

INSTITUTE OF ENVIRONMENTAL SCIENCES AND TECHNOLOGY

Design, Test, and Evaluation Division Reference Document 012.2

IEST-RD-DTE012.2

Handbook for Dynamic Data Acquisition and Analysis

INSTITUTE OF ENVIRONMENTAL SCIENCES AND TECHNOLOGY

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Second printing, July 2017

ISBN 978-0-9787868-0-9

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FOREWORD

This document is the second edition of the Handbook for Dynamic Data Acquisition and Analysis.

Background of the Second Edition

This second edition of the Handbook was prepared directly for IEST by Harry Himelblau, Consultant, Los Angeles, CA, and Allan G. Piersol, The Piersol Engineering Company, Woodland Hills, CA. They were strongly assisted through major contributions to the technical material in Chapter 3 by Ronald Merritt, Naval Air Warfare Center, China Lake, CA. Other important contributions were provided by David Banaszak, Wright-Patterson Air Force Base, OH and Strether Smith, DSPCon (West), Cupertino, CA. Additional assistance in the form of valuable comments were provided by Skip Connon, US Army Aberdeen Test Center, MD; Abraham Hanor and Zev Sherf, Rafael, Haifa, Israel; and Karl-Friedrich Ziegahn, CEEES, Pfinztal, Germany.

The purpose of this second edition is to update the technical material and references to reflect changes since the publication of the first edition. The primary changes are in Section 3 (Data Acquisition), where there have been substantial improvements in the available instrumentation since the publication of the first edition. A few additions have also been made in Sections 4 (Data Validation and Editing) and 5 (Data Analysis) to cover new procedures. In all sections and the appendices, wording changes have been made to improve clarity, and references have been updated and expanded to provide more current information.

Background of the First Edition

The first edition of this Handbook was prepared by the Jet Propulsion Laboratory (JPL), California Institute of Technology, for the Space and Missile Systems Center, U.S. Air Force Materiel Command, through an agreement with the National Aeronautics and Space Administration. Support was also provided by The Aerospace Corporation. The original intent was to publish this document as a Military Handbook. Subsequently, the sponsor decided against dissemination in this form and turned the Handbook over to JPL for publication elsewhere. Since the Institute of Environmental Sciences and Technology (IEST) had long been interested in using the document as a Recommended Practice, the authors considered it appropriate to turn the document over to the IEST for that purpose. The Air Force has released the copyright to JPL control with the stipulation that the U.S. Government retain an unrestricted license for its use.

The authors received substantial assistance in the preparation of the first edition of this Handbook from a number of reviewers. The most important of these reviewers were as follows: Larry Bement and James Schoenster of NASA Langley Research Center; Robert Bohle of Kistler Instrument Corp.; Anthony Chu of Endevco; Charles Coe of NASA Ames Research Center; John Favour and Clark Beck of Boeing Aerospace Corp.; Dennis Foti of Metrum Information Storage; Arnold Galef, George Scott, Charles Wright, and Glenn Wasz of TRW Space and Electronics Group; Gerry Kahre, Marc Hoskins, Dan Powers, David Sherry, and Paul Spas of McDonnell Douglas Space Systems Co.; Dennis Kern of

JPL; Ronald Merritt of NAWC/China Lake; James Nagy of PRC/Patuxent; Dennis Nelson and David Smallwood of Sandia National Laboratories; Peter Rentz of Syscon Corp.; Karl Siwiecki and James Lally of PCB Piezotronics; Strether Smith and William Hollowell of Lockheed Research Laboratory; Vladimir Valentekevich of Wyle Laboratories; Joseph Weatherstone and William Brennan of Brüel & Kjær Instruments; and Scott Walton of ACSTA/Aberdeen.

Some reviewers of the first edition read every word of several drafts, while others concentrated on sections that embodied their areas of expertise. Some furnished illustrations previously unknown to the authors, whereas others performed research to resolve controversial technical issues. Of particular value were independent studies of the pyroshock measurement problem performed by Dan Powers of McDonnell Douglas Space Systems Co., with the close support of Richard Chalmers of the Naval Ocean Systems Center, Howard Gaberson of the Naval Facilities Engineering Services Center, and Anthony Chu of Endevco. The results of those studies contributed substantially to the discussions and recommendations for the pyroshock data acquisition and analysis procedures presented in Appendix A of the Handbook.

Although not identified here, other reviewers made significant though less comprehensive suggestions to the first edition. All made substantial contribution to the list of references, which is considered the heart of the Handbook.

The first edition of the Handbook was published as IEST-RP-DTE012.1.

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LIST OF SYMBOLS

$a(t)$	acceleration signal time history	$P_x(f)$	Spectrum of periodic signal
B	Frequency bandwidth, Hz	Q	Quality factor $[1/(2\zeta)]$
B_{hp}, B_r	Half-power point bandwidth	$Q_{xy}(f)$	Quad-spectrum of $x(t)$ and $y(t)$
c	Damping coefficient	R	Resistance, radius, sampling rate
c_L	Longitudinal wave velocity	$R_{xy}(\tau)$	Cross-correlation of $x(t)$ and $y(t)$
c_B	Bending wave velocity	$S_x(f_n)$	Shock response spectrum of $x(t)$
C	Capacitance, various constants	t	Time, thickness
$C_{xy}(f)$	Co-spectrum of $x(t)$ and $y(t)$	T	Averaging time, block duration
d	Diameter	T_r	Measurement duration
D	Modulus of rigidity	$u(t)$	Tapering function, displacement time history
$E[]$	Expected value of $[]$	$U(f)$	Fourier transform of $u(t)$
$E_{xx}(f)$	Energy spectrum of $x(t)$	U	Peak displacement
f	Cyclical frequency (Hz)	U_0	Propagation velocity
f_c	Cut-off frequency	V	Voltage
f_n	Undamped natural frequency	$x(t), y(t)$	Signal time histories
f_N	Nyquist frequency	Z	Impedance
f_r	Resonance frequency	α	Spectral parameter, level of signif.
$F(t)$	Force time history	δ	Relative displacement
$F_x(f)$	Fourier spectrum of $x(t)$	Δd	Separation distance
$G_{xx}(f)$	Auto- (power) spectrum of $x(t)$	Δf	Frequency resolution, frequency difference
$G_{xy}(f)$	Cross-spectrum of $x(t)$ and $y(t)$	ε	Normalized error
$h_{xy}(\tau)$	impulse response function	$\phi_{xy}(f)$	Phase between $x(t)$ and $y(t)$
$H_{xy}(f)$	Frequency response function	$\gamma_{xy}^2(f)$	Coherence between $x(t)$ and $y(t)$
i	index	λ	Wave length
j	$\sqrt{-1}$	μ_x	Mean value of $x(t)$
k	Spring constant, index	θ, ϕ	Phase angles
K	RC time constant	$\theta_{xy}(f)$	Cross-spectrum phase
L	Length	ρ_s	Surface mass density
L_x	Sound or fluctuating pressure level	$\rho_{xy}(\tau)$	Correlation coefficient function
m	Lag number, mass	σ_x	Standard deviation of $x(t)$
M	Step size, Mach number	τ	Time delay, rise time
n	index	ψ_x	rms value of $x(t)$
n_d	Number of disjoint averages	ζ	Damping ratio
N	Number of data values	$*$	Complex conjugate
p	Integer	$\wedge$	Estimate of
$p(t)$	Periodic signal time history		
$p(x)$	Probability density of $x(t)$		
$p_p(x)$	Probability density of peaks		

LIST OF ABBREVIATIONS

ADARIO	Analog/Digital/Adaptable Recorder Input/Output	MIL-STD	Military Standard
AC	Alternating current	MUX	Multiplexer
ADC	Analog-to-digital converter	NASA	National Aeronautics and Space Administration
AGC	Automatic gain control	NIST	National Institute of Standards and Technology
ANSI	American National Standards Institute	NRZ	Non-return to zero
ARMOR	Asynchronous real-time multiplexer and output reconstructor	PAM	Pulse amplitude modulation
ASA	Acoustical Society of America	PBW	Proportional bandwidth
Bi-f	Bi-phase	PC	Personal computer
CBW	Constant bandwidth	PCM	Pulse code modulation
CD	Compact disk	PE	Piezoelectric element
CE	Capacitance element	PM	Phase modulation
COTS	Commercial off-the-shelf	PR	Piezoresistive element
CVSD	Continuous variable slope delta	PSK	Phase shift keyed
DAC	Digital-to-analog converter	PSNR	Peak signal-to-noise ratio (linear)
dB	decibel	PS/N	Peak signal-to-noise level (dB)
DC	Direct current	RCR	Telemetry receiver
DEMUX	Demultiplexer	RF	Radio frequency
DR	Dynamic range (dB)	RMS	root mean square
EDS	Electrodynamic system	RNRZ	Randomized non-return to zero
EMR	Electromagnetic radiation	RSS	Root sum of squares
EOS	Electro-optical system	RZ	Return to zero
FDM	Frequency division multiplexing	S/C	Signal conditioner
FFT	Fast Fourier transform	SCS	Servo-control system
FLSC	Flexible linear shaped charge	SDF	Single-degree-of-freedom
FM	Frequency modulation	SNR	Signal-to-noise ratio (linear)
GB	Giga-Bytes	S/N	Signal-to-noise level (dB)
HDDR	High density digital PCM Recorder	SPL	Sound pressure level (dB)
ICE	International Electromechanical Commission	SRB	Solid rocket booster
IEEE	Institute of Electrical and Electronic Engineers	SRS	Shock response spectrum
IF	Intermediate frequency	SS	Strain sensitive
IRIG	Inter-Range Instrumentation Group	SSME	Space Shuttle Main Engines
ISO	International Standards Organization	TDM	Time division multiplexing
LDV	Laser Doppler vibrometer	TEDS	Transducer electronics data sheet
MEMS	Miniture Electrodynamic Systems	TFE	Telemetry front end
		TSC	Tape speed control
		TTL	Transistor-transistor logic
		VC	Variable capacitance
		VCO	Voltage control oscillator
		XDR	Transducer
		XMR	Telemetry receiver

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1. INTRODUCTION

1.1 Historical Background. The original motivation for this Handbook came from personnel of The Aerospace Corporation (TAC), who are technical advisors to the Air Force Space and Missile Systems Center. Over the preceding two decades, TAC had observed a seemingly endless series of errors and anomalies in the acquisition and analysis of structural dynamic and aeroacoustic data. To evaluate the scope of data analysis errors alone, TAC arranged a "round robin", where identical magnetic tapes dubs of short time-limited stationary random signals were sent to several data processing centers for a 1/3 octave band analysis with their normally-used equipment. Ten centers responded with analyzed data that revealed discrepancies of nearly 20 dB at some frequencies [1.1, 1.2]. Rather than continue to accept this situation, Don Wong of TAC arranged to have the Air Force fund the development of a Handbook that would help reduce the variability and eliminate the errors commonly found in measured dynamic data. The Jet Propulsion Laboratory (JPL) was selected to prepare the Handbook, as well as perform any research required to achieve the Handbook objectives. Harry Himmelblau of JPL was appointed the Task Manager for the preparation of the Handbook. He was assisted by Allan Piersol of the Piersol Engineering Co., James Wise of JPL, and Max Grundvig, who was brought out of retirement from TAC for this assignment. Additional assistance was provided by the numerous reviewers acknowledged in the Foreword.

1.2 Purpose. The purpose of this Handbook is to provide guidelines for acquiring and analyzing structural (or mechanical) shock and vibration, and acoustic and aerodynamic noise data from flight and ground tests for all categories of aerospace vehicles. The guidelines may also be used for dynamic measurements on a variety of ground and sea transportation vehicles, industrial machinery, and civil engineering structures (e.g., the response of buildings to earthquake loads). The objectives of the guidelines are to ensure the accuracy and reduce the errors and variability often associated with the acquisition and analysis of dynamic data. Specific procedures are provided unless they are highly dependent on the particular applications or instruments utilized. The ultimate goal is to make accurate measurements of the dynamic phenomenon of interest, without that or any other phenomenon influencing the measurement process.

1.3 Inclusions and Exclusions. Most dynamic analyses involve the transformation of data from the time domain to the frequency domain. The main reason for employing this transformation is that most structures have frequency-dependent resonant responses. Many potential structural failures, such as those due to fatigue, crack propagation, and single peak load exceedance, are highly dependent on these resonances.

Most current measurement systems employ mainly analog or a combination of analog and digital instruments for data acquisition, digital instruments for data analysis, and primarily digital devices for data storage, including PCs, although analog tape recorders are sometimes still in use. In general, these guidelines are written assuming current instrumentation is utilized.

In many cases, errors are encountered because certain traditional methods have been followed even though they can produce erroneous results, e.g., computing vibration spectra using a frequency resolution bandwidth insufficiently narrow compared to the bandwidth of critical structural resonances, or the misapplication of random data analysis procedures to periodic and/or transient data. Utilization of this Handbook is intended to avoid most of these types of problems. Certain errors, however, cannot be avoided by the application of these guidelines. These are the human errors that no set of guidelines can avoid, e.g., misidentification of measurement or channel numbers, incorrect or mislabeled calibration data, or erroneously reported instrumentation gain settings. Only adequate care, planning, communication, and documentation, coupled with personal motivation, can circumvent these errors. Excluding on-line analysis, errors usually have much more serious consequences during data acquisition than during data analysis. Errors in data analysis can usually be corrected by a reanalysis of recorded data, unless there is a serious deficiency in the analysis instruments or in the knowledge and/or training of analysis personnel. On the other hand, errors in data acquisition may necessitate an extremely costly retest, or the complete loss of the information.

There are some special cases of dynamic measurements that will not be covered by this Handbook because of their unique nature and/or the rapid advances currently taking place in the state-of-the-art of their technology. These topics include modal testing or system identification, power and intensity measurements, mechanical impedance measurements, equipment health monitoring, determination of system stability, and a wide variety of biodynamic, human hearing and speech measurements. Even in these cases, some portions of the Handbook may be useful. The technical literature generally provides adequate sources of information on these topics.

1.4 References.

- 1.1 Himmelblau, H., and Piersol, A. G., "Summary of Guidelines for Dynamic Data Acquisition and Analysis", *Proc., 64th Shock and Vibration Symp.*, Vol. I, pp. 121-132, Oct. 1993.
- 1.2 Tanner, C. S., "Shuttle Acoustics Data Reduction Methods", *Aerospace Corporation Rept TOR-0082(2463-03)-1*, 30 Oct. 1981.

2. DYNAMIC MEASUREMENT PLANNING

2.1 Introduction. Some of the most important measurement activities should take place long before data are acquired. Planning for data acquisition and analysis should be initiated as early as possible, preferably during the proposal stage of a new program. There are several issues that should be addressed during this planning, particularly the ultimate uses of the data, the selection of the number and type of transducers and their frequency ranges, i.e., the maximum and minimum frequencies to be measured, and whether the transducer is to measure more than one event or condition. For example, a single accelerometer on a space vehicle may be used to measure the structural responses induced by the engine ignition overpressure and acoustic noise during liftoff, and the boundary layer pressure fluctuations during the transonic and maximum (fluid) dynamic pressure (max q) flight conditions, all with different magnitudes and spectra. These various events are illustrated in Figure 2.1, which shows a typical high frequency flight vibration measurement [2.1]. The instantaneous and rms time histories are shown at the top. Four random vibration spectra from 20 Hz to 3 kHz are shown below, corresponding to four important flight events: liftoff, transonic, and at the beginning and end of upper stage engine burn. The time histories do not show the quasi-static acceleration because the instrumentation system did not respond to signals at frequencies below 10 Hz.

The summation of the channel maximum frequencies of all selected measurements is called the total or system data bandwidth. Two of the most important parameters for selecting instruments for data acquisition are the total data bandwidth and the number of measurements. Another important part of the planning is determining the possible need for multi-channel measurements, e.g., microphone pairs required to define or confirm the time-dependent spatial distribution of the fluctuating pressure loading on a structure. Such paired measurements require special considerations to minimize relative time or phase errors within critical instruments of the data acquisition and analysis system.

Careful consideration should be given to the tradeoff between the overall cost of the measurement program and the potential consequences of an insufficient number of measurements, e.g., not enough data to help determine the cause of flight failures, or an insufficient amount data to determine or verify design or test criteria. Obviously, relatively few measurements may suffice when a comprehensive measurement program has been previously carried out on a similar vehicle or structural configuration. On the other hand, a substantially greater number of measurements may be required when dynamic loads are suspected to have caused a failure. In many cases, the use of ground tests with high-quality simulation and a comprehensive measurement program can substitute for extensive flight tests to establish environmental and load criteria, with a modest number of supplemental flight test measurements to confirm or modify the ground test results.

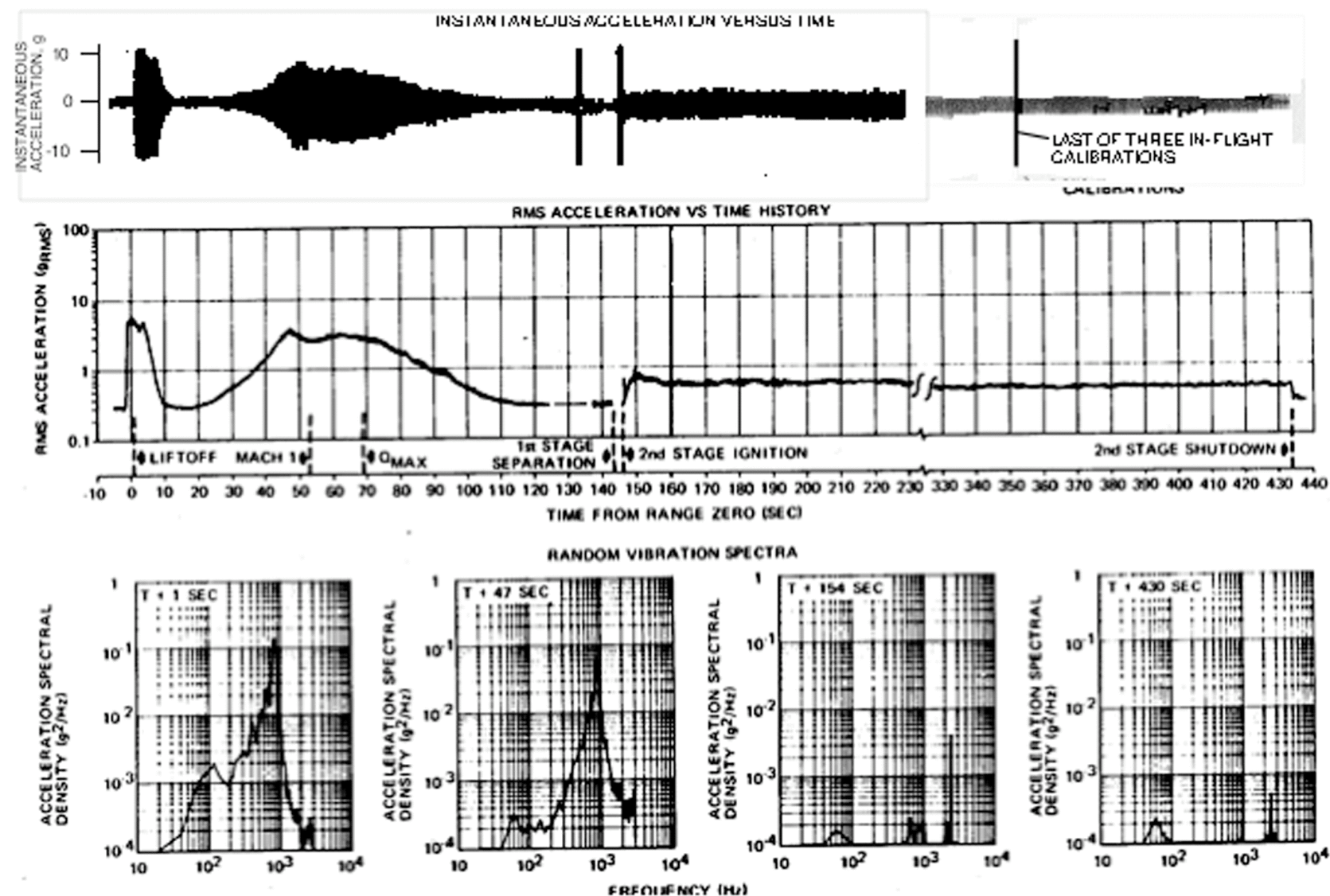
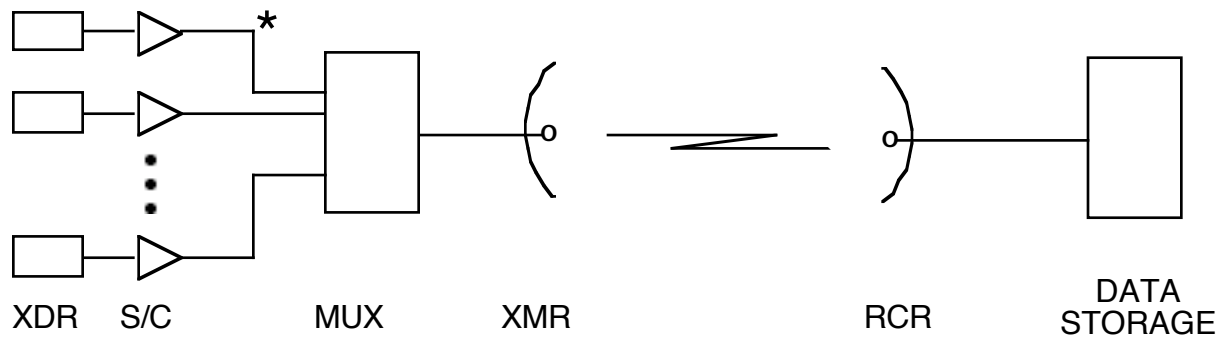


Figure 2.1. Vibration Measured on S-IVB Stage of the Up-rated Saturn I Space Vehicle during Apollo-Saturn Flight SA-203. Spectral Analyses were Performed using a Freq. Resolution Bandwidth of 40 Hz and a Time Duration of 1 sec.

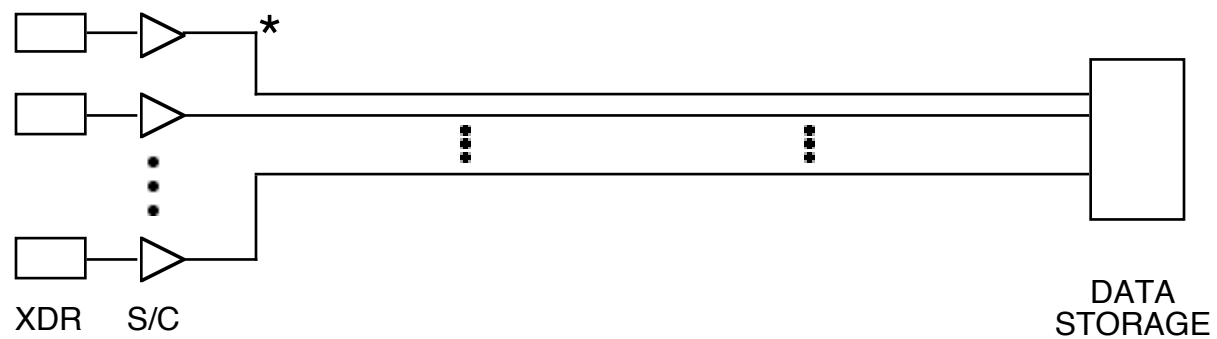
A detailed knowledge of the various instruments of the measurement system is required for their selection and utilization. Figure 2.2 shows block diagrams for a typical dynamic data analysis system, and for two of the most common types of dynamic data acquisition systems. A telemetry system, such as shown in Figure 2.2a, can be used on a wide variety of vehicles, where the transducers (XDR), signal conditioners (S/C) and power supplies, multiplexers (MUX), and a telemetry transmitter (XMR) are located on the vehicle, and the telemetry receiver (RCR), demultiplexers (DEMUX), tape recorders or digital memory (DATA STORAGE), and accessories are located in a ground station. In particular, telemetry systems are used on expendable launch vehicles and payloads, small aircraft when there is insufficient room for on-board recording, and for ground or flight tests of rotating machinery when the use of slip rings is inadequate or impractical. Hardwire systems, such as shown in Figure 2.2b, are commonly used for ground tests, and on larger aircraft where sufficient room exists for on-board recording. The Space Shuttle has used hardwire systems with on-board tape recording, as well as telemetry, for dynamic data acquisition. Data analysis is usually performed after the time the data are acquired, and often at a facility remote from the data acquisition location, requiring the stored data to be transferred to the data analysis facility. Data analysis is commonly performed on a wide variety of stand-alone analyzers, or by software on computers ranging in size from a personal computer (PC) to a mainframe, as indicated in Figure 2.2c. Figure 2.2 shows by asterisk the several possible locations of an analog-to-digital converter (ADC). Of course, there are many variations of the systems outlined in the simple block diagrams of Figure 2.2. For example, Figure 2.3 shows the dynamic data acquisition system for recording 120 fluctuating pressure measurements of aerodynamic noise on a scale model in a wind tunnel [2.2].

2.2 Measurement Numbers, Locations, and Directions. The initial task in dynamic measurement planning is the selection of the transducer locations and directions, which determines the total number of measurements. The experience and knowledge of instrumentation personnel and the user(s) should be important factors in this selection.

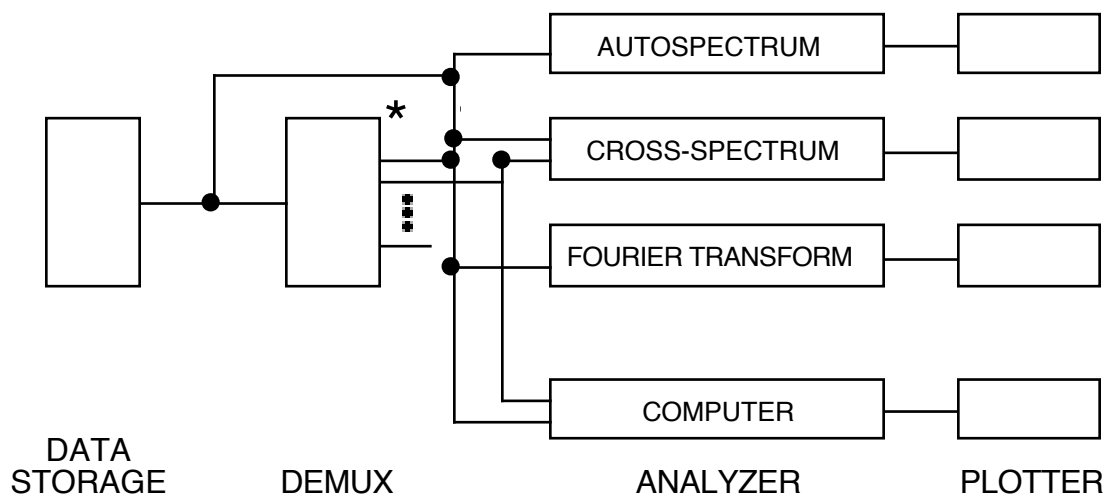
For aerospace applications, low frequency (usually below 100 Hz) strain gages and accelerometers are generally installed based on critical locations and directions computed from dynamic or combined static and dynamic analyses using elaborate finite element method (FEM) models [2.3-2.8], and/or experience gained from previous programs. High frequency (usually above 20 Hz) accelerometers are often located on external structures, or internally near critical hardware. For high frequency accelerometers to be located on external (and often internal) structures, a mix of unidirectional (or uniaxial) and sets of three orthogonal tri-directional (or triaxial) accelerometers is usually selected with most of the uniaxial accelerometers sensing the normal or transverse dynamic response of the structural surface in order to measure the maximum response value. For wide frequency strain gages located on external (and often internal) structures, their number and directions are usually based on computed dynamic responses using FEM models of these "local" structures, statistical energy analysis (SEA) of the overall structure, and/or predictions from simple plate or shell theory, e.g., [2.5 - 2.9, 2.14].



(a) Typical Telemetry System for Dynamic Data Acquisition.



(b) Typical Hardwire System for Dynamic Data Acquisition.



(c) Typical System for Dynamic Data Analysis.

*An analog-to-digital converter (ADC) can be located at any asterisk

Figure 2.2. Typical Instrumentation Systems for Data Acquisition and Analysis.

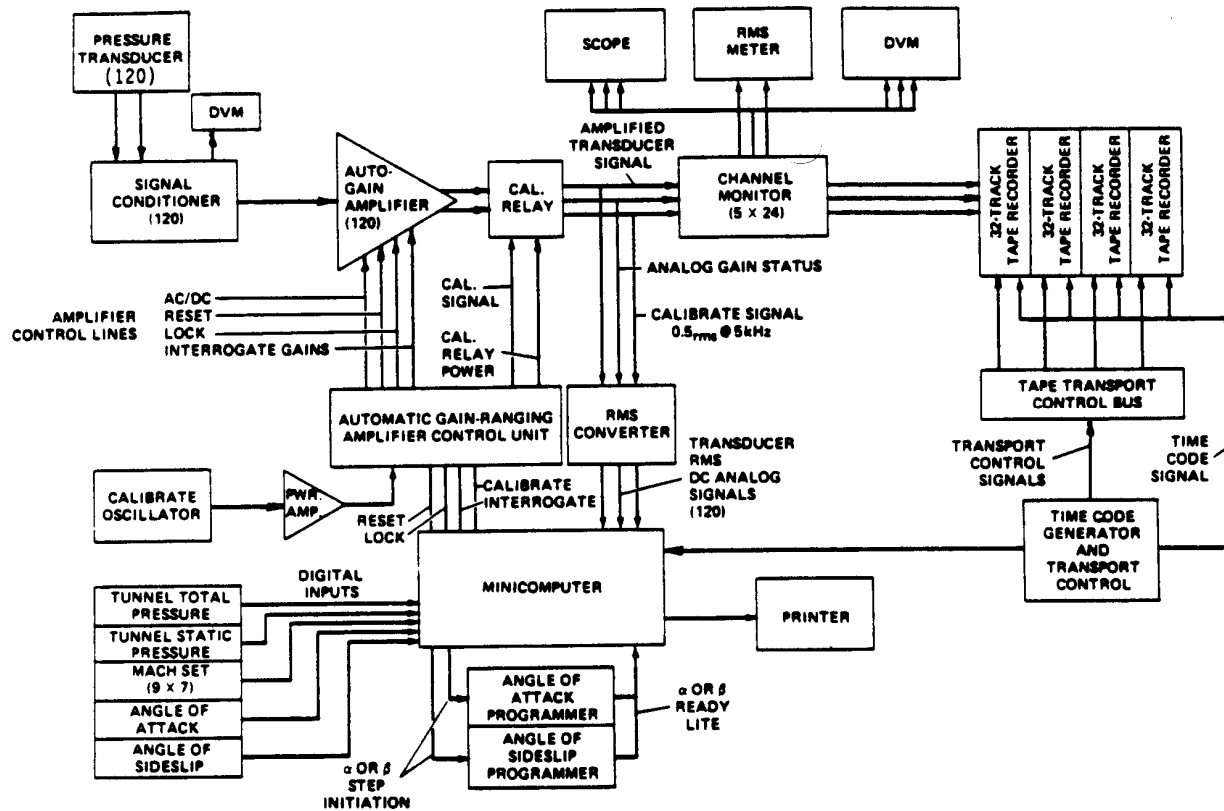


Figure 2.3. Diagram of Data Acquisition System for Wind Tunnel Aerodynamic Noise Tests.

For all strain gage measurements, care must be taken to intentionally include or exclude the effects of local strain distributions (i.e., stress concentrations), depending on the subsequent utilization of the strain data. For high frequency accelerometers to be located near aerospace hardware/structural interfaces, triaxial measurements are usually made to help generate or verify dynamic design and test criteria. Renewed interest has been observed in making force measurements at the structure/hardware interface to improve criteria development and test control [2.15 - 2.17]. For all types of measurements, each transducer should be as small and lightweight as possible, consistent with the product of the anticipated (static and/or dynamic) magnitude times the sensitivity of the transducer. The sensitivity is defined as the ratio of the transducer electrical output to the magnitude of the measured input.

For low frequency measurements, it is fairly common to spatially arrange a group of transducers to determine the global response of the structure [2.5, 2.6], often using multi-channel measurements described in Section 2.6. On the other hand, local structure response is often obtained at high frequencies, with little or no coherence observed among measurements. For a new aerospace vehicle, it is common to divide regions of similar structures and/or external environments into vibroacoustic zones, with at least a few measurements selected for each zone to be used to establish zonal vibroacoustic design and test criteria [2.18 - 2.19]. For example, the Shuttle Orbiter

has over 60 vibration zones. As a result, the number of high-frequency measurements is often a function of vehicle size. Sources that cause high-magnitude vibration, such as reciprocating and rotating machinery, and jet and rocket engines, often receive a large number of measurements.

Pressure transducers are used to measure pressure fluctuations. Some measure quasi-static or combined quasi-static and dynamic pressures, whereas others measure dynamic pressures only. These devices are often installed flush with the external surface to measure engine-induced acoustic noise, as well as aerodynamic pressure fluctuations called aerodynamic noise. In most cases, engine-induced acoustic noise fields change gradually between measurement locations, requiring relatively few measurements. On the other hand, aerodynamic noise can often change drastically even between closely-spaced transducers, especially in the transonic regime at vehicle Mach numbers from 0.7 to 1.3, due to separated flow that results from shock wave-boundary layer interactions. This situation often requires a significant number of measurements to define adequately the spatially distributed fluctuating pressure loads.

The determination of acoustic and aerodynamic (i.e., aeroacoustic) noise can be characterized as an experimental rather than a theoretical art, due mainly to an inability to quantify analytically the basic sources of the noise (e.g., the volume distribution of fluctuating fluid shear stresses) after decades of attempts. As a result, it is common to perform ground tests using vehicle scale models to measure aeroacoustic noise early in a new program. For example, scale model vehicles with scale model engines, and scale models of nearby facilities, such as launch pads, are sometimes used to define engine-induced acoustic noise on vehicle external surfaces. Similarly, wind tunnel tests of scale model vehicles are sometimes used to define aerodynamic noise on vehicle external surfaces, usually in transonic and max q regimes and under flight conditions involving high angles of attack and yaw. A comprehensive scale model program can significantly reduce the need for flight aeroacoustic measurements. However, scale models usually require miniature microphones with very high maximum frequencies to provide full-scale data with a nominal frequency range. For example, a 4% model requires a data acquisition system with a maximum frequency of 50 kHz to provide full-scale data up to 2 kHz. Internal acoustic noise fields are usually measured whenever significant loads or vibratory responses are anticipated for internal structures, or if the cavity is used for human habitation.

If the test is costly or impossible to rerun and/or if the non-dynamic environments applied to the transducers are not adequately known, and if the test results are highly dependent on accurate dynamic data, redundant adjacent transducers may be required to ensure that the desired data are obtained even if some transducers fail. Also, if the magnitude of the quasi-static and/or dynamic load or environment is difficult to predict, redundant transducers with different sensitivities may be needed to ensure that the desired test data are obtained.

If the above selection procedure results in too many measurements, a careful reevaluation should be initiated. Consideration should be given to spreading many of the measurements over several flights or ground tests. Lastly, a priority list should be made to assist in the selection if a fewer number of measurements are approved. In most cases, it is cheaper to make a large number of measurements in a ground test than a flight test. On this basis, consideration should be given to an increased emphasis on ground testing for dynamic measurements. In many cases, individual measurements are more important than a collection of measurements that cannot be directly correlated because of the large degree of independence between the various sources of dynamic excitation.

2.3 Frequency Ranges. After measurement numbers, locations and directions have been selected, the next task is to establish the frequency range for each measurement, i.e., the maximum and minimum frequencies to be recorded and analyzed. For those transducers used to determine combined static and dynamic loads (usually strain gages and low frequency accelerometers), the minimum frequency is obviously zero, i.e., DC. However, under many circumstances, not all low frequency accelerometers need go down to zero frequency, when other DC accelerometers can be used for interpolation. The definition of pressure fields may also require measurements down to or close to zero frequency. For example, the transient pressure from engine ignition often has a substantial very low frequency component whose phase relationship to high frequency components can be vital to load definition. Also, high intensity aerodynamic pressure fluctuations, sometimes called buffet at low frequencies, are usually accompanied by substantial low frequency pressures, which should also be measured for proper environmental definition.

The selection of the maximum frequency is often the most challenging part of this task. It usually has the greatest impact on the total data or system bandwidth and on the various instruments of the measurement system. The maximum frequency is usually selected to equal (a) the maximum significant frequency of the anticipated environment or load, or (b) the maximum frequency that can be simulated in laboratory tests, or (c) the maximum frequency achievable by the data acquisition system. Alternative (a) is recommended over the other two. Experience from previous programs, when available, and theoretical analyses should be of great assistance in establishing the maximum significant frequency.

Before completing a list of the desired frequency ranges, consideration should also be given to available instrumentation options. For example, it may be desired to make six flight vibration measurements up to 2 kHz, using IRIG standard telemetry for data acquisition with constant bandwidth frequency modulation (FM) subcarriers (used for frequency division multiplexing) [2.20]. Later, it may be found that the data acquisition facility only has the capacity for six C channels (0 - 1.6 kHz) or three D channels (0 - 3.2 kHz). The user may then be required to decide which alternative to use, i.e., to get by without data in the 1.6 - 2 kHz range for the six desired measurements, or lose three of the measurements while obtaining the desired range (and more) for

the remaining measurements. Similar options may need to be considered for recording digital data, including PCM [2.21 – 2.23]. In addition, it is often worthwhile to consider the frequency ranges used in common aerospace practice, which is based for the most part on past experience and failures, e.g., (a) 0 - 100 Hz (or sometimes less) for low frequency shock, vibration and strain, due mainly to vehicle transient events, (b) 10 Hz - 2 kHz for high frequency vibration and strain, (c) 10 Hz - 10 kHz for high frequency aeroacoustics, and (d) 100 Hz - 1MHz for near field pyroshock (i.e., within a 6 inch distance from the pyrotechnic source to the transducer) and a lesser high frequency limit (100 Hz to 10 kHz) as the source-to-transducer distance increases. A few measurements in the later two categories have a substantial impact on the total data bandwidth and, therefore, on the data acquisition system. However, it would be a serious mistake to arbitrarily use these frequency ranges when technical considerations justify their modification. It is recommended that Appendix A be reviewed before the planning of pyroshock measurements is initiated.

2.4 Dynamic Ranges. The dynamic range of a measurement system is defined as

$$DR = 10 \log_{10} \left(\frac{x_{\max}}{x_{\min}} \right)^2 \quad (\text{dB}) \quad (2.1)$$

where $x_{\max}$ is the maximum instantaneous value (either the positive or negative) of the signal that can be transmitted by the system without distortion, and $x_{\min}$ is the minimum detectable value of the signal generated by the transducer at the output display. The minimum detectable signal is dependent upon

- (a) the magnitude of undesired electrical noise in the measurement system,
- (b) the quantization of the measurement by an analog-to-digital converter (digital noise),
- (c) low magnitude distortion of the signal, and/or
- (d) interference from other measurements.

Factor (a) usually dominates to produce the background noise floor for the analog instruments of a measurement system, and (b) produces the theoretical noise floor of analog-to-digital converters. The theoretical measures for the dynamic range of analog-to-digital converters, and a discussion of practical limitations, are presented in Section 3.7.1.3.

For analog systems, assuming the signal is symmetric about its mean value, it is common to express the dynamic range of instruments in terms of a peak signal-to-noise ratio given by

$$\text{PSNR} = \left(\frac{X_{\max}}{\sigma_n} \right)^2 \quad (2.2)$$

where σ_n is the standard deviation of the background noise (or the rms value of the background noise if the mean value is zero). The dynamic range of the measurement system may also be defined in terms of an rms signal-to-noise ratio given by

$$\text{SNR} = \left(\frac{\sigma_x}{\sigma_n} \right)^2 \quad (2.3)$$

where σ_x is the standard deviation of the signal (or the rms value of the signal if the mean value is zero). However, this latter description is meaningful only if the specific characteristics of the signal are defined. It is often assumed that $x(t) = X_s \sin(2\pi f_s t)$, so that $X_s = x_{\max} = \sqrt{2} \sigma_x$.

It is common practice to express signal-to-noise ratios for measurement systems in dB to obtain what will henceforth be called signal-to-noise levels. The peak and rms signal-to-noise levels are then given by

$$\text{PS/N} = 10 \log_{10}(\text{PSNR}) = 10 \log_{10} \left(\frac{X_{\max}}{\sigma_n} \right)^2 \quad (\text{dB}) \quad (2.4)$$

and

$$\text{S/N} = 10 \log_{10}(\text{SNR}) = 10 \log_{10} \left(\frac{\sigma_s}{\sigma_n} \right)^2 \quad (\text{dB}) \quad (2.5)$$

For example, $\text{S/N} = 40 \text{ dB}$ corresponds to $\text{SNR} = 10,000$. Note that some sources provide alternate definitions of dynamic range and/or signal-to-noise ratio, which use the ratio on the right hand side of Equations (2.1) - (2.3) without the ratio squared. When these definitions are used, the ratio must be squared to obtain the correct DR, PS/N or S/N.

Another useful ratio is the actual signal-to-noise ratio of a specific measurement, as opposed to the maximum signal-to-noise ratio provided by the measurement system. The actual signal-to-noise ratio, which can never exceed the system signal-to-noise ratio without clipping, is denoted in terms of the actual peak signal-to-noise ratio and level, and the actual rms signal-to-noise ratio and level by

$$\text{PSNR}_a = \left(\frac{x_{\text{ma}}}{\sigma_n}\right)^2 \quad \text{or} \quad \text{PS/N}_a = 10 \log_{10} \left(\frac{x_{\text{ma}}}{\sigma_n}\right)^2 \quad (\text{dB}) \quad (2.6)$$

and

$$\text{SNR}_a = \left(\frac{\sigma_{xa}}{\sigma_n}\right)^2 \quad \text{or} \quad \text{S/N}_a = 10 \log_{10} \left(\frac{\sigma_{xa}}{\sigma_n}\right)^2 \quad (\text{dB}) \quad (2.7)$$

The determination of the maximum anticipated instantaneous value, x_{ma} , for a measurement is usually the most challenging task associated with the selection of system gain settings to optimize the actual signal-to-noise ratio of a measurement. This value is usually selected to equal (a) the maximum anticipated instantaneous value (either plus or minus) of a transient or a periodic signal, or (b) the product of a crest factor times the standard deviation of a maximum anticipated random signal, whichever is greater. The crest factor, or peak-to-standard deviation ratio, of a random signal may be as low as three for a short duration random signal, or in excess of six for a very long duration random signal or a signal representing the response of a highly nonlinear structure to random excitation.

The value of x_{max} for the data acquisition system is usually selected to be a little more than the anticipated value of x_{ma} , say by a factor of $\sqrt{2}$ or 3 dB, to leave a little spread (or "head room") for the lack of a precise estimate of x_{ma} , or for flight-to-flight variations. On the other hand, a much greater spread, say 6 to even 10 dB, is often used for the first few flights to compensate for even less confidence in the estimate. Of course, everything else being equal, the additional spread reduces the useful PS/N_a of the measurement. Usually the greatest need for a large system dynamic range (DR) is when it is intended to measure widely diverse multiple events, such as low frequency structural response to gust loading as well as stage separation, or high frequency structural response to aerodynamic noise at max q as well as pyroshock. In many cases, it may be impossible to measure multiple events properly with only one measurement channel. An example is shown in Figure 2.1, where S/N_a is an adequate 24, 21 and 20 dB for the liftoff, transonic and max q events, respectively, but only 6 and 4 dB at the beginning and end, respectively, of the second stage engine burn. See Section 4.6.1 for excessive background noise corrections.

Usually a single instrument of the system is responsible for limiting the dynamic range, e.g., high noise floor of the signal conditioner, or the PS/N of the subcarrier used for the frequency division multiplexing (FDM) of several signals prior to telemetering, or data recording. Often the electrical noise of the signal conditioner can be reduced by better grounding or shielding, but a system change may be required to improve the PS/N_m of the FDM subcarrier. For example, the PS/N_m of an IRIG standard FM subcarrier is approximately 45 dB. However, once the DR of the critical instrument is determined, the DR for the other instruments need only to exceed that of the critical instrument by a reasonable amount, say 6 dB, to avoid additional degradation of the system DR.

In certain cases, if the load or environment to be measured is of low magnitude, there may be a problem in achieving both the desired useful amplitude range and frequency range. For a particular transducer design, a wide frequency range may only be achieved at the expense of transducer sensitivity, even with amplification, and vice versa. Thus, this situation may have a substantial influence on the selection of both the frequency range and dynamic range. In other cases, it may be impossible to measure the low-magnitude condition, e.g., turbulent flow-induced aerodynamic noise applied to certain regions of a wind tunnel model may be less than the acoustic noise transmitted from other wind tunnel sources [2.24]. To determine the magnitude of these sources, another pressure transducer can be located in the laminar flow region of the model (usually near the nose). Spectral comparison can then be used to determine if and where the desired aerodynamic noise spectrum exceeds that of the tunnel noise, and is therefore valid data for flight vehicle design.

In many cases, the purchasing department places orders for needed instruments with the various instrument vendors shortly after the completion of measurement planning, especially for long-lead items. Once placed, proposed changes to these purchase orders are likely to meet with great resistance. When signal conditioners are purchased, one of the characteristics specified is the amplifier gain setting (see Sections 3.3 and 3.9), which is determined by the user's estimate of the various values of x_{ma} . Later, loads or response analyses, or ground or early flight tests may show the need for changes in the various values of x_{ma} . If the signal conditioners have been ordered with unadjustable fixed-gain amplifiers, there may not be enough time to reorder, return, make the required changes, redeliver and reinstall the signal conditioners before the next test, or the purchasing department may want to show its reluctance to reorder without program management approval, who by then are probably working on several higher priority problems, potentially causing an extended delay. Either will probably result in (a) delay of the next test, or (b) much data lost due to signal clipping or saturation, or insufficient PS/N_a. See Sections 4.3-4.6 for details on Alternative (b). To avoid these problems, it is recommended that all signal conditioners be ordered initially with (1) manually-adjustable fixed-gain amplifiers, over a gain range of ± 10 dB or more (referenced to the original x_{ma}), so that gain settings may be changed if necessary or (2) computer-controlled amplifiers with continuous gain-ranges or autoranging. Even in large test programs, the relative cost difference should be small for Alternative (1). The higher initial cost of Alternative (2) is offset by the elimination of time-consuming manual adjustments (which could be substantial with many measurements) and the risk of human error.

2.5 Measurement Durations. It is sometimes necessary and always desirable to measure dynamic loads and/or environments during the complete period of excitation. If this is impossible with the data recording and storage instruments selected, then at least the loads and/or environments should be measured during periods of significant excitation, and when the excitation changes. For example, a duration-limited instrumentation system for a space vehicle should acquire data for the entire period of powered ascent, and may be turned off until shortly before upper stage engine ignition. If the engine burn duration is still too long for the capacity of the data recording

instrument, then it may have to be turned off again until shortly before engine cutoff if the risk is acceptable.

In most cases, the factor limiting the total duration of data acquisition is the capacity of the data storage instrument (e.g., magnetic tape or digital memory). IRIG standard tape recorders used for dynamic measurements usually accommodate 10.5 in. or 14 in. diameter reels, with resulting tape lengths of about 4600 ft and 9200 ft, respectively. The total recording duration can be calculated from

$$T_t = \frac{L_t}{5V} \quad (\text{minutes}) \quad (2.8)$$

where L_t is the total tape length in feet, and V is the tape speed in in./sec (ips). Using an IRIG standard tape speed of 60 ips, as is common for wideband and frequency division multiplex (FDM) dynamic data recording, a total duration of 15 min, 20 sec and 30 min, 40 sec is obtained for the 10.5 in. and 14 in. tape reels, respectively. Pretest and (whenever possible) post test calibrations (or cals) should be included on the tape with the dynamic data, once the minimum time is determined for each cal period. (One minute each for recording a DC step cal, an AC sine cal, and background noise is often used). Little time may then be left for the dynamic data. Of course, if the useful frequency ranges of the measurements can be achieved with a slower tape speed (30 or 15 ips), then a substantially longer recording duration may be obtained. If the signals are to be tape recorded using FM recording (see Section 3.6.3.2) and if the frequency range of the cal can be recorded with a much slower tape speed, then a longer data recording duration at a higher speed can be achieved.

When it is necessary to use higher tape speeds for FM recording, a simple solution to the duration problem may be to record the cals on one tape and the dynamic data on another, taking care not to change any gain settings between the cals and the data. However, this may not be used for direct, e.g., amplitude modulation (AM), recording, due to potential tape-to-tape magnetic density variations, unless it can be verified that both tapes came from the same batch. Another solution is to use twice as many (or three times as many) tape recorders, first recording data on the first recorder (or first set), and then recording data on the second recorder (or second set) with a little overlap, etc. This obviously complicates the data acquisition process and substantially increases the cost. Similar procedures may be utilized for recording digital data, e.g., when a PC is used, recording the cal on one CD and the dynamic data on another.

2.6 Multi-Channel Measurements. In most cases, the dynamic response of a spatially-distributed aerospace structure is caused by an external distributed load over its various surfaces, or by multi-point loading. In many of these cases, it is necessary or desirable to determine or verify the spatial distribution of these loads, or the dynamic response they produce. In addition, sometimes it is desirable to establish the frequency response function (sometimes called a transfer function)

between a load and a response at a single or at different locations. In other cases, it is desired to ascertain the transit time of a wave or waves between two locations. Other applications are given in [2.26]. For all of the above, multiple channel measurements are required.

Examination of the analytical equations which govern the dynamic response of distributed structures shows that the response is dependent on the loading expressed in terms of parameters which are dependent on location pairs [2.1, 2.5, 2.25, 2.26]. Thus the analysis of multiple channel measurements is actually performed in terms of dual channel analysis, considerably simplifying the data analysis, but not the data acquisition. The capability of the instrumentation system to measure dual channel data accurately must be evaluated prior to the acquisition of multi-channel data. The two parts of this evaluation are the determination of (a) magnitude, and (b) relative phase or time delay. The evaluation of the system for dual channel magnitude turns out to be identical to that for individual measurements, i.e., by conventional single channel calibration (see Section 3.8). The evaluation of the instrumentation system for dual channel phase or time delay requires that the same calibration signal be applied to all multi-channels simultaneously, so that the relative phase between channels over the selected spectrum can be observed. The most common calibration in present use is the simultaneous application of an electrical random signal, usually with a white spectrum (constant autospectral density function described in Section 5.4.3) over the frequency range of interest (see Section 3.8). The between-channel coherence and cross-spectrum phase of this signal is later measured for all desired dual channels. Unity coherence and zero phase of this calibration signal over the desired frequency range indicate that an accurate dual channel analysis of the measurements should be expected. A coherence less than unity shows that there is some distortion, interference, or noise on one or both channels that must be reduced, no matter what the phase is. Obviously, zero phase is preferred. However, the situation is not lost even when the phase is other than zero, as long as the coherence is unity. All that is necessary is to have the dual channel data, once it is acquired and analyzed, corrected with the phase data obtained from this calibration. See Section 3.8 for details.

It should be emphasized that it is currently impractical to control the relative phase between measurements recorded on separate tape recorders, no matter what measures are taken to try to synchronize the recorders (although such techniques have been proposed, e.g. [2.28]). Thus it is mandatory that acquisition of multi-channel data intended for dual channel analysis be limited to a single tape recorder, using either wideband recording or multiplexing. For wideband recording, the applicable signals should be recorded on adjacent tracks (odd or even) of the same head stack. If the number of multi-channel measurements exceeds the capacity of a single recorder, then one or more measurements must be recorded on two (or more) tape recorders to maintain a proper phase reference for later analysis. Therefore, if it is necessary or desirable to obtain multi-channel data for dual channel analyses, the measurement plan must make provisions for unambiguous phase determination during the data acquisition of these measurements, and the application of a single calibration to all multi-channels simultaneously.

2.7 Time Codes. For all flight tests and nearly all ground tests, it is necessary to record an unambiguous time code on all recorders used for dynamic data acquisition. A properly formatted time code can be used to detect, and sometimes correct, time errors in the recording process, as well as be used in the selection and implementation of spectral analysis intervals during data analysis. In most cases, one of the standard IRIG time formats is selected for the time code [2.29]. For dynamic measurements, this is usually IRIG-B. See Section 3.6.6 for details. Many PC-based systems use computer-controlled, battery-operated clocks that may not be synchronized with IRIG timers.

2.8 Error Budgets. A simple concept that is often ignored during the data acquisition and analysis planning is called the "error budget", which consists of a clear definition and tabulation of all potential errors in the data acquisition and analysis instrumentation, including the statistical estimation errors in the final analysis of random data signals. An error budget is valuable in four basic ways, as follows:

- (1) It forces the planner to think about all possible sources of error before data are acquired and analyzed, and in so doing greatly reduces the risk that the experiment will fail to provide the desired information due to obscuring uncertainties in the results.
- (2) It immediately identifies the primary sources of errors (the "weak links") in the system instrumentation and, hence, allows the consideration of pre-experiment changes in specific instruments to minimize the overall potential error in the experimental results.
- (3) For the case of random data, it allows the logical selection of the measurement durations that will be needed for the data analysis to assure that the statistical sampling errors are consistent with the potential error due to the data acquisition and analysis instruments.
- (4) It permits the objective estimation of an overall system potential error in the final results of the experiment.

Although an error budget is probably most useful during measurement planning, it can provide valuable information anytime during the measurement program.

2.8.1 Error Source Identification and Quantification. The first step in preparing an error budget is to identify and quantify the potential errors associated with each instrument in the data acquisition and analysis system, and for the case of random data, the statistical sampling errors in each data analysis procedure. To assist this task, Section 3 details potential error sources and quanti-

fies certain error values for a wide range of data acquisition instruments, including (a) transducers, (b) signal conditioners, (c) multiplexers and demultiplexers, (d) communication links, and (e) data recording, playback, and storage devices. Section 3 covers not only intrinsic errors, but also the environmentally-induced errors, e.g., the influence of temperature on the accuracy of an accelerometer. Section 4 presents procedures for identifying and, in some cases, suppressing various errors in data signals after they have been acquired. Section 5 summarizes the statistical sampling errors (both random and bias) in the analysis of random data signals. Beyond the information in this Handbook, definitive details on the errors to be expected in various data acquisition and analysis instruments are often provided in the manufacturers' specs and literature. Finally, there are a number of textbooks that develop and discuss error expressions for various types of instruments [2.30-2.33]. See [2.34] for an illustration of the identification and quantification of errors for the Space Shuttle dynamic data acquisition and analysis system.

2.8.2 Error Budget Preparation. Using a flow chart for the system instrumentation, the error budget should be prepared by making a detailed listing of each instrument and its potential error contributions. This may include several error sources for each instrument. For example, error sources for an accelerometer may include, (a) frequency linearity, (b) amplitude linearity, (c) installation effects, (d) base strain sensitivity, and (e) transverse vibration sensitivity. It is important that the listed errors include estimates for all environmental-induced errors [e.g., (d) and (e) above], particularly for measurements made under extreme conditions. The error budget preparation must be very carefully examined to assure that no significant error sources are omitted. It will be complete only when every link in the flow chart for the data acquisition and analysis system has been assigned an error value. If the error for one or more links in the flow chart is missing, it should be approximated based upon good engineering judgment.

2.8.3 System Error Calculation. The total system error should be computed by taking the square root of the sum of squares (called the RSS error) for the individual errors listed in the error budget. In computing an RSS error, it is important that the constituent errors be defined on a common basis. For example, many data acquisition instrument errors are quoted in terms of a "percent of full scale", while most data analysis statistical sampling errors are presented in terms of a "percent of reading". The errors must be converted to a common format before computing the RSS.

2.8.4 System Error Utilization. Once the system RSS error has been computed, if it is too large to allow a meaningful interpretation of experimental results, the various elements in the error budget should be reviewed to establish where and how the constituent errors could be reduced to bring the RSS error down to an acceptable level. Remembering that the RSS computation involves a sum of squared error terms, it follows that attention should be focused on the largest error sources, since they dominant in the RSS computation. For example, if there were six error sources, where one was 5% and the other five were 1% each, totally eliminating all five of the 1%

error sources would reduce the RSS error only from about 5.5% to 5.0%. This same reduction in the RSS error could be accomplished by reducing the single 5% error source to 4.5%.

For the case where the acquired data are random in character, meaning there will be statistical sampling errors in the data analysis, the RSS error for the data acquisition instruments is a key factor in the selection of the measurement durations for the later data analysis. Specifically, the duration of the acquired data signals directly influences the statistical accuracy of the data analysis results, as well as the duration and, hence, the cost of the experiment. If the RSS for the data acquisition instrumentation were, say 20%, it would clearly serve no purpose to spend the money needed to collect sufficient data to allow an analysis with a statistical sampling error of 5%. In this fashion, the error budget plays a key roll in the selection of measurement durations during the data acquisition and analysis planning. See [2.30 – 2.33] for further discussions of error budgets.

2.9 Instruments and/or Software Selection and Vendor Evaluation. Once the requirements have been determined for the number and type of measurements, their locations and directions, their frequency and dynamic ranges, and measurement durations, plus the need for multi-channel data and special types of data analysis, then available on-site instruments and/or software should be examined to ascertain that the requirements could be satisfied. It may be found that no single instrument can meet all the requirements, e.g., dynamic or frequency range. Then consideration should be given to the potential use of two or more instruments, or modification of the requirements. Occasionally, only one type of instrument can satisfy a unique requirement, e.g., water-cooled accelerometers for measuring vibration at high temperature, or vibration-compensated microphones for measuring aeroacoustic noise near structures responding with high magnitude vibration. Deficiencies should be identified and plans made to correct them, including the potential purchase of new instruments and/or software.

The process of determining if commercial instruments and/or software can satisfy user requirements should then be initiated using the most knowledgeable and experienced instrumentation and user personnel available. This process should start with the careful examination of instrument manufacturers' catalogs and specification (spec) sheets, and/or software developers' descriptions and spec sheets (plus instructions on their utilization on certain computers), to identify the applicable characteristics and inherent limitations of the candidate instruments and/or software. Other important factors should also be considered: environmental effects, size and weight, mounting provisions, power requirements, ease of operation, and various precautions that may be needed in instrument utilization. The user should be aware that even the most respected vendors may permit excessive optimism to creep into their catalogs, descriptions, and spec sheets, e.g., software that works perfectly in one application may be seriously deficient in another application. Hence, it is recommended that the process of determining if available instruments and/or software satisfy user requirements be continued by contacting current and previous users of the product concerning their evaluation. It is not uncommon for users from competing organizations to discuss these

products freely and openly. However, concentration on current and past designs can tend to perpetuate obsolete technology, which can in the long run hinder the future development of better instruments and software.

Most instrument manufacturers and software developers are happy to provide detailed data on their products, services and applications, usually by knowledgeable and experienced personnel. However, some may be unwilling to provide unbiased information on the relative merits of competitors' products. Another data source is the instrumentation consultant, who usually can be counted on to provide an independent assessment of competing products. Manufacturers, developers and consultants should all be knowledgeable of the current state-of-the-art. In addition, business-related factors should have an important influence on vendor evaluation and selection: price and delivery, quality control, calibration services, past performance, financial stability, innovation, ability and willingness to make modifications, and overall cooperation [2.30]. Vendor facilities should be visited to verify current capabilities.

Standards are available for many instruments of the data acquisition and analysis system. IRIG and military standards are available for telemetry, muxs and demuxs, tape and digital memory recorders, time codes, calibration system, magnetic tape, and special formats such as CVSD, ADARIO, ARMOR, and MIL-STD-1533 [2.20 – 2.23, 2.35]. Nearly all test ranges have instruments built to IRIG standards in their ground stations. If the user's instrumentation requirements fall outside of the IRIG instruments capabilities, then one or more non-IRIG systems will need to be considered or requirements will need to be modified. There are a variety of non-IRIG systems available that can be compared with user requirements, some of which are comprised of MEMS components assembled into small light-weight packages that consume very little electrical power [2.30, 2.36]. If the user requirements include a telemetry transmitter, as shown in Figure 2.2a (now called wireless), substantial power may need to be added based on the transmitter intended range, direction, and total bandwidth, although some alternatives might be considered [2.36]. Some non-IRIG systems utilize IEEE standards or proposed standards, such as the IEEE 802 family of standards, which has been grouped into the following four Wireless Area Network categories; WPAN (for Personal), WMAN (for Metropolitan), WLAN (for Local), and WWAN (for Wide including telemetry systems), as shown in Figure 2.4. Some well-known subcategories include 802.11 (Wi-Fi), 802.15.1 and .2 (Bluetooth), and 802.15.4 (ZigBee) [2.37, 2.38]. The latest is the IEEE 1451.4, Smart Transducer Interface [2.38], which accepts analog signals from transducers and digital data from TEDS, a very useful digital record keeping subsystem, as outlined in Figures 2.5 and 2.6. In addition, there are a variety of ANSI, ISO, and IEC standards for various instruments, such as transducers and their calibration, spectral analysis, and procedures for a variety of vibration and acoustic measurements, e.g., [2.39 --2.41], some of which used to be military standards until DoD acquisition personnel decided that military systems should be replaced with COTS systems in order to reduce costs. If available non-IRIG systems do not meet user requirements, a proprietary or special system may need to be developed and validated, usually at considerable expense and delay. When this process is completed, discussions with program

managers and customer representatives should be entered into to obtain their concurrence with the instrumentation plan and cost, or to establish alternatives.

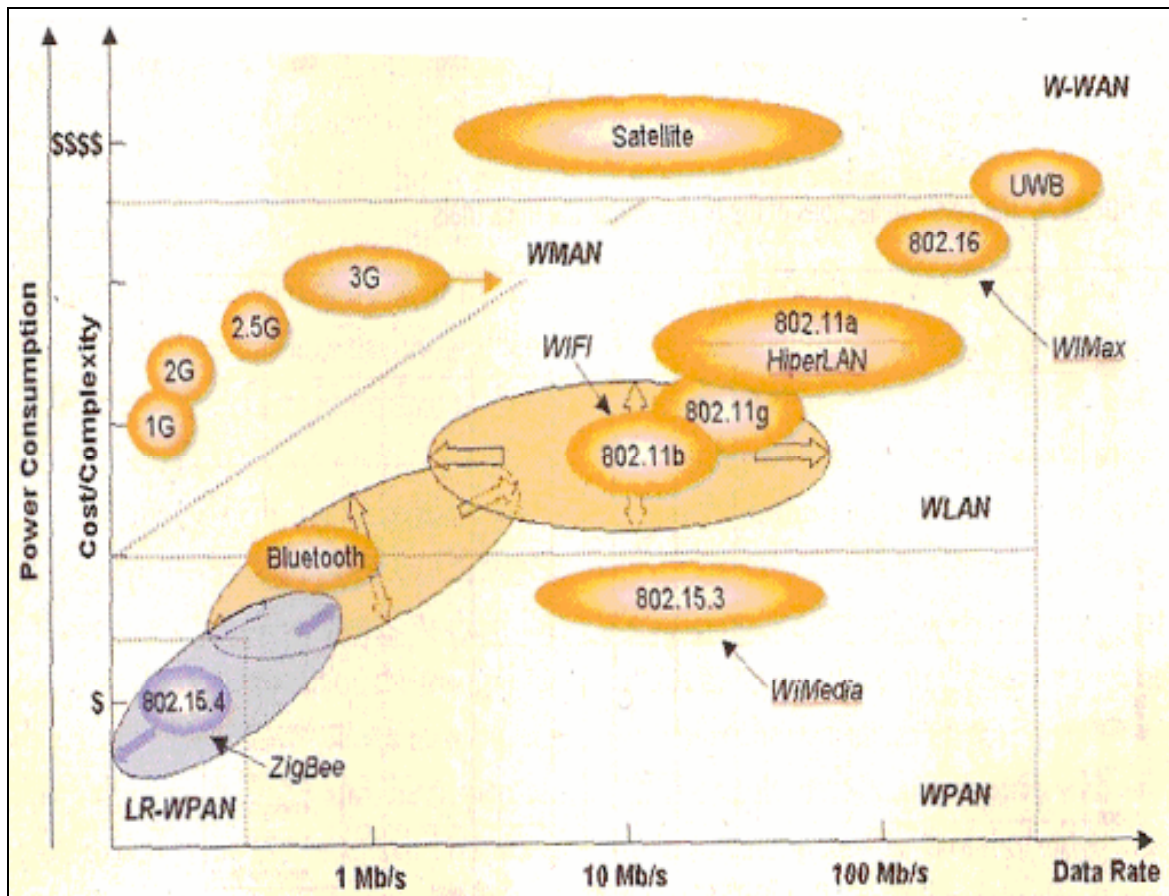


Figure 2.4. An Overview of the IEEE 802 Family of Standards [2.37].

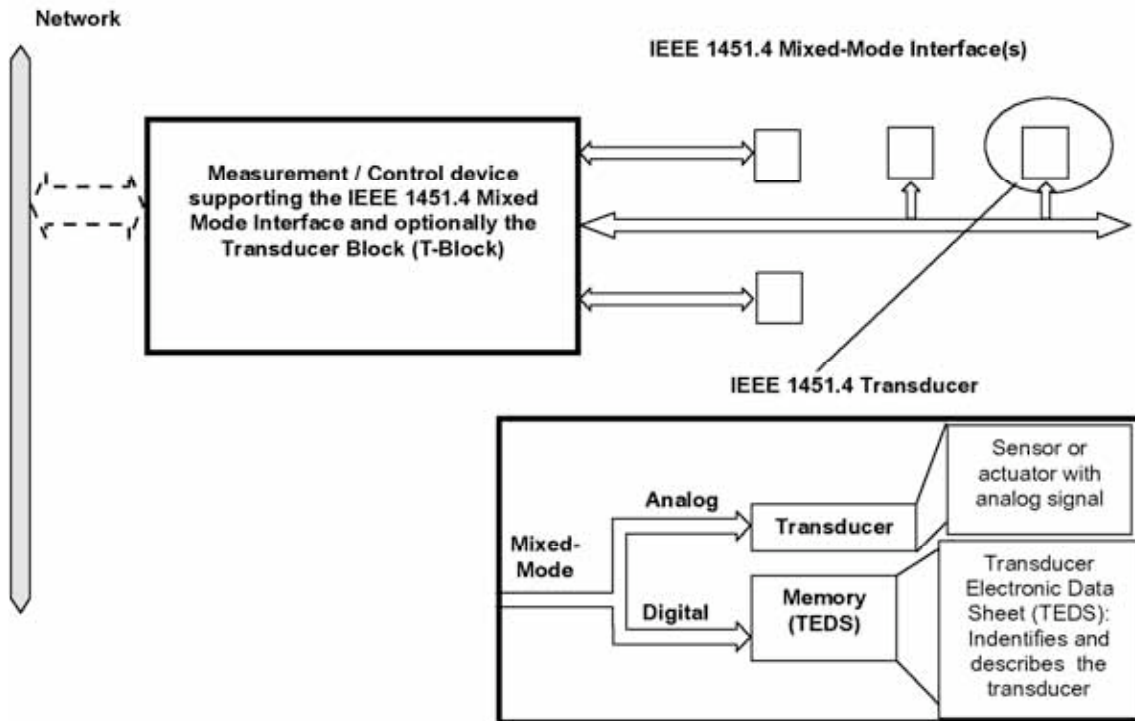


Figure 2.5. IEEE 1451.4 Transducer and Interface.

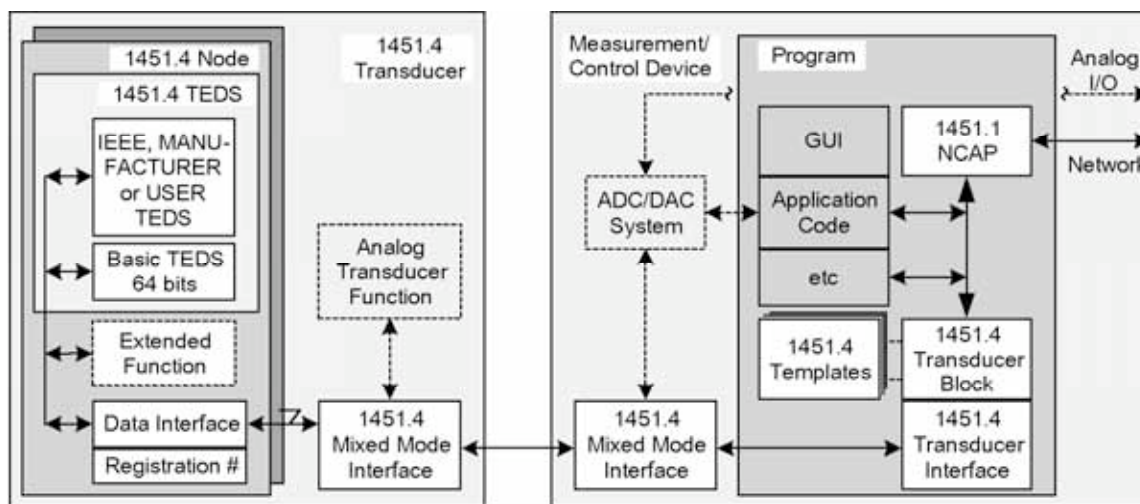


Figure 2.6. IEEE 1451.4 TEDS Block Diagram.

2.10 Major Causes Of Errors. As a closing comment related to measurement planning, it may be useful to note what are considered the most common causes of errors and variability in dynamic data acquisition and analysis:

- (1) No end-to-end calibration, especially important in flight and major ground tests, permitting a large number of potential error sources to influence the determination of instrumentation calibration factors.
- (2) Advanced purchase of a large number of incorrectly set unadjustable fixed-gain amplifiers, resulting in uncorrectable cases of signal loss due to saturation, or serious contamination by background noise.
- (3) Ignoring the effects of non-dynamic environments and other dynamic loads on dynamic transducers and signal conditioners, such as base bending of accelerometers, vibration response of microphones, and moisture penetration into signal conditioners, causing unknown errors in the measured output.
- (4) Failure to properly evaluate the effects of the installation or mounting on the transducer response to the dynamic load to be measured, causing an erroneous output.
- (5) Locating low pass filters after signal conditioners, rather than ahead of them, allowing high frequency components to saturate the conditioners and invalidate the data at all frequencies.
- (6) Lack of an anti-aliasing filter prior to analog-to-digital conversion, leading to Nyquist fold-over, despite all warnings to the contrary, especially important for critical pyroshock measurements.
- (7) When nonstationary flight data are analyzed, the initiation of time windows manually by data processing personnel rather than by a time code-activated switch, resulting in erroneous spectra caused by uncontrollable time translations.
- (8) Selecting a frequency resolution bandwidth wider than structural resonant bandwidths in random vibration data analysis, causing significant errors in the accurate determination of spectral peaks.
- (9) Making pyroshock accelerometer measurements too close to the pyrotechnic source, allowing intense high frequency response components, including a possible accelerometer resonant response, to saturate the transducer and/or signal conditioner, and invalidate the resulting data at all frequencies.

- (10) Human errors, often due to the lack of proper planning, training, communication, attention to details, and/or personal motivation in the data acquisition and analysis process, which can often be circumvented by direct user involvement in all aspects of these activities. The most common error is the utilization of spectral data (e.g., for the purpose of specifying design and test criteria) without examination of the instantaneous time histories, which might show anomalies occurring within the time duration used for determining the spectra, as detailed in Chapter 4. Substantial errors can also occur if incorrect settings are made on data acquisition cards used for selecting signal gains, frequency resolution bandwidths, sample rates, etc. One possible solution to minimizing these human error problems is to put all measurement functions, from instrument selection through processing data plots, under one organization made responsible by management for the accuracy of resulting data

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* IRIG documents (including recent revisions) may be obtained from:

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