Analog Noise Documentation and Suppression in Flight and Ground Based Instrumentation Systems

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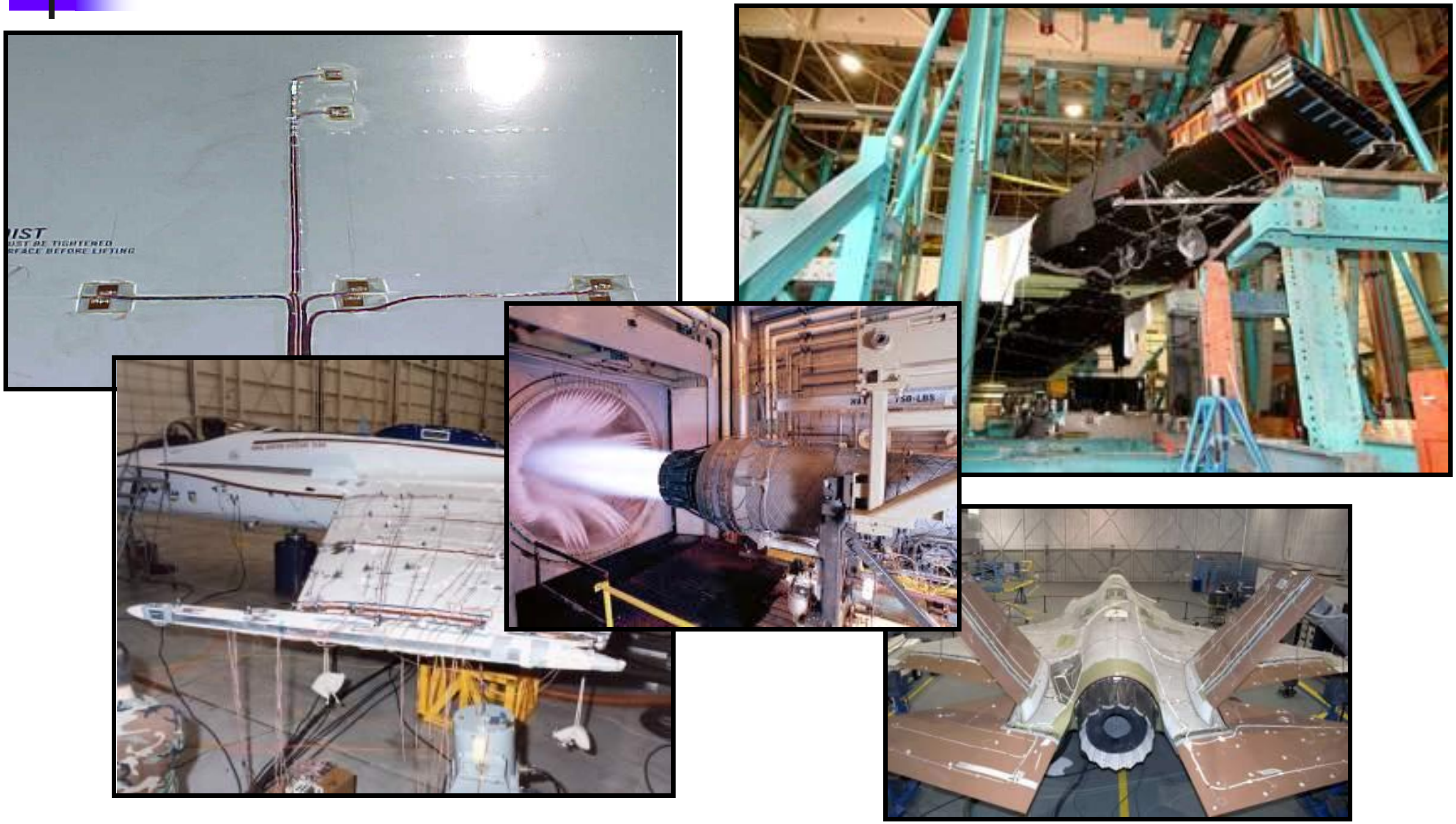
A **Few** Common Airframe and Engine Sensors Used During T&E

Sensor	Measurement	Challenges
Strain gage	Fatigue cycles, loads, structural design margins, …	➢ mV signal levels ➢ Long cable runs
Thermocouple	Engine temperatures, thermal management, …	➢ mV signal levels ➢ Long cable runs
Accelerometer	Flutter, buffeting, engine out of balance, …	➢ High impedances ➢ Triboelectric noise in long cables
ΔR pressure and force transducers	Cockpit noise, surface profiling, …	➢ mV signal levels ➢ Long cable runs

Observation: Challenges associate with low signal levels, long cable runs, and in some instances high output impedances must be overcome before meaningful T&E data can be successfully digitized and recorded.

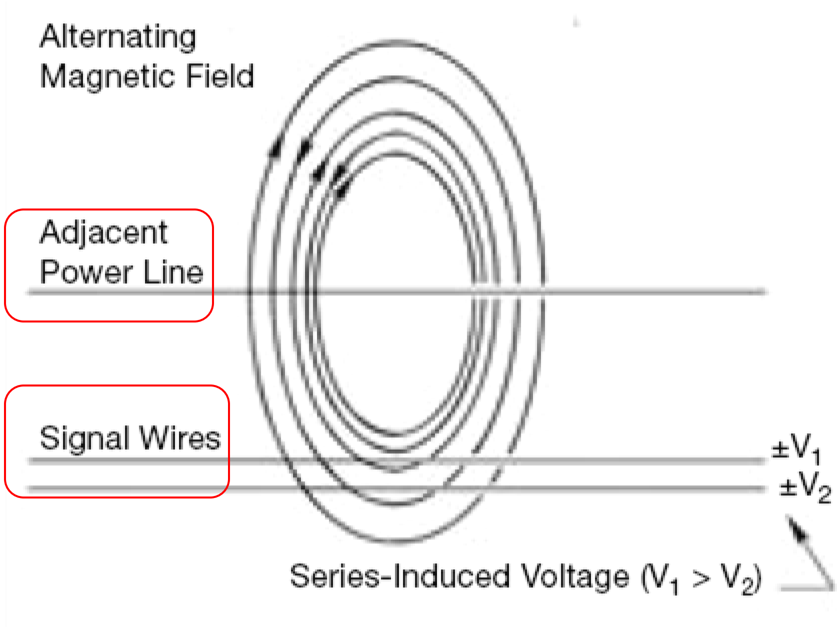
These Type Sensors Support Both Ground and Flight Testing

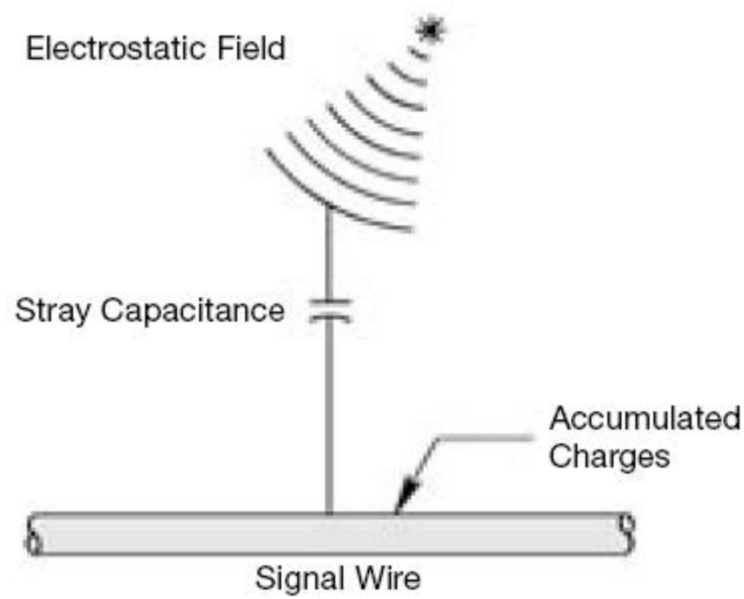


Some Basic Electrical Noise Considerations

- Noise
  - We should protect against electromagnetic and electrostatic fields and currents coupling through common impedances.
    - electromagnetic: time-varying magnetic fields (solenoids, motors, power transformers)
      - shield by completely enclosing the susceptible circuit (use high permeable material such as Permalloy)*
    - electrostatic: time-varying potential difference between two conductors coupled by stray capacitance
      - shield with stranded braid mesh and screens of good electrical conductors*

e.g., Electrical Noise Considerations

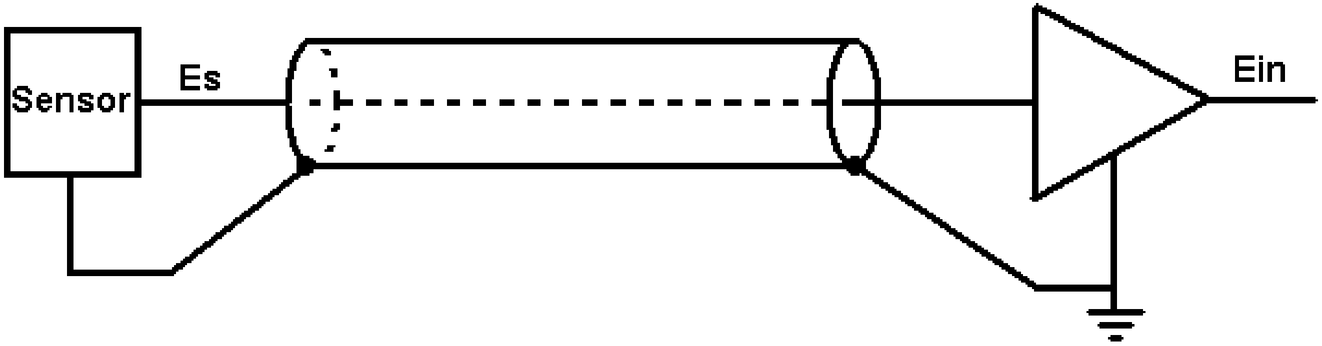




e.g., Electrical Noise Considerations

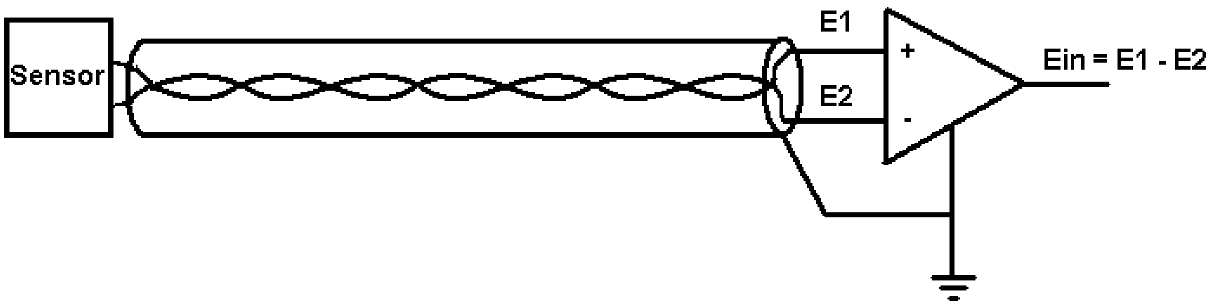
Good magnetic shields are relatively good electrostatic shields but the converse is not true.

- current coupled: signal currents share a common path with other undesired currents
  - provide a single ground
  - keep cables short



e.g., Electrical Noise Considerations

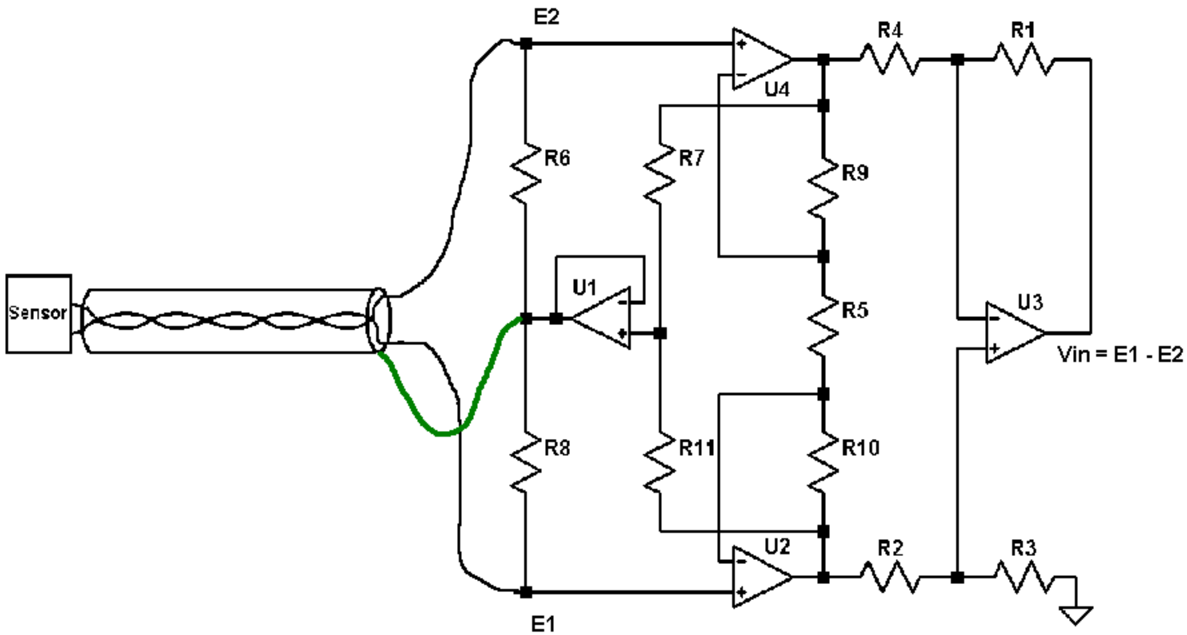
- Grounding considerations:



  - Twisted/Shielded pair most commonly used cable for differential inputs.
  - Shield may be separated from the signal path, reducing noise coupling to the input.

e.g., Electrical Noise Considerations

- Grounding considerations:

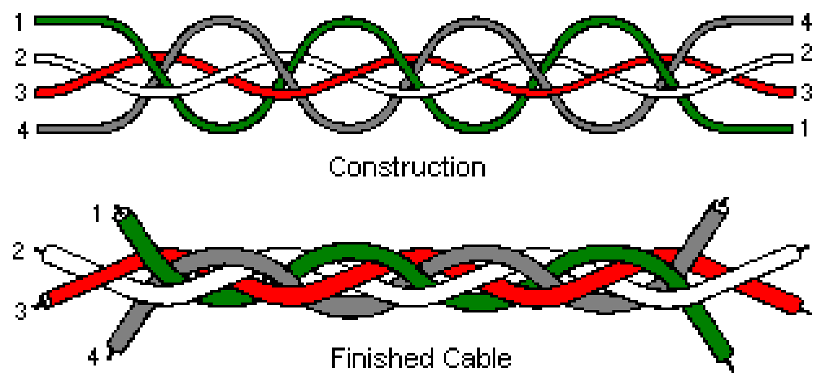


  - If the shield is driven, the loading effect of the different capacitors will no longer exist

e.g., Electrical Noise Considerations

Permalloy- An 80/20 alloy of nickel and iron; easily magnetized and demagnetized

magnetic shields



Magnetic Shield Corporation
Bensenville, IL
shields@magnetic-shield.com

A More Functional System Noise Definition Follows:

*Noise is anything but **the desired response** from a transducer to the **desired environment.***

Undesired Environments in Aircraft and Launch Vehicles

Walter: "Test Magazine", Nov. 2007

For an aircraft, we might encounter temperatures on the tarmac as high as 54 degrees C (130 degrees F). In flight these external temperatures may drop to –35 degrees C (-30 degrees F). Rocket systems encounter much greater temperature extremes. Aside from influencing the various sensors, these temperature variations can result in internal condensation and/or ice formation, which attempts to lower electrical impedances in the components of the on-board measurement system.

Strain and acceleration are induced into the flight system's structure at various times due to turbulence, engine and motor burns, jettisoning of equipment, ordnance release, sonic booms, staging separation, and more. Acoustic noise is transmitted through the air frame or structure to its interior. Some of the events in the preceding list that induce acceleration can result in high levels of pyrotechnic shock.

At both anticipated and unanticipated times in flight, radars may illuminate the flight vehicle. In addition, radio frequency transmissions can be received by and emitted from the vehicle. Thunder and lightning storms, as well as snow and sleet, can randomly be encountered producing mechanical, thermal, and electrical inputs to the flight vehicle. Considering only rocket systems, we may have partial loss of signal (LOS) while transmitting the desired measurements to the ground. Plume interference during motor burn can be one of the causes. During atmospheric reentry, the extreme temperatures due to aerodynamic heating produce plasma causing progressive LOS and eventual black-out (all communications are temporarily lost). Last, flight test vehicles can contain as much as 50 miles of routed instrumentation wiring. A significant number of these wires carry only millivolt level signals exacerbating the challenge of maintaining an adequate signal/noise ratio.

Keep in mind that every sensor in the flight vehicle is experiencing all of the aforementioned environmental inputs (many concurrently) to some degree, but the goal is that each measuring sensor responds only to the single desired environment it is designed to measure. The other environmental inputs to the sensor are undesired. In addition, at any given time it may never be precisely known what combination of these environments a sensor is encountering. It is also possible that other environments may exist that we haven't even mentioned or anticipated. All of these environments have the potential to influence our measured data in some manner. For the analyst performing measurement uncertainty analysis, much of the above discussion would go under the brief caption of "blunders". However, I prefer to think that the preceding discussion accurately portrays the challenges associated with making meameasurements in the "real world".

Environmental Response Combinations

Testing is preferred in controlled laboratory conditions. However, these controlled laboratory conditions are not always available.

multiple measurements desired

Global Hawk: steady state and transient temperature, condensation, rain, radars, signal transmission, buffeting, strain fields, …

Environmental Response Combinations

Testing is preferred in controlled laboratory conditions. However, these controlled laboratory conditions are not always available.

acceleration desired

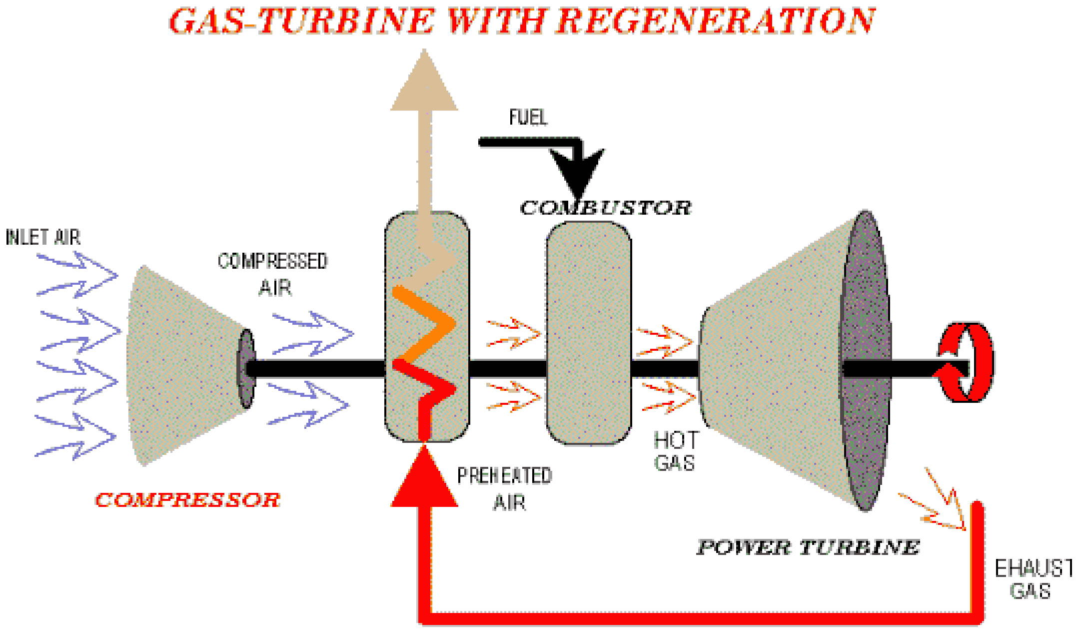
Sandia Labs

modal testing: *temperature, humidity, rfi, base strain, …*

Environmental Response Responses

Testing is preferred in controlled laboratory conditions. However, these controlled laboratory conditions are not always available.

pressure desired



gas turbine: thermal transient, steady state temperature, ionized gases, strain, accel-eration, pickup on cables,…

Environmental Response Combinations

Testing is preferred in controlled laboratory conditions. However, these controlled laboratory conditions are not always available.

pressure desired

Sandia Labs

shock tube: thermal transient, ionized gases, strain, moisture, pickup on long lines, …

Pressure Transducer Outputs are Combinations of Responses to Environments

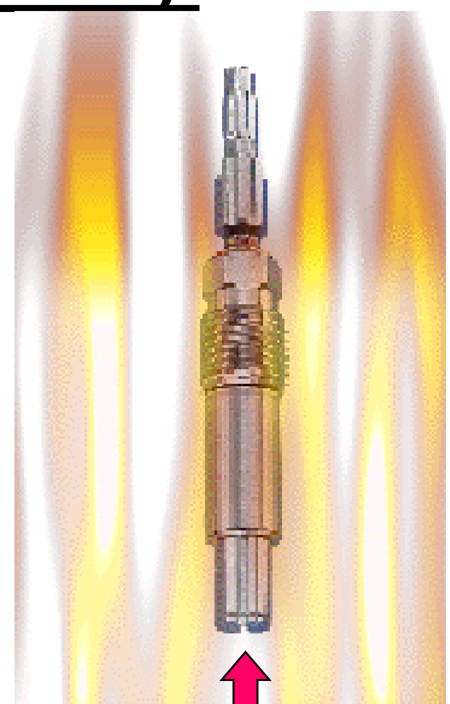
FROM ISA 37.10 (PIEZOELECTRIC PRESSURE TRANSDUCERS):

& ACCELERATION!

STEADY STATE TEMPERATURE

TRANSIENT TEMPERATURE

ETC.



PRESSURE

AMBIENT PRESSURE

CABLE NOISE

Accelerometer Outputs are Combinations of Responses to Environments

FROM ISA 37.2 (PIEZOELECTRIC ACCELEROMETERS) :

& ACOUSTIC PRESSURE!

STEADY STATE TEMPERATURE

HUMIDITY

ACCELERATION!

TRANSIENT TEMPERATURE

NUCLEAR RADIATION

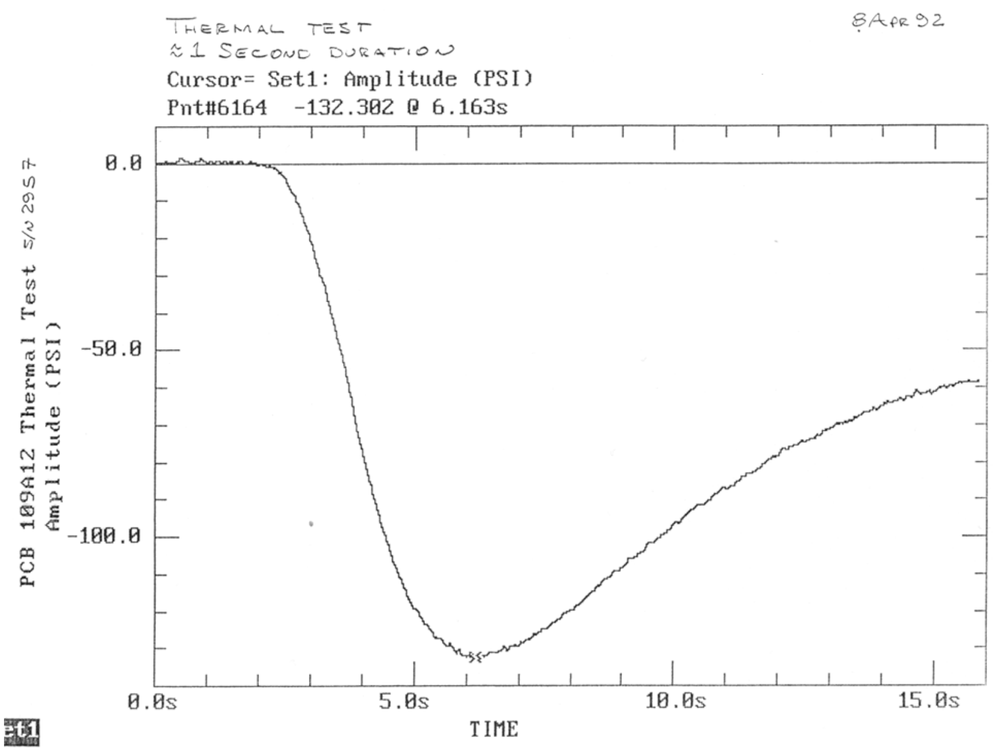
RFI

ELECTROMAGNETIC INTERFERENCE

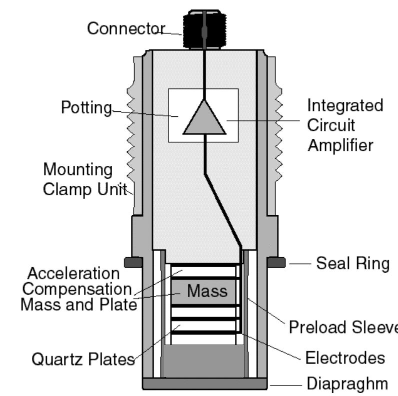
ACCELERATION

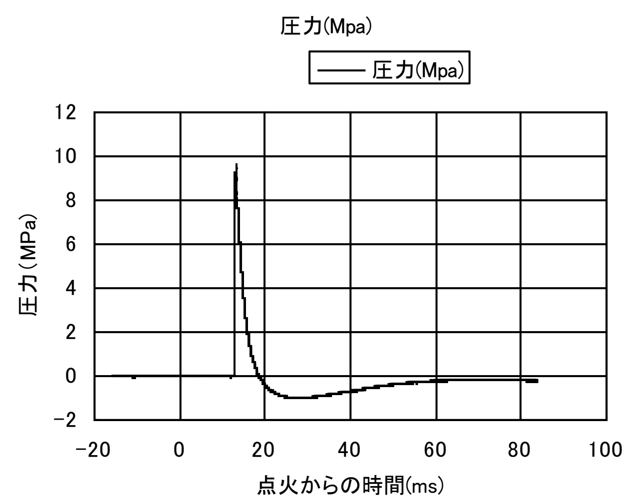
ETC.

e.g., Undesired Thermal Response in Quartz Pressure Transducer



Thermal input to pressure transducer

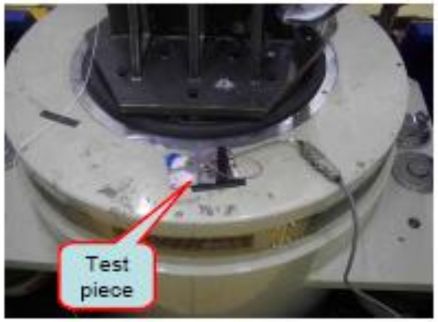




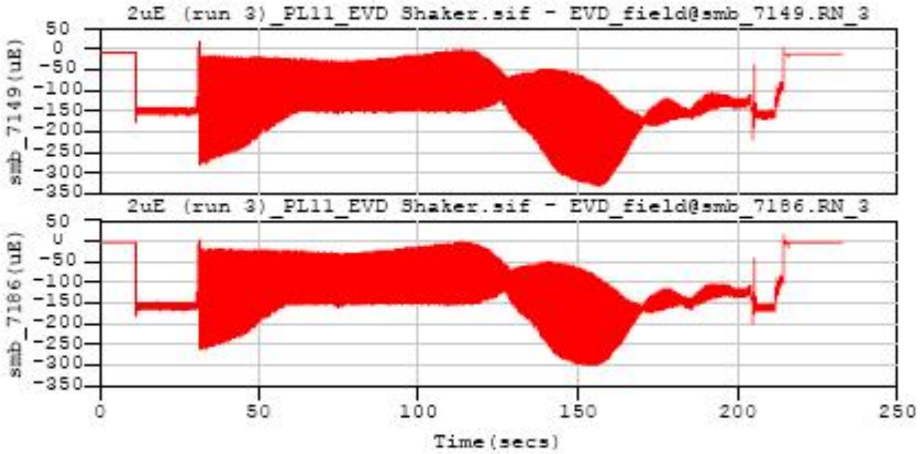
and even in Japan (MPa)

e.g., Undesired Magnetic Fields Response in a Strain Gage

EVD shaker is electromagnetic vibration device, and electromagnetic interference (EMI) effects strain gauge greatly.

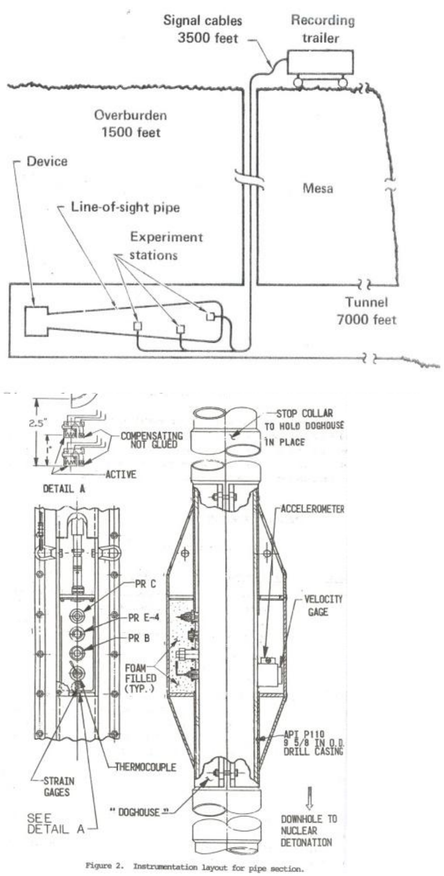


It is about 300 uE during sweeping test using quarter bridge.

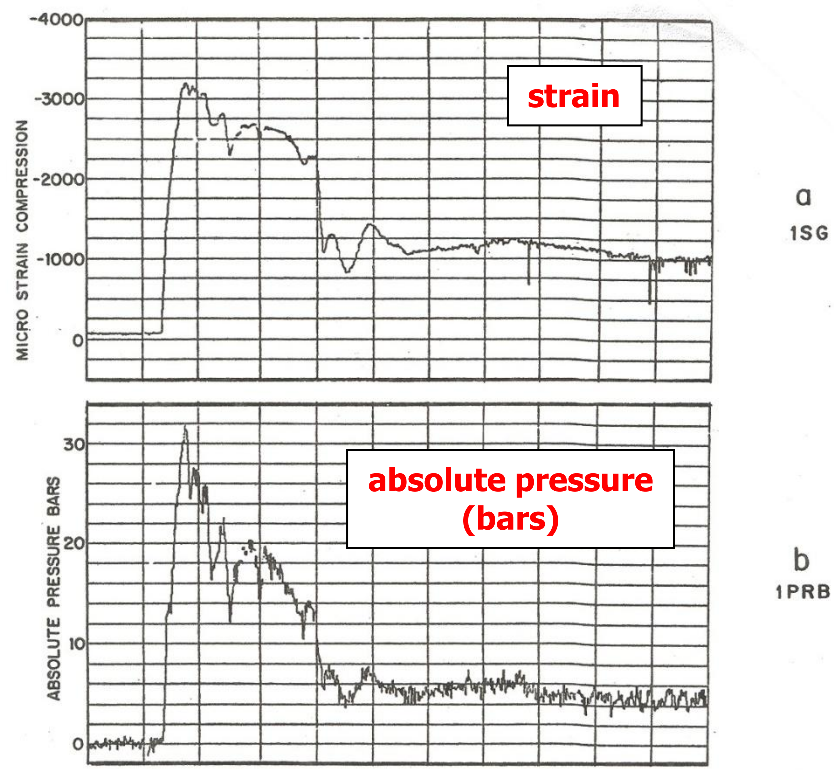


Tenneco/2009

e.g., Undesired Strain Response in a Resistance Based Pressure Transducer



Line of sight pipe



0 milliseconds 500

Olsen, Strain Sensitivity of Pressure Transducers in a Dynamic Environment, 8th Transducer Workshop

A test example

Base Strain Errors in Modal Testing – One Example

PARENT STRUCTURE - VERY COMPLIANT, SHELL-TYPE, LOW-FREQUENCY
STRUCTURE

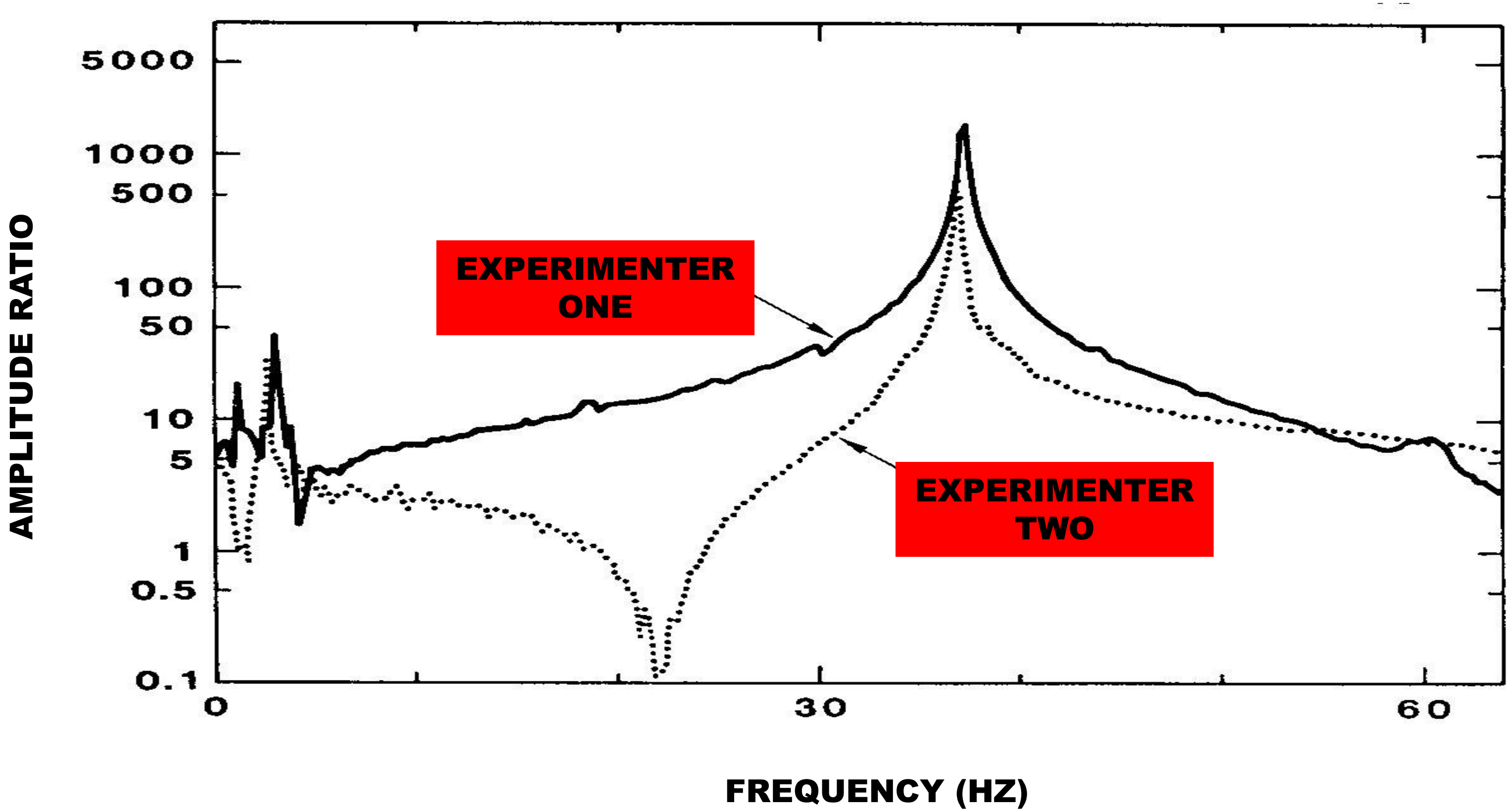
- ONE GRAM ACCELEROMETERS WERE RIGIDLY ATTACHED TO THE STRUCTURE AND MODAL TESTING WAS PERFORMED BY EXPERIMENTER #1

- EXPERIMENTER # 2 TRIED TO REPLICATE RESULTS OF EXPERIMENTER #1 AT A LATER DATE WITH DIF-FERENT ACCELEROMETERS (ONE GRAM COMPRESSION VERSUS SHEAR TYPE)

- *DIFFERENT RESULTS WERE OBTAINED!*

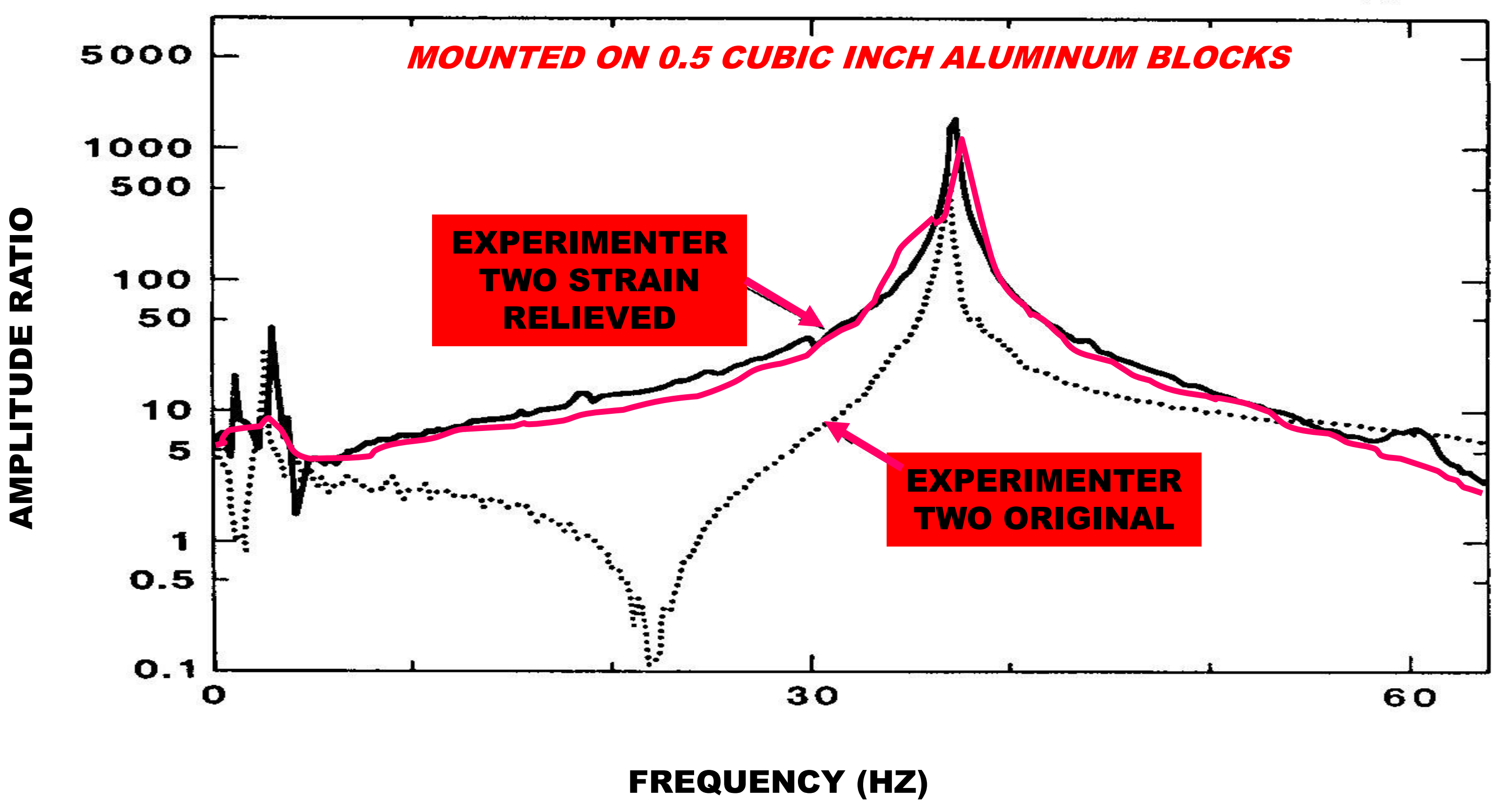
Base Strain Errors in Modal Testing – One Example

BOTH EXPERIMENTER'S RESULTS:



Base Strain Errors in Modal Testing – One Example

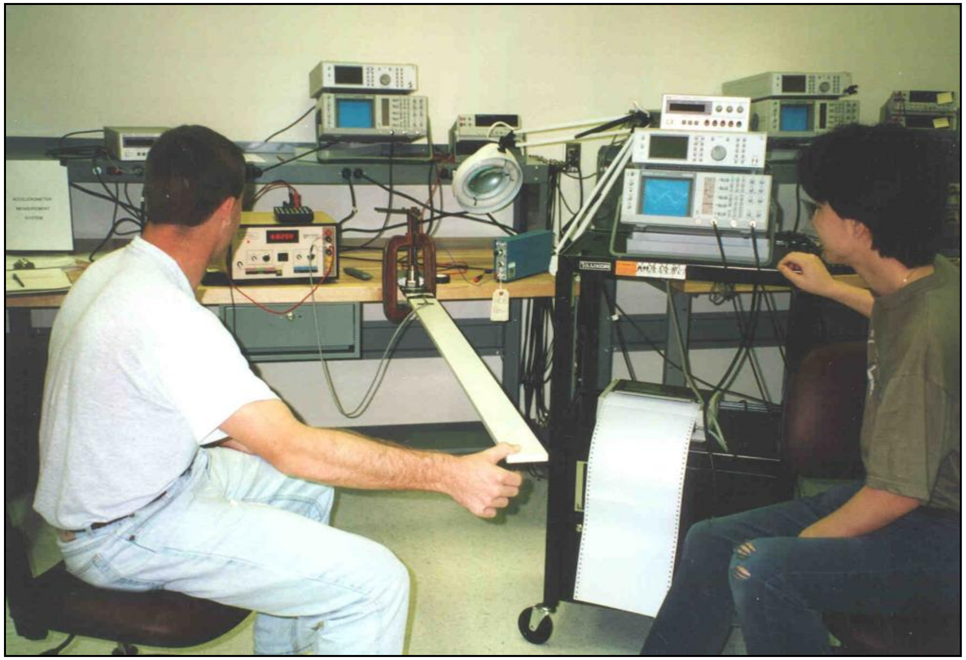
EXPERIMENTER #2'S ACCELEROMETERS STRAIN RELIEVED:



Base Strain Errors In Modal Testing – An Explanation

IN GENERAL: STRAIN MINIMUMS CAN OCCUR AT ACCELERATION MAXIMUMS, THE OPPOSITE CAN OCCUR, OR ANY SITUATION IN BETWEEN CAN OCCUR. WHEN TESTING COMPLEX STRUCTURES, THEIR ACCELERATION OR STRAIN DISTRIBUTION CANNOT BE ANTICIPATED!. ***In the preceding experiment, Experimenter #2's accelerometers were strain sensitive!***

Base Strain Errors In Modal Testing



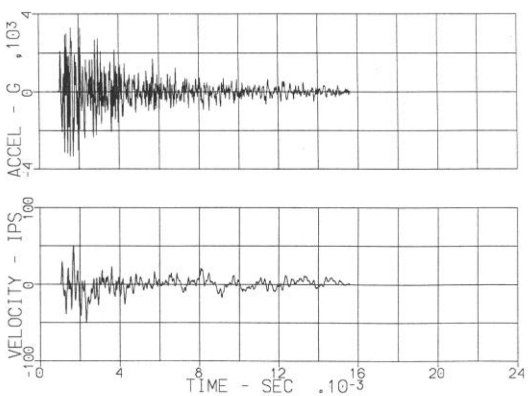
TCU

Test methods for intercomparison of base strain in accelerometers exist.

QUESTION: Should **ACCURACY** or **VALIDITY** be the first concern?

In some situations the discussion changes from how accurate are the data to do the data mean anything at all?

Answers Needed to Validate Data: One Example



Assume:

- an uncertainty analysis has been perform-ed and channel error bounds assigned
- and, the latest micro-P controlled DAQ has ideally digitized the test record shown to megabits resolution at a sample rate approaching infinity and it somehow gets transmitted and recorded.

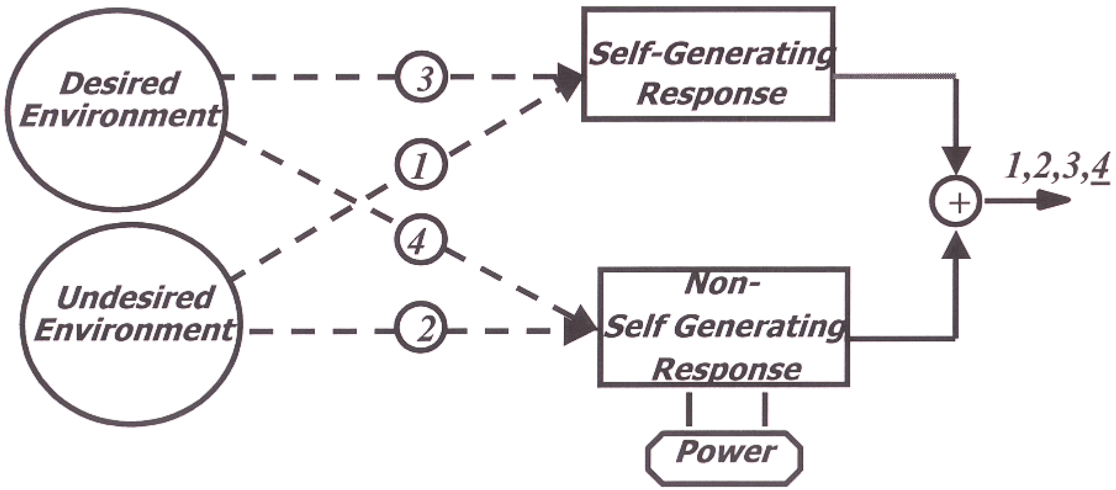
These questions remain:

1) Is the transducer responding only to its desired environment or are the data contaminated by other environments?
2) Is the signal frequency content compatible with the recording capability of the data acquisition system?

Deal with Question #1: Is the transducer responding only to its Desired Environment?

Non-self Generating Transducer Model (Impedance Based ΔL, ΔC, ΔR)

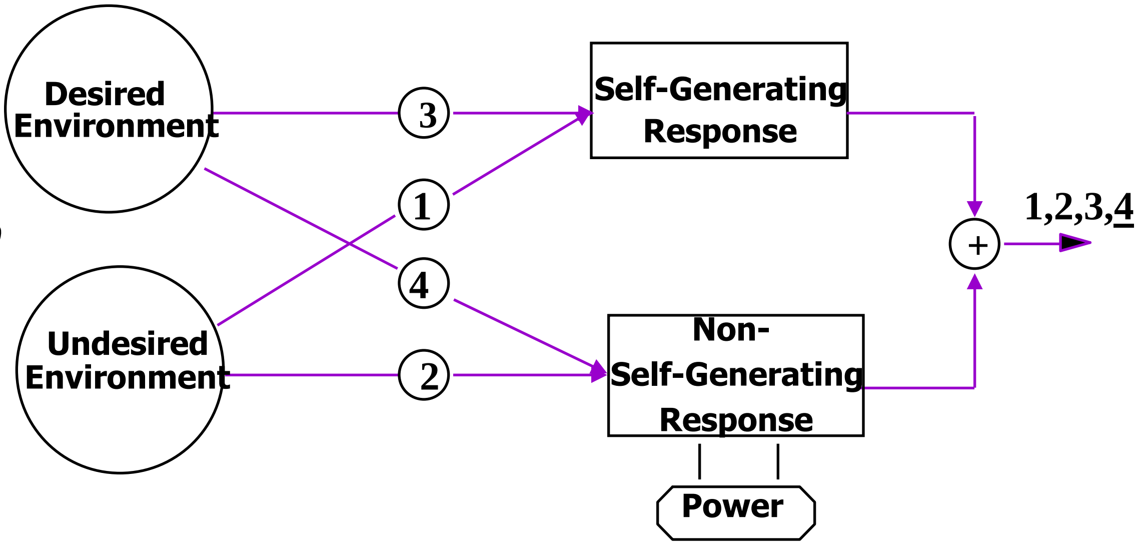
Response Type	Environmental Input
Non-self generating	*Desired*
Self-generating	*Undesired*



Noise Documentation Channel Example (Bridge type)

e.g., Metal Strain Gage (e.g. strain [desired] and temperature [undesired] responses)

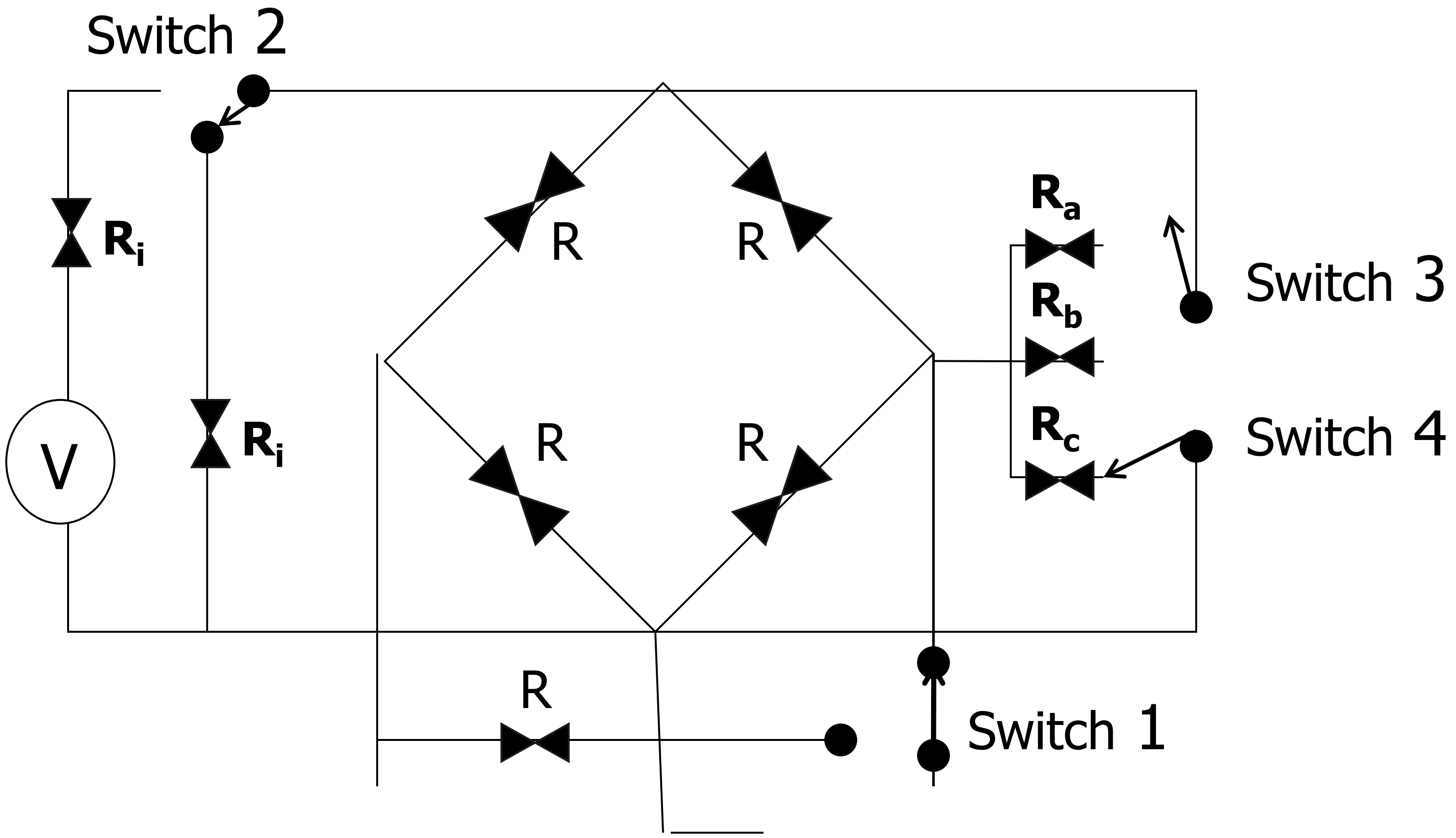
Ref. Stein, ISBN 1-881472-00-0



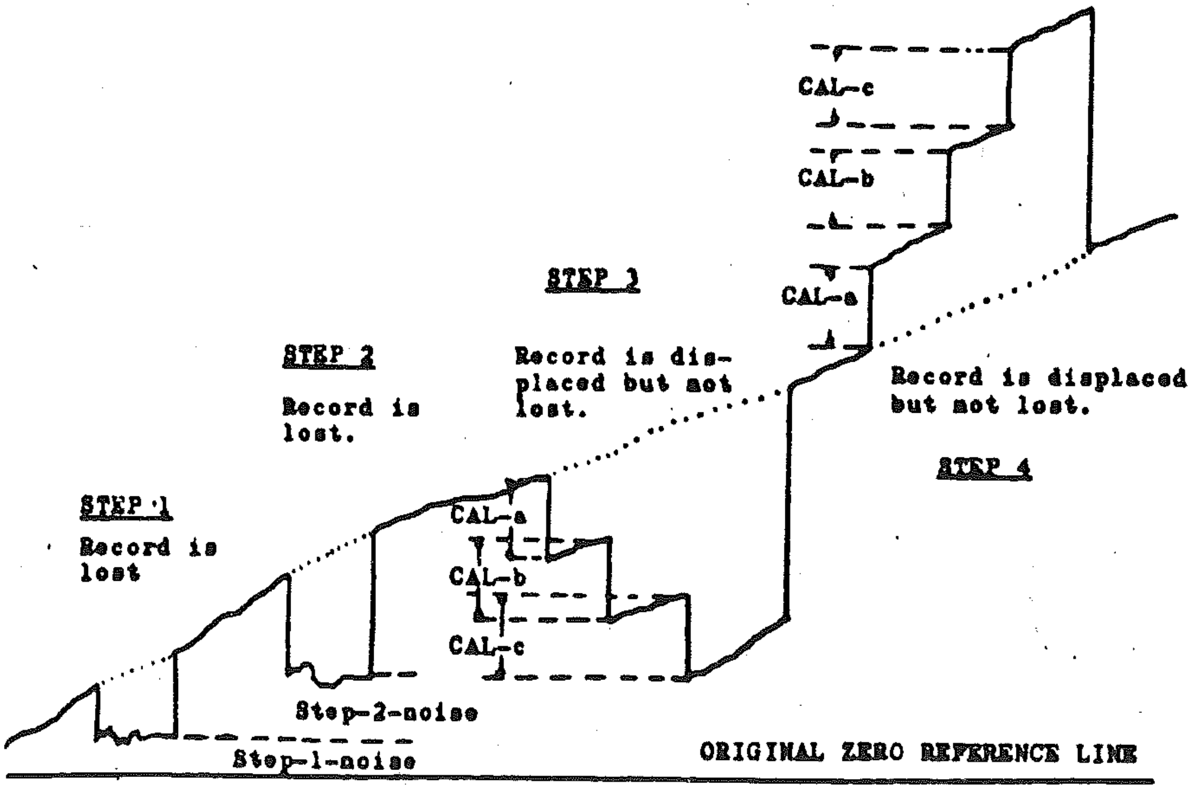
path 4: signal
path 1: thermoelectric (noise)
path 2: thermoresistive (noise)
path 3: piezoelectric (noise)

kill power → paths 1,3
(field unpowered strain bridge)
remove desired environment → paths 1,2
(field mechanically isolated strain gage)
field hard mounted and powered strain gage → paths 1,2,3,**4**

An In-Flight Implementation Scheme



Implementation



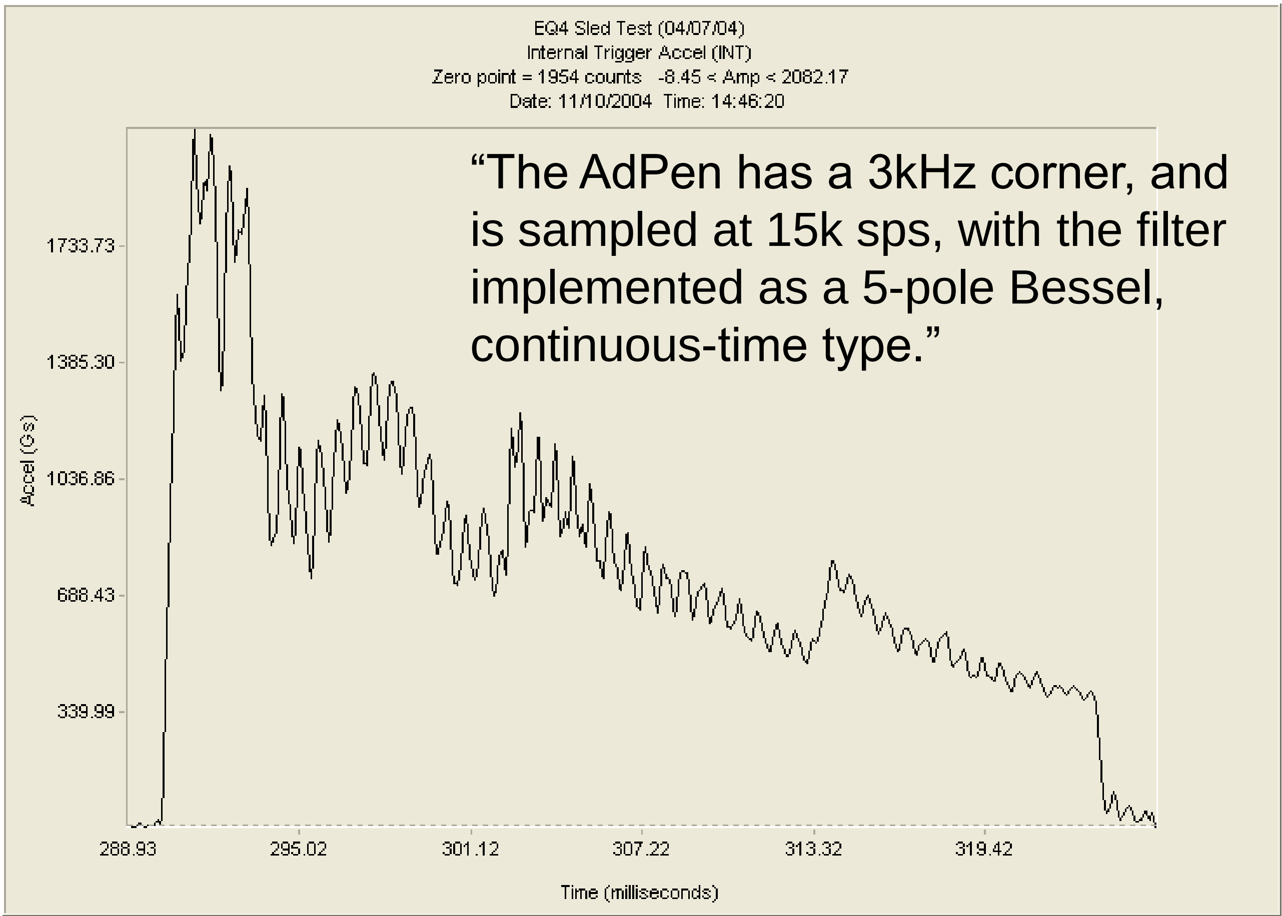
SIMPLE SEQUENTIAL SWITCHING SYSTEM FOR RECORDING PRESENCE/ABSENCE OF NOISE LEVEL, AND SYSTEM CALIBRATION AND LINEARITY AT THE OPERATING POINT.

PR Noise Documentation Example: Self-Generating

The following example was provided by Mike Partridge, Senior Member of the Technical Staff, Sandia National Laboratories, on November 16, 2004. Mike graciously sponsored a course at Sandia under TCU's Extended Ed Department in May 2004. Mike designs and builds data recording systems for penetrators. The AdPen is a legacy system and the AdPen-NV a developmental system. Mike's quotes follow:

"The AdPen-NV and AdPen were used in two separate tests, but with very similar test conditions. Both were fired in a 71-pound penetrator from a gas gun into 6 ksi reinforced concrete (since the targets were so old, the assumption is that the concrete was closer to 7ksi). We only have launch data for both tests."

Current Data Recorder – Legacy System



“The AdPen has a 3kHz corner, and is sampled at 15k sps, with the filter implemented as a 5-pole Bessel, continuous-time type.”

Provided courtesy Mike Partridge, SNL, 11/16/2004

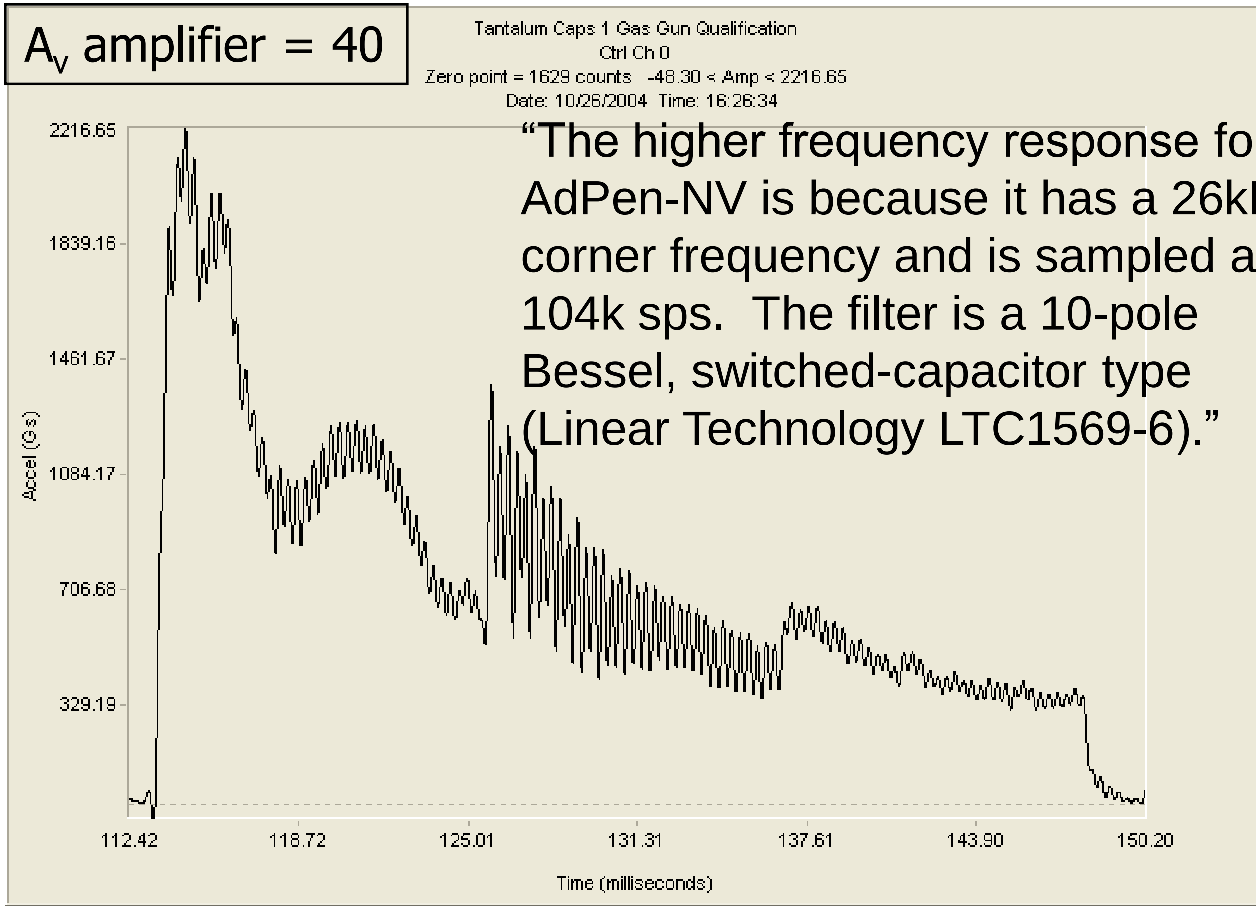
Why Is The Legacy System Believed?

"we have done experiments on a rocket rail where we could confirm measurements using external instrumentation cabled to the unit. Secondly, dummy channels on it show 0.1 mV or less at impact."

Provided courtesy Mike Partridge, SNL, 11/16/2004

New AdPen-NV Data Recorder

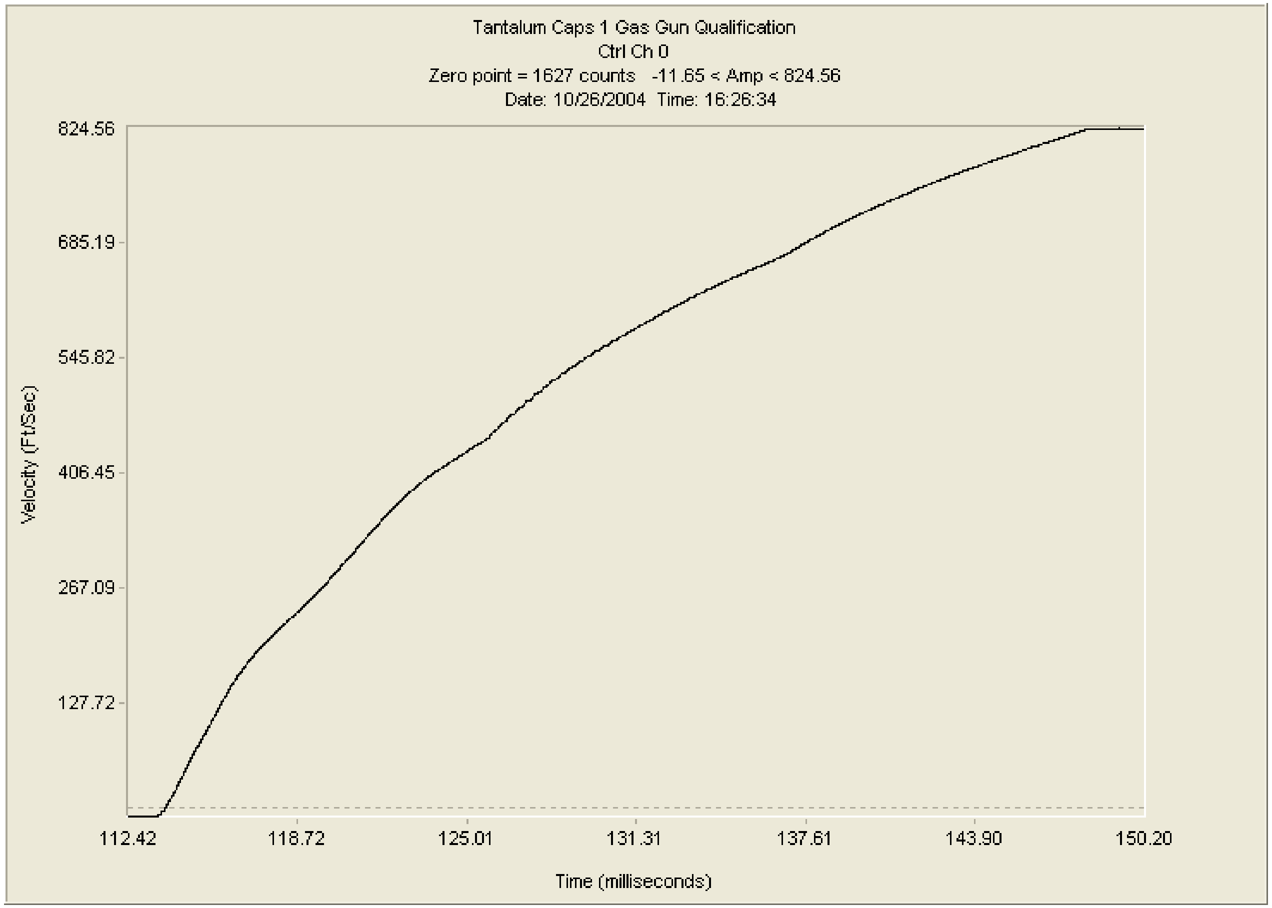
A_v amplifier = 40



"The higher frequency response for AdPen-NV is because it has a 26kHz corner frequency and is sampled at 104k sps. The filter is a 10-pole Bessel, switched-capacitor type (Linear Technology LTC1569-6)."

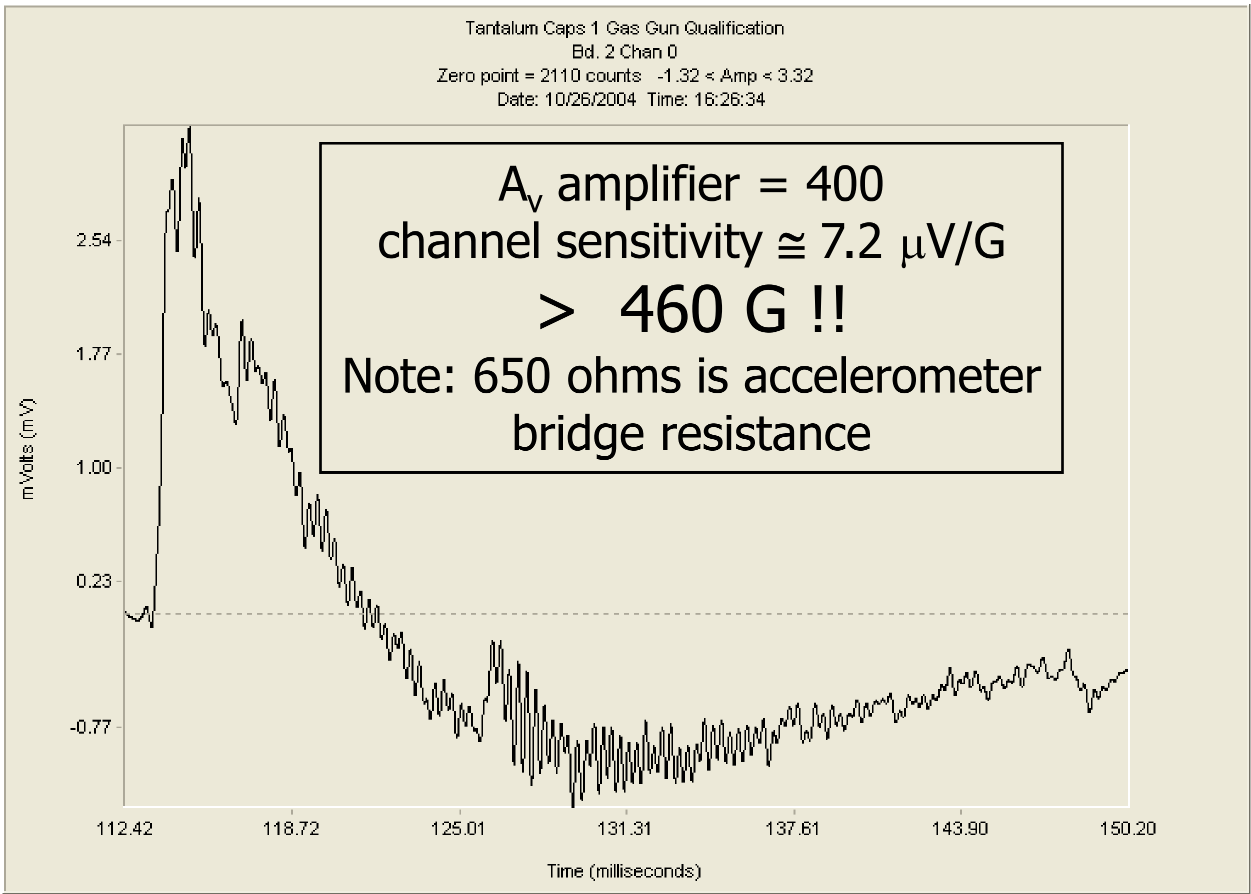
Provided courtesy Mike Partridge, SNL, 11/16/2004

AdPen-NV Data Recorder Integration



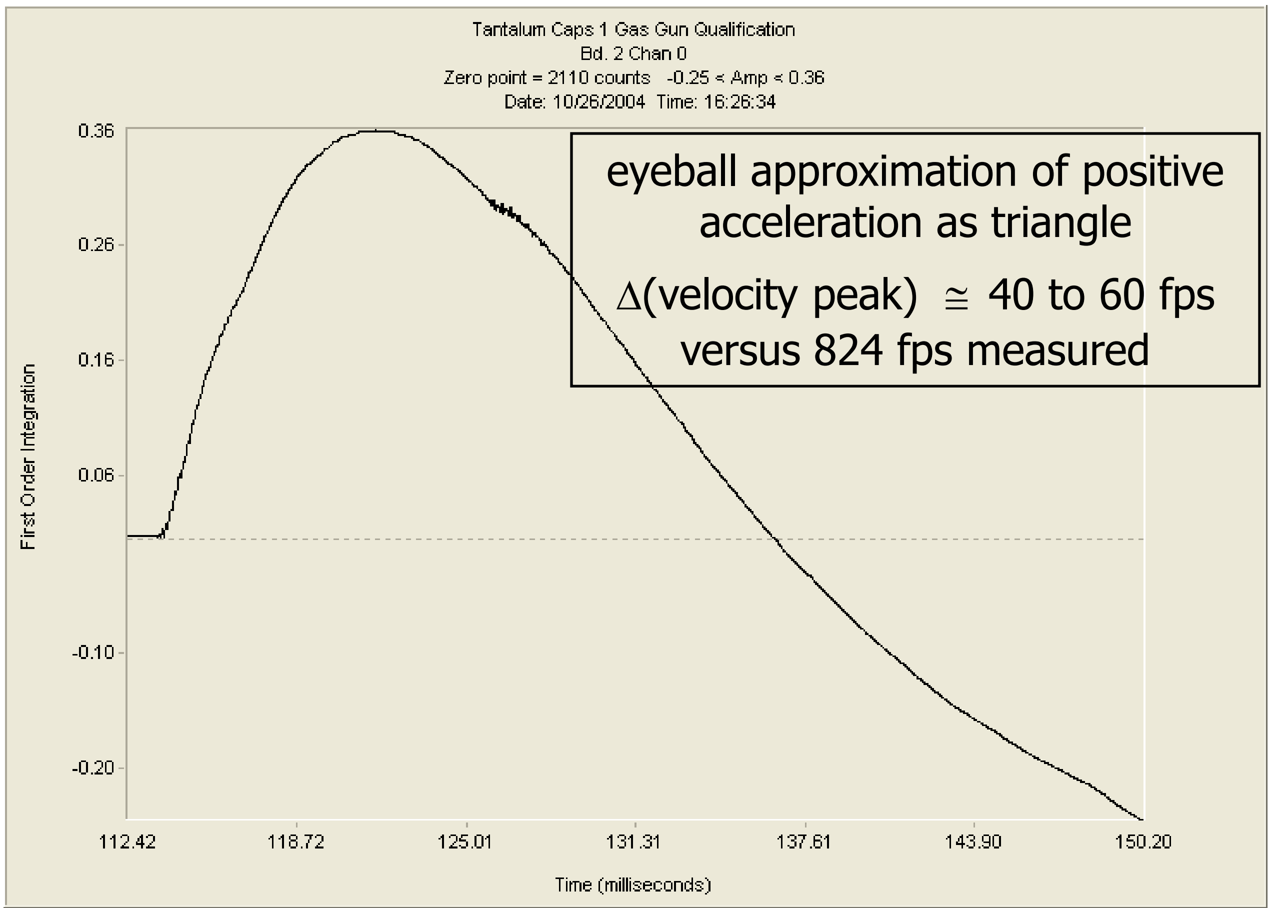
Provided courtesy Mike Partridge, SNL, 11/16/2004

AdPen-NV Recorder; 650 Ohm R_{input} Dummy Channel



Provided courtesy Mike Partridge, SNL, 11/16/2004

AdPen-NV Recorder 650 Ohm Dummy Channel Integration



Provided courtesy Mike Partridge, SNL, 11/16/2004

Analysis of Dummy Channel

“Our analysis so far based on the flight tests plus additional shock lab tests is that we are seeing a piezoelectric effect in the signal conditioning circuitry ceramic capacitors, plus possibly something similar at high energy levels (>2000G for 10's of milliseconds) in integrated circuits with internal capacitors (in this instance, a switched-capacitor filter).”

Provided courtesy Mike Partridge, SNL, 11/16/2004

Analysis of Dummy Channel

“we've learned that even tantalum capacitors have some piezoelectric effect, but supposedly orders of magnitude lower than X7R or Y5V ceramics. Our penetrator instrumentation design rules have been modified to use film capacitors where possible, tantalum for large capacitance, and the only use of ceramic capacitors on the analog side C0G dielectrics for filters.”

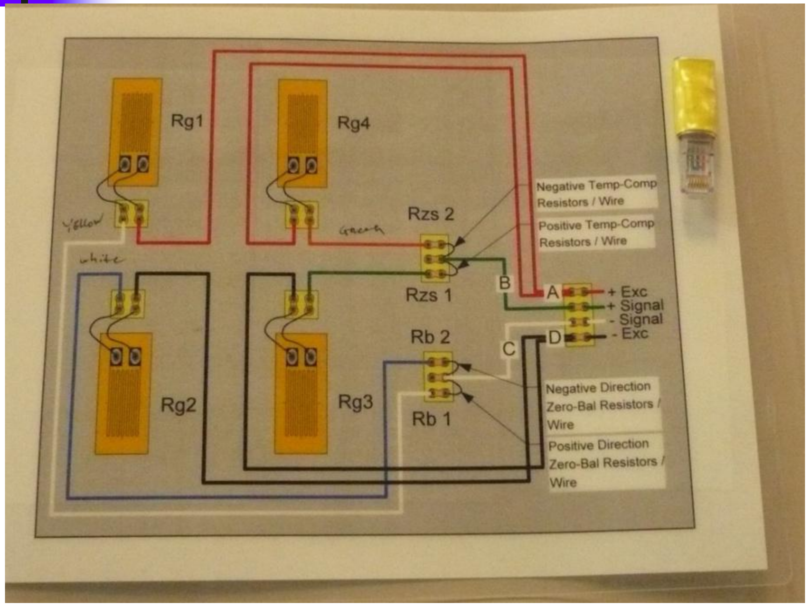
Provided courtesy Mike Partridge, SNL, 11/16/2004

Analysis of Dummy Channel

"The dummy channel error seems to correlate well with the assumed testing error. In the last gun test the axial acceleration integrates to produce the independently measured exit velocity from the gun barrel to within 1%. Previously, we would have accepted that as proof the instrumentation worked properly. The dummy channel error does not integrate to zero over the acceleration pulse, so maybe there was a fortuitous cancellation."

Provided courtesy Mike Partridge, SNL, 11/16/2004

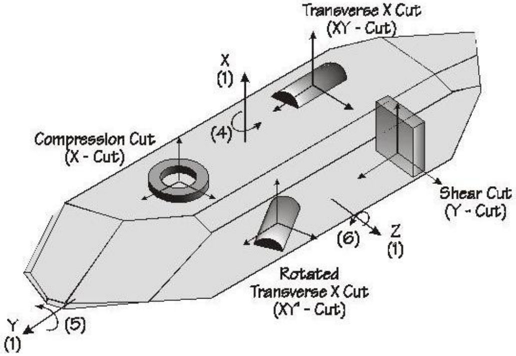
Boeing Implementation, May 2009 (Renton, WA)



Remove the desired input: non-self generating transducer

Self Generating Piezoelectric Type Transducer Noise Validation

Quartz Boule



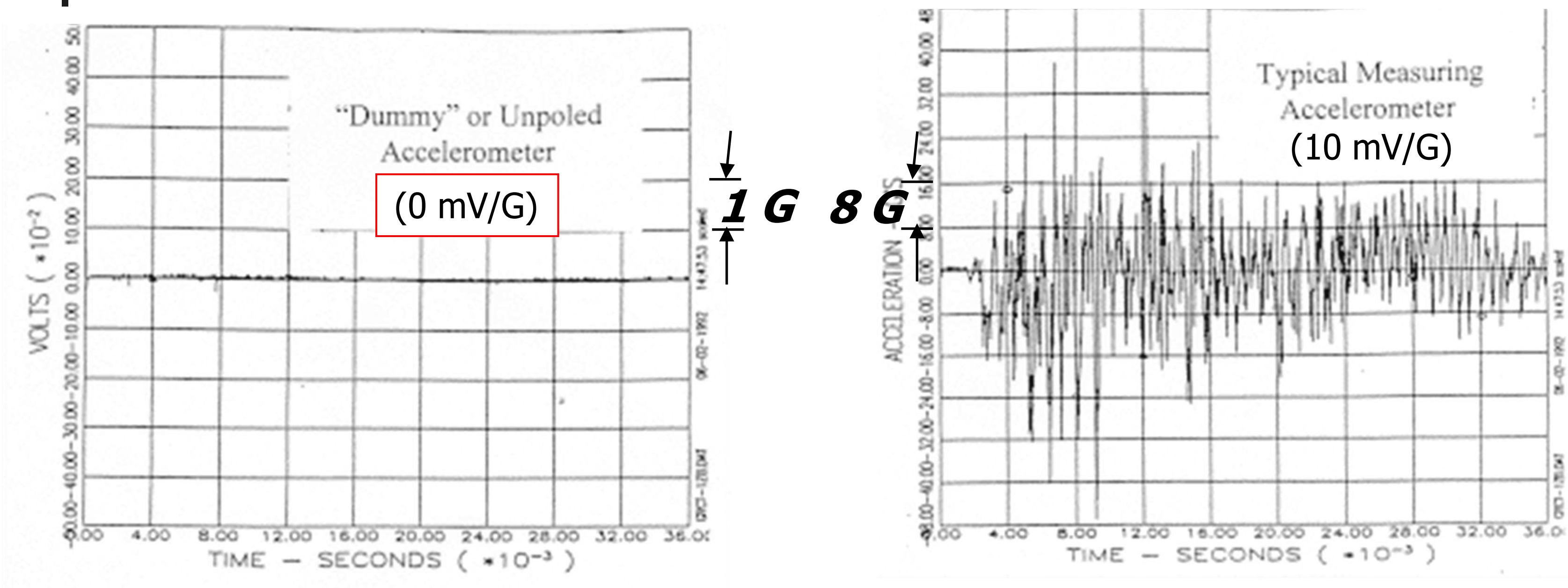
Poling Ceramics

$$P_{xx} = d_{11}\sigma_{xx} - d_{11}\sigma_{yy} + 0\,\sigma_{zz} + d_{14}\tau_{yz} + 0\,\tau_{zx} + 0\,\tau_{xy}$$
$$P_{yy} = 0\,\sigma_{xx} + 0\,\sigma_{yy} + 0\,\sigma_{zz} + 0\,\tau_{yz} - d_{14}\tau_{zx} - 2d_{11}\tau_{xy}$$
$$P_{zz} = 0\,\sigma_{xx} + 0\,\sigma_{yy} + 0\,\sigma_{zz} + 0\,\tau_{yz} + 0\,\tau_{zx} + 0\,\tau_{xy}$$

where a "P" is a piezoelectric directional constant, a "d" is a piezoelectric coefficient, and a "σ" is a stress component

integrate the piezoelectric material into a "noise monitoring" transducer

IEPE Data Channel (Application Example #1)



noise monitor (NM) channel ***typical data channel***

low impedance (IEPE)

Ref Shay, Lawrence Livermore National Lab

Random Vibration Measurement (Application Example #2)

Statement of Problem:

In the B61, it was desired to measure random vibration to determine its effect on a switch concurrent with parachute deployment. Testing was to be performed on a sled track. Data acquisition would be by RF telemetry.

Anticipated environments:

Acceleration pulse: 150 G, spectral content to 50 Hz
Random vibration: +/- 10 G

Random Vibration Measurement (Application Example #2)

Instrumentation:

(8 ea) Airborne charge amplifiers
-3 dB point @ 2 Hz
(8 ea) Piezoelectric accelerometers
6 active and 2 depolarized
(8 ea) VCOs
(2 ea) RF transmitters at 239.4 & 248.6 MHz
(3 active accelerometers & 1 noise monitor/transmitter)

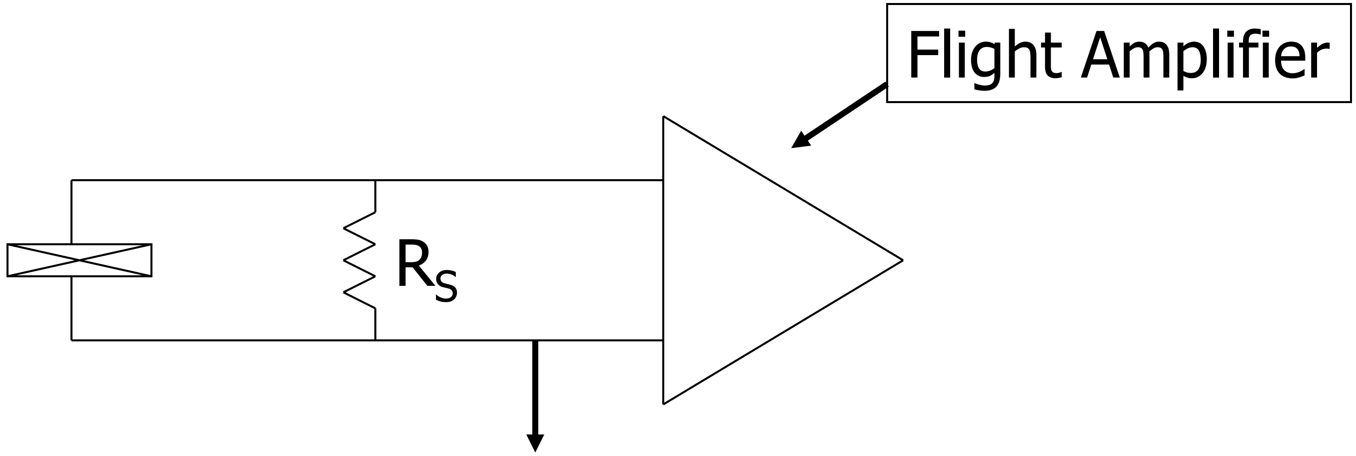
Random Vibration Measurement (Application Example #2)

The challenge was to eliminate the effects of the 150 G parachute pulse from the data to enable adequate amplitude resolution to resolve the anticipated +/- 10 G random vibration. Otherwise, the parachute pulse would saturate the channels.

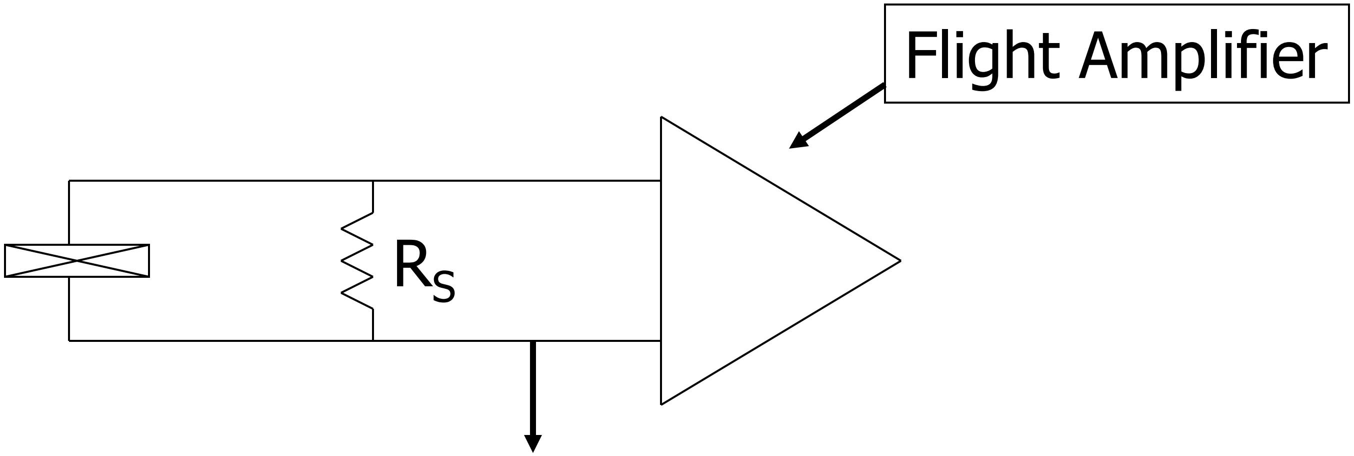
The proposed solution follows.

Random Vibration Measurement (Application Example #2)

The low frequency –3 dB point of the amplifiers was moved to 50 Hz by the addition of shunt resistance (R_S). This should effectively filter (high-pass) out the effects of the parachute pulse.



Random Vibration Measurement (Application Example #2)



Shunt resistance of 6-8KΩ was inserted at a "tee" placed In the coaxial cable of each charge amplifier.

Random Vibration Measurement (Application Example #2)

Eight (8) systems were used and multiplexed into two (2) groups of four (4) through the VCOs. Each set of four (4) VCOs was put into one of the two (2) transmitters. Each set had 3 active accelerometers and one depolarized accelerometer as inputs.

Complication:

Before parachute deployment a gas generator fired. The Effect of this was to saturate all six (6) active accelerometer channels and obscure the event to be recorded. The noise monitor channels also saturated!!!

Random Vibration Measurement (Application Example #2)

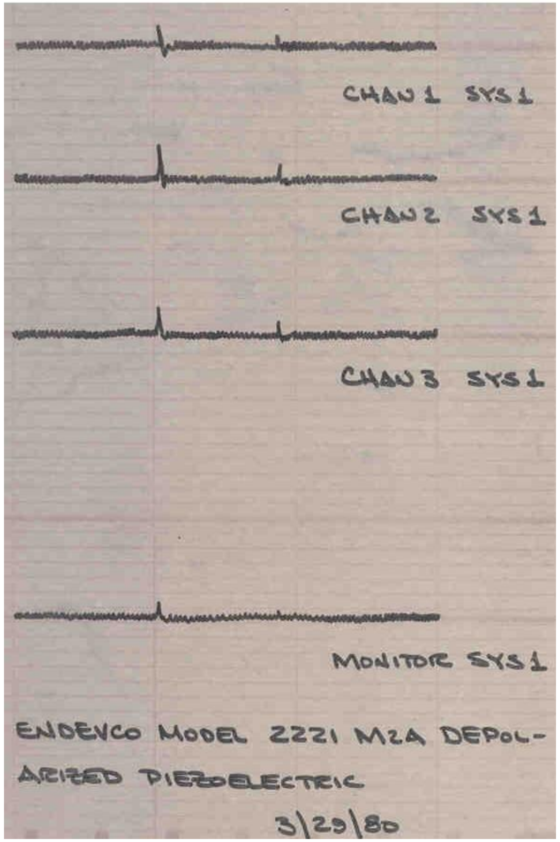
Investigation after the fact:

Post test the 4 accelerometers on the 239.4 MHz transmitter were pulled from the vehicle skin and placed on a metal plate. Hitting the plate with a hammer caused all channels on this transmitter (noise monitor too) to respond. In addition, signals were also coupled into the 246.8 MHz channels!! NO MECHANICAL EXCITATION WAS APPLIED TO THESE??

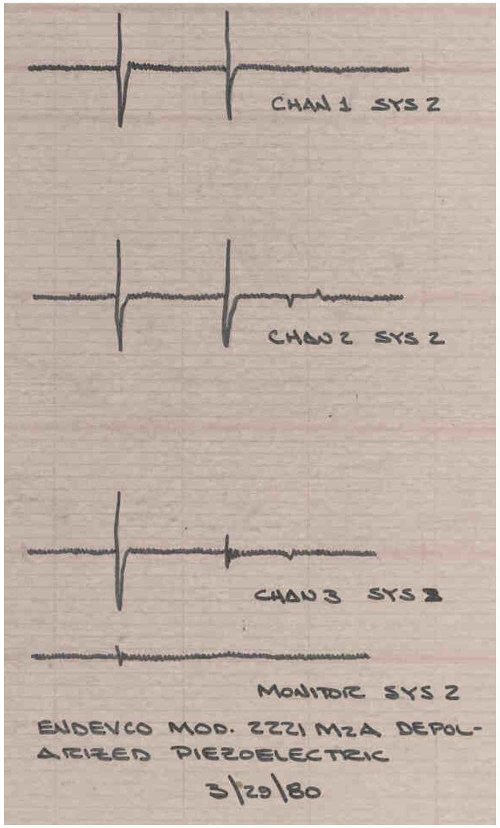
Random Vibration Measurement (Application Example #2)

Investigation results:

239.4 MHz



248.6 MHz

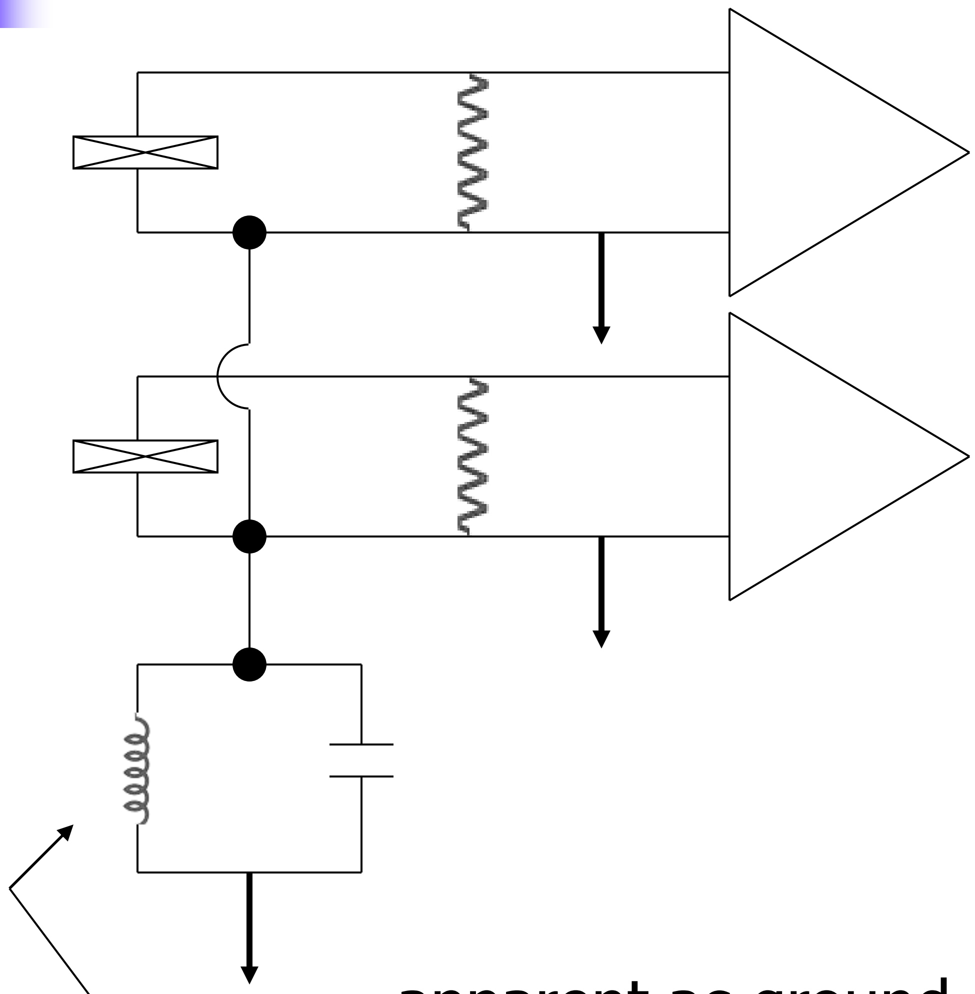


Random Vibration Measurement (Application Example #2)

WHY?

All of the ”tees” in the cables of the accelerometers to both transmitters had been made common to a metal block to which they were all attached. This block was isolated from ground. When hit with a hammer, or the gas generator fires, the accelerometers ring at their 40 KHz resonant frequencies and an apparent ac ground was formed coupling all eight (8) channels together.

Random Vibration Measurement (Application Example #2)



Investigation Results

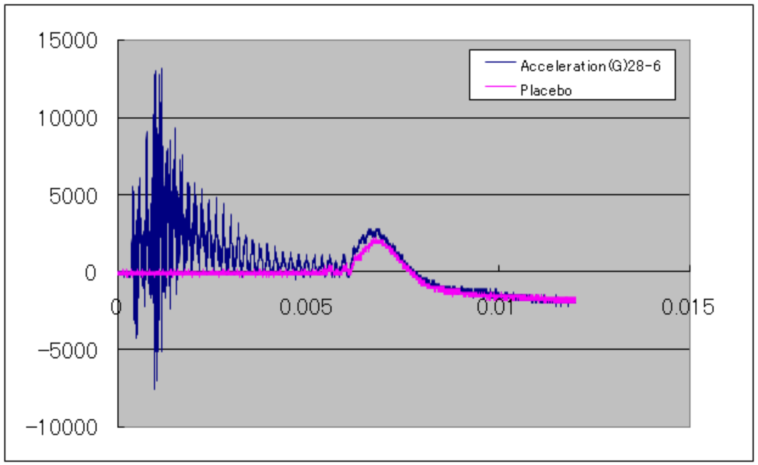
etc. (4 total)

apparent ac ground

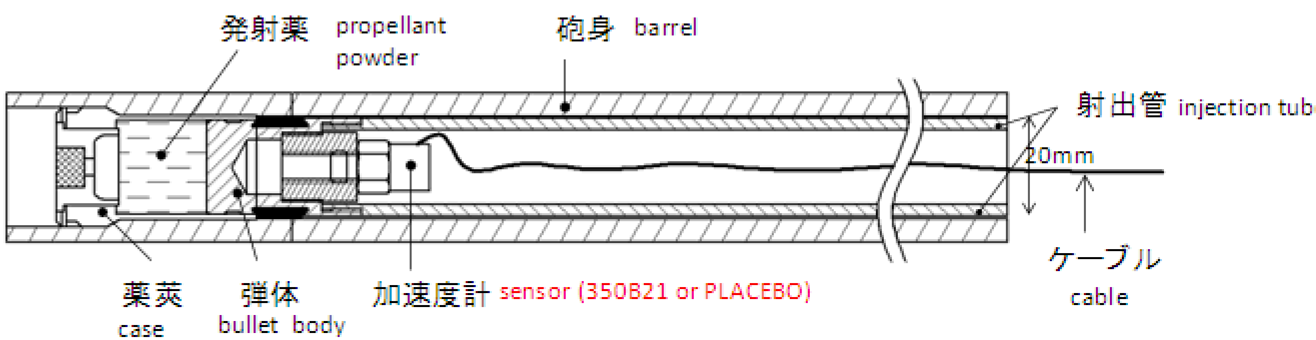
Random Vibration Measurement (Application Example #2)

Due to the check channels in flight, bad data were not accepted as good and corrective action could be taken on subsequent flights.

Application Example #3

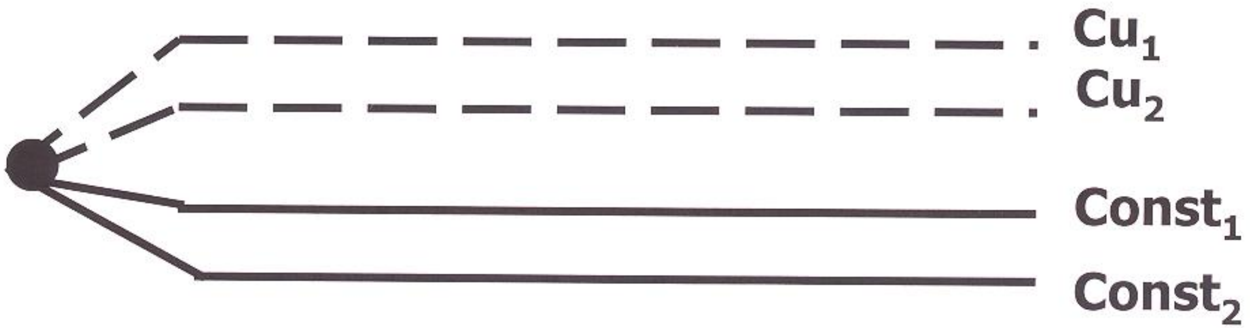


Gun Test Japan April 2010
Placebo is showing a problem exists!



Self Generating Thermoelectric Type Transducer Noise Validation

T/C type is irrelevant



Monitor:

Cu_1-Cu_2: noise

$Const_1$-$Const_2$: noise

Cu_1-$Const_1$: signal

Cu_2-$Const_2$: signal

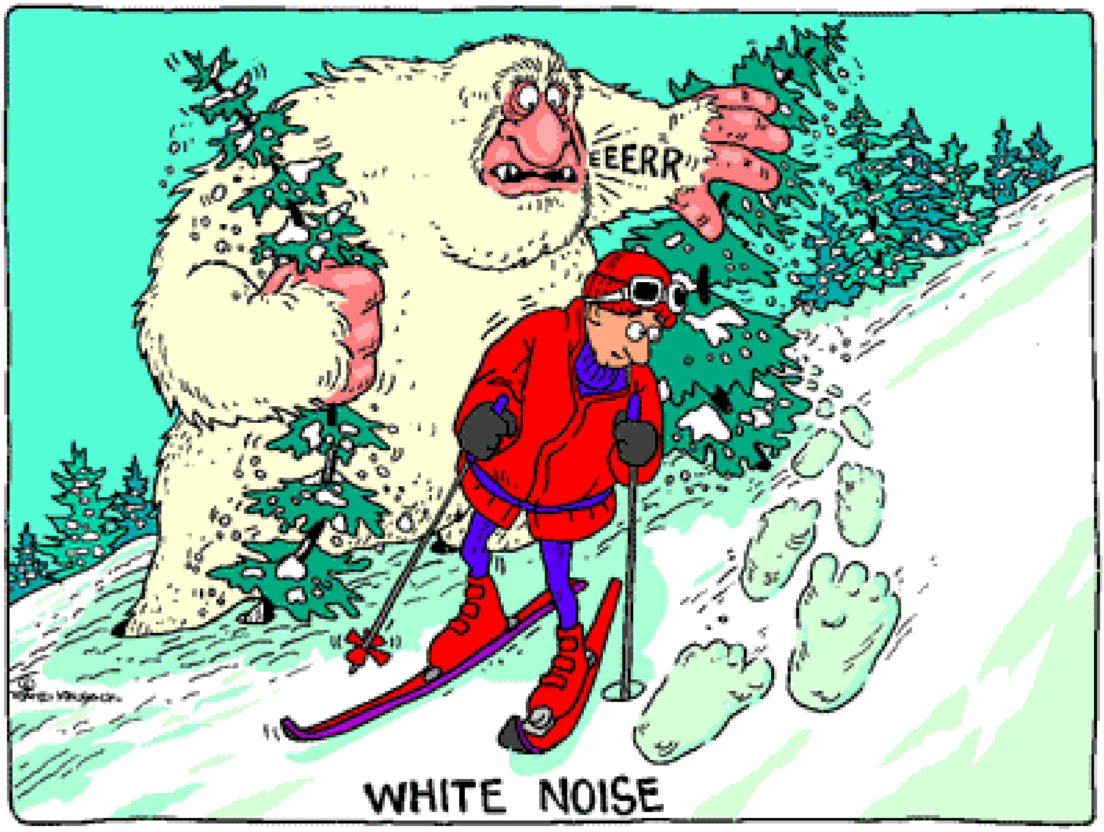
Solutions Exist *Once the Problem is Documented*

Shield: not only undesired electrical inputs
but also undesired thermal, strain, acceleration,
light, acoustic, …

Isolate: bushings for pressure transducers,
accelerometer blocks in high strain gradients, gyros
from vibration inputs, …

Low output impedance piezoelectric sensors: ICP

Frequency translation: carrier systems can move the
signal away from the noise in the frequency domain



In conclusion, please remember:

The noise source can always be defeated once it is identified.