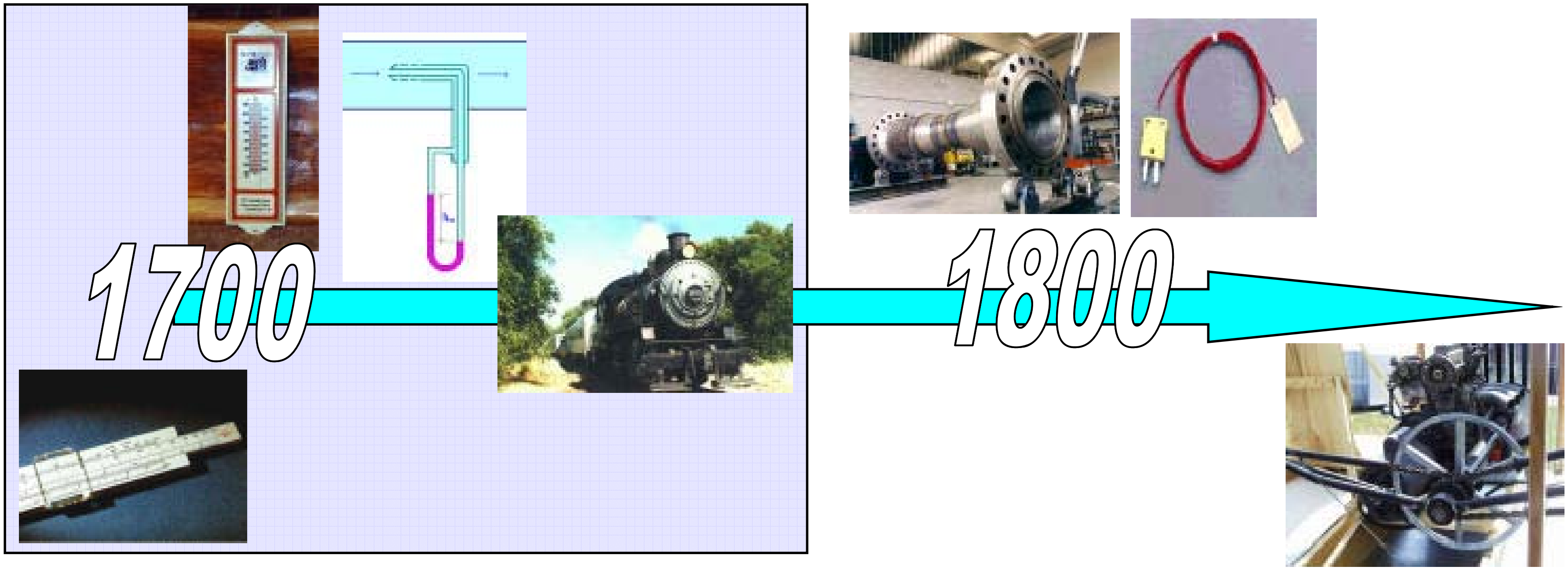
Sensor Applications and Data Validation

Presented at
Alabama A & M University

John Wiley
Marshall Space Flight Center
Advanced Sensors Development and Testing

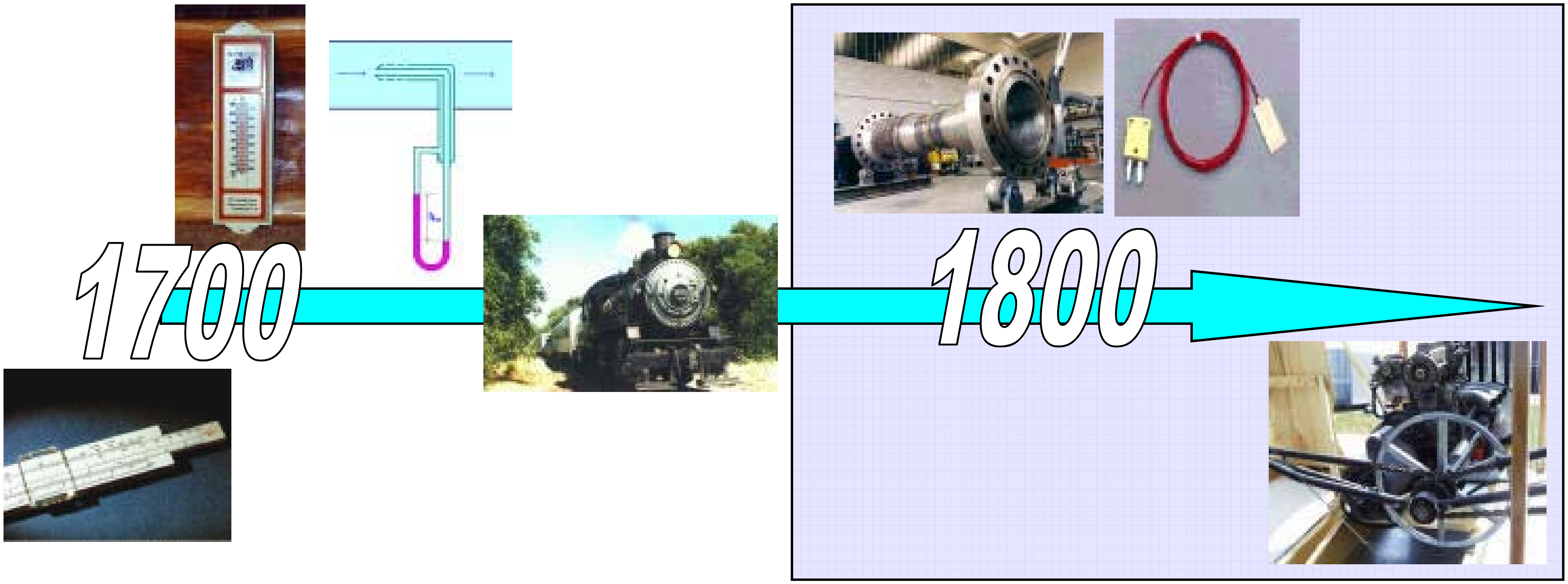
Sensor and Transportation Timeline

Timeline of Sensor and Transportation History



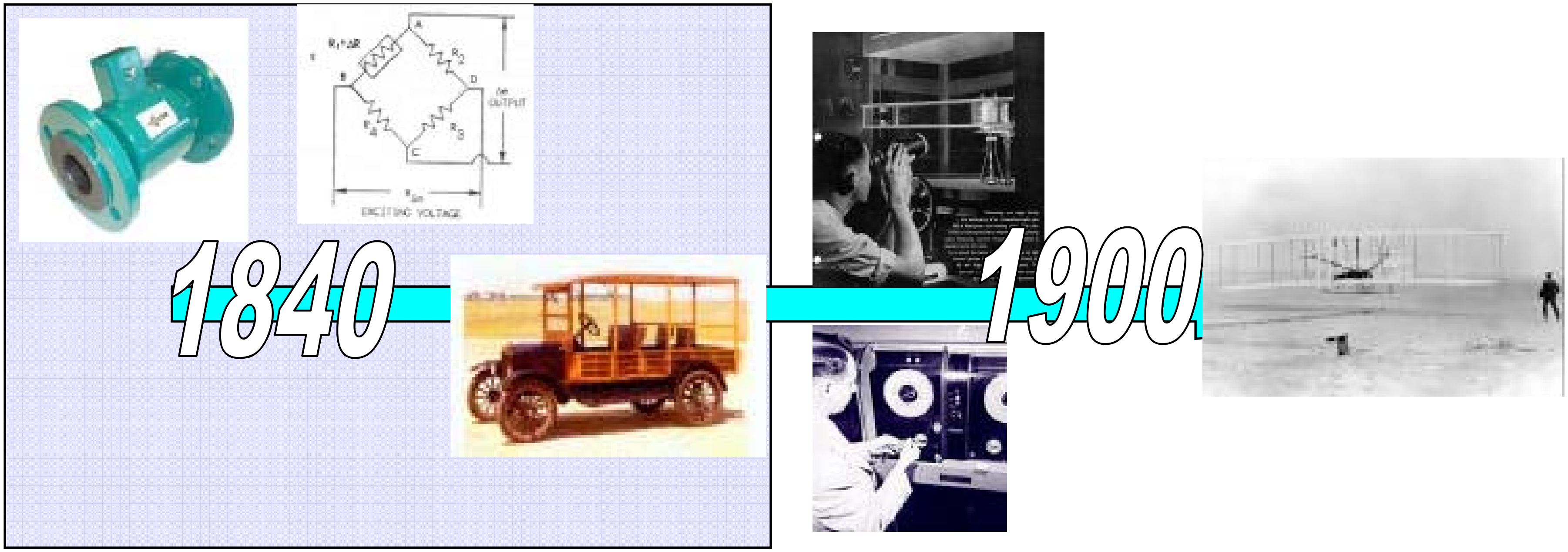
In 1622 the invention of the slide rule along with fundamental physical sensors (thermometer and Pitot tube) led the way for the earliest mechanically fuel propulsion system – ***steam locomotion***.

Timeline of Sensor and Transportation History



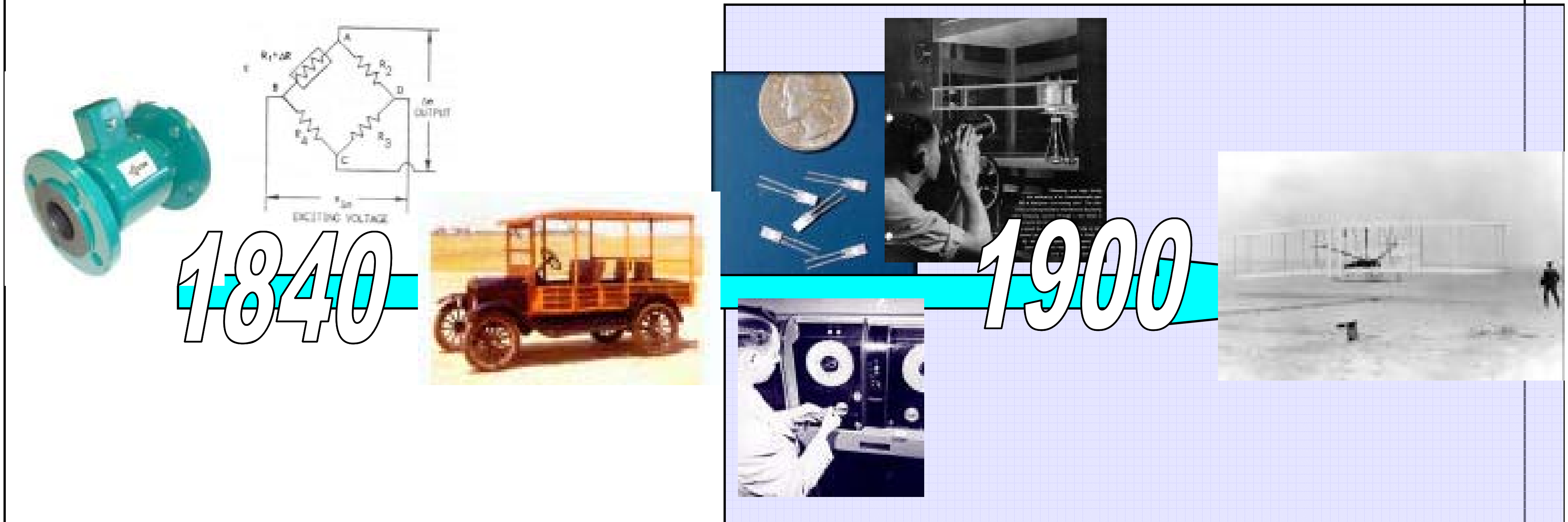
The first ***electric motor*** in 1821 came in use along with the Venturi tube. This year also marked the invention of the thermocouple still in common use today!

Timeline of Sensor and Transportation History



Sensor engineering was revolutionized with the invention of the magnetic flow meter and the Wheatstone bridge. A few decades later the first gasoline powered automobile hit the streets.

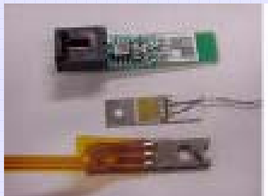
Timeline of Sensor and Transportation History



Man's first powered flight followed on the heels of the earliest magnetic recordings, the resistance thermal device (RTD) and the optical pyrometer.
Still a century to go!

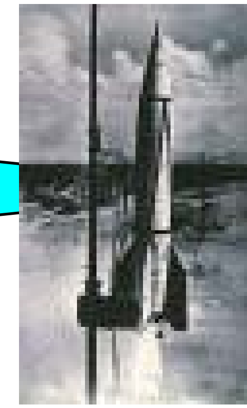
Timeline of Sensor and Transportation History

No significant sensor development



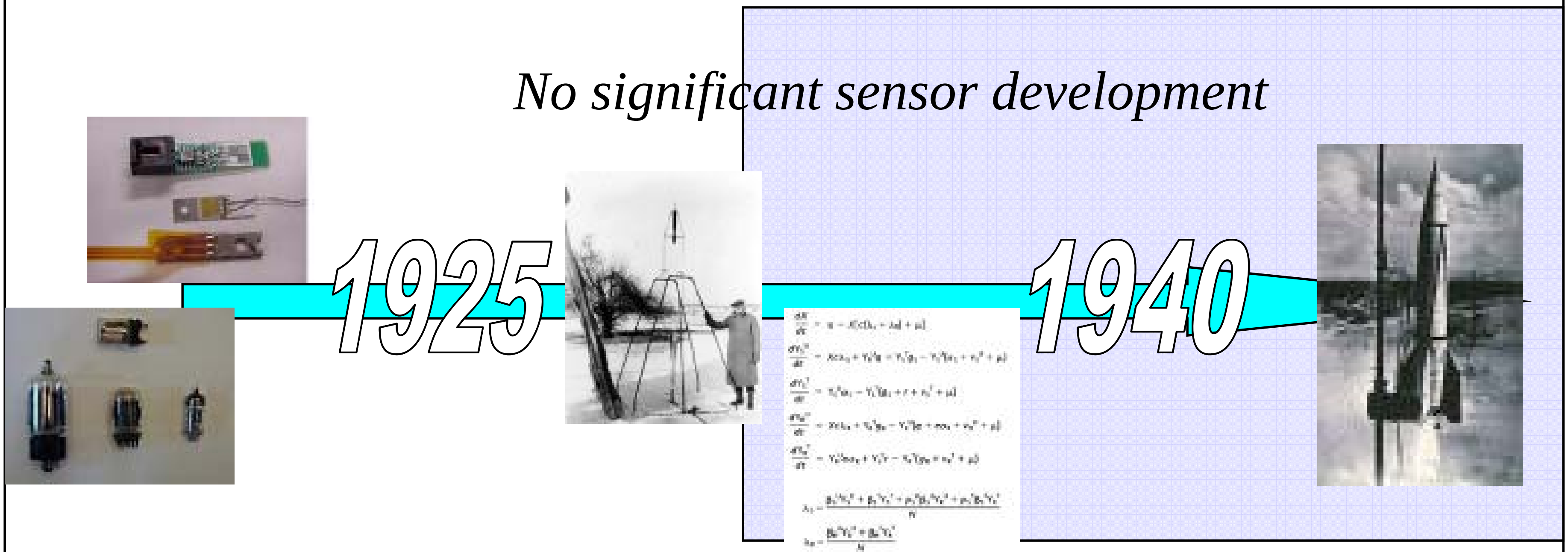

1925


1940



With electronic amplifying tubes and the 1908 development of the strain gauge Man's first steps are taken toward space with the first liquid fueled rocket. Sadly, this also begins a void in fundamental sensors innovation.

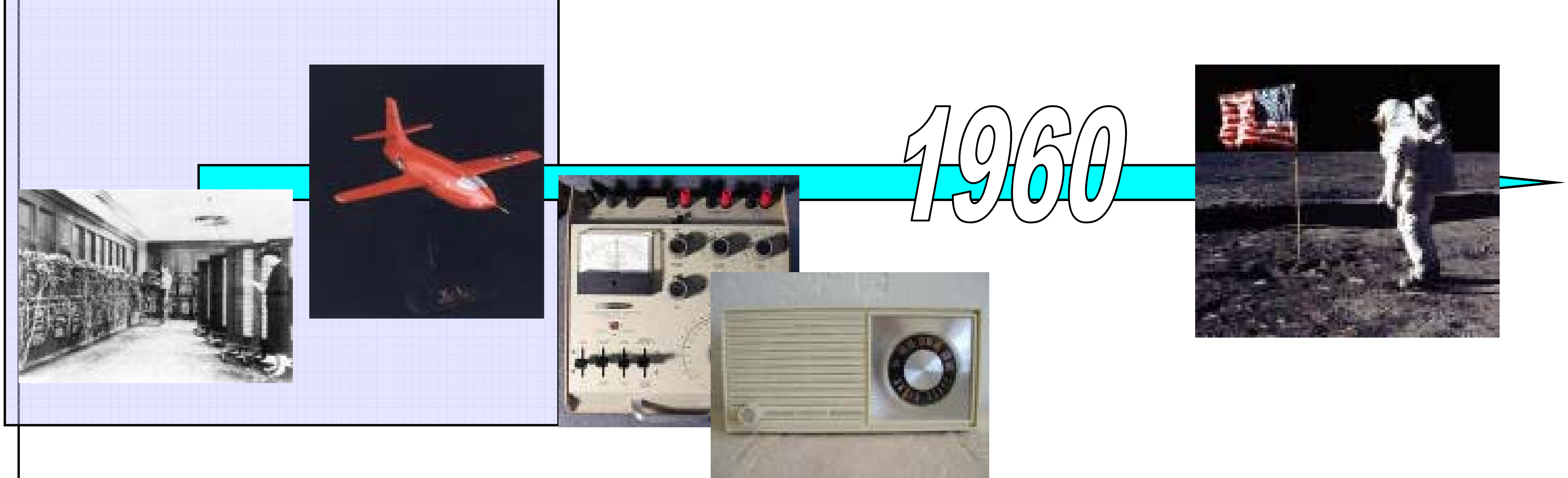
Timeline of Sensor and Transportation History



In 1930 computer solutions to differential equations were available. Existing sensors helped engineer and test larger chemical rockets.

Timeline of Sensor and Transportation History

No significant sensor development



The1947 ***supersonic flight*** followed the creation of the ENIAC. Data systems and supporting electronics continue to advance. Still no significant sensor development!

Timeline of Sensor and Transportation History

No significant sensor development

1960

Enter in the age of the transistor. Electronics are revolutionized. Mankind challenges the Moon. Again, no sensor advancement

Timeline of Sensor and Transportation History

Man's first ***powered flight*** followed on the heels of the earliest magnetic recordings, calculators and optical pyrometer. There is still a century to go!

Sensor Enabled Technology Advancements

The mechanical configuration of automobiles have changed marginally while improvements in sensors and control have dramatically improved engine efficiency, reliability and useful life.

The aviation industry has also taken advantage of sensors and control systems to reduce operational costs.   Sensors and high fidelity control systems fly planes at levels of performance beyond human capability.

Sophisticated environmental controls allow a greater level of comfort and efficiency in our homes.

Sensors have given the medical field a better understanding of the human body and the environment in which we live.

Sensor Applications

Sensor applications are the process of selecting the correct sensor for the desired measurement.

- Define a well thought out measurement problem.
- Define how the data will be used.
- Have an open mind regarding the best solution to the measurements problem. Don't get trapped by "catalog engineering".
- Identify all of the desired parameters to be measured.
- Identify all of the environmental parameters that will affect the measurement.
- Determine a validation plan.
- Determine calibration requirements
- Write a statement and assessment of necessary technical assumptions
- Write a statement and assessment of the risks to the data.

Data Validation

"Valid Data are data that represent the process being observed as though the Measurement System had not been there, interfering with the process being observed and distorting the information flow through the system."

Peter K. Stein

Validation is the process of analyzing the complete measurement system for undesired sensitivities or insensitivities that will distort data.

Sensor Applications

Sensor Applications

Sensor Applications

- What is a Measurement ?
- Measurement Tenets
- The Complete Measurement System
  - Measurand
  - Boundary Layers
  - Sensor Sensitivities
  - Sensor Response

Sensors Measure Physical Parameters

Pressure

Temperature

Flow

Acceleration

Heat Flux

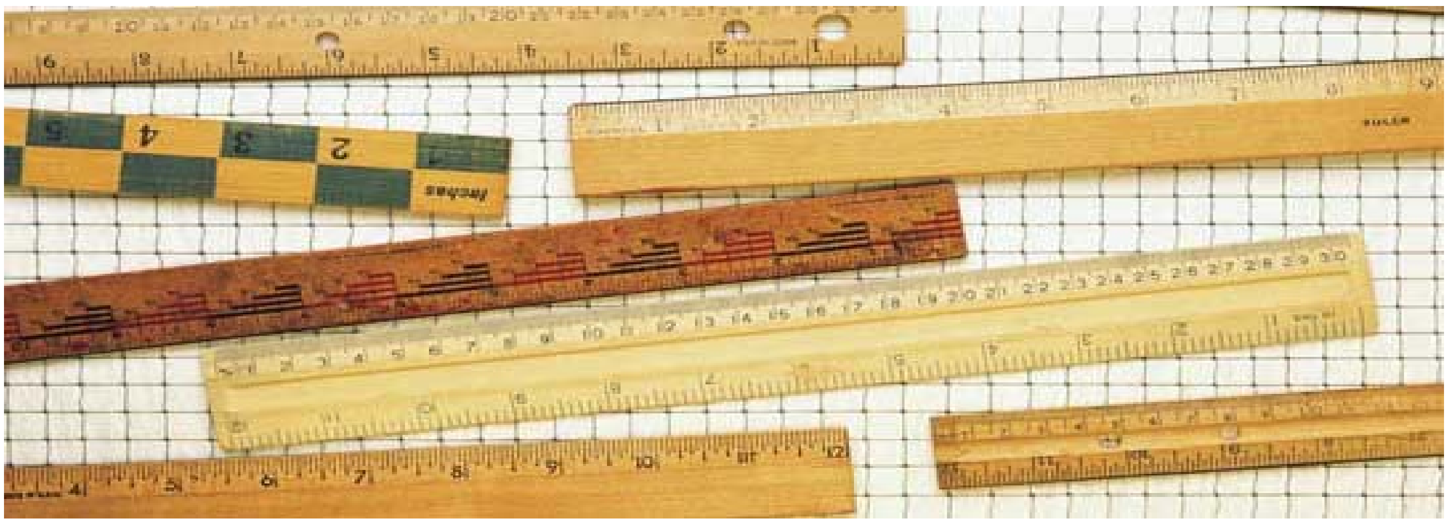
Optical Intensity

Etc,

What is a Measurement ?

A measurement is the process of converting energy from some physical phenomena into a form that can be analytically manipulated into engineering units in order to obtain information about the phenomena under consideration.

Information Transfer Requires Energy Transfer !



Measurement Tenets

1. What do you really need to measure?
2. How are you going to use the measured information?
3. Recognize that each boundary layer or component between you and the fundamental measurand affects delay, response, repeatability, linearity and hysteresis.
4. Do not change what you are attempting to measure by making the measurement!

"What would the measurement system have read if it had not been there transferring energy with the physical phenomena you are measuring?"

Peter K. Stein

The Complete Measurement System

Electronic Signal Conditioning
- Frequency to DC
- Amplification
- Bridge conditioning
- Temp reference

Power

Output

Sensors/Transducers
- Pressure
- Temperature
- Optical Detector

Boundary Layers
Sense Lines
Diaphragms
Wires

Undesired Physical Phenomena

Input

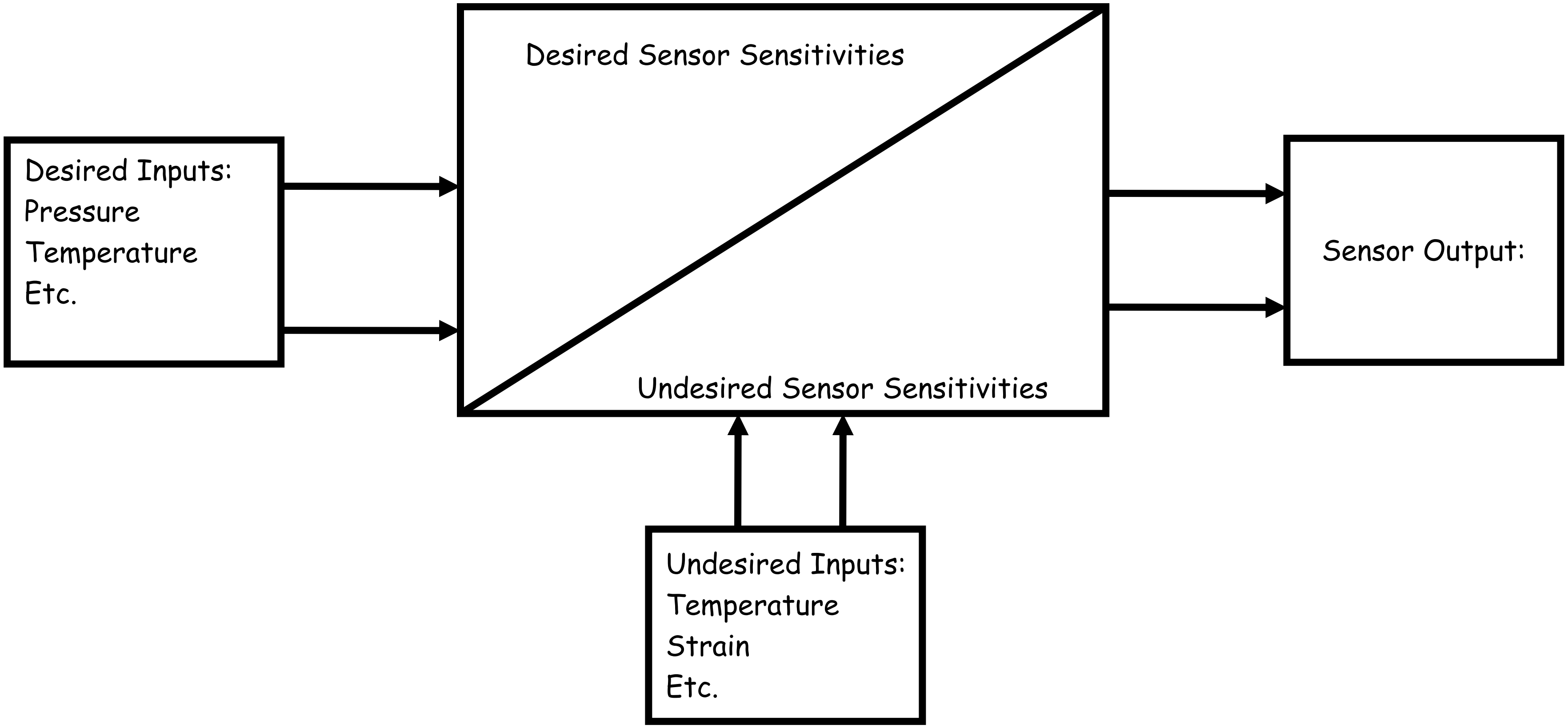
Measurand
Desired Physical Phenomena

Digital Data Acquisition (DAQ)
Filtering
Temporal Response
Frequency Response
Boundary Layers
Equations
Lookup Tables

Human Data Analysis

Reference: 2

Basic Sensor Model



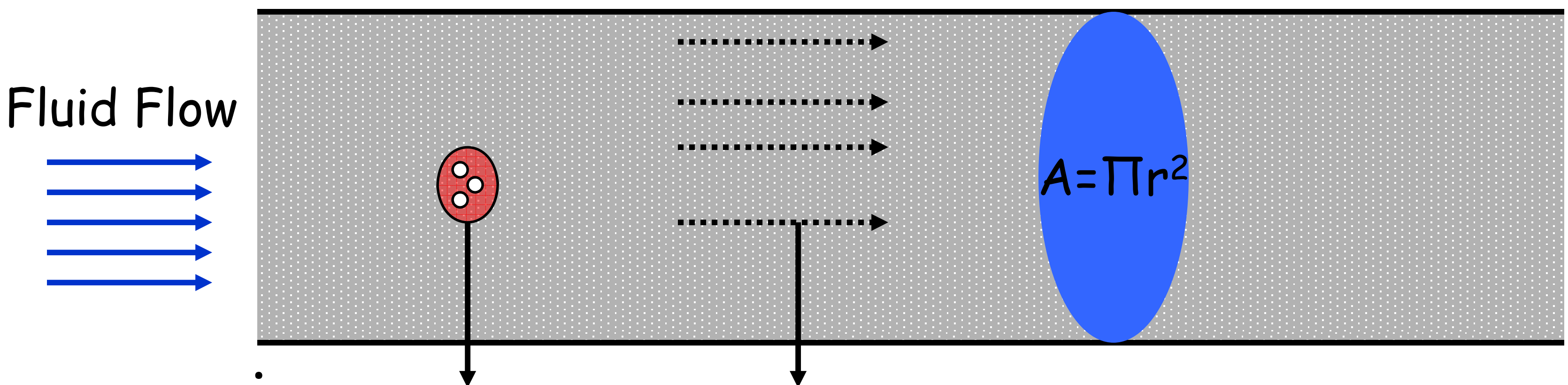
Undesired Sensor sensitivities are physical phenomena that that causes your sensor or electronics to produce an output.

‼ Both Desired and Undesired inputs will produce an output if the sensor is sensitive to those inputs ‼

The Measurand -Desired Physical Phenomena
Mass Flow Measurement Example

The physical phenomena that you would like to measure.
This is also your desired sensor sensitivity.

$$\text{Mass Flow Rate} = \dot{M} = \partial m/\partial t = \rho \times \vec{\upsilon} \times A$$



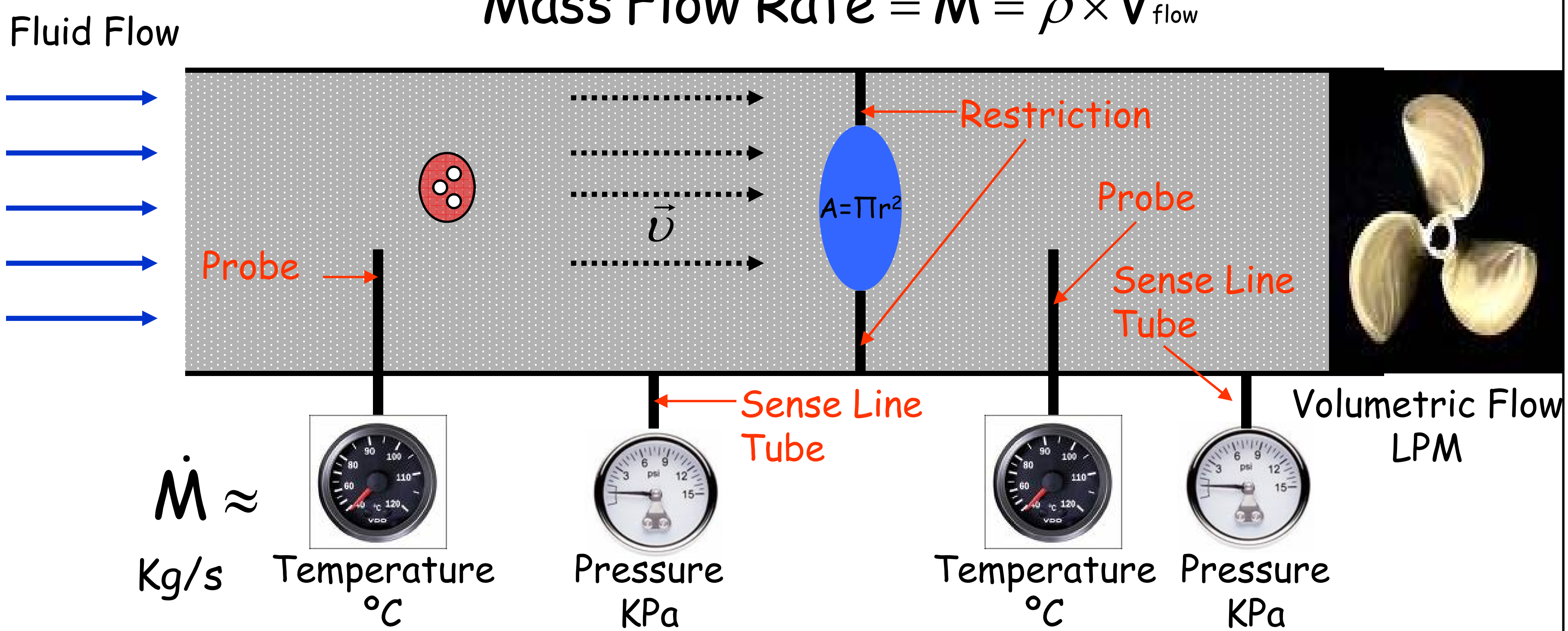
$\dot{M}$ = Density (ρ) X Velocity ($\vec{\upsilon}$) X Cross-Sectional Area (A)

Kg/s kg/m³ m/s m²

Analytic & Physical Boundary Layers

$$\text{Mass Flow Rate} = \dot{M} = \frac{\pi}{4}\sqrt{2}\,\frac{CY_1 d_f^{\,2}}{\sqrt{1-\left(d_f/D_f\right)^4}}\sqrt{\rho_{flow}}\sqrt{\Delta P}$$

$$\text{Mass Flow Rate} = \dot{M} = \rho \times V_{flow}$$



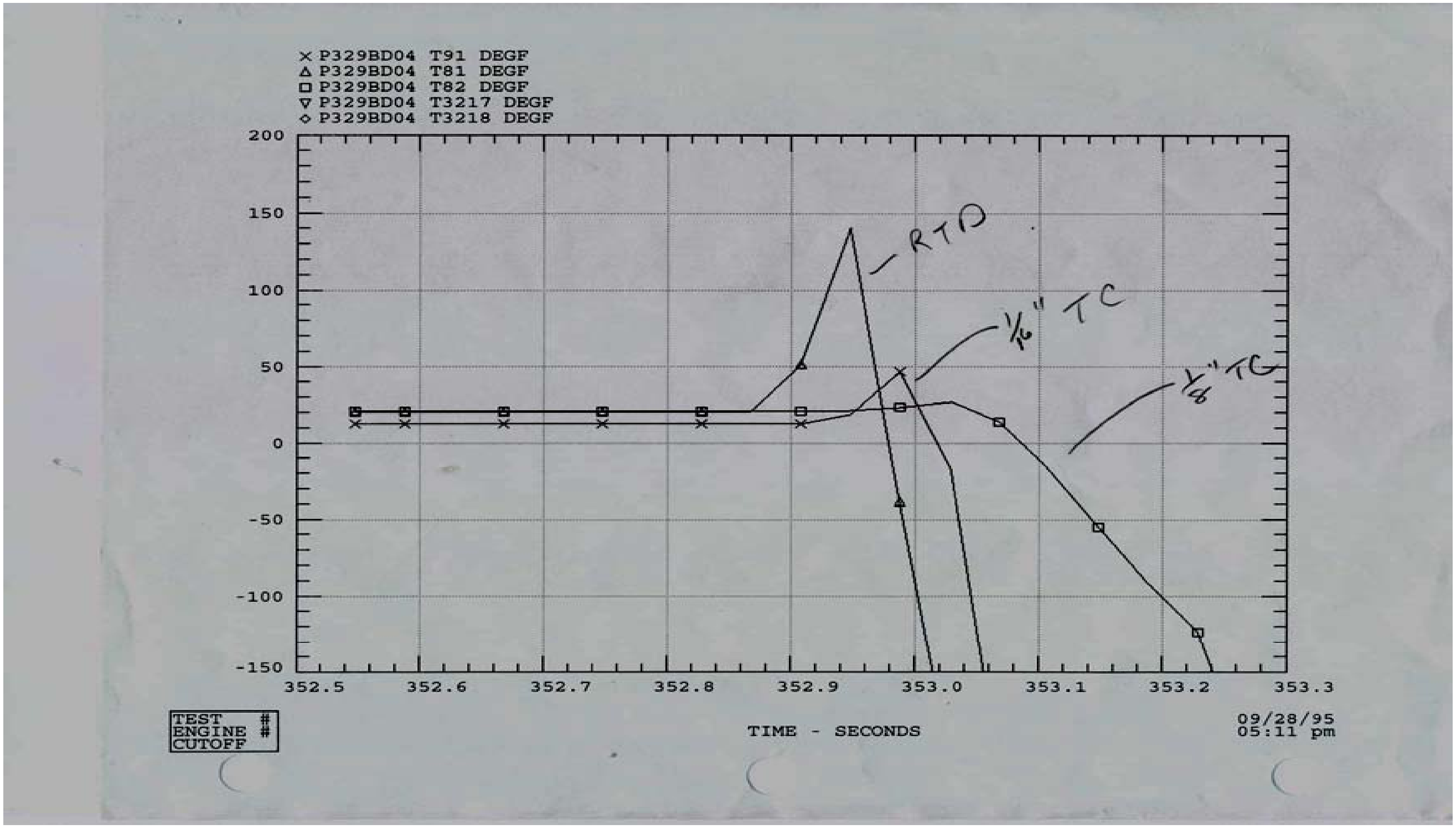
Sensor Response

- Temporal Response
  - The time constant or rise time of the sensor.
- Frequency Response
  - The "bandwidth" of frequencies that the sensor can respond to.
- Phase Response
  - The associated delay of individual frequencies the sensor responds to.
- Indicial Response
  - Sensor system response to a step function input.

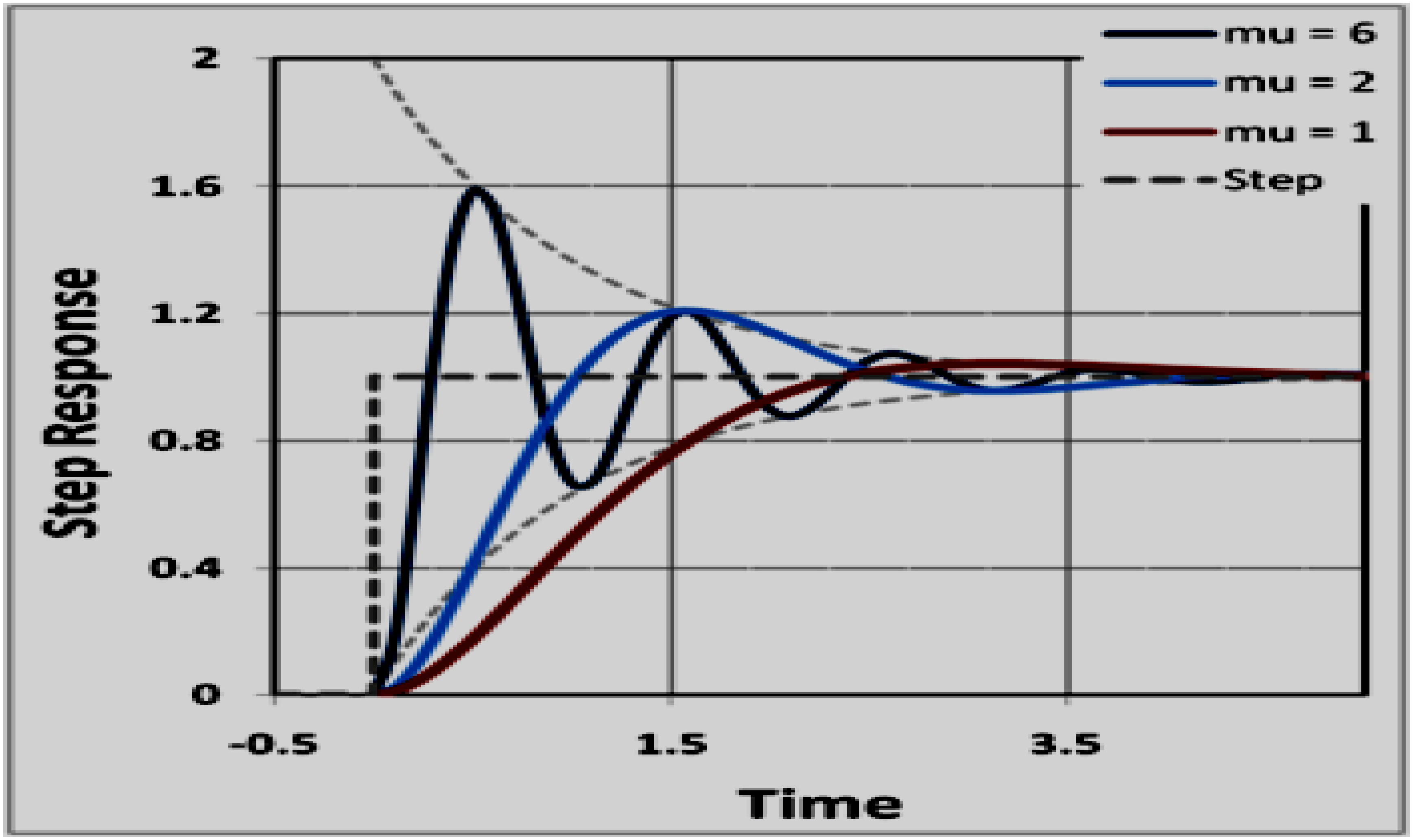
Temporal Response

- Rise Time
  - The time it takes for a sensor to go from 10% to 90% of a step input.
- 1st Time Constant (tau)
  - The time it takes for a sensor to go from 0 to 63.2% of a step input. It takes approximately 5 tau to reach 99.9% of a step input.

Temporal Response



Indicial Response

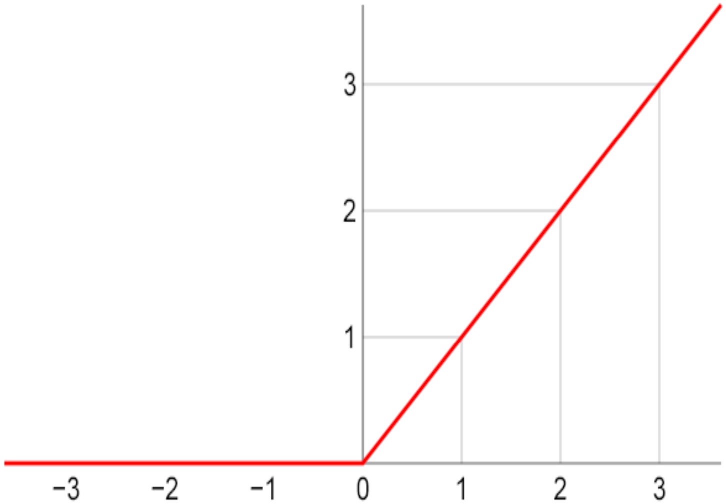


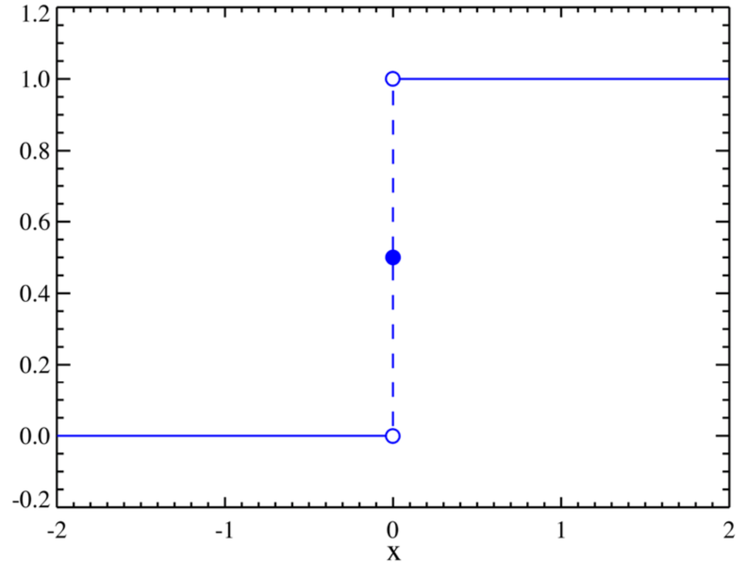
Time Domain Deconvolution

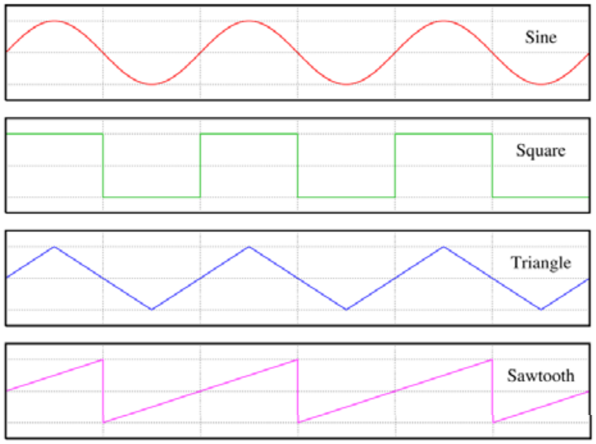
The systems indicial response can be separated from the phenomena you are measuring using time domain deconvolution.

$$F(i) = \frac{\left[R(i) - \sum_{j=2}^{j=i} s(j) F(i - j + 1) \right]}{s_1}$$

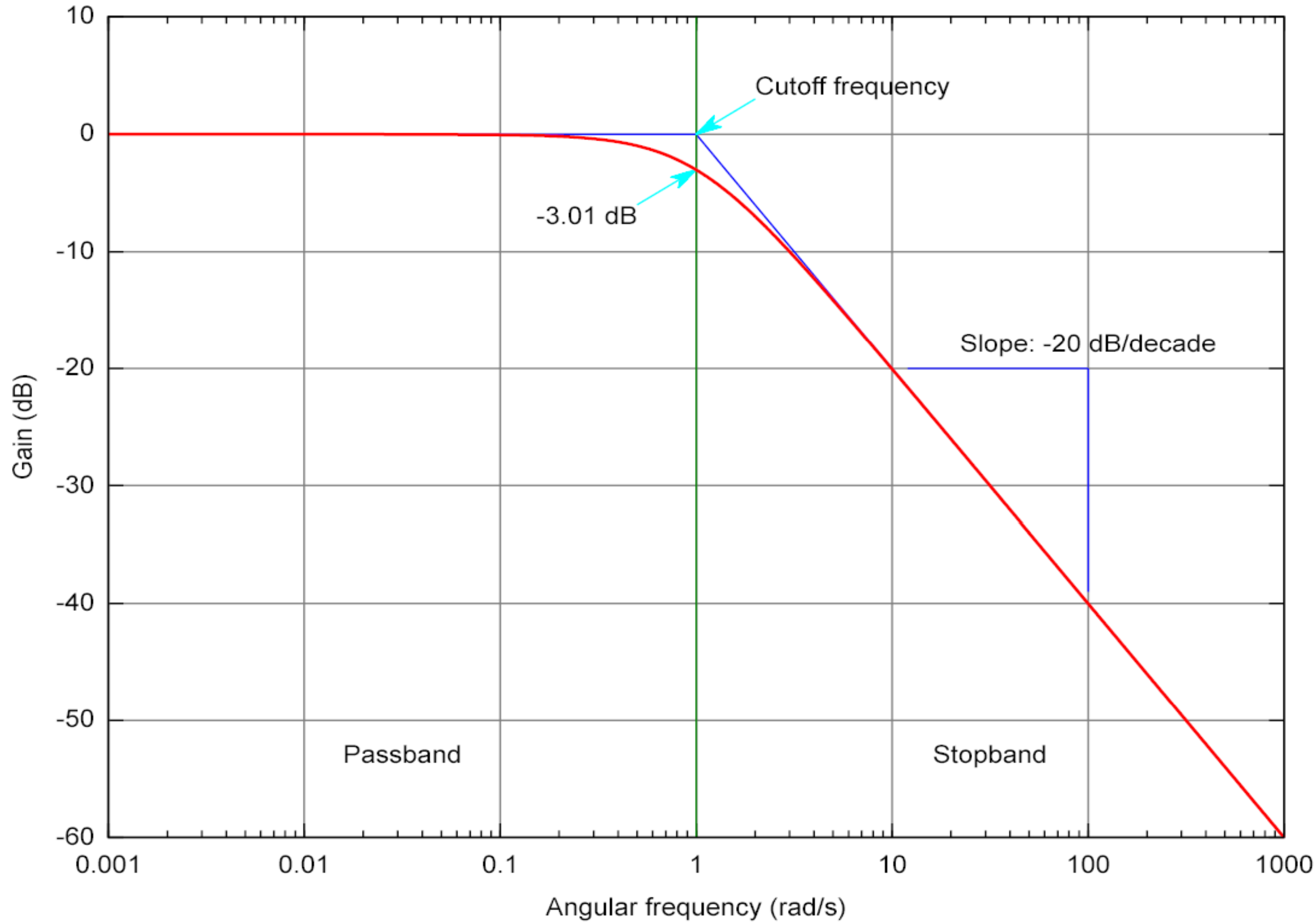
Sensor Frequency Response
Where do you see frequency ?



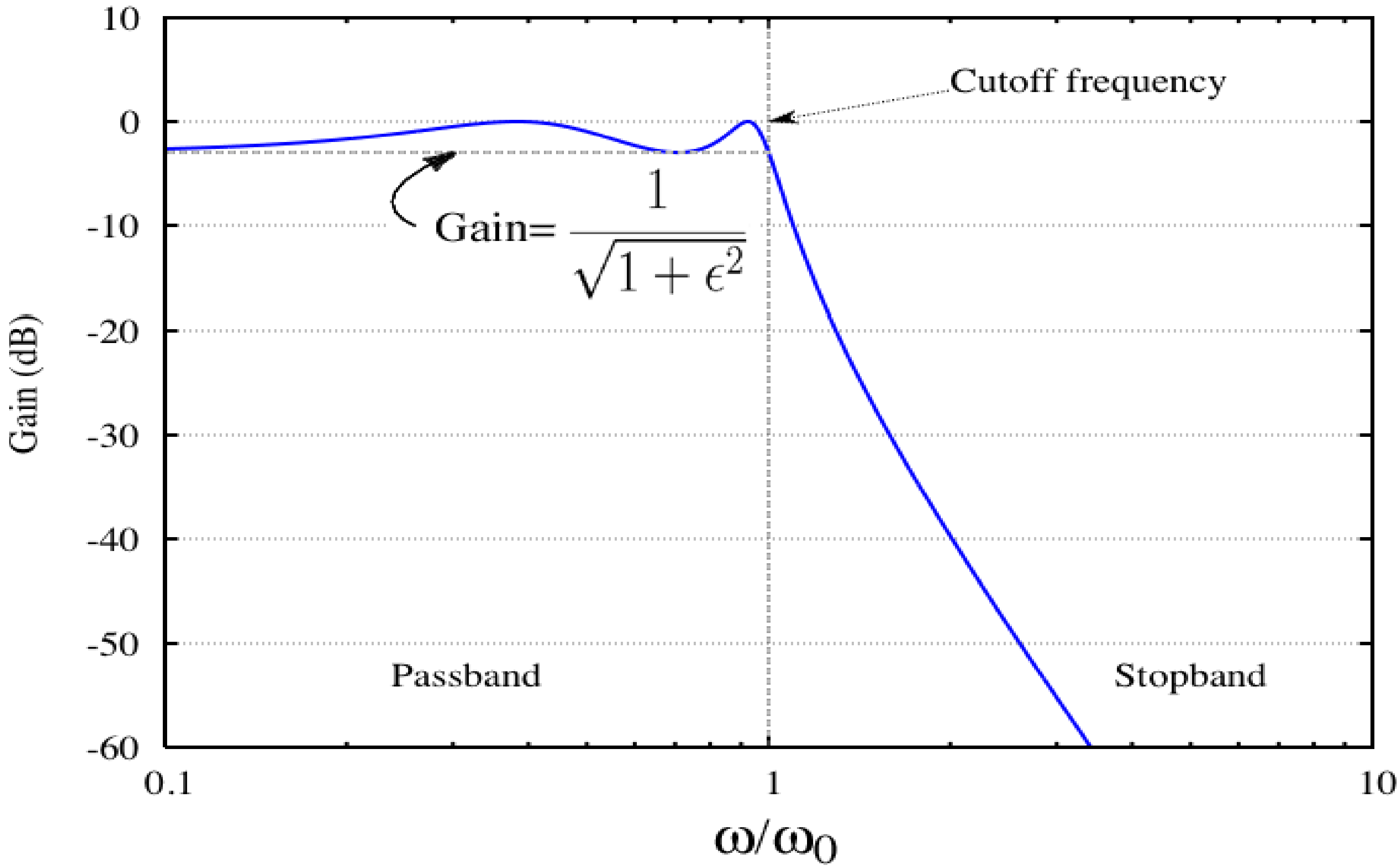




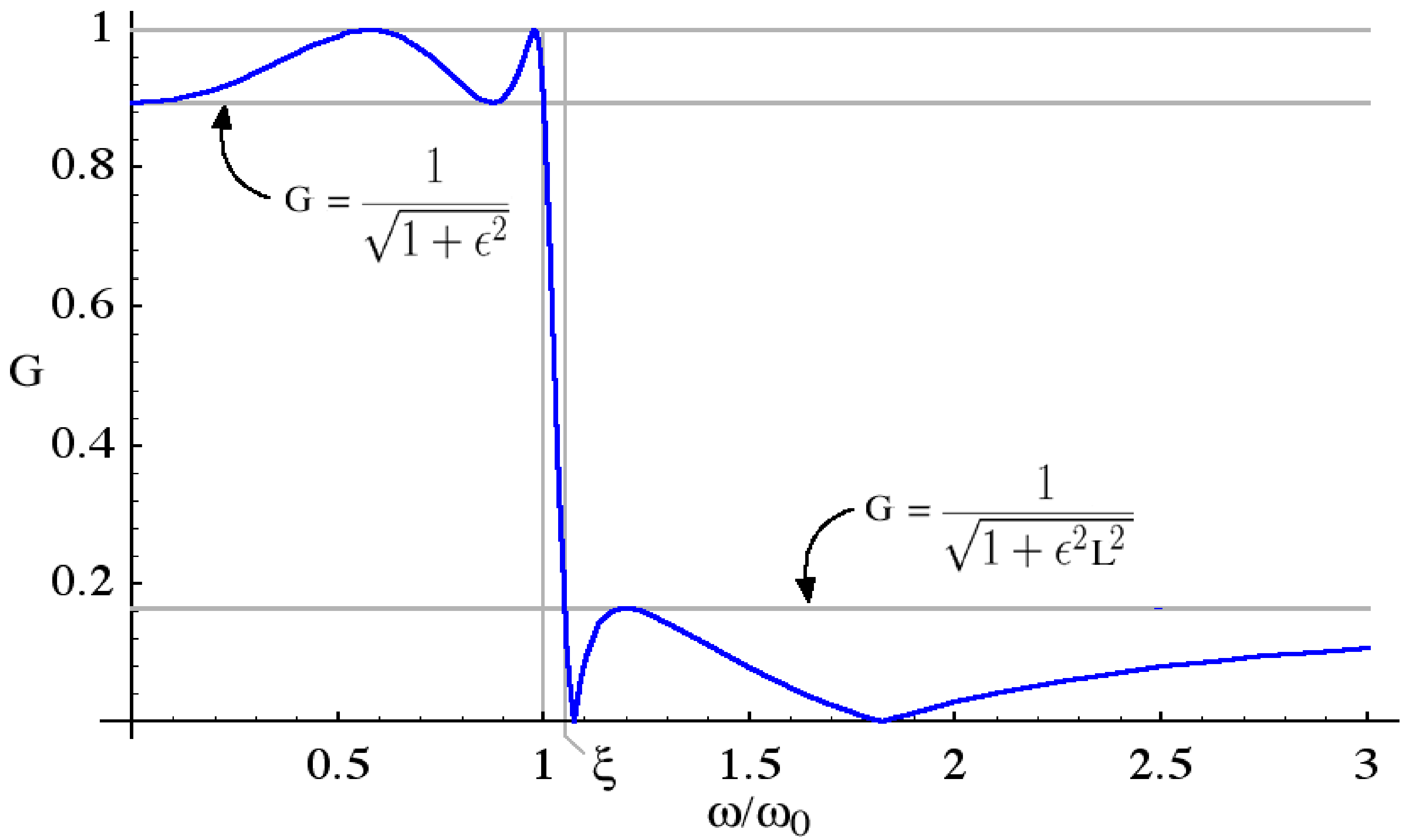
Frequency Response (Butterworth)



Frequency Response (Chebychev)



Frequency Response (Elliptic)



Boundary Layers

- Physical Boundary Layers
  - Pressure sense line tubes
  - Material Thickness
  - Gradients; density, thermal, acoustic
- Analytic Boundary Layers
  - Undesired sensor sensitivities
  - Complex equations
  - Calibrations

Analytic Boundary

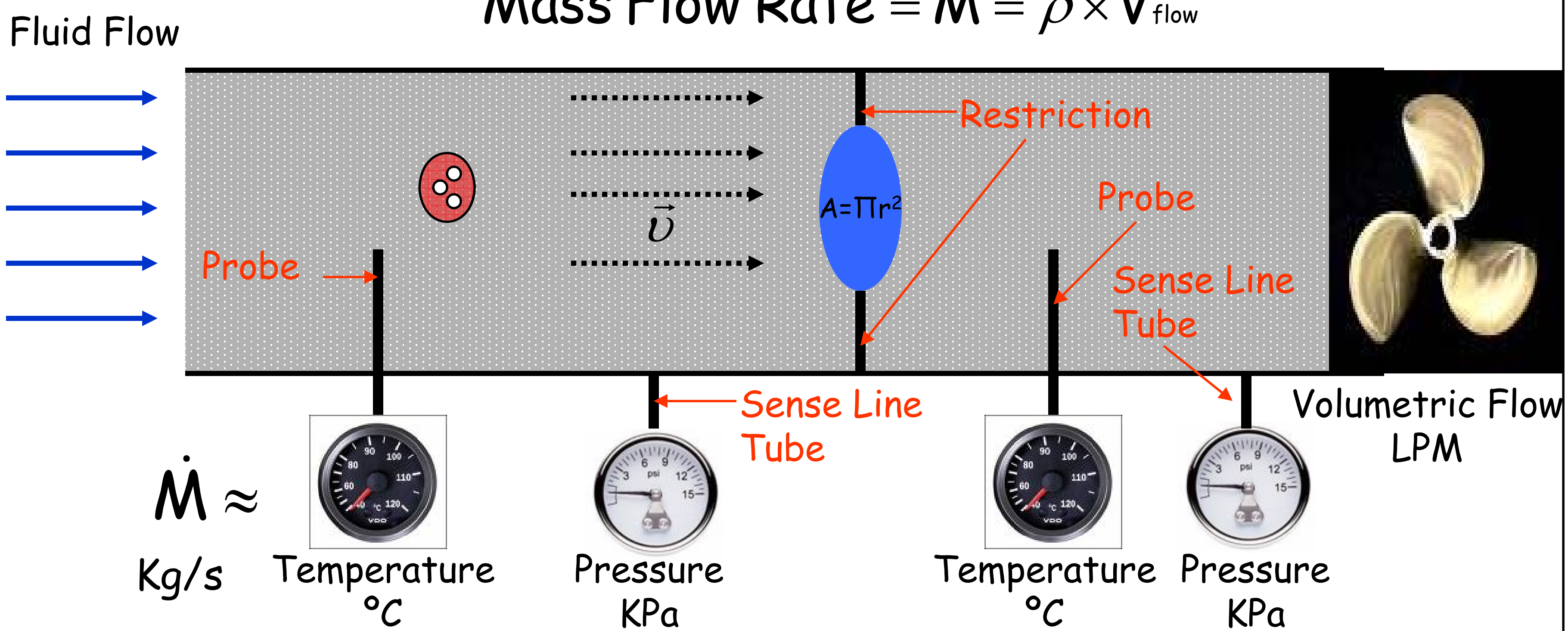
C= discharge coefficient [unitless]
Y1= adiabatic expansion factor [unitless]
df= primary contraction diameter during actual flow conditions [m]
Df= pipe diameter during actual flow conditions [m]
ρ_{flow} = density at flowing conditions [kg/m3]
ΔP= pressure differential [Pa]

$$\dot{M} = \frac{\pi}{4}\sqrt{2}\,\frac{C Y_1 d_f^{\;2}}{\sqrt{1-\left(\frac{d_f}{D_f}\right)^4}}\sqrt{\rho_{flow}}\sqrt{\Delta P}$$

Analytic & Physical Boundary Layers, Insensitivities

$$\text{Mass Flow Rate} = \dot{M} = \frac{\pi}{4}\sqrt{2}\,\frac{CY_1 d_f^{\,2}}{\sqrt{1-\left(\frac{d_f}{D_f}\right)^4}}\sqrt{\rho_{flow}}\sqrt{\Delta P}$$

$$\text{Mass Flow Rate} = \dot{M} = \rho \times V_{flow}$$

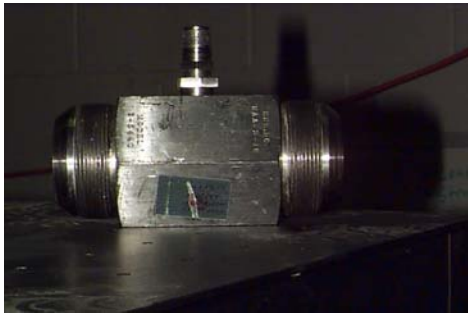


Sensor Insensitivities

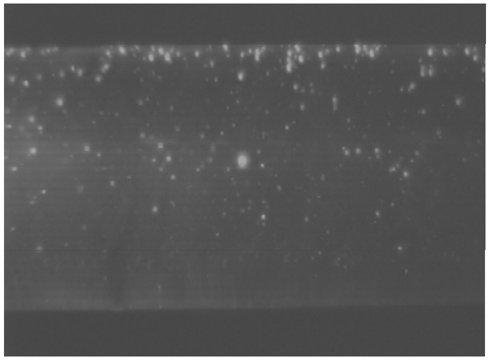
Sometimes there are physical phenomena that goes undetected by your sensor that can cause error in your.

All sensors are sensitive or insensitive to physical phenomena other than what you are trying to measure!

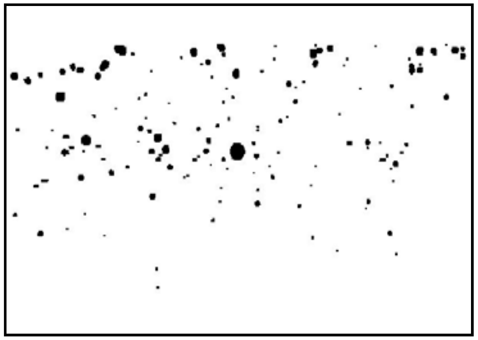
Turbine flow meter



Raw data

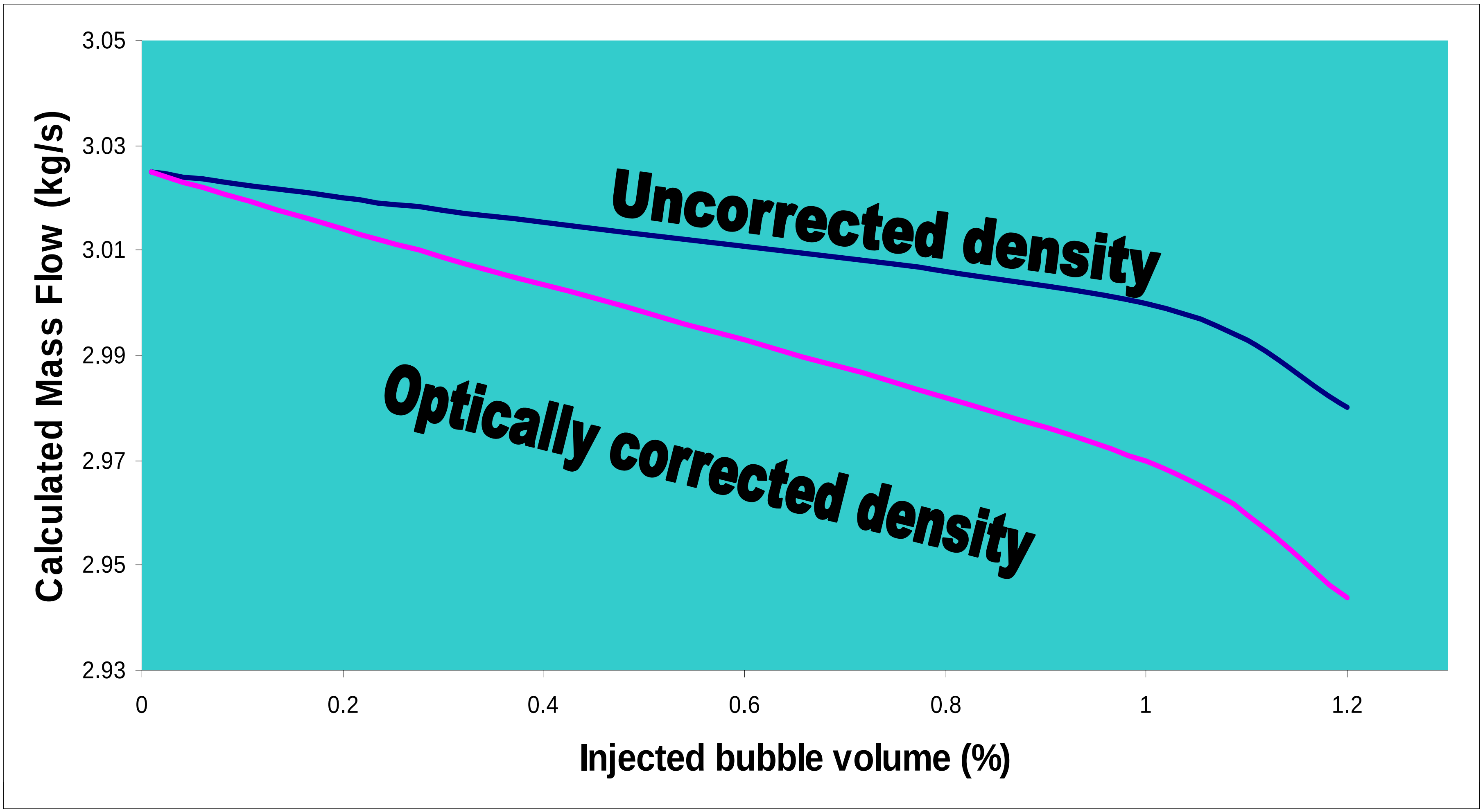


Processed image

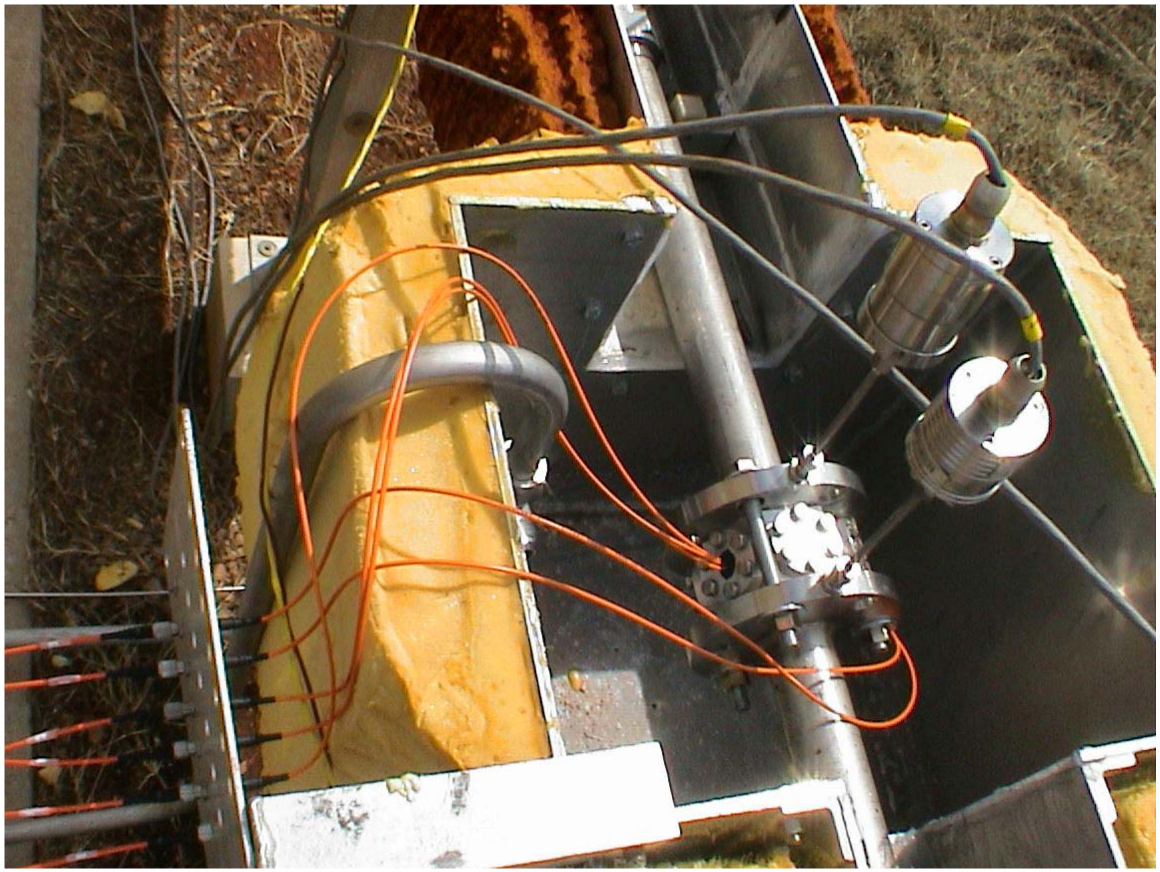


Reference: 3

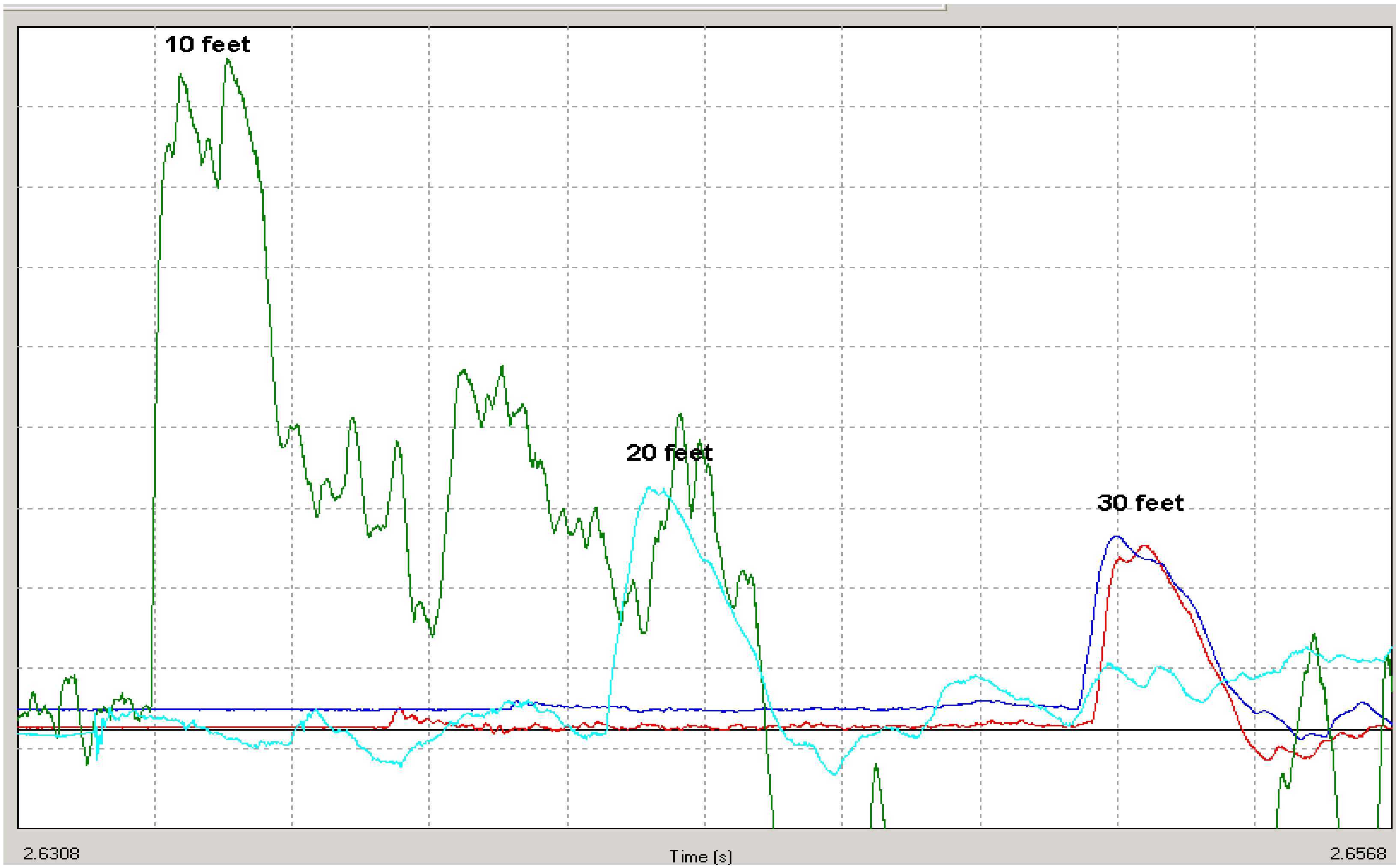
Sensor Insensitivities can result in invalid data



Pressure Sense Lines



Attenuation of pressure measurement



Helmholtz Frequencies

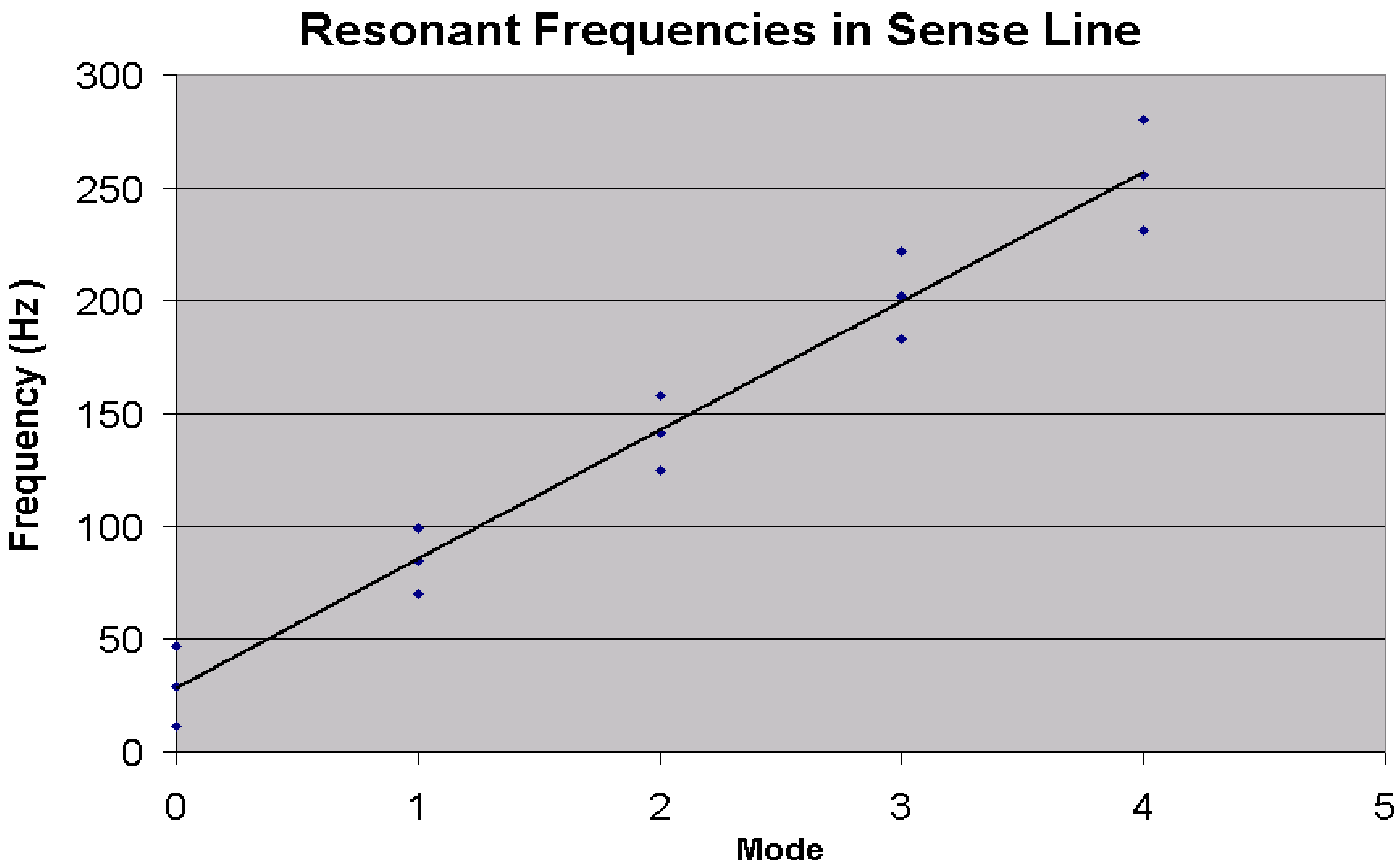
Tube length must be an odd integer number of quarter wavelengths, i.e.,

$$L = \frac{2n+1}{4}\lambda \quad \text{for n = 0,1,2…}$$

Substituting $\lambda = v/f$, we obtain

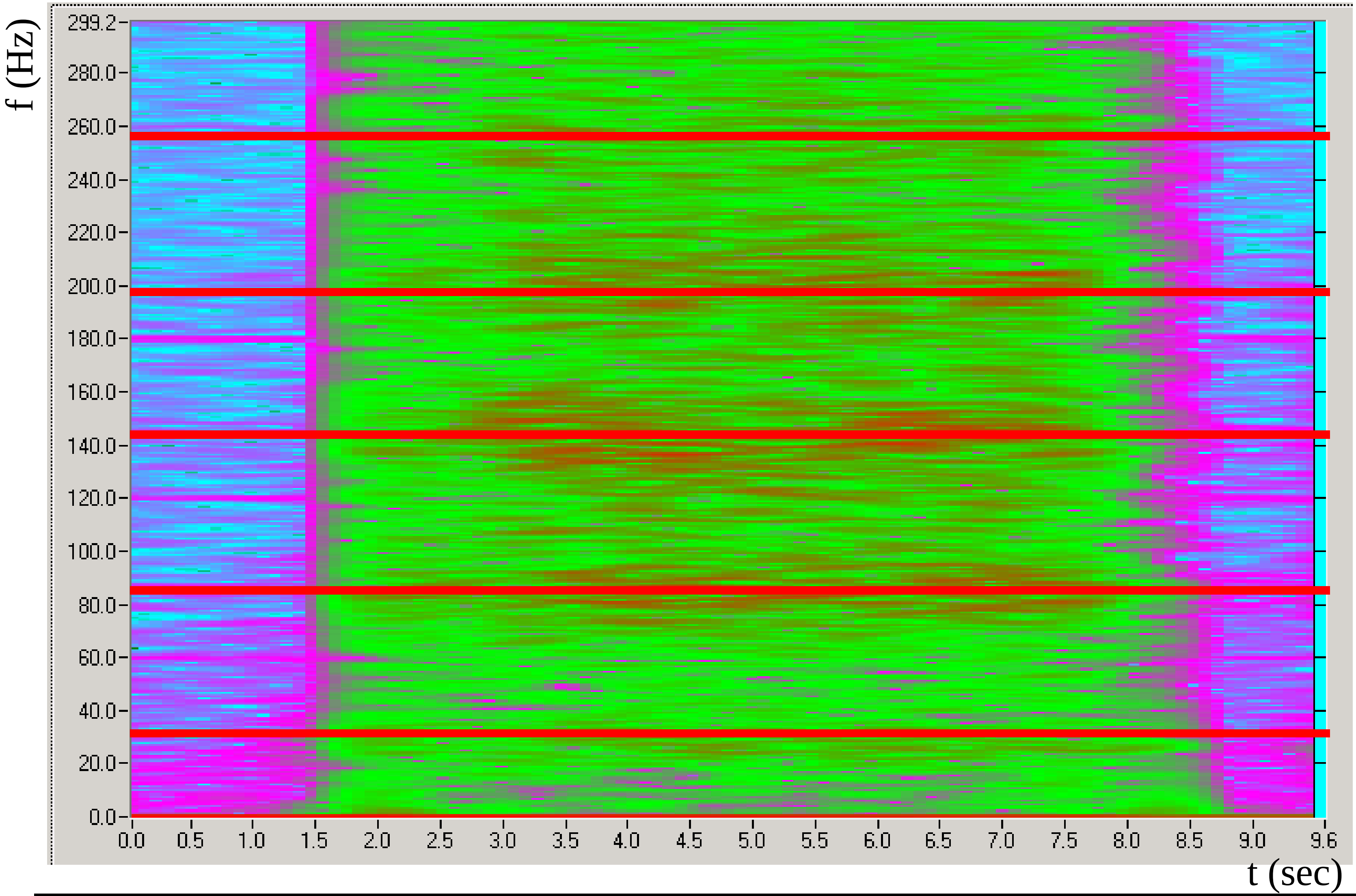
$$f = \frac{v}{4L}(2n+1) \quad \text{for n = 0,1,2…}$$

Resonance



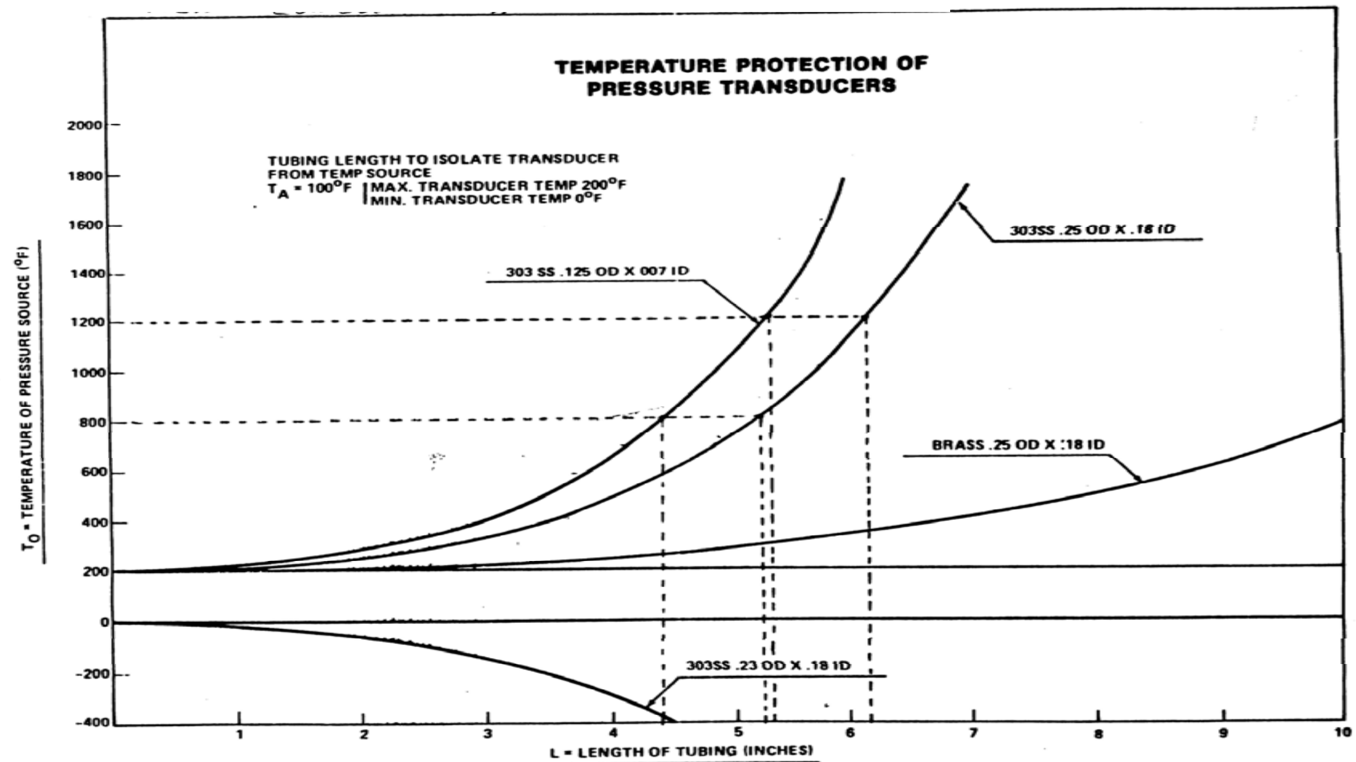
Resonant Frequencies in Sense Line
Frequency (Hz)
300
250
200
150
100
50
0
0
1
2
3
4
5
Mode

Empirical Helmholtz Frequencies

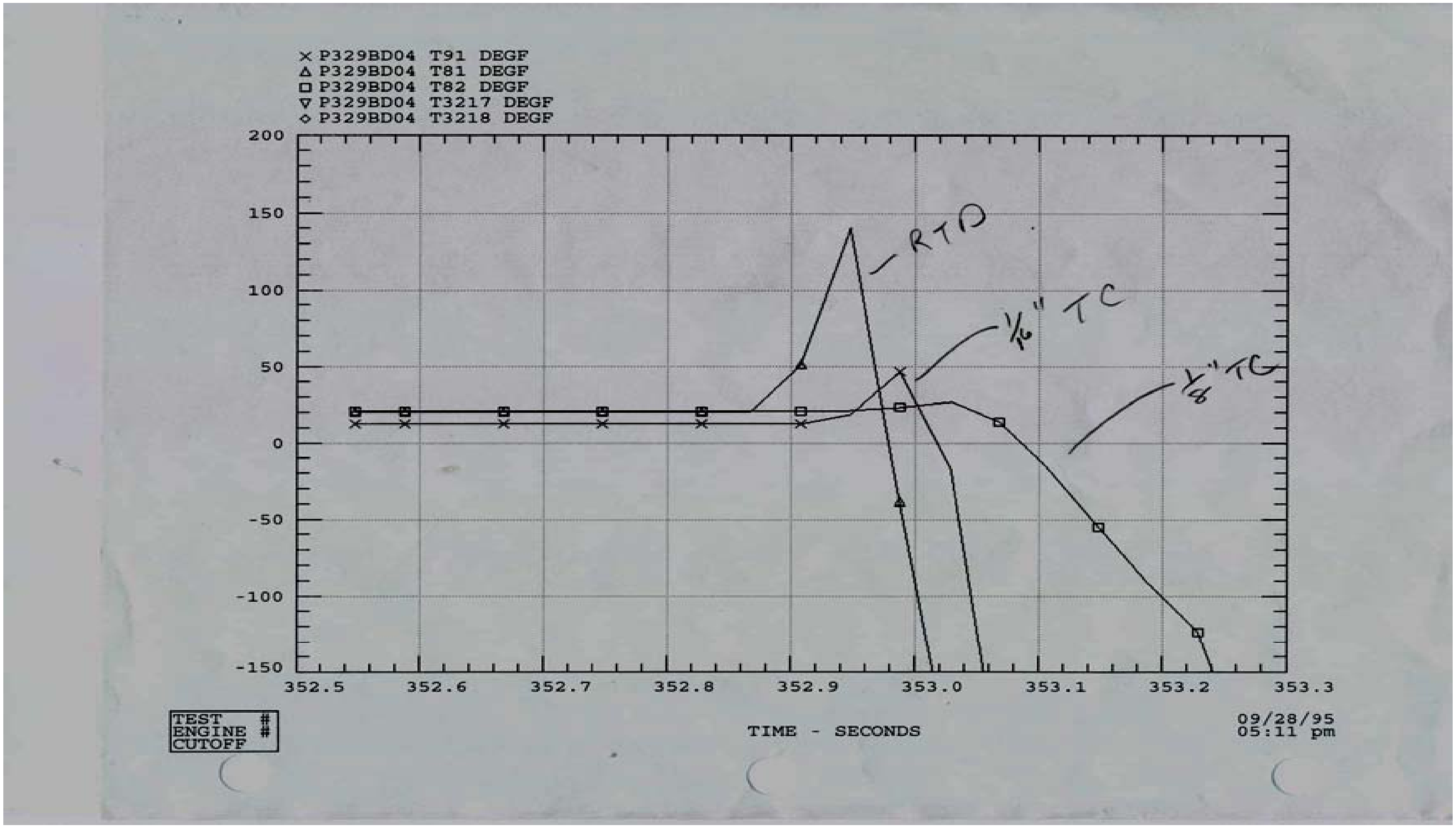


Pressure Sense lines with thermal Gradients

Thermal Gradients in Pressure Sense Lines



Material Thickness Affects Temporal Response

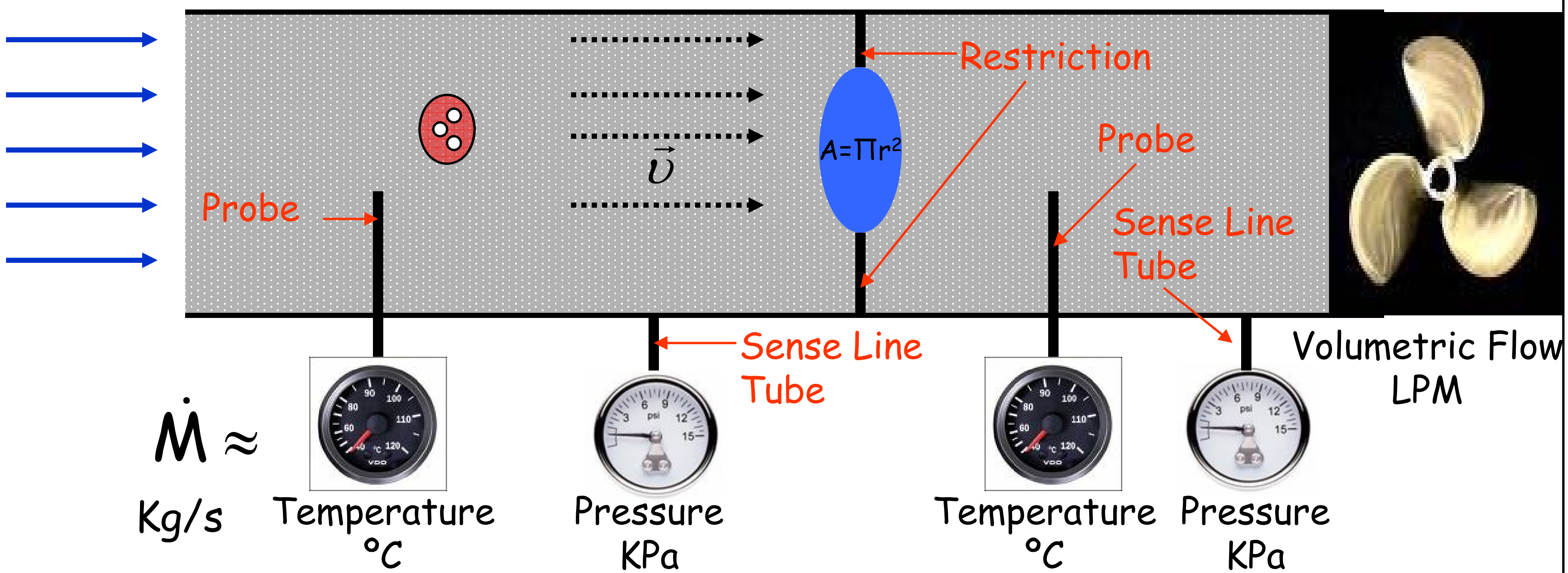


Analytic & Physical Boundary Layers Data

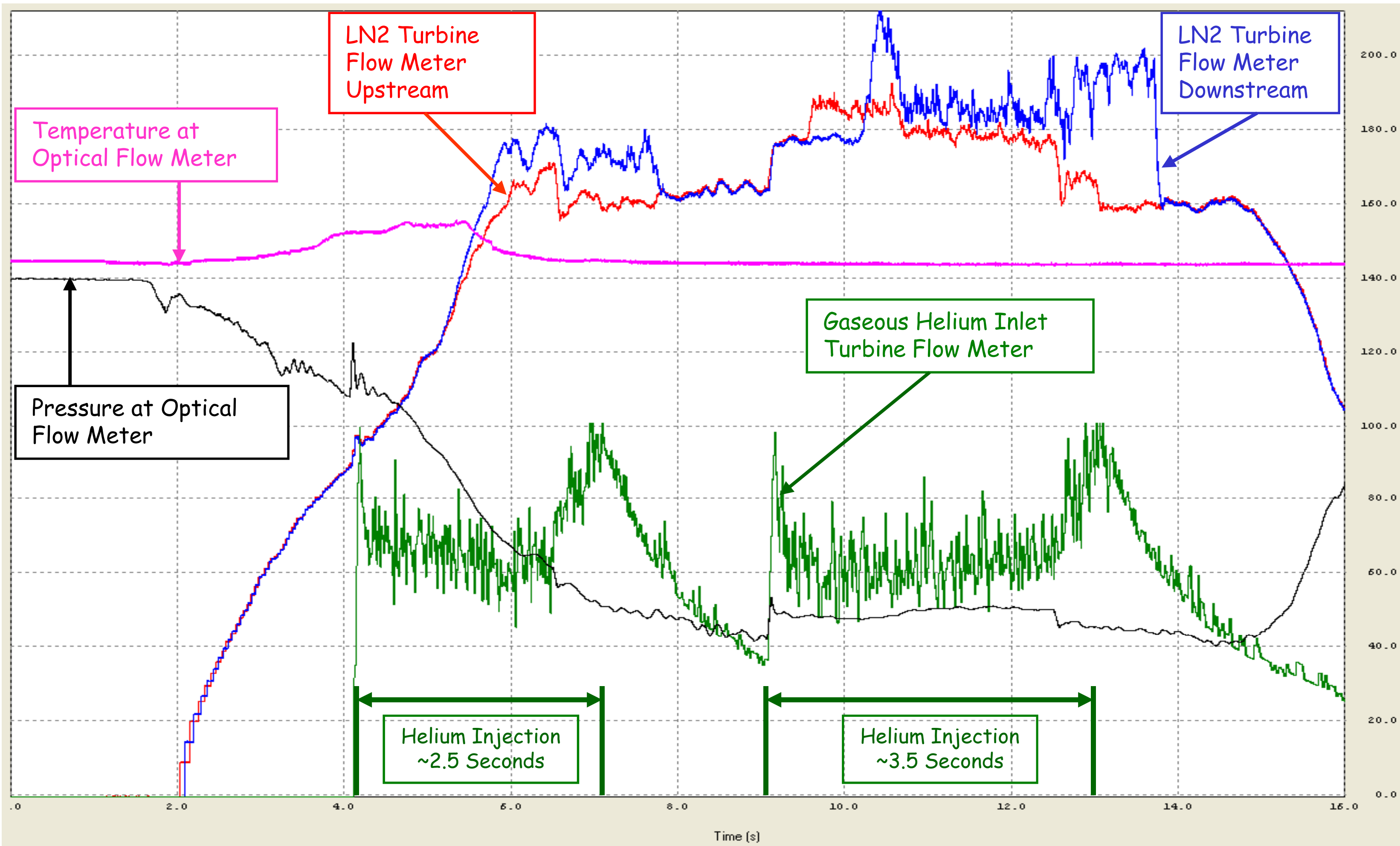
$$\text{Mass Flow Rate} = \dot{M} = \frac{\pi}{4}\sqrt{2}\,\frac{C Y_1 d_f^{\,2}}{\sqrt{1-\left(\frac{d_f}{D_f}\right)^4}}\sqrt{\rho_{flow}}\sqrt{\Delta P}$$

$$\text{Mass Flow Rate} = \dot{M} = \rho \times V_{flow}$$

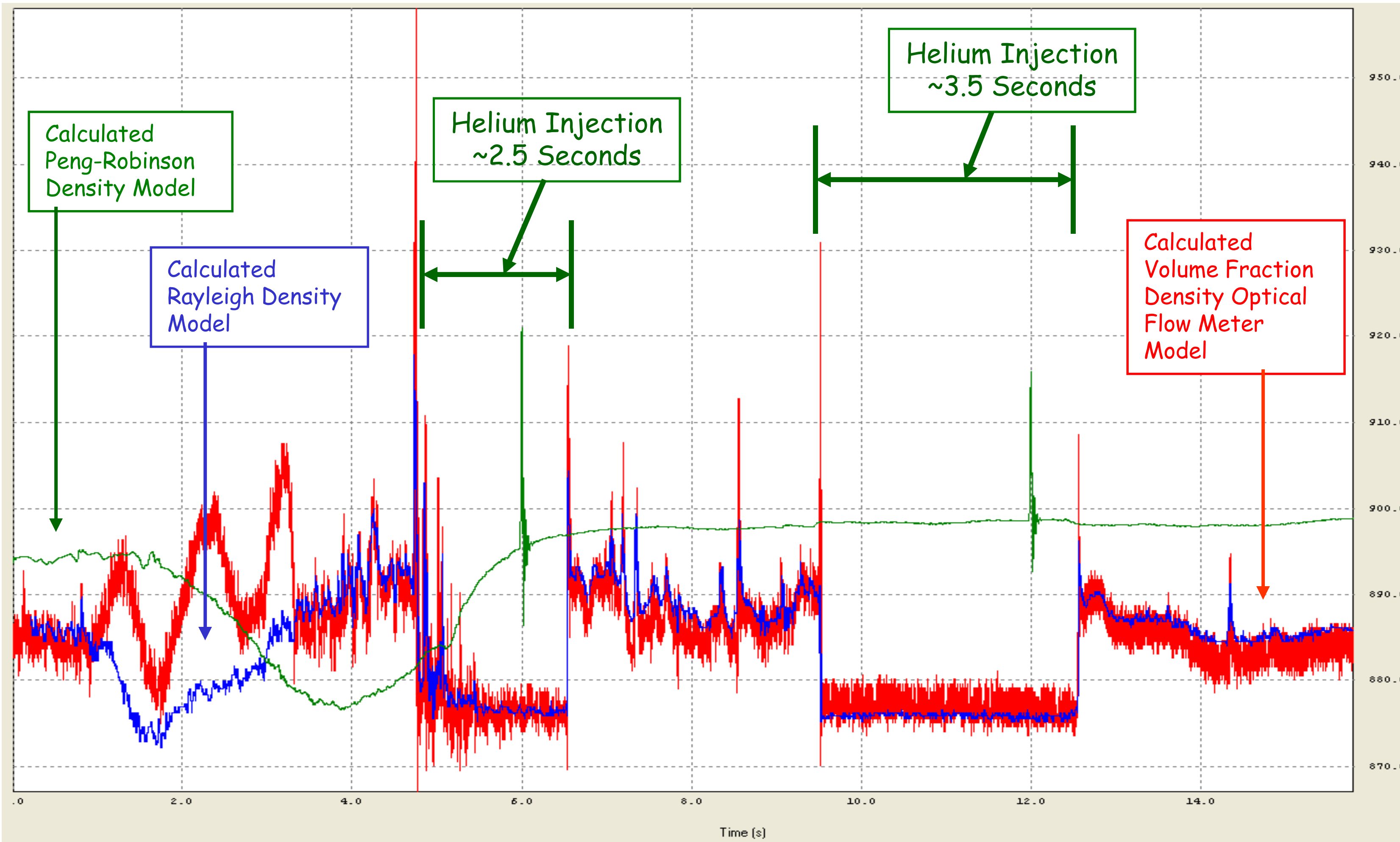
Fluid Flow



Undesired Sensor Sensitivities – Mass Flow Example
Pressure, Temperature and Turbine Flow Meter Data



Processed Optical Flow Meter Data



Data Validation

Data Validation

- Data Validation
  - Validation versus calibration
  - System characterization
  - Data acquisition

Data Validation

"Valid Data are data that represent the process being observed as though the Measurement System had not been there, interfering with the process being observed and distorting the information flow through the system."

Peter K. Stein

Validation is the process of analyzing the complete measurement system for undesired sensitivities or insensitivities that will distort data.

Calibration

Sensors output voltages and current, not pressure, temperature, acceleration, etc.

Calibration is the process of establishing a traceable mathematical relationship between the physical parameter measured in engineering units (psi, degrees, g's, btu/hr, etc.) and the output voltage or current of the sensor. For example a pressure sensor calibration would determine the following:

Sensitivity-volts/psi

Offset-psi

psi = volt*psi/volt + offset psi (linear relationship)

Calibrations should be relevant to the environment the sensor will be used in!

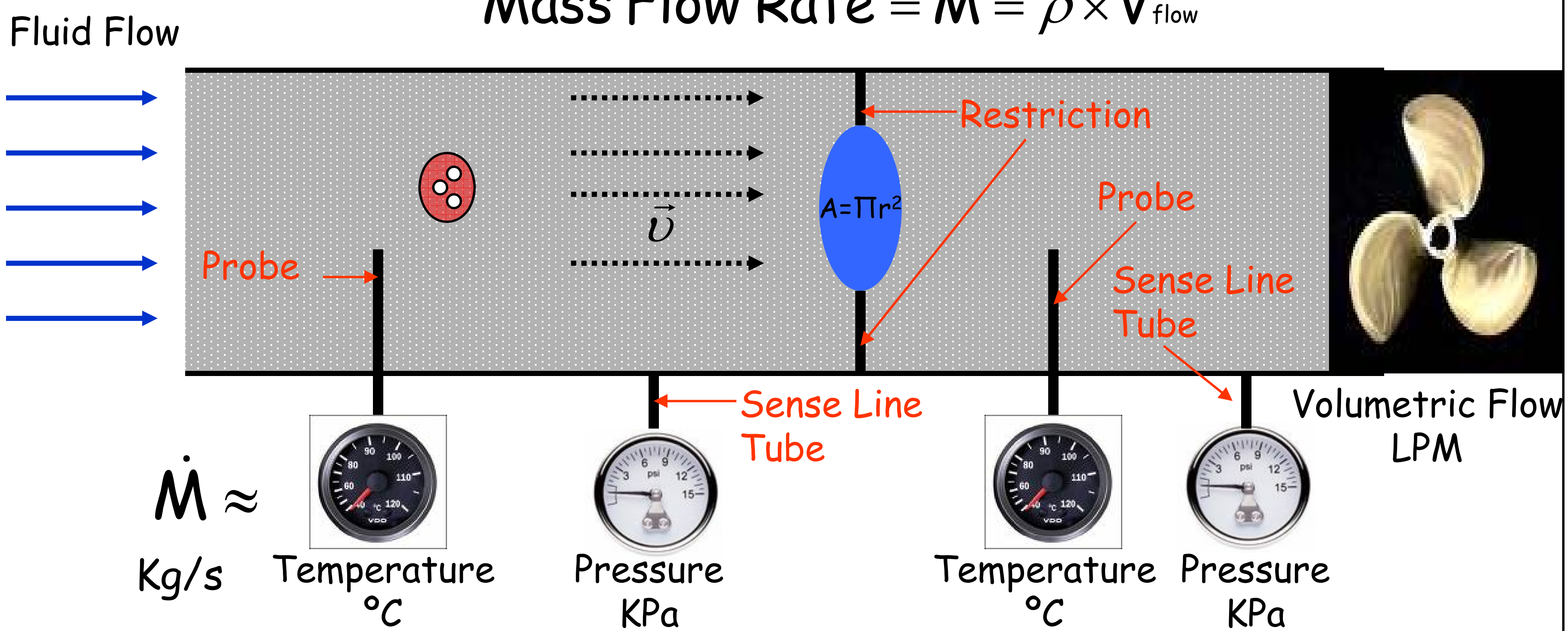
Data Collection and Sensors

- Data collected should correctly reflect the phenomena being observed pressure, temperature, velocity, time, etc.
- Sensor data is always at least one step removed from reality
- Sensor response time is a familiar effect
- Dynamic range of the sensor is always a concern
- Linearity: 50 mV/psi is not always the case
- Averaging as a low-pass filter
- A low digital sampling rate is comparable to a low pass filter (ignoring aliasing problems)

Analytic & Physical Boundary Layers

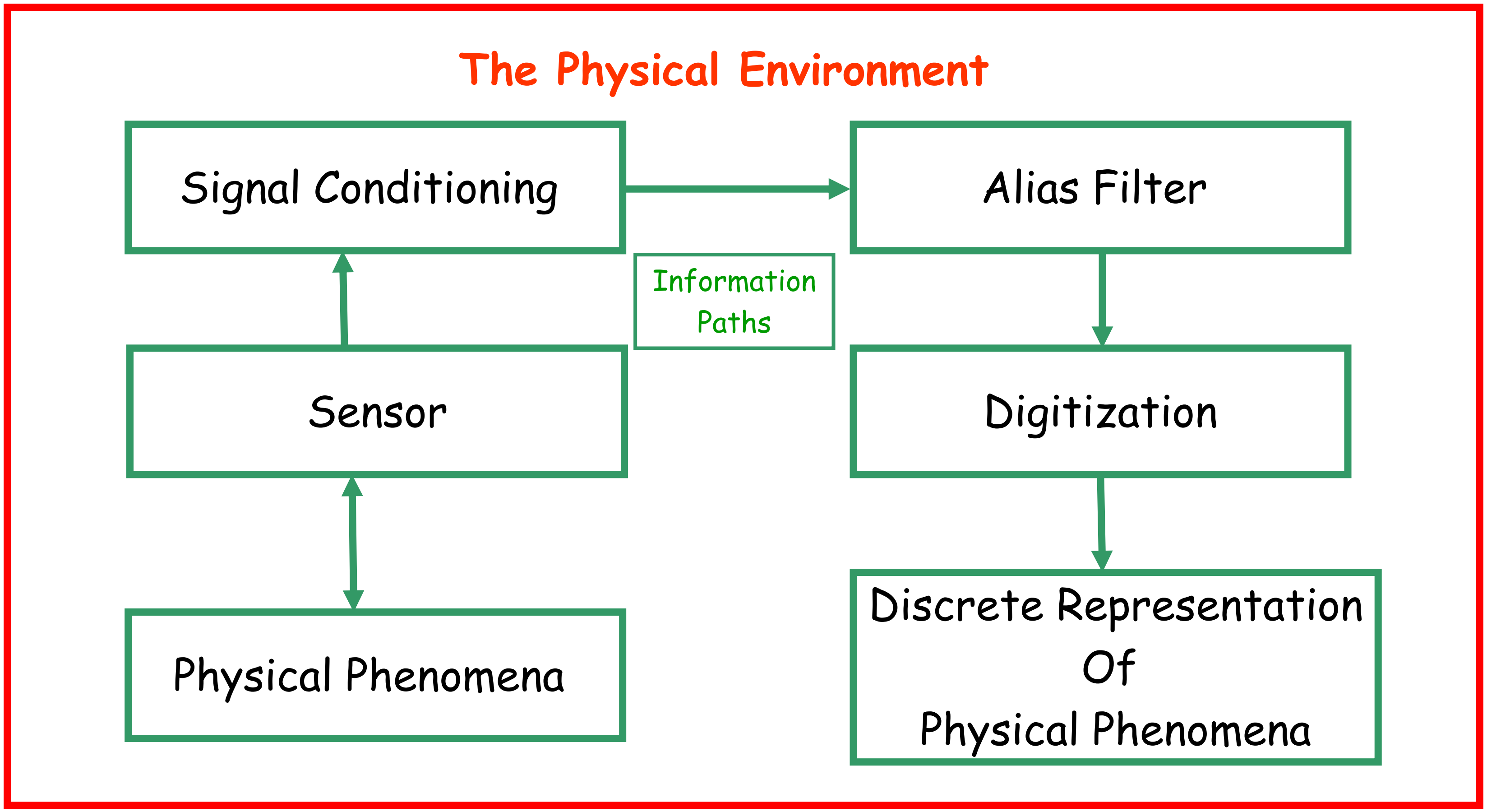
$$\text{Mass Flow Rate} = \dot{M} = \frac{\pi}{4}\sqrt{2}\,\frac{CY_1 d_f^{\,2}}{\sqrt{1-\left(\frac{d_f}{D_f}\right)^4}}\sqrt{\rho_{flow}}\sqrt{\Delta P}$$

$$\text{Mass Flow Rate} = \dot{M} = \rho \times V_{flow}$$



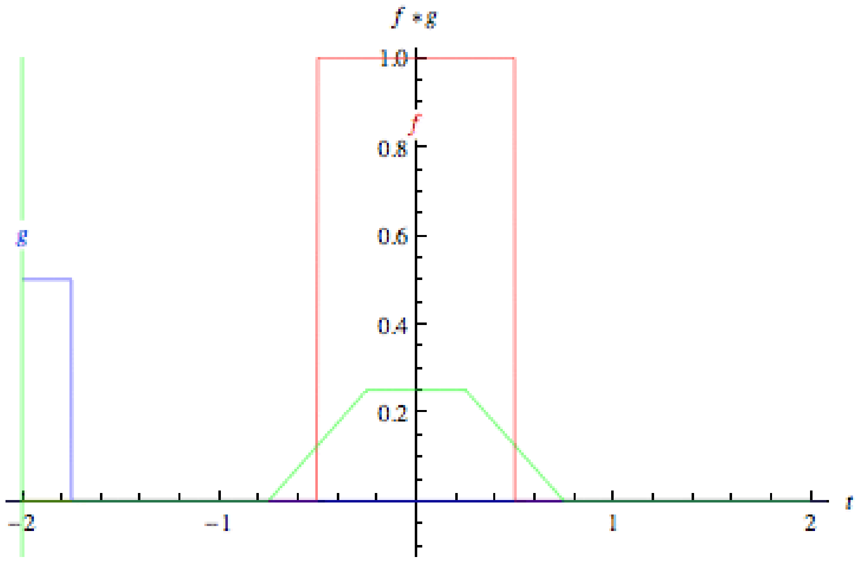
Analytic Sensor Model

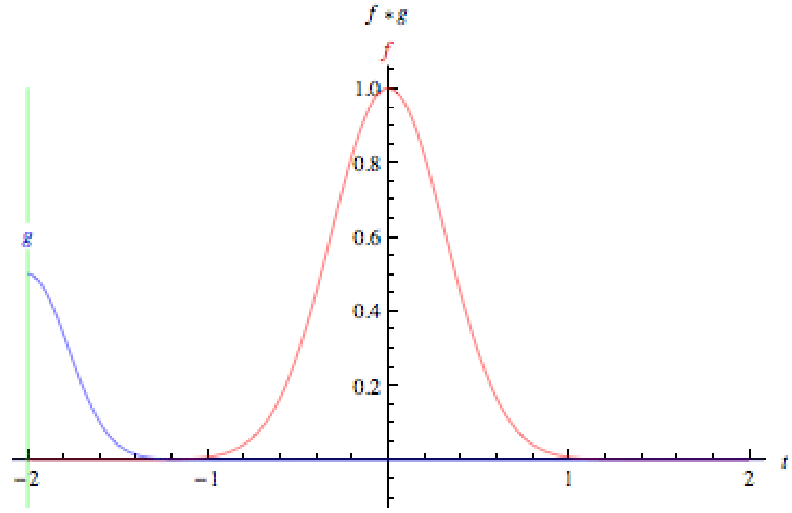
A measurement system performs a series of convolutions on the information from the energy from the physical parameter as it "passes" through each component. The physical environment parameters are convolved with each component.



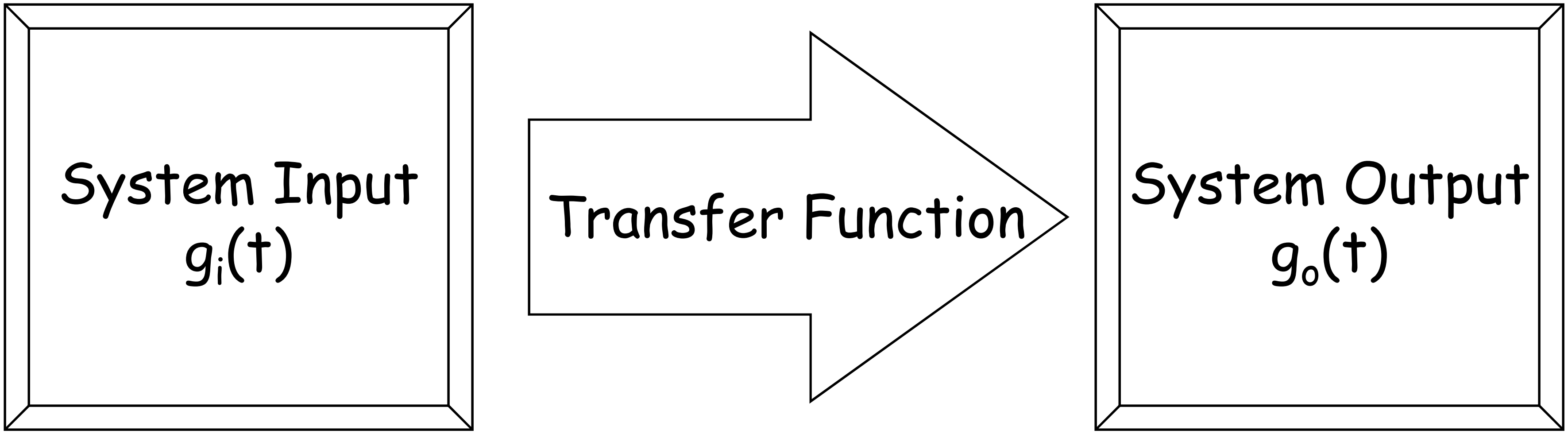
Convolution

Convolution is a mathematical operator that takes two functions and "convolves" them into a third function.





Transfer Functions



A transfer function maps the input of a system to the output of that system. For time invariant systems, transfer functions are multiplicative in the frequency domain.

$$g_o(t) = S\{g_i(t)\}$$

$H(\omega)$, the Transfer Function

$$H(\omega) = \frac{G_o(\omega)}{Gi(\omega)}$$

If the right sort of function is inputted into the system, this quotient will yield the transfer function of the system.

Flat Spectrum Inputs are good choices !

Frequency Response

Frequency response of the system is a plot of the transfer function ($H(\omega)$) of the system. The transfer function can be determined by inputting a flat spectrum signal such as an impulse response function or white noise.

Impulse Response Function

$$g_o(t) = \int_{-\infty}^{\infty} g_i(\tau)\,\delta(t-\tau)d\tau \quad \text{(sifting property)}$$

$$g_o(t) = S\{\int g_i(\tau)\delta(t-\tau)d\tau\}$$

$$g_o(t) = \int g_i(\tau)S\{\delta(t-\tau\}d\tau$$

$$h(t,\tau) \equiv S\{\delta(t-\tau)\}$$

The function $h(t,\tau)$ is called the **impulse response function**.

We can now write

$$g_o(t) = \int g_i(\tau)h(t,\tau)d\tau$$

Time Invariant Systems

A system having components whose characteristics do not change in time is considered **time invariant**. For such a system, the impulse response function depends only on the time since the impulse,

$$h(t,\tau) = h(t-\tau)$$

Time Invariant Systems (cont.)

$$g_o(t) = \int g_i(\tau)h(t-\tau)d\tau$$

which is a convolution, and can be written as:

$$g_o(t) = g_i * h$$

Fourier transform both sides, using a capital letter to represent the F.T. Since the F.T. of the convolution is the product of F.T.'s:

$$G_o(\omega) = G_i(\omega)H(\omega)$$

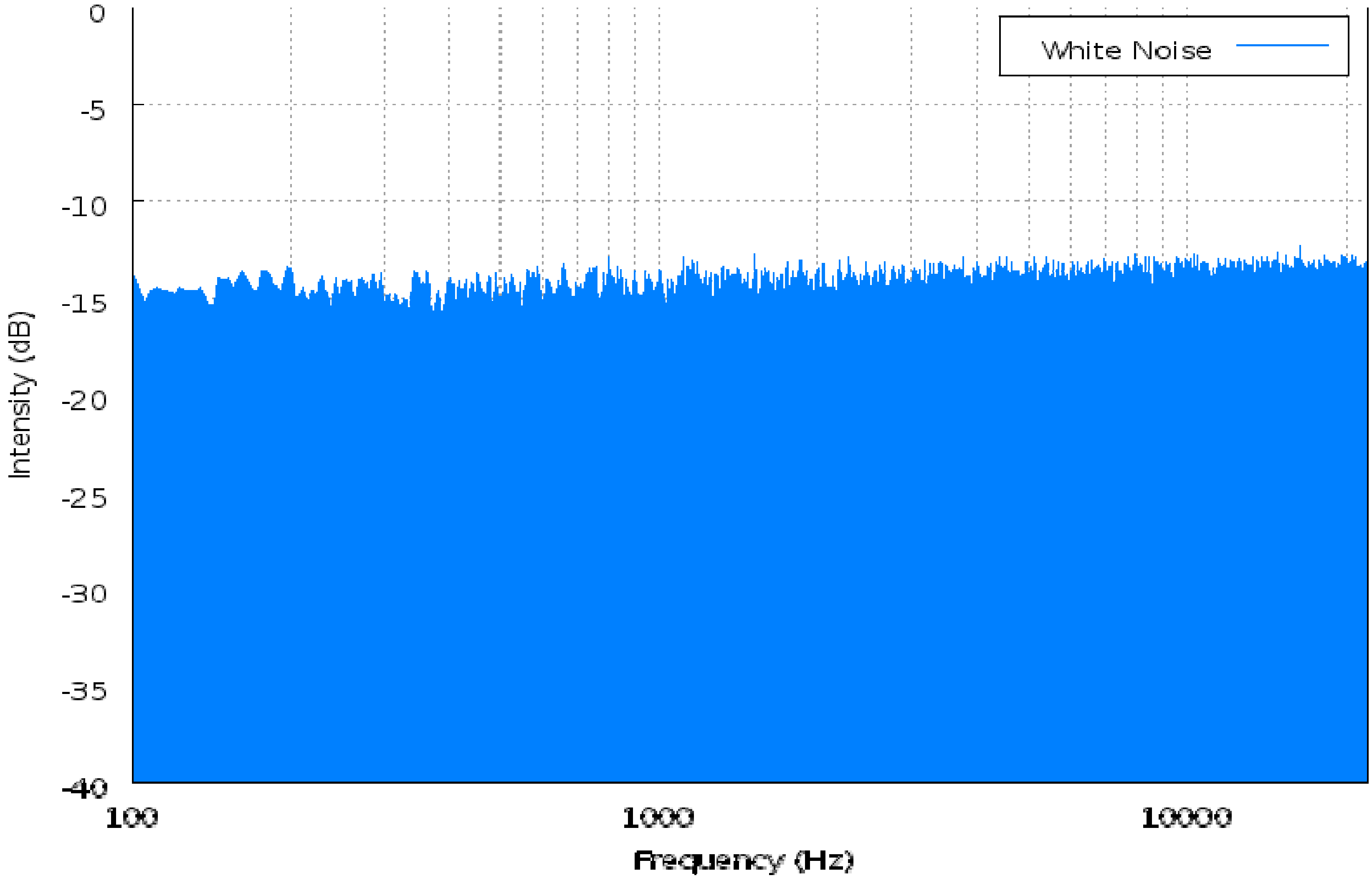
Using Empirically Derived Transfer functions to Determine the System's Frequency Response

Electrical and Mechanical system transfer functions can be empirically derived using impulse response functions.

Thrust Structures- Smart Hammers

Electrical Systems-Pink/White Noise

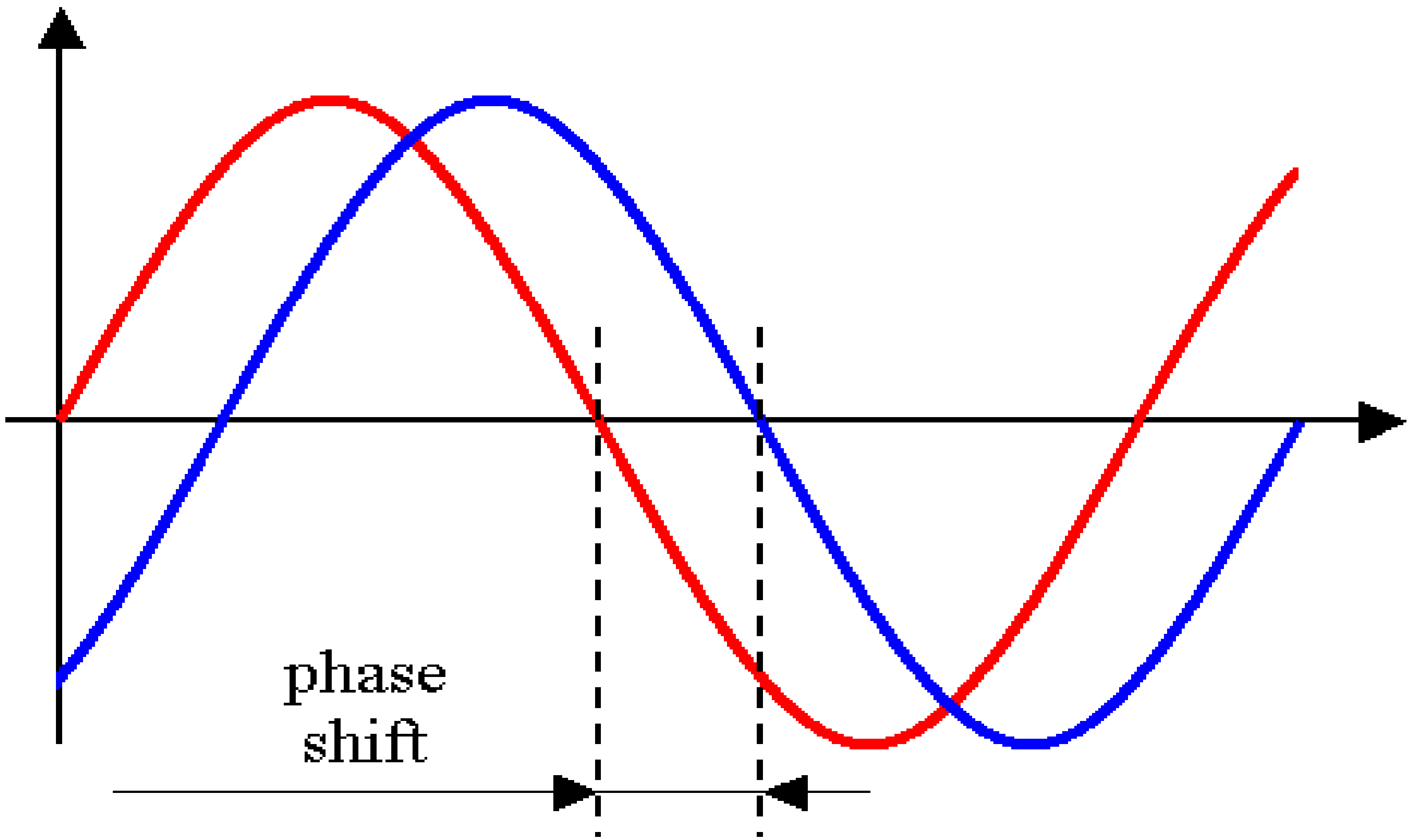
Analytic White Noise



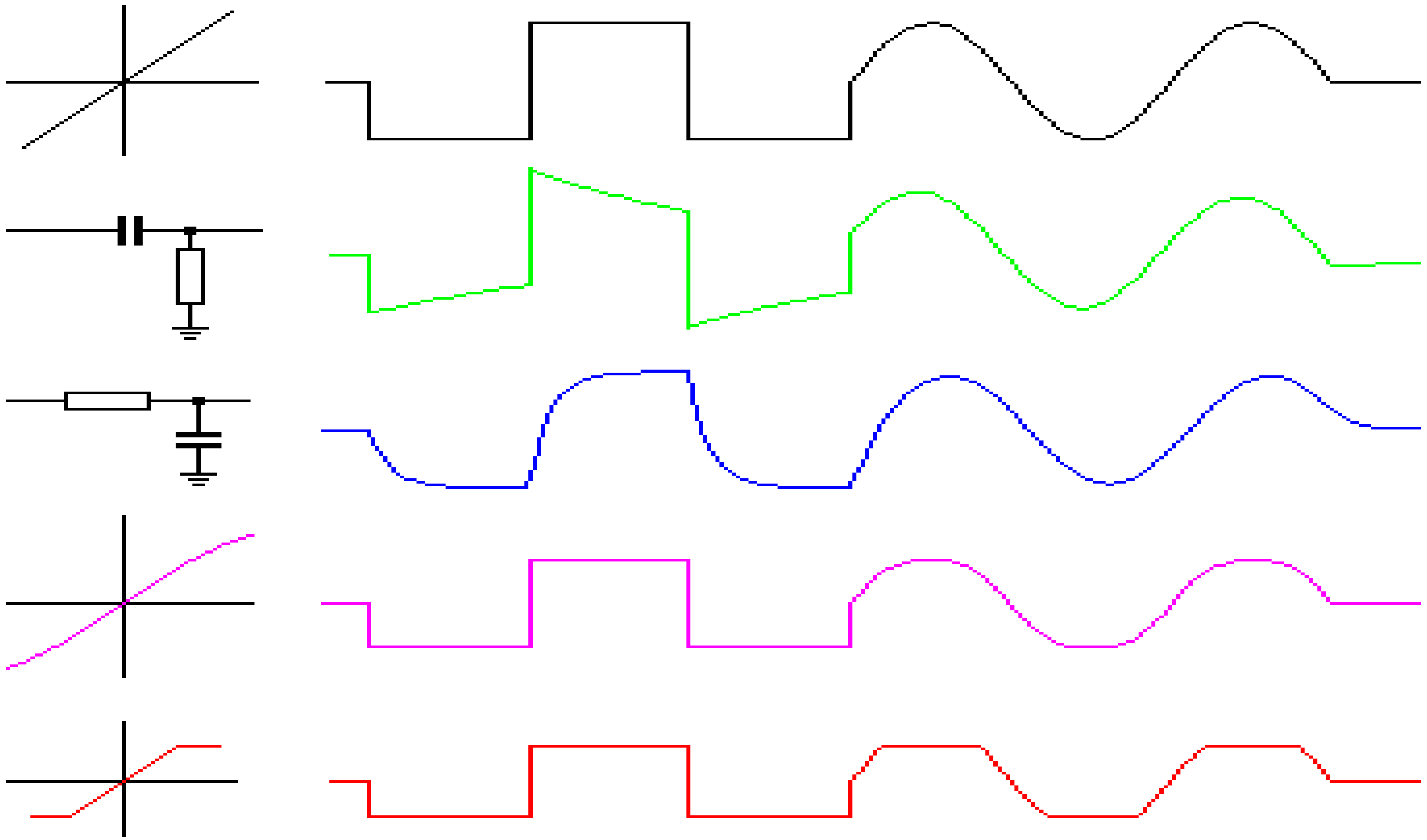
Phase Response

- The phase response of a system defines the delay (phase shift) of individual frequencies. Poor phase response of a measurement system will distort the final time domain waveform.
- Constant Phase- All frequencies are delayed by the same increment of time.
- Linear phase- The phase shifts for all frequencies are linearly related.

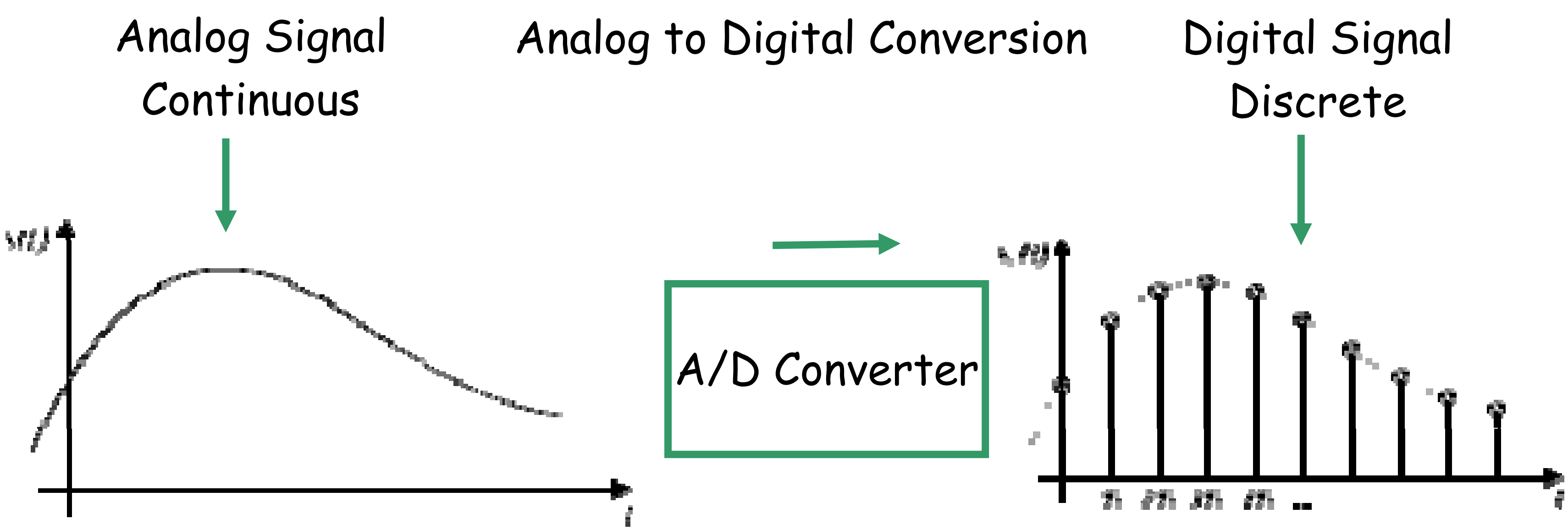
Phase Response



Phase Response



Analog to Digital Conversion
Data Sampling



Data Sampling

The sampling rate or sampling frequency is the number of samples per unit of time.

A sample rate of (Hz is 1/sec)

50Hz = 50 samples per second

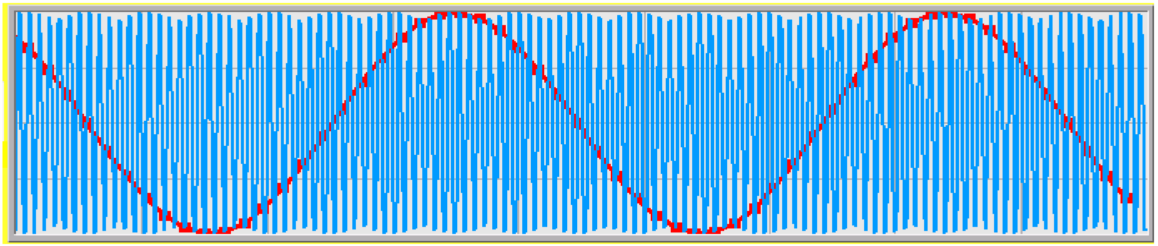
The sample period or sample time is the amount of time between samples and is the reciprocal of the sample rate.

sample period = 1/sample rate

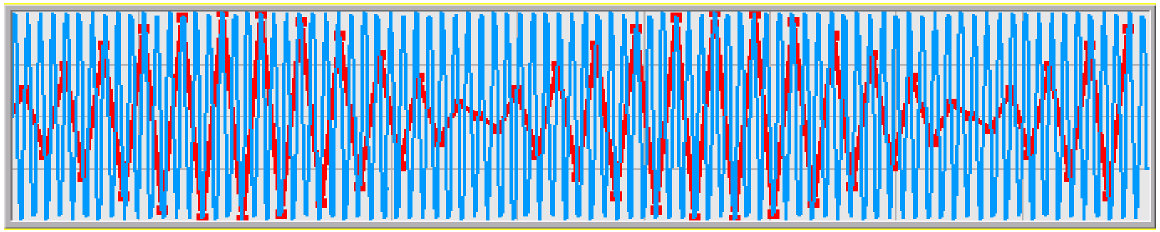
A sample rate of 50 Hz would have a sample period of

1/50 Hz = 20 milliseconds

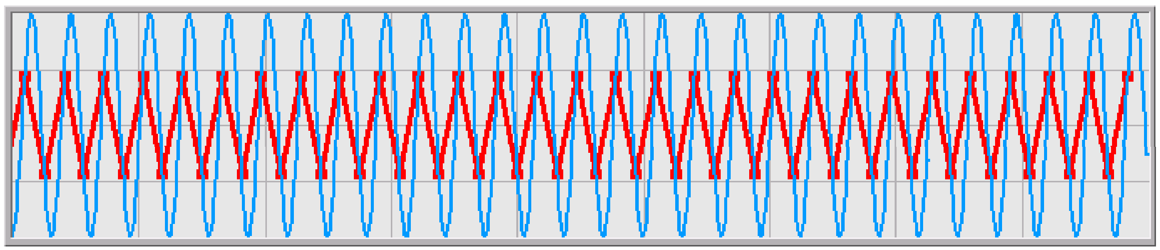
Is the Nyquist theorem good enough?



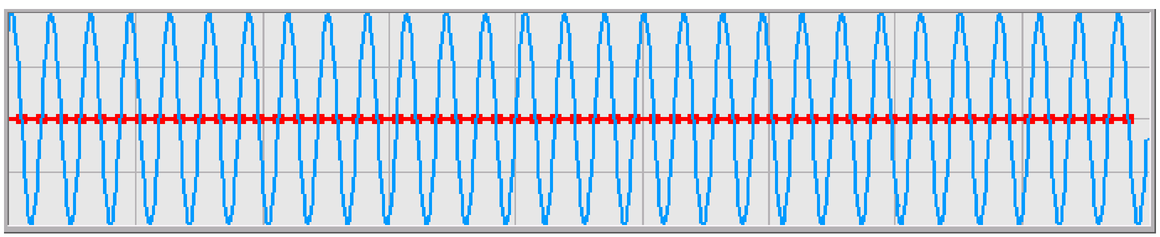
1.06 samples/cycle



0.65 samples/cycle



2.00 samples/cycle
Nyquist Theorem



1.00 samples/cycle

Adherence to the Nyquist criteria will not result in an accurate temporal representation!

Acoustics burn.avi

LLT 1.5 Inch Nozzle, Test

References

1. *Applied Measurement Engineering, Charles P. Wright, 1995 Prentice Hall*
2. *Peter K. Stein, The Engineering of Measurement Systems*
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5. Patrick Vitarius, Acoustic Characterization of Pressure Sense Lines
6. Val Korman, Multiphase Mass Flow using Optical Techniques
7. Don Gregory, Transfer functions
8. Wikipedia-http://en.wikipedia.org/wiki/Main_Page
9. Wofram-http://mathworld.wolfram.com/