fast” response) and ξ is a dummy variable of integration.

The difference between the exponential time-averaged sound level and the Leq is the exponential weighting factor of $e^{-\xi(t-x)/\tau}$ which results in more recent sound levels being weighted higher than previous sound levels in any averaging period. In a similar manner to the Leq, we the above integral is written as the following discrete sum:

$$L = 10 \log \left(\frac{\Delta t}{t} \sum_{n=0}^N P_A^2(n) \left(e^{-\xi(N\Delta t - n\Delta t)/\tau} \right) \right) - 10 \log(P_0^2)$$

This sum can be computed with a simple algorithm in firmware.

L_{min} , L_{10} , L_{50} and L_{90} for each 1-hour period. L_{max} and L_{min} are computed by continuously keeping track of the current maximum and minimum sound levels and comparing these to each sound level computed, updating the L_{max} and L_{min} if a new maximum or minimum is found.

Power – The current system draws approximately 2 Watts of power, of which 0.25 is the analog front end and ADC, and 1.75 is the processor. This power is supplied by sealed rechargeable gel-cell batteries rated at approximately 24 amp-hours. A 4Watt solar panel is attached to continuously charge the batteries.

RESULTS

Temperature and Accuracy. The analog system specifications require that ANSI standards must be met over a temperature range of 0° to 70°C. All components are necessarily of very high precision, i.e. low temperature coefficients of less than 100 ppm/°C and a tolerance of 2% or better. Simulation and hardware test results confirmed that specification has been met for all analog components including filters.

Event Identification. The preliminary results obtained in the summer of 2001 as part of the project are focused on event identification. This is a critical issue in a low complexity noise monitoring system without spectral analysis and target tracking capabilities. After recording 1-second C and A weighted Leq’s, the user may be able to use this information to identify the source of certain events. The software developed for this system can analyze these events in both a temporal fashion, i.e., how the sound levels change over time, and in a static fashion; i.e. what the maximum A and C weighted sound levels are. By combining these analysis methods, we may draw inferences regarding the sound source.

For example, airplane overflights can be differentiated from a car passby in the monitoring results simply by comparing the rise time from and fall time to the background level. While both events are characterized by a generally Gaussian rise to a maximum and fall to a residual level, an airplane overflight can last generally in the order of a minute, while a car passing by at 35 mph may take only 15 seconds to rise from and fall to the background level. In addition, since the airplane is heard from a much longer distance than a car, its C to A weighted noise level ratio will change as the airplane approaches. This is because the atmosphere absorbs

higher frequency sounds more readily. As a result, the C to A ratio of an airplane overflight will decline as an airplane approaches and increase as it moves away.

Figure 3 shows characteristics of example 20-second events. The industrial ventilation fan shows a steady level with a relatively narrow difference between C and A levels. The vehicle passby is short and the difference between the C and A levels is relatively constant. For the airplane overflight, there is a large difference between C and A levels, that widens as the plane gets further away. Finally, for the four hits of a baseball, the A and C levels are identical, a result that confirms the broadband characteristics associated with the crack of a bat.

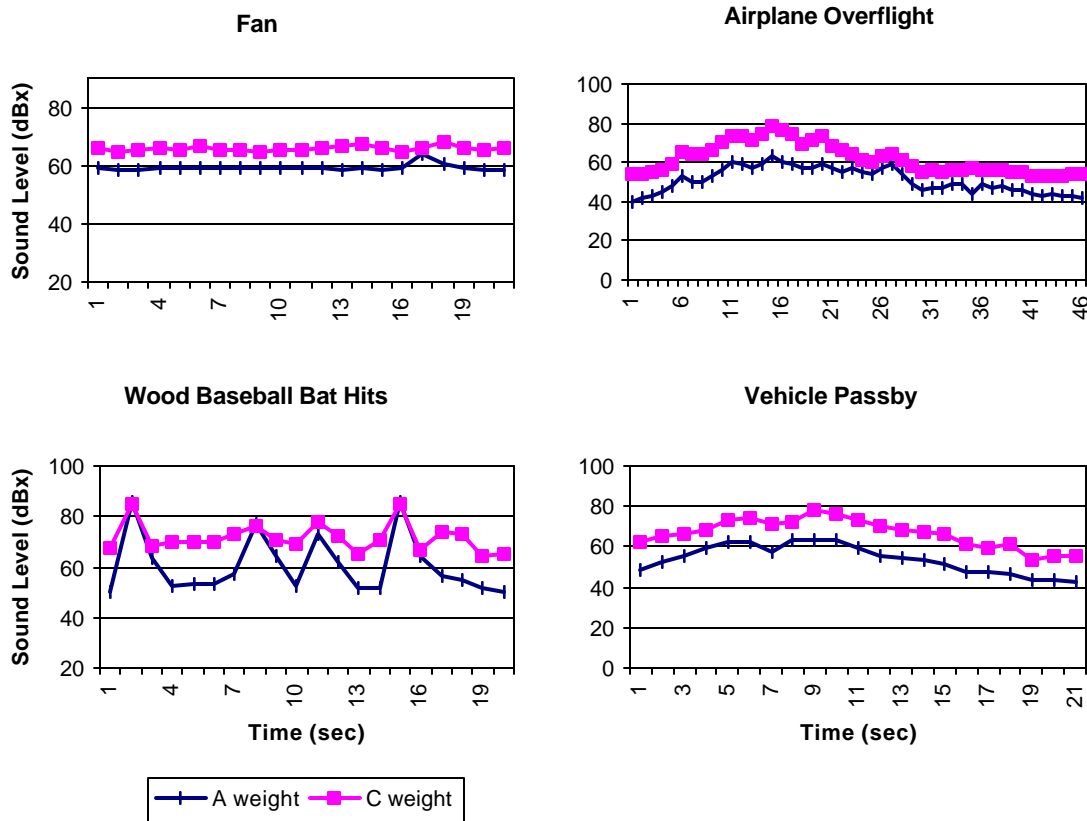


Figure 1: C and A weight time series for various noise sources

In analyzing these events, it is important to subtract out the background C and A levels from the event. In this way, it is much easier to see the temporal changes towards the beginning and end of the event that help to characterize a source.

CONCLUSIONS

The overall project objectives and design specifications have been met and the prototype noise monitoring system has been build and tested with encouraging results. Future developments will be focused on system optimization, and manufacturing and cost analyses. In addition, full-scale noise investigations and system evaluations in airport and community applications are planned including testing in remote locations such as national and state parks.

ACKNOWLEDGEMENTS

The authors wish to acknowledge the preliminary studies of David Moreland and Michelle Ott under prior engineering design projects at the Thayer School of Engineering, Dartmouth College. The support and advice of Douglas Fraser, Research Engineer in the Thayer School and Professor Keith Paulsen has been most helpful. Mr. Robert Miller and his colleagues at Harris Miller, Miller, and Hanson, Inc. have provided the microphone system and practical project guidance.