Basics of Aircraft Instrumentation

2019 ITEA Test Instrumentation Workshop

Topics and Schedule

• Data, Telemetry, and the Instrumentation System Block Diagram	9:00am
• Standards	
• Data Requirements	
• BREAK	10 min
• Transducers / Specifications	
• Video	
• 1553 Bus	
• LUNCH	11:45am – 1:15pm
• Using Requirements to Configure an Analog Data Channel	
• BREAK	10 min
• Creating a PCM Map to Obtain a Sample Rate	
• Telemetry Bandwidth	
• Record Time	
• BREAK	10 min
• Time, GPS	
• Audio	
• Telemetry Attributes Transfer Standard (TMATS)	
• Measurement Uncertainty – Interpreting the Results	
• Finish	5:00pm

Break for lunch will be 90 min, but the time may be adjusted as needed.

Data, Telemetry, and the Instrumentation Block Diagram

Instrumentation

- Instrumentation is a varied field that contains many specialties. This training provides an overview of the many components that make up an aircraft instrumentation system.

- The goal of this training is to provide an understanding of the equipment used to make measurements and the technical decisions made to condition, filter, and digitize the signals.

Decision Quality Data

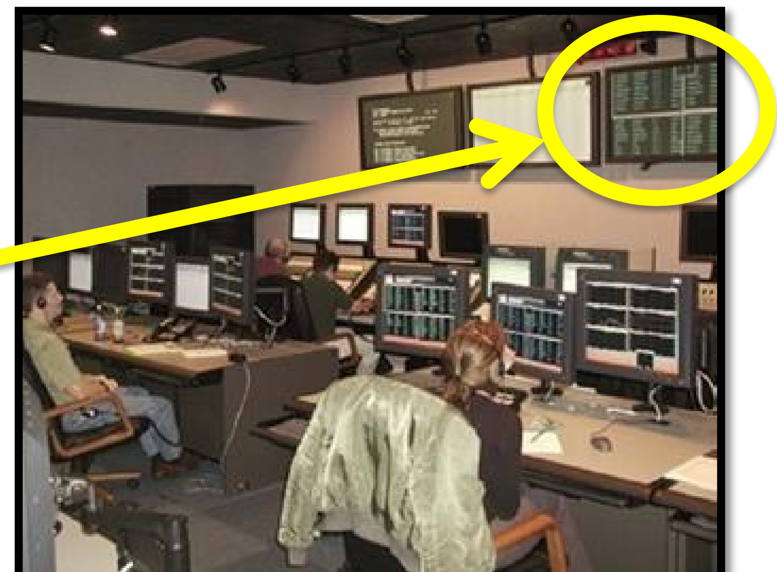
Decision Quality Data is data produced using sound technical and analytical methods that: meets customer defined decision criteria, is repeatable, and has documented and verifiable uncertainty.

You may not think of it, but the product being delivered to your customer is data. The instrumentation system is the means of creating that data.

From an Aircraft Sensor to the Ground Station Display

- Engineers analyze and make decisions upon data generated by the instrumentation system. There are many decisions that must be made in the selection and configuration of the equipment along the measurement path from the sensor on the aircraft to the display of the engineering unit value at the ground station.

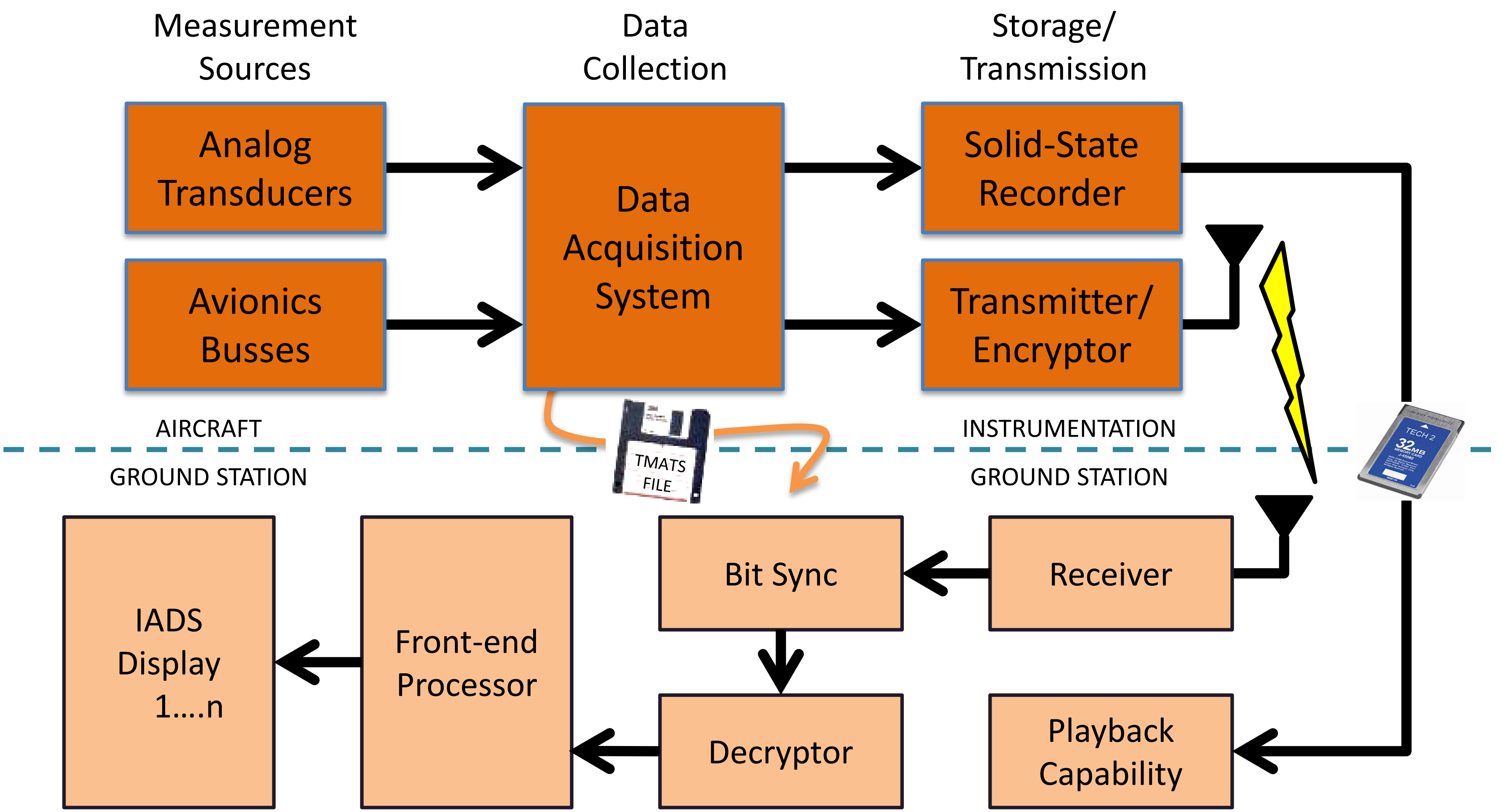
Displacement sensor on a landing gear



Ground station display of displacement as +1.208 in

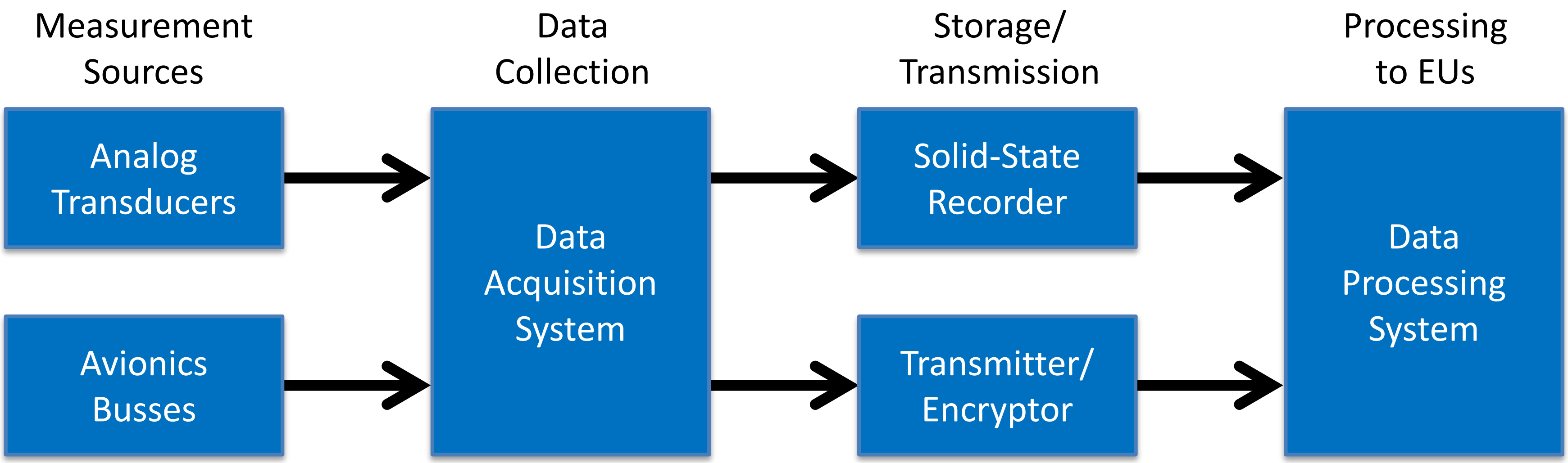
Telemetry: The Remote Sensing of Measurements

- This is the block diagram of the instrumentation system and the receiving ground station.



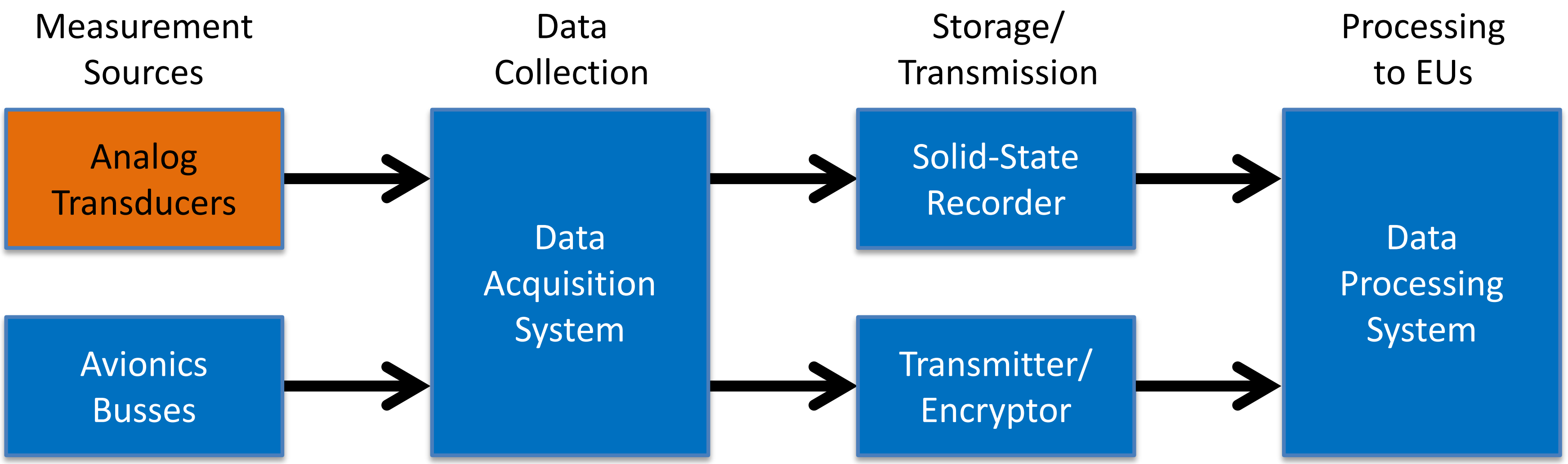
Block Diagram of an Instrumentation System

- All data starts off as an analog signal. All of the measurements on the avionics busses were at one time an analog signal. The data acquisition system converts analog signals or formats digital data to a standard form such that it can be stored to solid state media, or transmitted to a ground station. The final step is the data processing system where digital data is converted back into Engineering Units (EU) for display to the flight test engineer.



Analog Transducers

- Internal to a transducer is a sensing element which responds to the physical phenomena being measured. Electronic circuitry (the transducer) then converts the changing properties of the sensor to an electrical signal that can be measured within the data acquisition system. Simply stated, a transducer converts a physical quantity to an electrical signal.

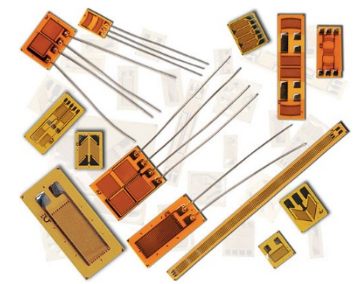


Types of Analog Transducers

- Transducers take on many forms. A few of them are shown below.

Accelerometer:
Measures acceleration, vibration, shock

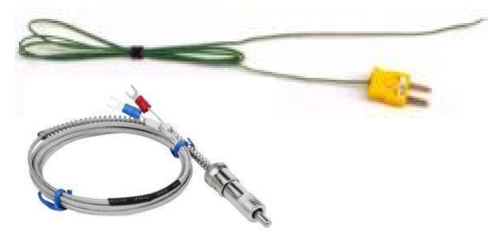
Strain Gage:
Measures strain or load



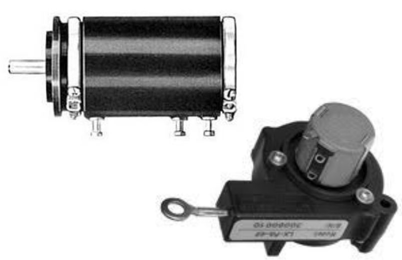
Pressure Transducer:
Measures absolute, gage, or differential pressure

Thermocouple/ RTD:
(Resistive Temperature Device)

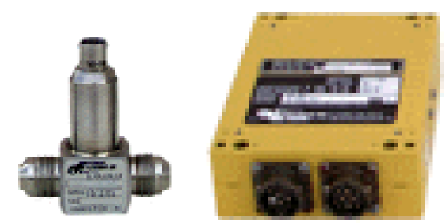
Measures temperature



Potentiometer/ Synchro:
Measures distance or angle



Flow Meter:
Measures fuel flow, total fuel used

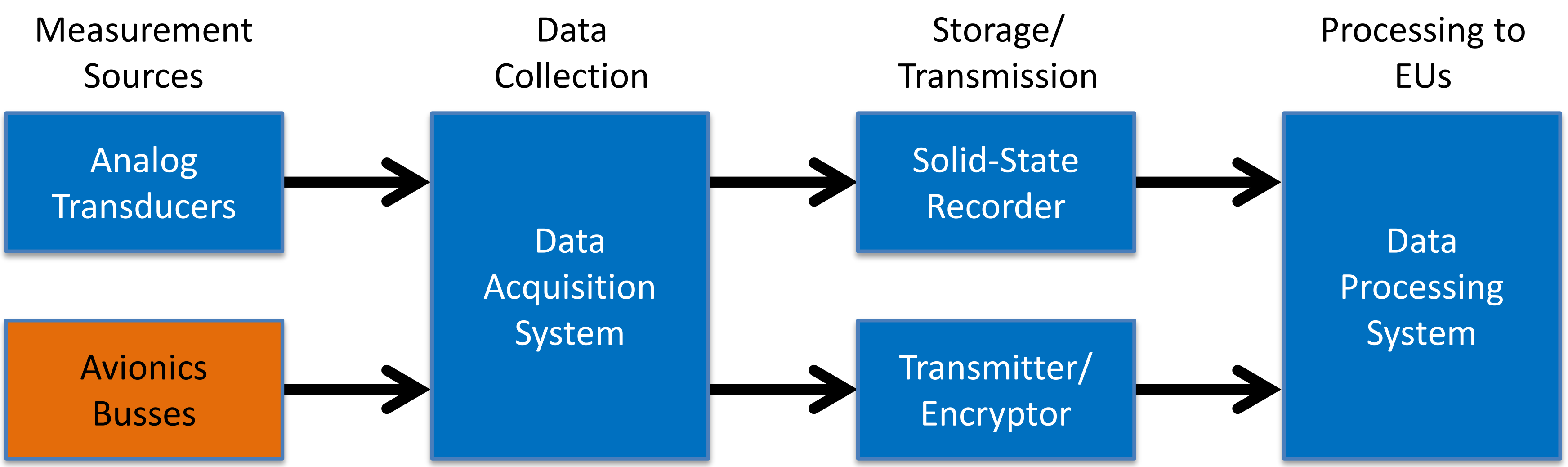


Transducer Characteristics

- Transducers have many characteristics that must be considered in order to provide data that meets the requirements of the test.
- These characteristics include:
  - Engineering Unit Range
  - Frequency Response
  - Output Level
  - Uncertainty (error bound due to environmental effects)
  - Power Requirements
  - Size
  - Environmental Specifications

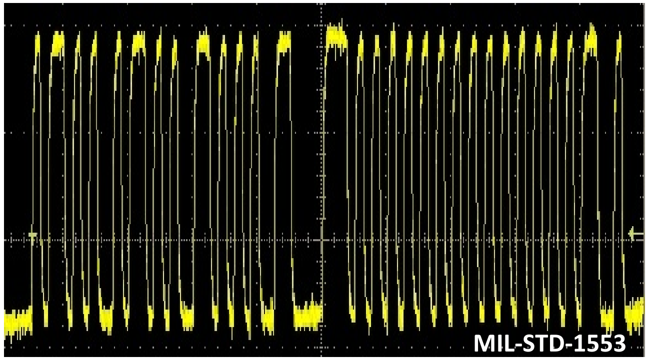
Avionics Busses

- Avionics busses are production-installed communication busses on an aircraft which connect the various avionics systems. Many times, these busses are monitored by the Data Acquisition System. When doing so, a document known as an Interface Control Document (ICD) or bus catalog is needed to decode the information on the bus. Without it, the data is useless.



Avionics Busses

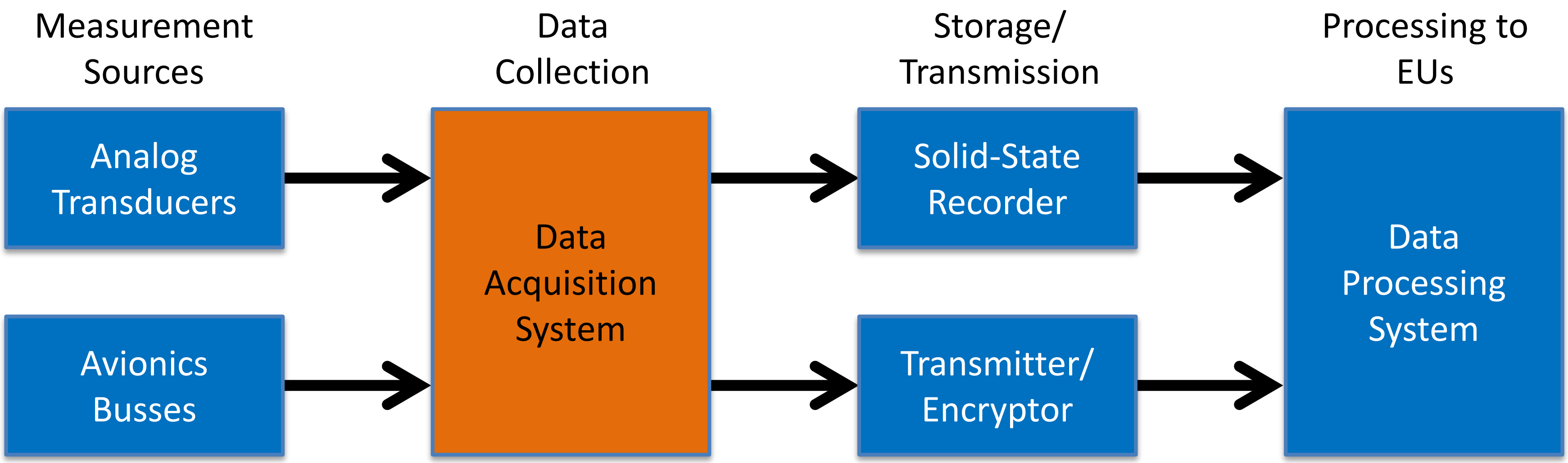
- Avionics busses can include the protocols:
  - MIL-STD-1553
  - ARINC-429
  - RS-232
  - RS-422
  - Ethernet
  - Fire Wire
  - Fibre Channel



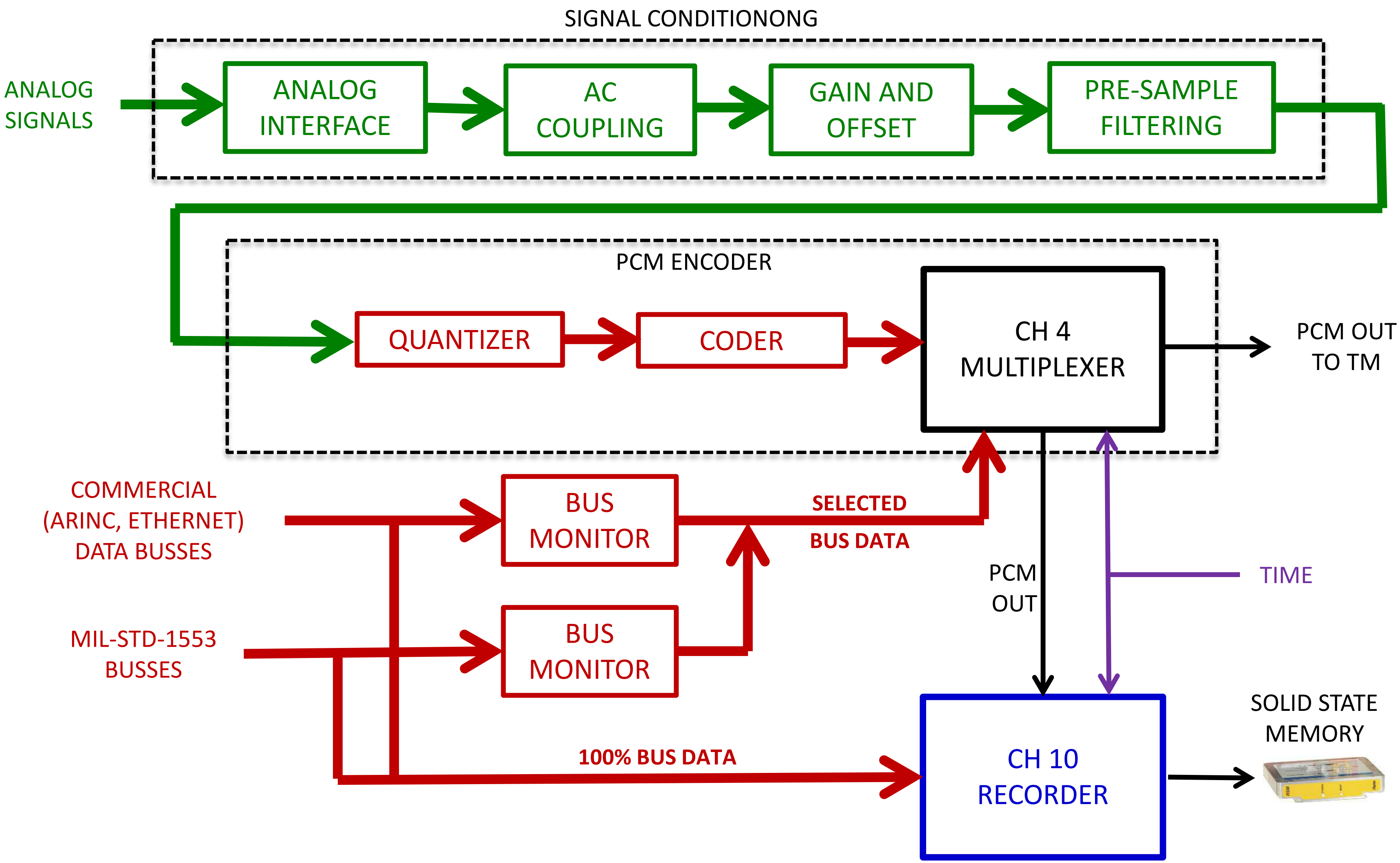
- Each of these bus types require specific hardware to tap into the bus. It is not as simple as splicing into the bus signal wires. External hardware is needed to prevent distortions to the signal and failures in the data acquisition system causing failures in the avionics.
- The ICD or bus catalog for each of these busses provides the information needed to identify the requested parameters and format them to a standard telemetry format. Not having this information early on delays the project completion.

Data Acquisition System

- The data acquisition system is the center of the instrumentation system. It conditions, digitizes, and formats the input data signals for recording and transmission.
- Data acquisition systems can be complex depending on the amount of data it can sample, and the flexibility of the configuration. May consist of masters and remote units.

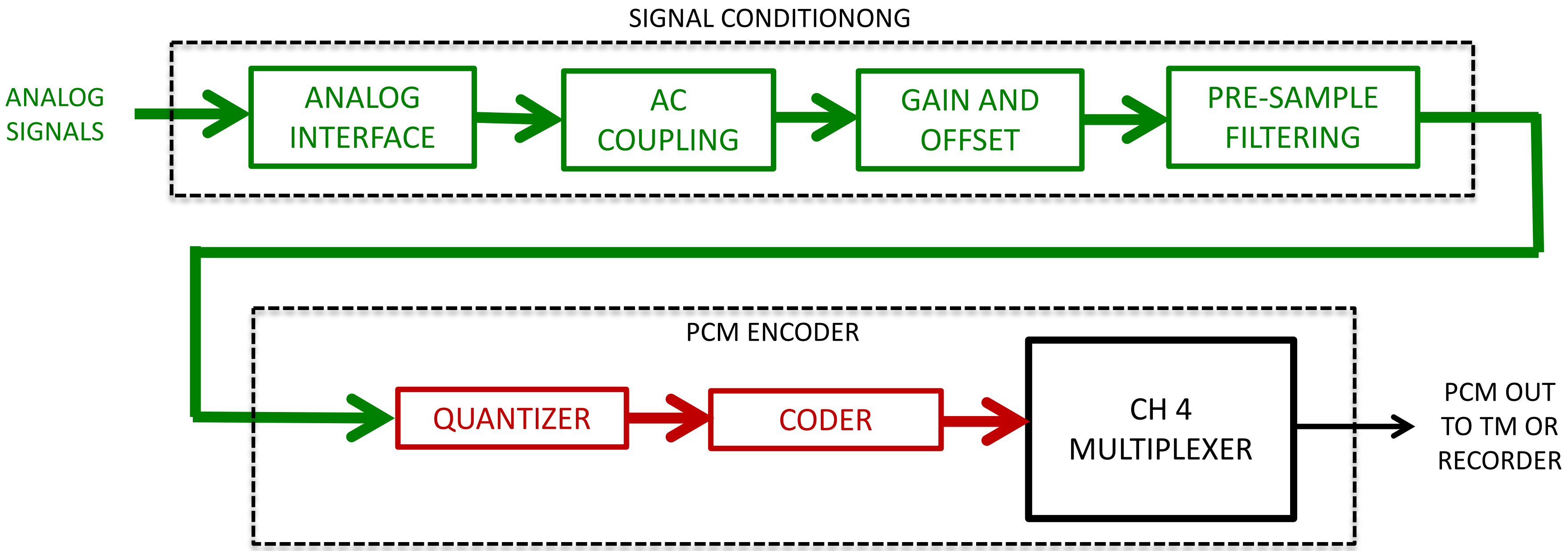


Detailed Block Diagram of a Data Acquisition System



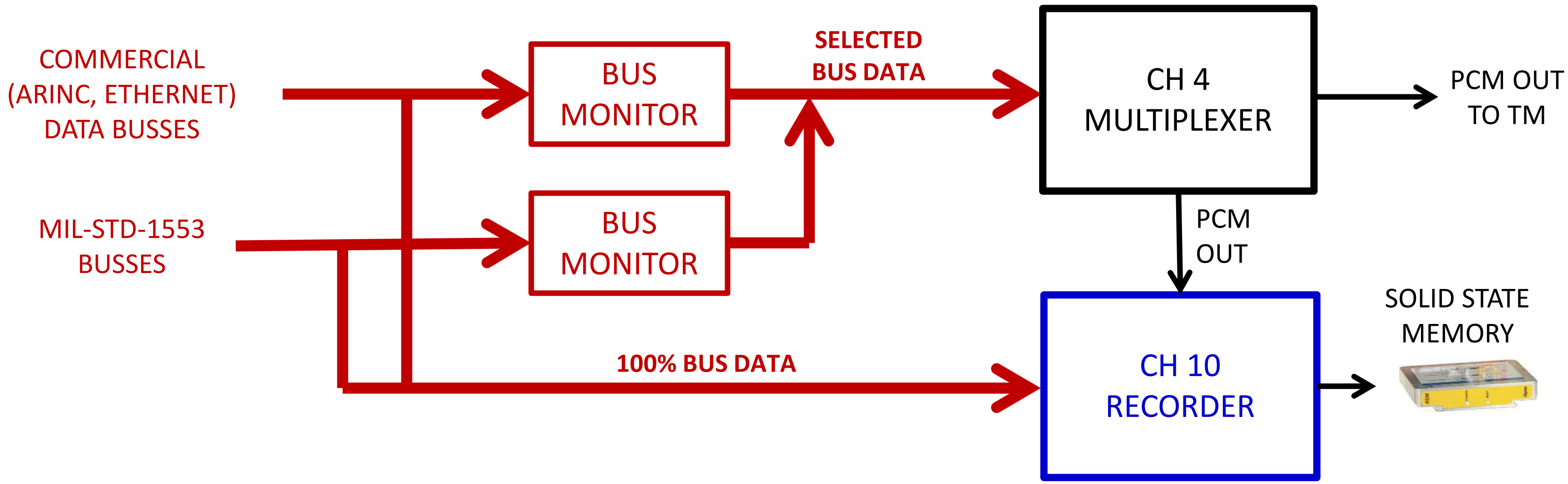
Data Acquisition System Block Diagram
Analog Conditioning

- Analog signals need a variety of signal conditioning to provide the correct EU ranges and frequency response for the measurement. The analog signal then is sampled, and digitized before being multiplexed with other signals. The output is a serial Pulse Code Modulation (PCM) bit stream of ones and zeros.



Data Acquisition System Block Diagram
Avionics Busses

- Avionics busses already have their data digitized. The data acquisition system formats the avionics busses such that it can be merged into a PCM stream. The data acquisition system can also capture 100% of the Commercial-type busses, 1553, and ARINC messages.

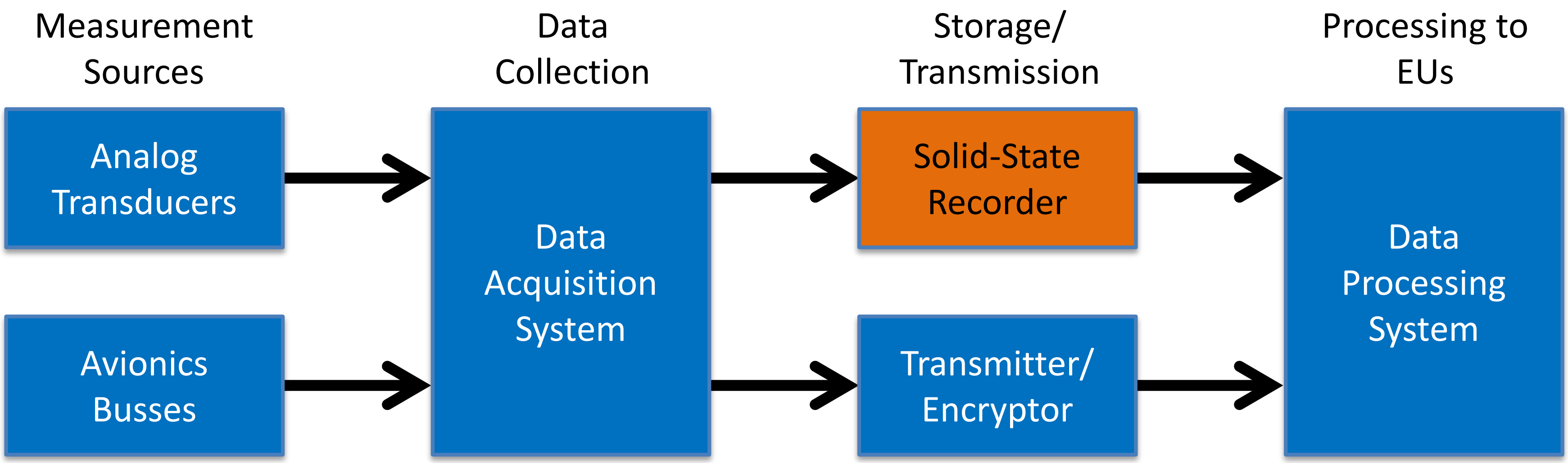


Data Acquisition System Hardware

- Data acquisition systems for use on aircraft are designed to operate and survive the harsh environments of flight test. This can include extreme temperature ranges, vibration, or high altitudes. The hardware conforms to the IRIG-106 Telemetry Standards which were written such that the data can be processed at any of the Department of Defense (DoD) ranges.

Solid State Recorder

- The solid state recorder receives the PCM stream and stores the data to a removable memory cartridge in a file format.
- Other recorders can take multiple PCM streams, avionics busses, and video directly. These recorders are described in Chapter 10 of the ***IRIG-106 Telemetry Standard*****,** and are known as “Chapter 10 recorders”.

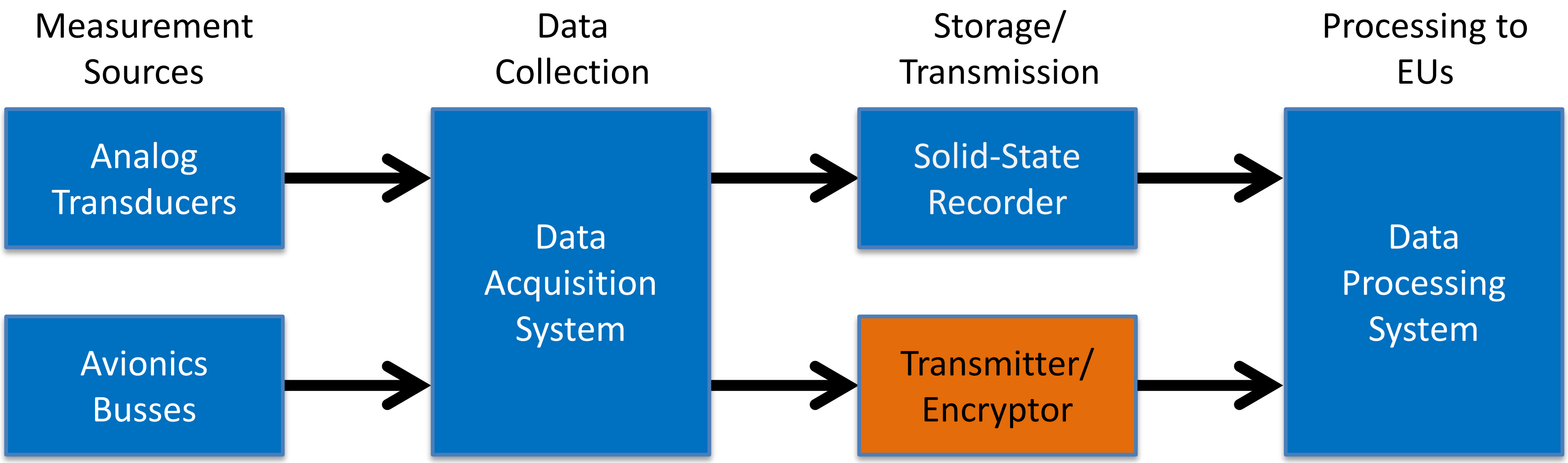


Various Types of Solid State Recorders

- Data was originally stored on magnetic tape, but now recorders use solid state memory as the storage media. The required capacity of the memory cartridge is dependent upon the speed of the data (bit rate) and the duration of the flight test.
- Chapter 10 based recorders have interface cards to directly record data streams, avionics busses, and video.

Transmitter

- Transmitters are used to accomplish the remote sensing of what is occurring real-time on the aircraft. Because bandwidth is at a premium, various types of modulation schemes are used to minimize the frequency band when transmitting the PCM streams.
- When data is classified, the PCM stream must first be encrypted before transmission.

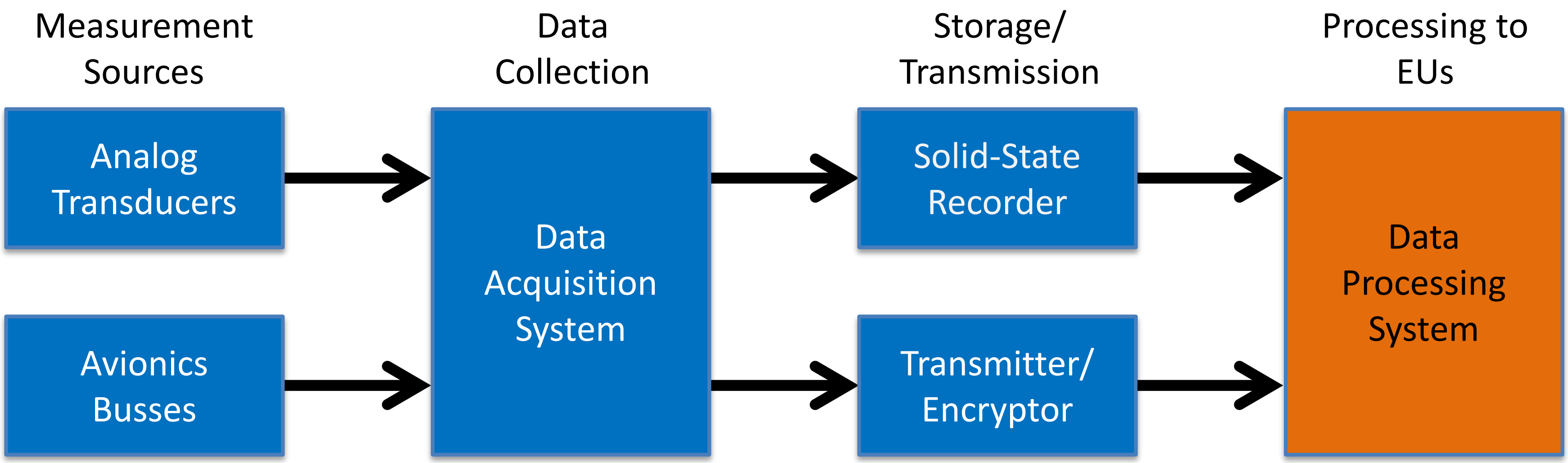


Telemetry System

- The telemetry system is made up of the transmitter, radio frequency (RF) cable, an RF splitter, and antennas.
- In order to provide the best signal such that there are limited drop-outs in data at the ground station, each element of the system must be carefully matched for the frequency band being utilized.

Data Processing System

- The data processing system can either be the ground station receiving transmitted data or a data lab playing back recorded data from a test flight. Received data is converted from a PCM stream of ones and zeros, where individual parameters are displayed in EU values. Recoded data is a binary file which is played back using software that can produce EU-converted data files.
- Data processing is included as part of the instrumentation system because it is a vital part of the validation process of the data.

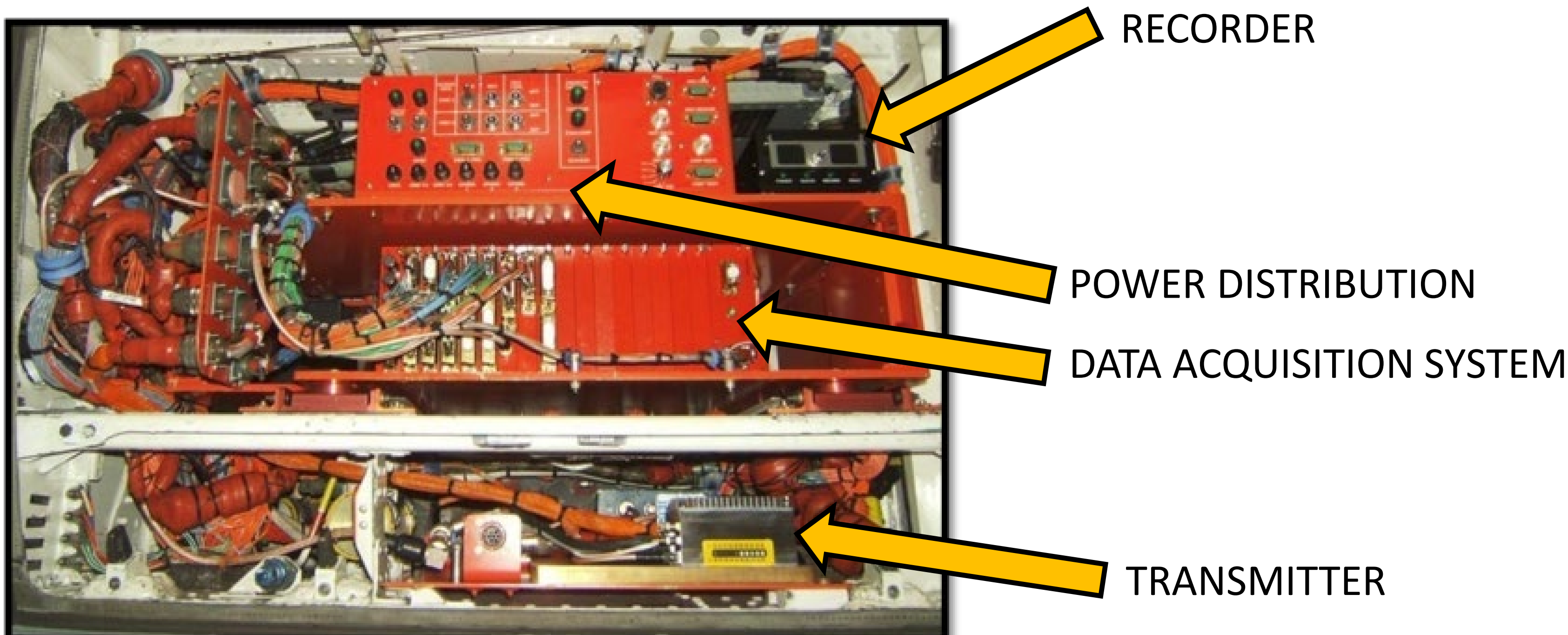


Data Processing System

- The data processing system must have the applicable information about all the measurements in order to identify the parameter and provide coefficients to convert the raw data into engineering units. The data can also be formatted to display in strip charts, dials, and graphical representations of the aircraft orientation.
- The data processing system can be a large ground station facility, within a trailer or van, on a portable cart, or even on a laptop; depending upon the complexity of the processing.

Designing an Instrumentation System

- Before an instrumentation system is designed, you must have well defined requirements. Later, we will discuss the requirements needed to design an instrumentation system that provides decision quality data using the least amount of TM bandwidth and solid-state memory.



Standards

Standards

- Interoperability between test ranges can only be accomplished when everyone follows the same standards.
- The Range Commanders Council (RCC) have written many Inter-Range Instrumentation Group (IRIG) standards to accomplish this interoperability.
- This allows an aircraft instrumented at Edwards AFB the ability to transmit data to the ground station at Patuxent River NAS.
- The following is a list of some of the standards, but by no means is it an exhaustive list.

Standards – IRIG Standards

Inter-Range Instrumentation Group (IRIG)-106 Telemetry Standards

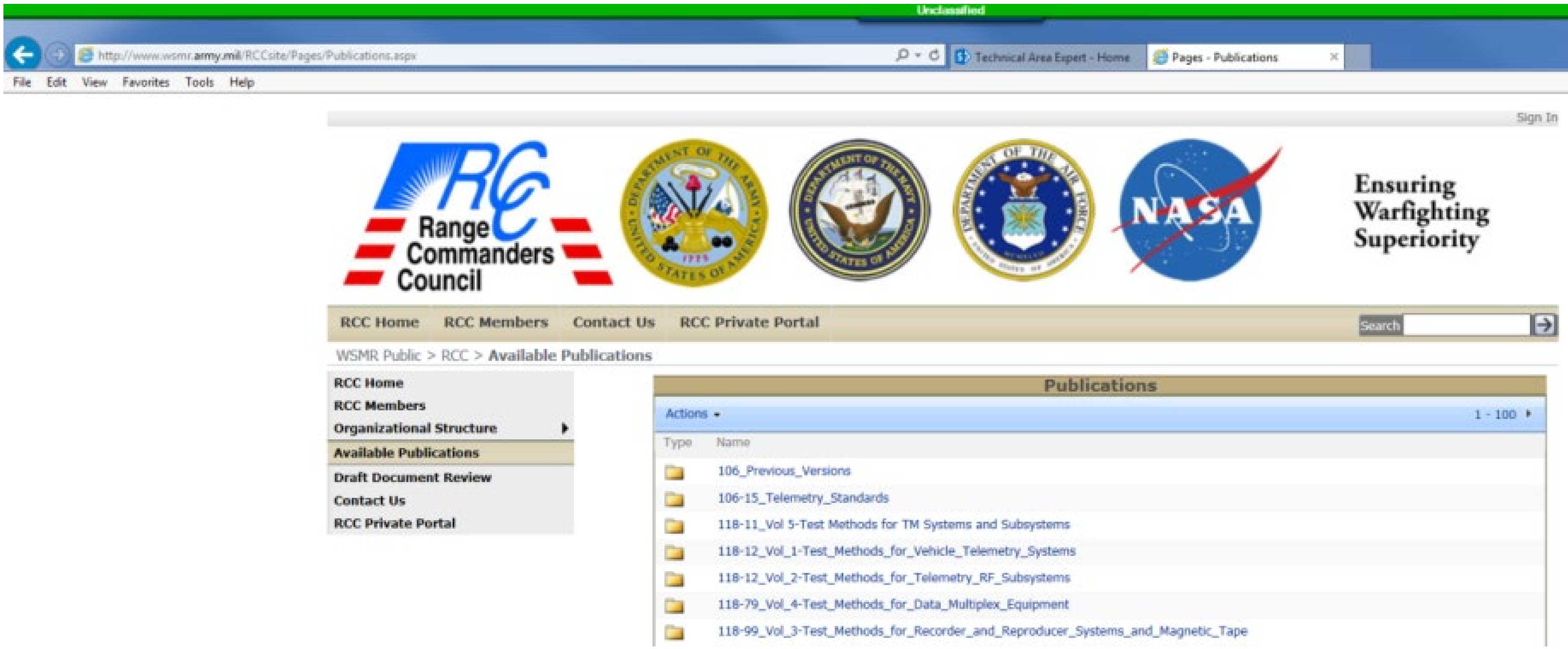
This document, prepared by the Telemetry Group (TG) of the Range Commanders Council (RCC), was written to foster compatibility of telemetry transmitting, receiving, and signal processing equipment at the member ranges under the cognizance of the RCC. When we used the term “Chapter 10 recorder”, it is referring to chapter 10 of this document. Chapters 2, 4, 5, 9, 10 and Appendix A will be mentioned in this training.

This standard is usually updated every two years, so always check for updates.

http://www.wsmr.army.mil/RCCsite/Documents/106-17_Telemetry_Standards/106-17_Telemetry_Standards.pdf

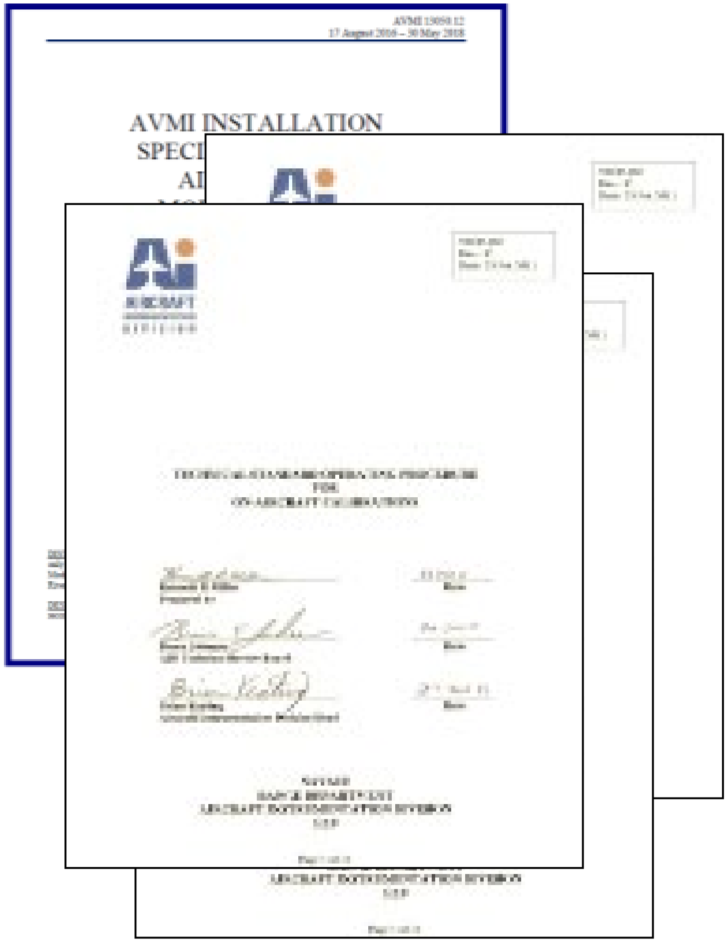
Standards – IRIG Standards

All the IRIG standards can be accessed on the Range Commander's Council website.



http://www.wsmr.army.mil/RCCsite/Pages/Publications.aspx

Standards – In-House Standards



Your organization probably has documented policies and procedures on how to instrument aircraft.

Many of these documents were created from lessons learned in the past and contain valuable information.

Standards – Military and Commercial Standards

There are numerous military and commercial standards that are followed in order to safely modify an aircraft with instrumentation. Some are listed below:

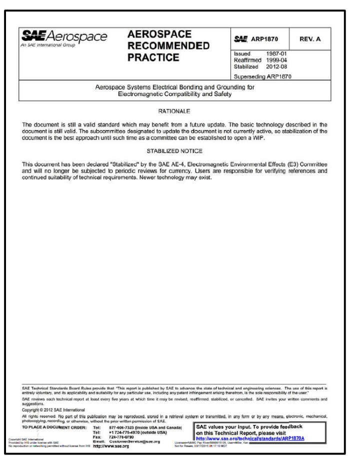
ARP1870 – Aerospace Systems Electrical Bonding and Grounding for Electromagnetic Compatibility and Safety

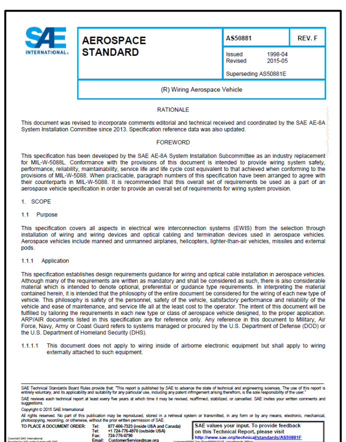
SAE AS50881 - Wiring Aerospace Vehicle

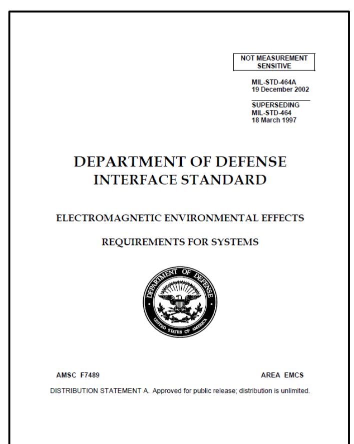
MIL-STD 464 - Electromagnetic Environmental Effects

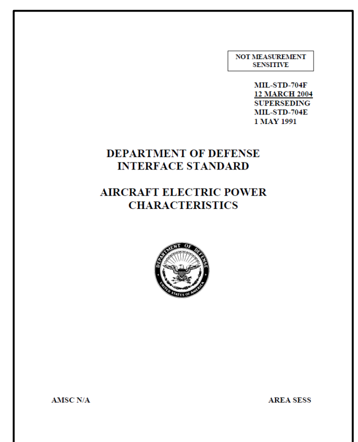
MIL-STD-704 - Aircraft Electric Power Characteristics

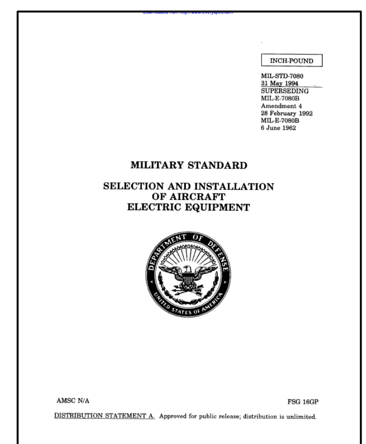
MIL-STD-7080 – Selection and Installation of Aircraft Electric Equipment





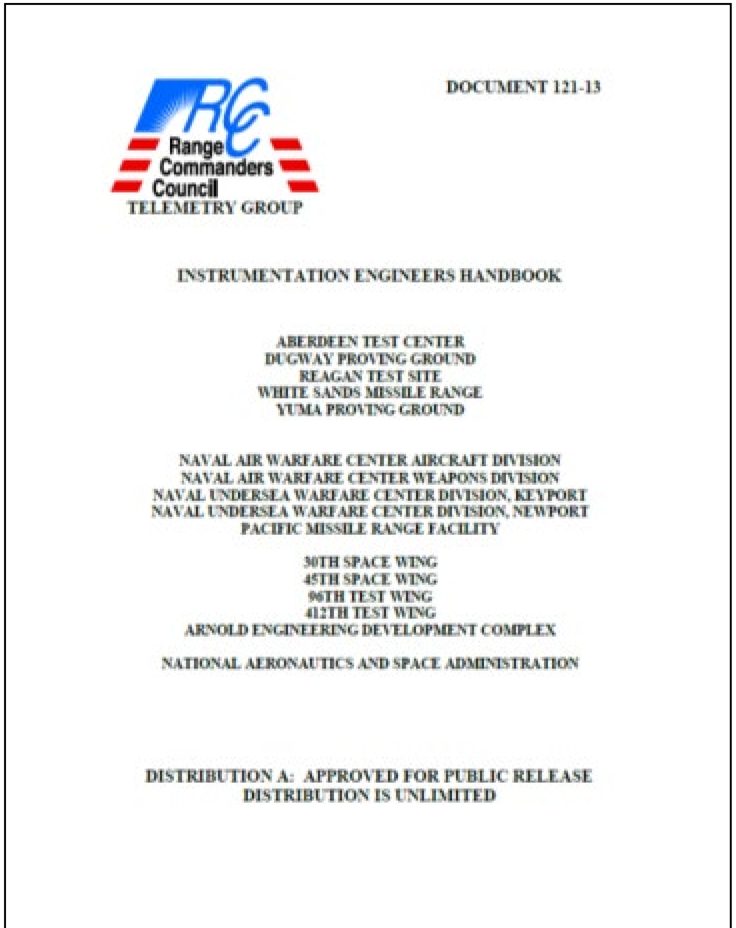






Valuable Resource

A great resource to use containing a wide array of instrumentation subjects is the Instrumentation Engineers Handbook.



DOCUMENT 121-13

Range Commanders Council
TELEMETRY GROUP

INSTRUMENTATION ENGINEERS HANDBOOK

ABERDEEN TEST CENTER
DUGWAY PROVING GROUND
REAGAN TEST SITE
WHITE SANDS MISSILE RANGE
YUMA PROVING GROUND

NAVAL AIR WARFARE CENTER AIRCRAFT DIVISION
NAVAL AIR WARFARE CENTER WEAPONS DIVISION
NAVAL UNDERSEA WARFARE CENTER DIVISION, KEYPORT
NAVAL UNDERSEA WARFARE CENTER DIVISION, NEWPORT
PACIFIC MISSILE RANGE FACILITY

30TH SPACE WING
45TH SPACE WING
96TH TEST WING
412TH TEST WING
ARNOLD ENGINEERING DEVELOPMENT COMPLEX

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

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Found on the RCC website, this document covers:

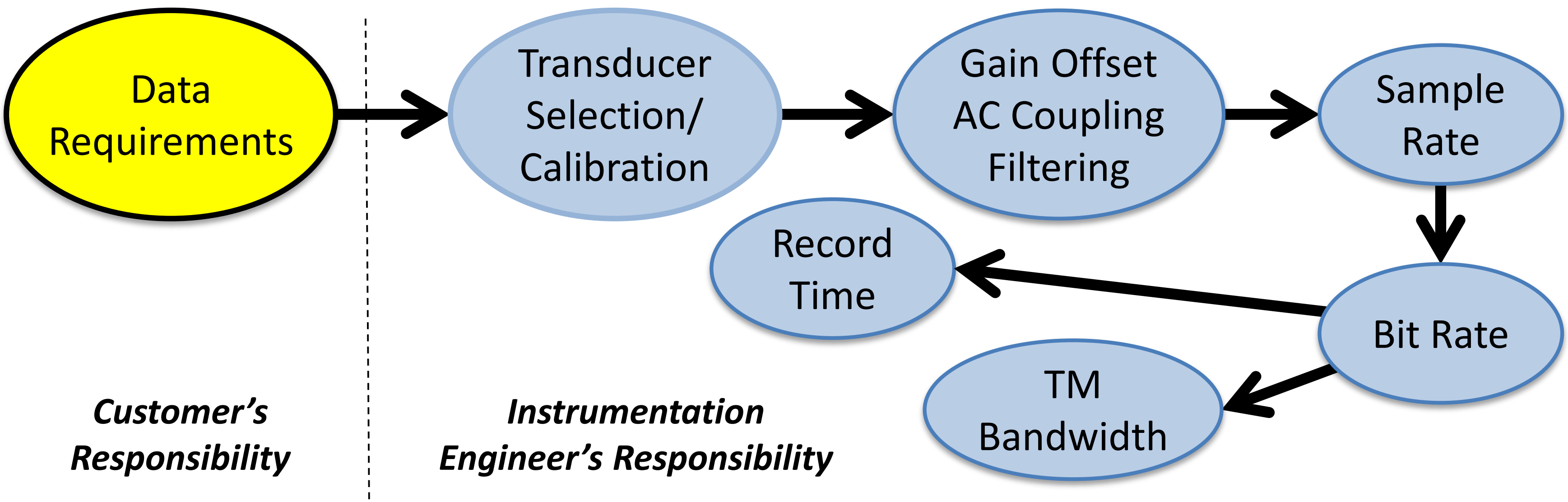
- Typical Instrumentation System Overview
- Signal sources
- Signal Conditioning
- Flow and Level Measurement
- Pulse Code Modulation Formats
- Calibrations
- Telemetry Transmission and Reception
- Recorders and Recording
- Practical Considerations
- Grounding, Shielding, and Noise Reduction
- Electrical Power Load Analysis

http://www.wsmr.army.mil/RCCsite/Documents/121-13_Instrumentation%20Engineers%20Handbook/121-13_Instrumentation_Engineers_Handbook.pdf

Data Requirements

Data Requirements

- The diagram below shows the process of the design of an instrumentation system. It all begins with the data requirements. When well defined and identified early in the process, the requirements will provide data that will allow flight test engineers to make quality decisions during the execution of the test.



Data Requirements

- Data Requirements are the most difficult piece of information to get defined.

- Must have defined requirements before designing an instrumentation system.

- Requirements should include:
  - Measurement Description
  - Signal Source
  - Frequency of Interest
  - Measurement Uncertainty
  - Engineering Units
  - Engineering Unit Range

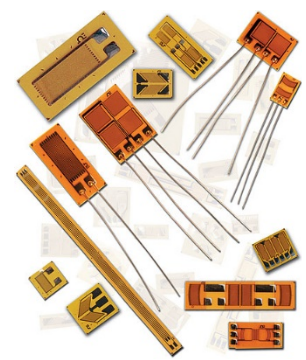
Measurement Description

- The **Measurement Description** indicates what type of measurement is to be made. This narrows down which family of transducers will be used.

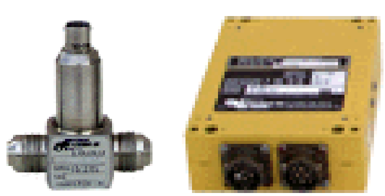
Acceleration, Vibration, Shock

Temperature

Loads, Strain

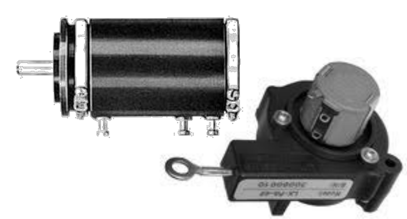


Fuel Flow



Pressure

Position



Signal Source

- The **Signal Source** indicates where the measurement is coming from.

- Various sources are available
  - from an installed instrumentation transducer
  - from a tap off of a production transducer
  - from an avionics bus
  - from a video image (yes this includes video, which is a transducer that senses light).

- In some cases, there may be different sources for the same measurement as a comparison when a system is being evaluated during a flight test.

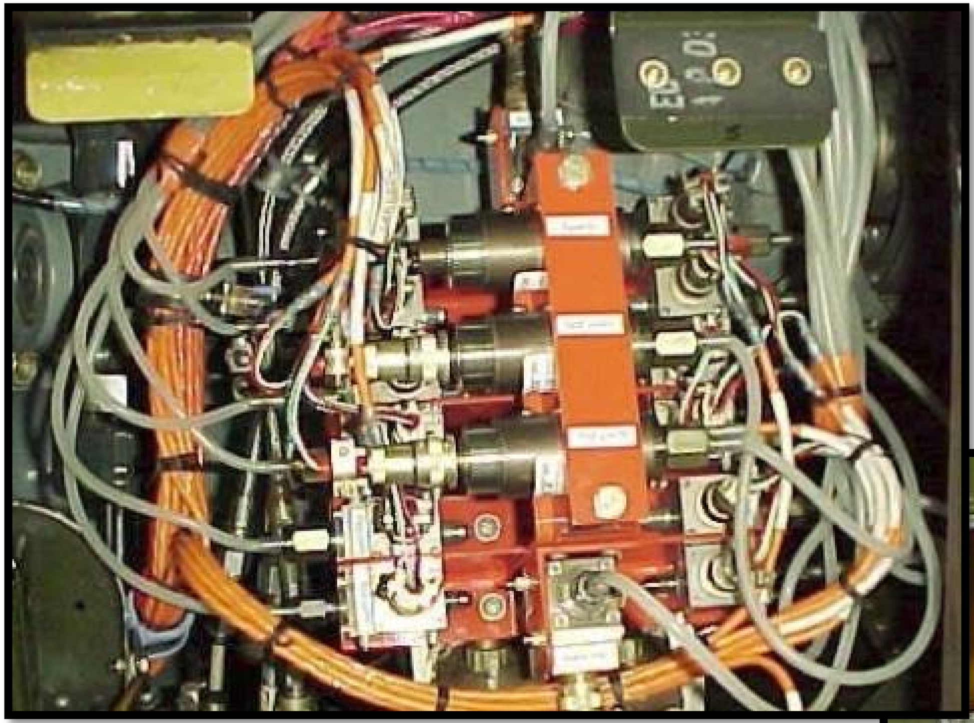
Signal Source: Instrumentation Transducer

Position Potentiometer
Measuring movement of
a linkage

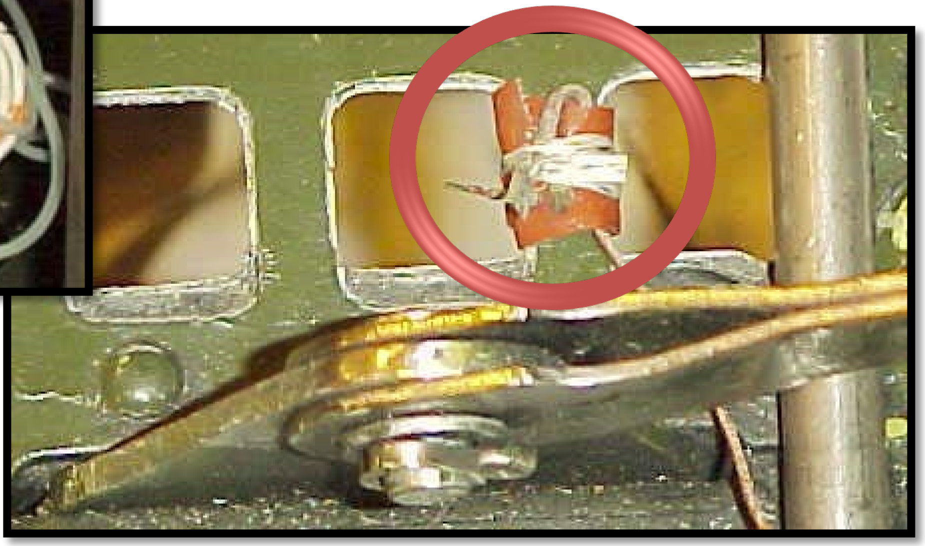
Accelerometer
Measuring vibration
on a rib

Current Transformers
Measuring AC current
from a generator

Signal Source: Instrumentation Transducer



Pressure Transducers
Measuring pressure ports on a rake



Thermocouple
Measuring air temperature

Signal Source: Instrumentation Transducer

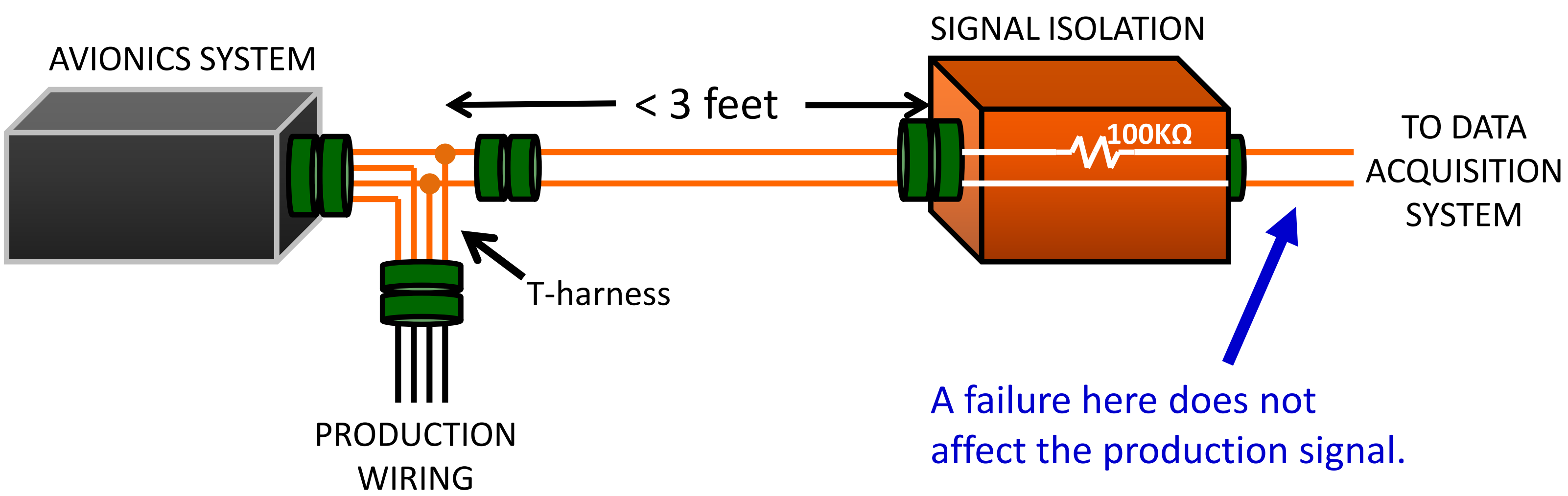
- An **Instrumentation Transducer** is used in the following situations:
  - When the measurement is not available on the production configured aircraft.
  - When the production measurement is not adequate for the test (ex: does not encompass the measurement range or frequency range needed).
- When an instrumentation transducer is installed, the transducer and data channel are uniquely designed for the data requirements.

Signal Source: Production Transducer

- Some aircraft have production systems which output analog and discrete signals.

- To tap into a production system it is best to use a “T-harness”. This will make it easy to remove when there are maintenance gripes on the system.

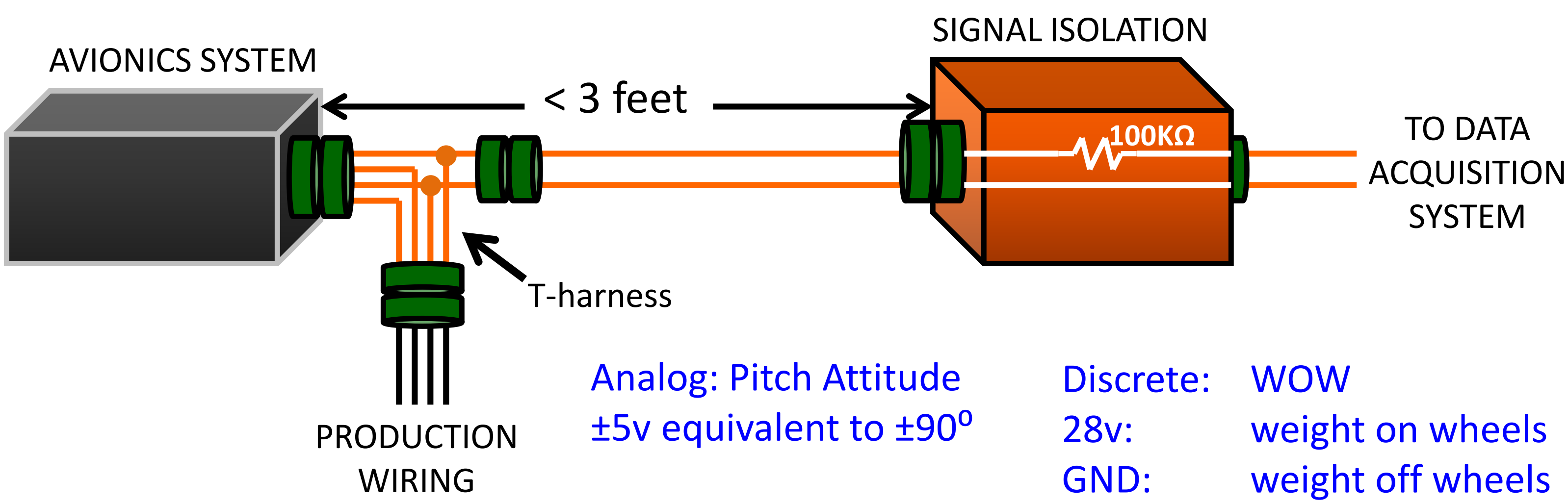
- When tapping into production signals, the instrumentation system must be *electrically isolated* preferably within 3 wire-feet of the production pick-up point. In this example, a resistor is used.



Signal Source: Production Transducer

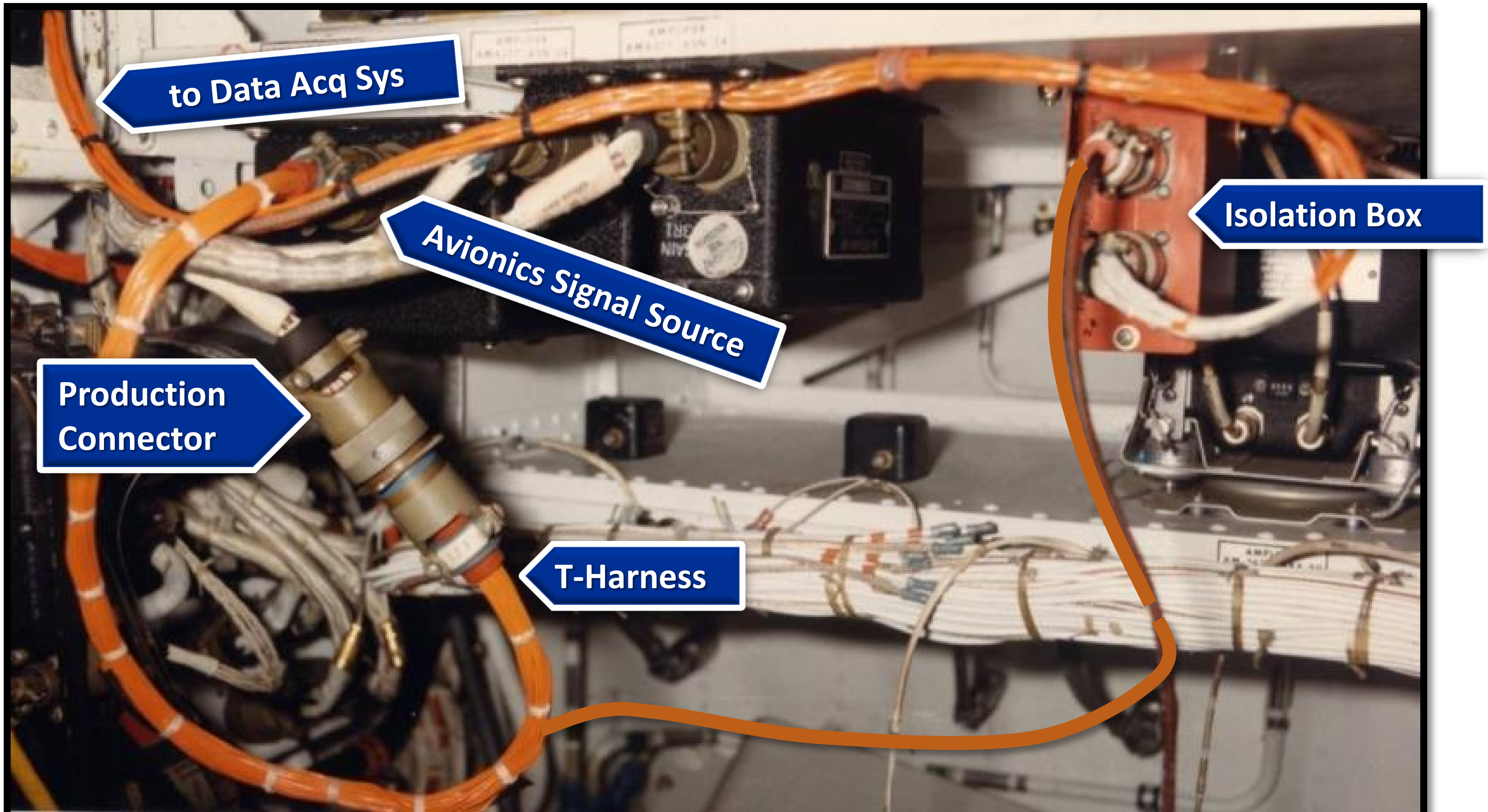
- Information on the voltage range, Engineering Units (EU) range, and scaling must be obtained from the specifications on the signal source's equipment. Sometimes this can be a difficult thing to obtain, but it is necessary in making the measurement.

- This information is needed to set up your signal conditioning in the data acquisition system and convert the raw data to EUs.



Signal Source: Production Transducer

In this photo, you can see the elements used to measure the production transducer signal. Note the Instrumentation wiring (orange) and the production wiring (white).



Signal Source: Production Transducer

- A **Production Transducer** is monitored in the following situations:
  - An instrumentation transducer cannot be mounted in the area that the measurement is to be made.
  - There is a question on the integrity of the production aircraft signal and it needs to be monitored (Sometimes an instrumentation transducer is also installed for comparison).
  - A new avionics system is being tested and the analog transducer inputs to that system needs to be monitored. An example would be an original production gyro and the replacement gyro both had their outputs monitored for comparison.

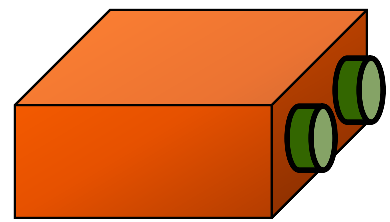
Signal Source: Avionics Bus

- **Avionics Bus** data is already available in a digitized form. All the steps done in the previous section to condition, filter, and sample the signal has been done by the avionics systems. So the sample rate of the data is limited to the designed update rate of a particular parameter on the bus.
- Sources of Avionics Bus Data:
  - MIL-STD-1553
  - ARINC-429
  - RS-232
  - RS-422
  - Ethernet
- Currently, the most common sources of avionics bus data being monitored are MIL-STD-1553 and ARINC-429.

Signal Source: Avionics Bus

- Because a production avionics signal is being tapped into, the instrumentation system must be isolated from the production system. The type of isolation depends on the type of bus.

MIL-STD-1553
Bus Coupler



RS-232/422
Buffer Box

ARINC-429
Repeater Box

Ethernet
Network Switch

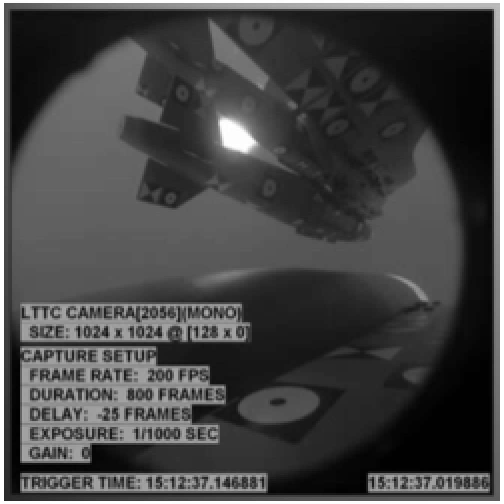
We will describe 1553 bus monitoring later in the training.

Signal Source: Video

- There are times where a flight test engineer needs to see what the aircrew sees or how a store separates from an aircraft.
- Qualitative video provides information of events happening during a test.
- Quantitative video provides an actual measurement from the image.

Qualitative Video

Quantitative Video



We will cover the two types of video later in the training

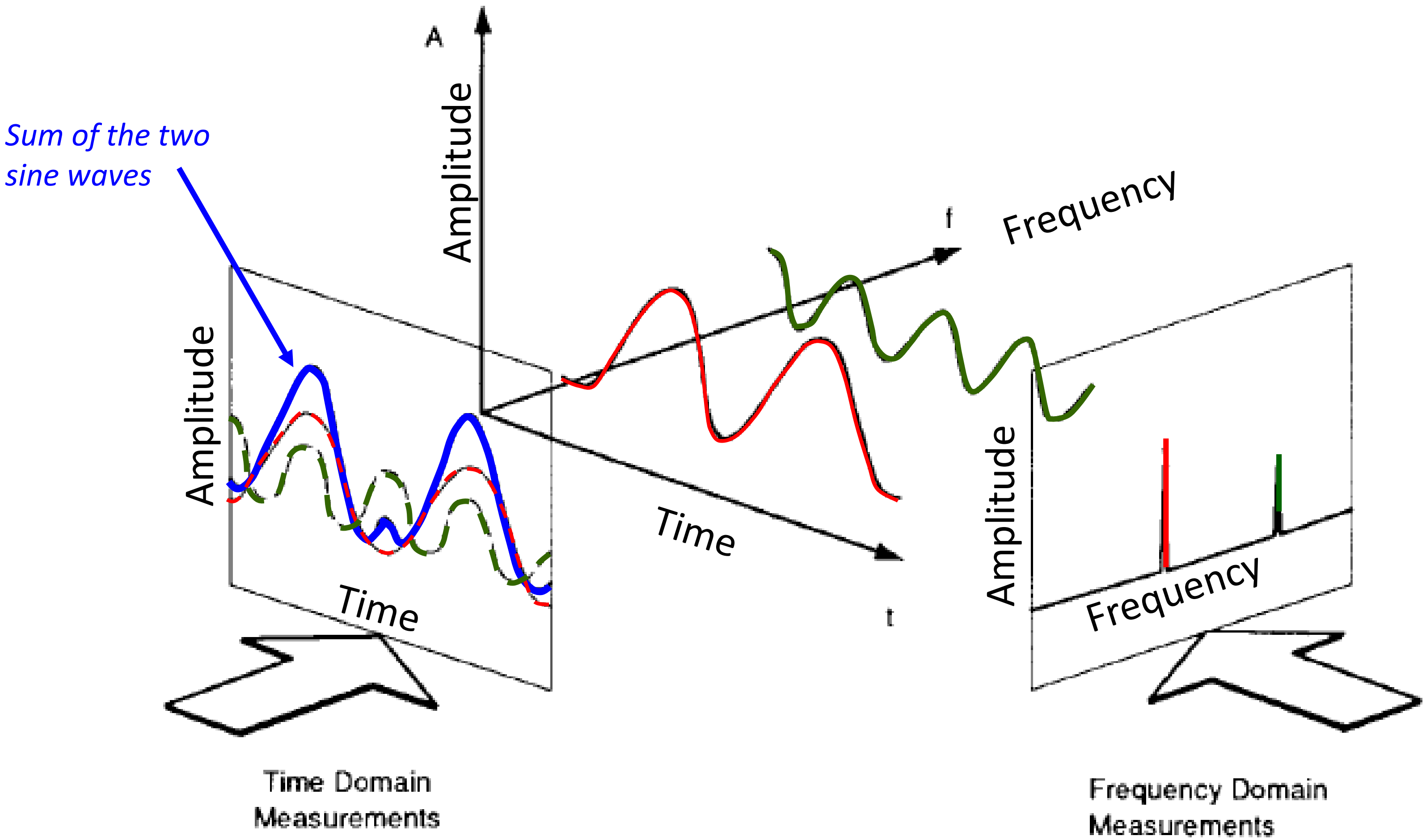
Frequency Range of Interest

- Frequency Range of Interest is the range of frequency components of a signal which must be measured with little to no attenuation in order to make the proper decisions during a flight test.

- This is probably the ***most misunderstood*** data requirement, and it is one of the ***most important*** requirements in the design of the instrumentation system.

- What frequency of interest is not…
  - it is ***not*** the sample rate.
  - it is ***not*** the cutoff frequency of the pre-sample filter.
  - However, the cutoff frequency and sample rate are derived from the frequency of interest.

Time and Frequency Domain of a Signal

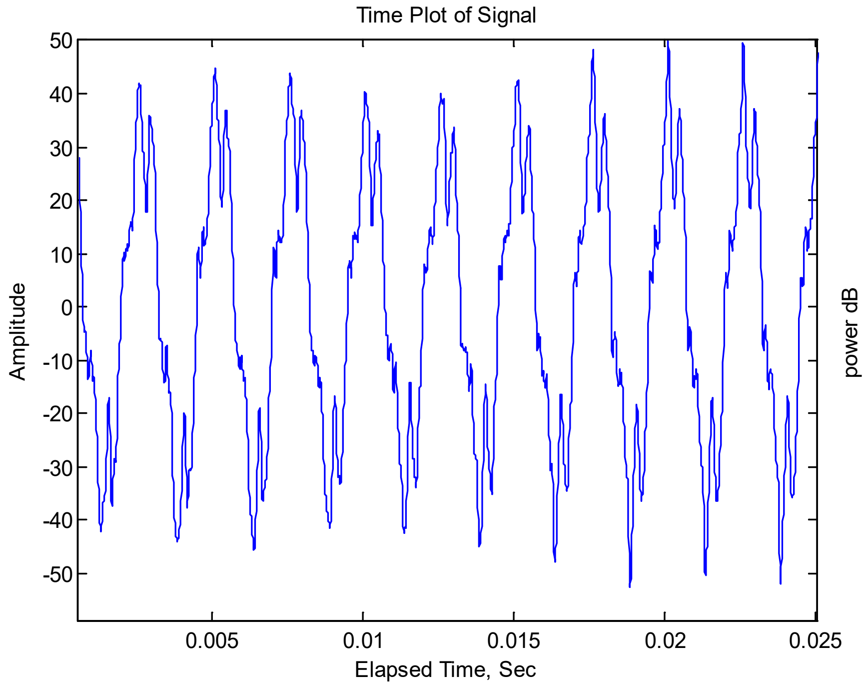


Oscilloscope View

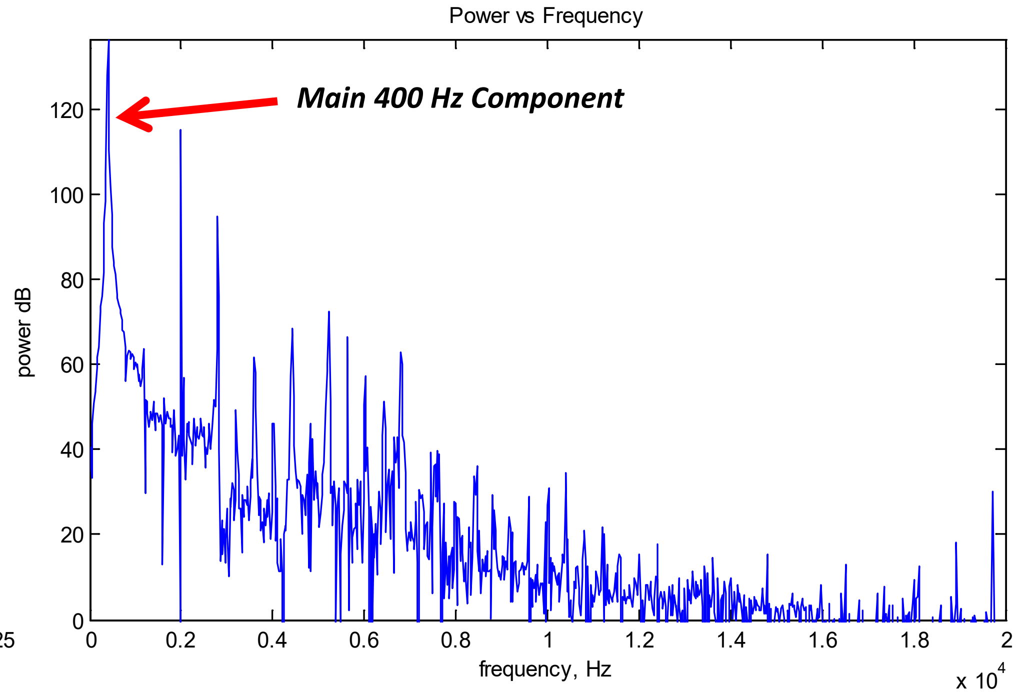
Spectrum Analyzer View

Time and Frequency Domain of a Signal

- All signals are made up of sine waves of different amplitudes and frequencies. This is a 400 Hz current measurement from a generator shown in both the time and frequency domain.



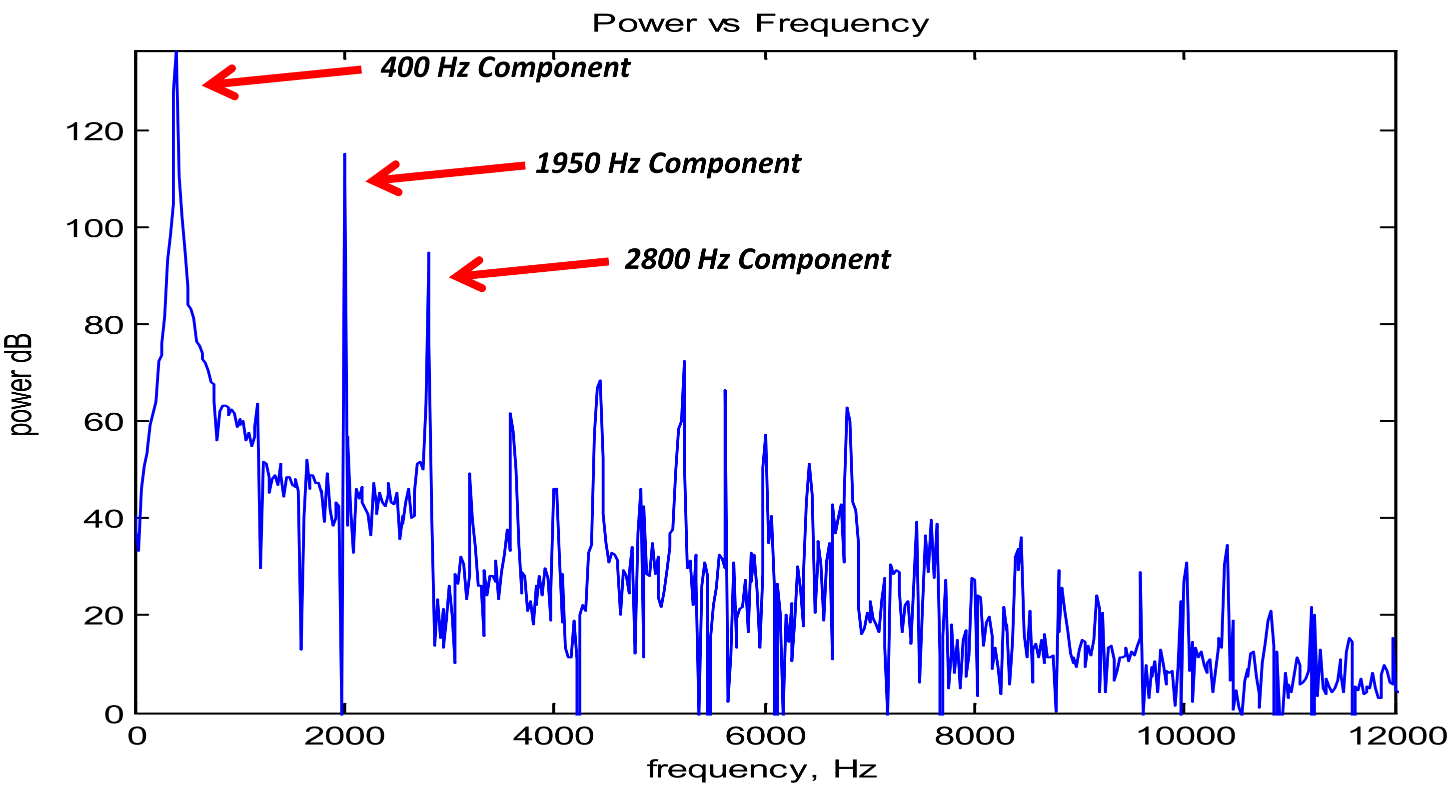
TIME DOMAIN



FREQUENCY DOMAIN

Frequency Range of Interest

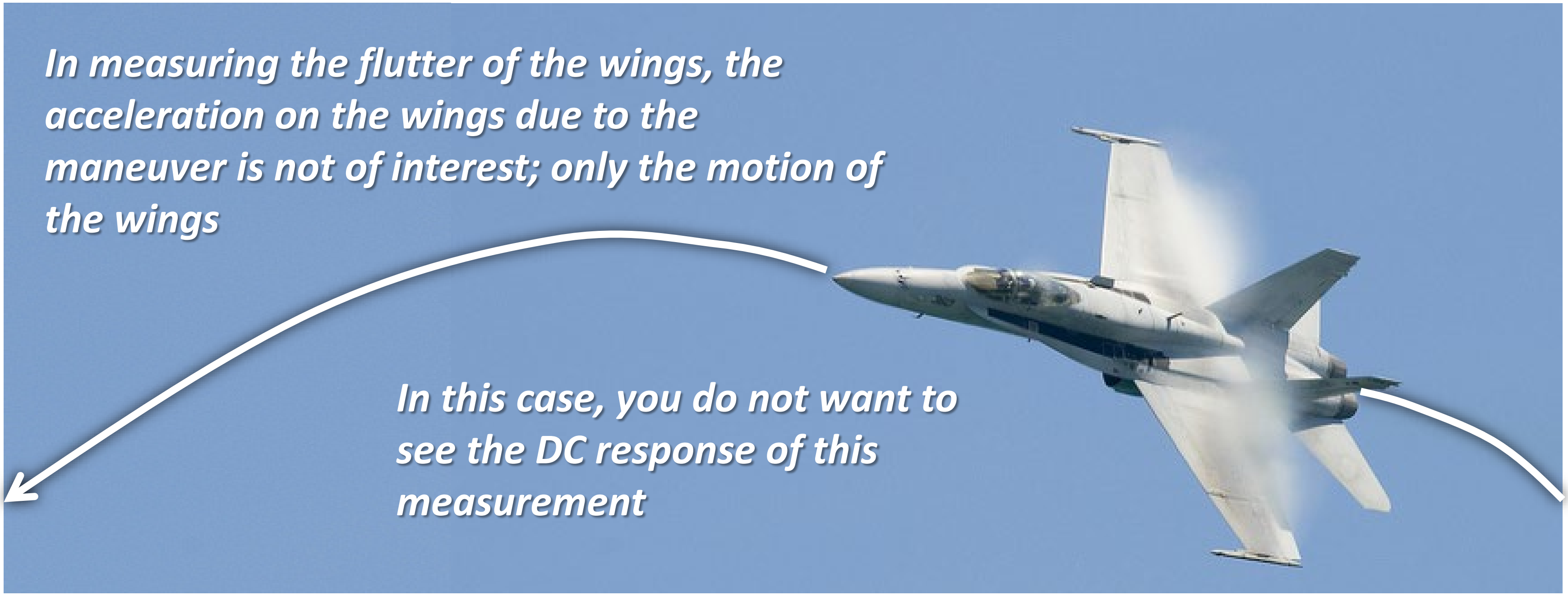
- Frequency of interest encompasses the frequency components the flight test engineer needs to see in the data. If the first three largest frequency components are important, but the higher ones are not, the three frequencies must not be attenuated significantly. Frequencies greater than 2800 Hz will be greatly reduced in amplitude by using low pass filtering.



DC Response

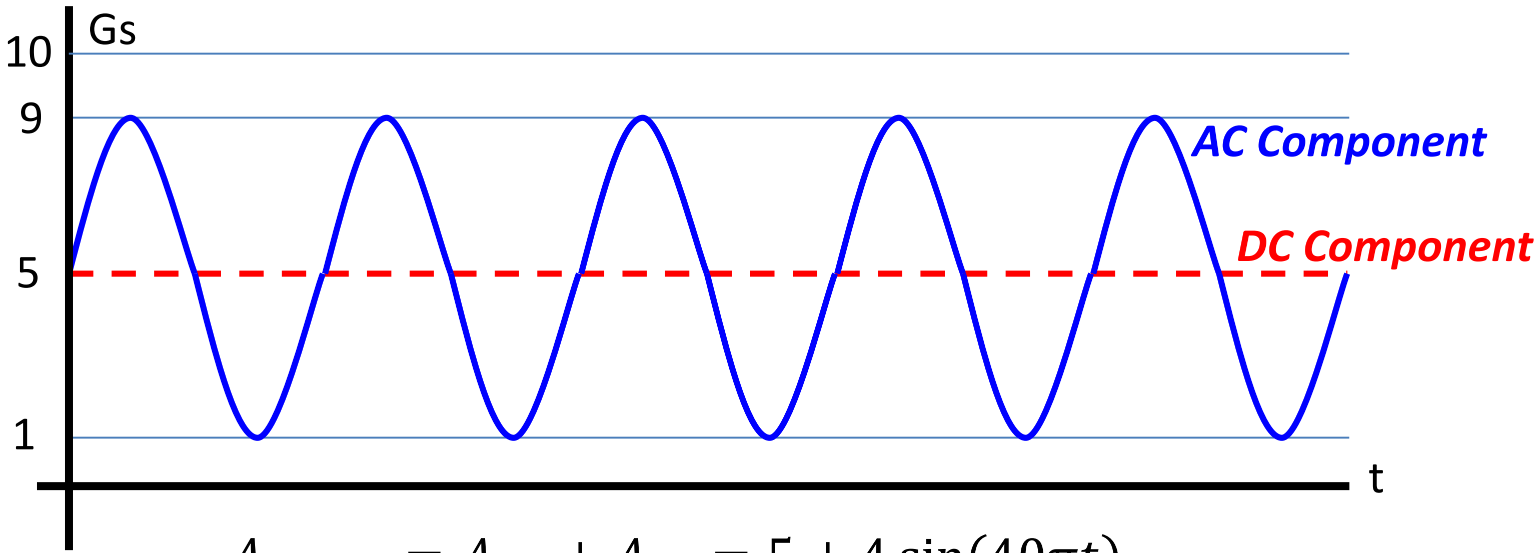
- Another frequency requirement to consider is, does the Direct Current (DC) response need to be removed from the data? DC response is the steady state response from the sensor. Some sensors may not have a DC response.

- Consider the example below:



AC and DC Component of a Signal

- The amount of acceleration due to the maneuver is 5 Gs, and the acceleration due to the flutter of the wing is sinusoidal with an amplitude of 4 Gs at 20 Hz. Below, they are shown graphically and mathematically.



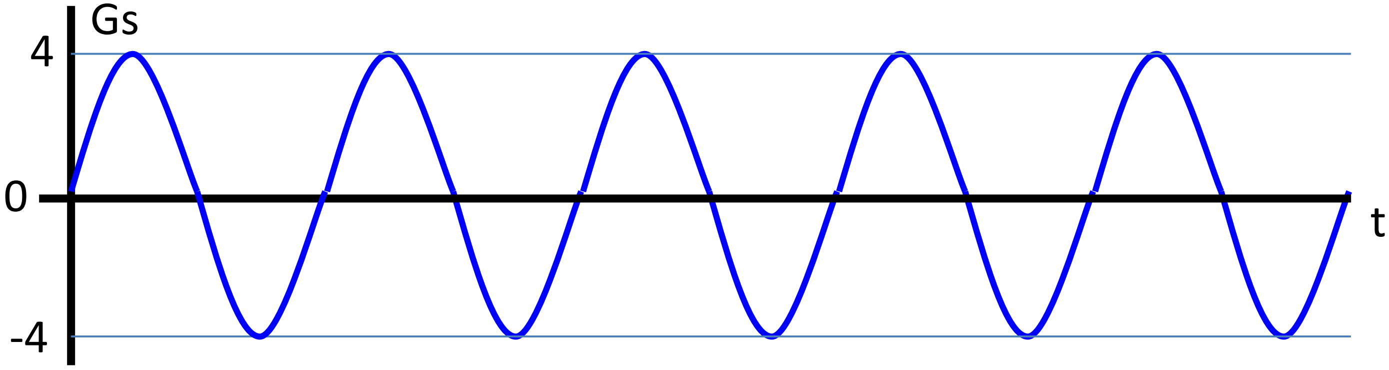
$$A_{TOTAL} = A_{DC} + A_{AC} = \underline{5} + \underline{4\sin(40\pi t)}$$

DC Component (from maneuver)

AC Component (from flutter)

AC Coupling

- If there is no interest in the 5 G DC component, it can be removed from the signal. When removing the DC component, the result is the flutter (AC component only) and the data is centered around 0 Gs.



$$A_{TOTAL} = A_{AC} = 4\sin(40\pi t)$$

- To remove the DC component, a technique called AC-coupling is used. However, the AC-coupling also attenuates very low frequencies (close to 0 Hz).

- DC-coupling (a wire) passes both the AC and DC components of the signal.

Frequency Range of Interest

- A minimum and maximum frequency range of interest must be defined for a measurement where the flight test engineer only wants to see the AC component. Example: 10 – 200 Hz.

- Also, note that AC-coupling is sometimes referred to has a high-pass filter because it rejects low frequencies and passes high frequencies.

- Later in the training we will go into more detail of filtering a signal in an example analog measurement.

Measurement Uncertainty

- If Frequency Range of Interest is the most misunderstood requirement, then **Measurement Uncertainty** is a close second.
- Many times you will not be given a required uncertainty of a measurement. In those cases, follow best practices and choose the best sensor and data acquisition system configurations to minimize errors.
- If you do get an uncertainty requirement make sure that it is not unrealistic for what your measurement system components can provide.
- Remember that all measurements contain errors. The end user of the data must determine how much uncertainty is acceptable to safely perform the test and make decisions.

Measurement Uncertainty

- Error sources come from every piece of equipment in the data path

$$X_{MEAS} = X_{TRUE} + X_{ERROR}$$

X_{MEAS}	The resulting engineering unit
X_{TRUE}	The true value of the physical phenomena you are trying to measure
X_{ERROR}	The combination of all the measurement errors within the instrumentation system

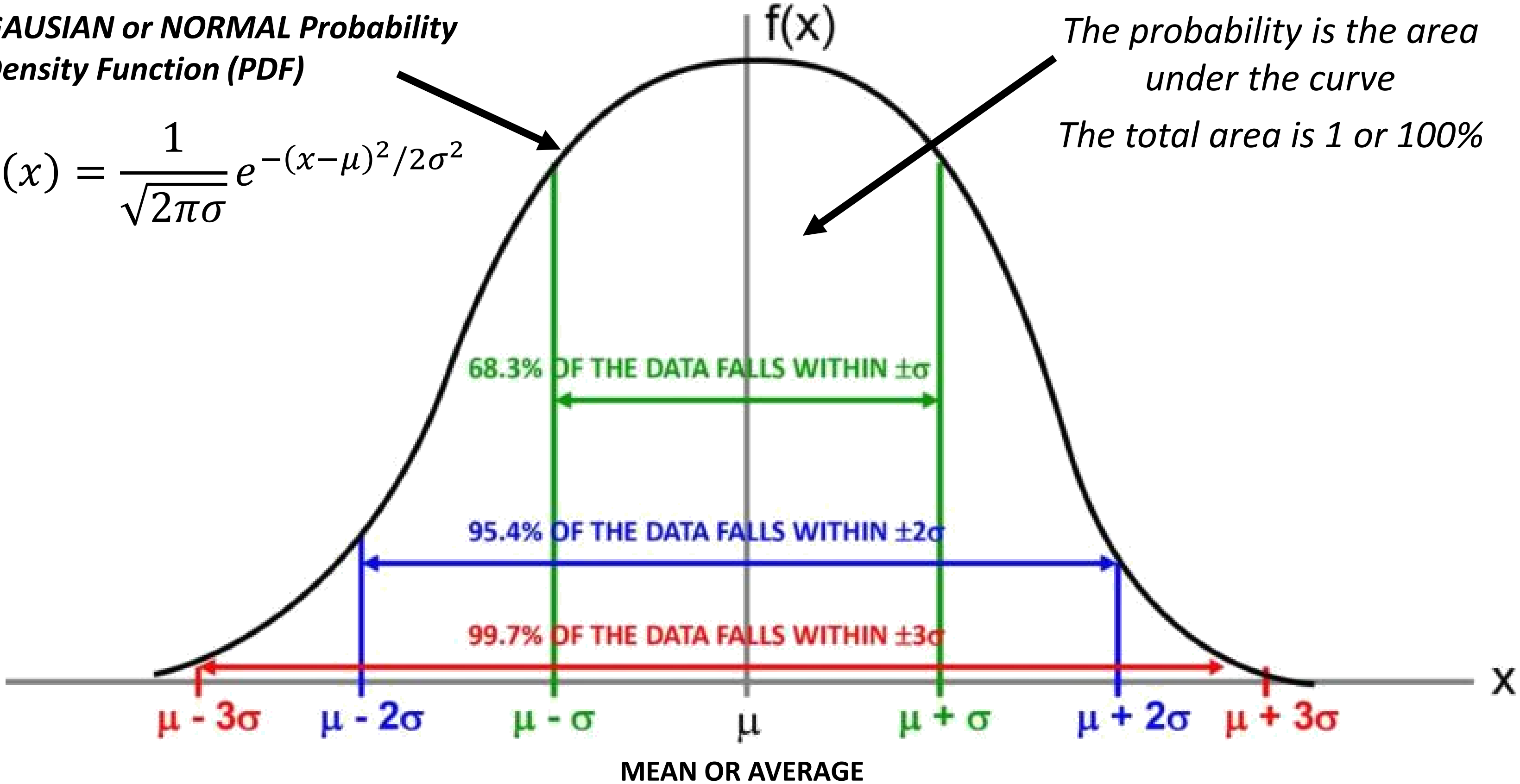
- Any time you make a measurement there is an error added to the true value.
- The reality is, X_{TRUE} is never known because X_{ERROR} is a random variable with a normal distribution.
- This is why the term ***uncertainty*** is used rather than *accuracy*. You are uncertain of the value of X_{TRUE} , but you can define a range or bound of the value of X_{TRUE}.

Measurement Uncertainty

- The combined standard deviations (σ) of all the errors in the instrumentation system is calculated in an uncertainty analysis and is characterized as a Gaussian Distribution.

GAUSIAN or NORMAL Probability Density Function (PDF)

$$f(x) = \frac{1}{\sqrt{2\pi\sigma}} e^{-(x-\mu)^2/2\sigma^2}$$



Measurement Uncertainty

- Once σ (the measurement uncertainty) is known, we can bound the value of X_{TRUE} within a region around the measured value (X_{MEAS}).

$$X_{TRUE} = X_{MEAS} \pm X_{ERROR}$$

X_{TRUE} FALLS BETWEEN (red lines)

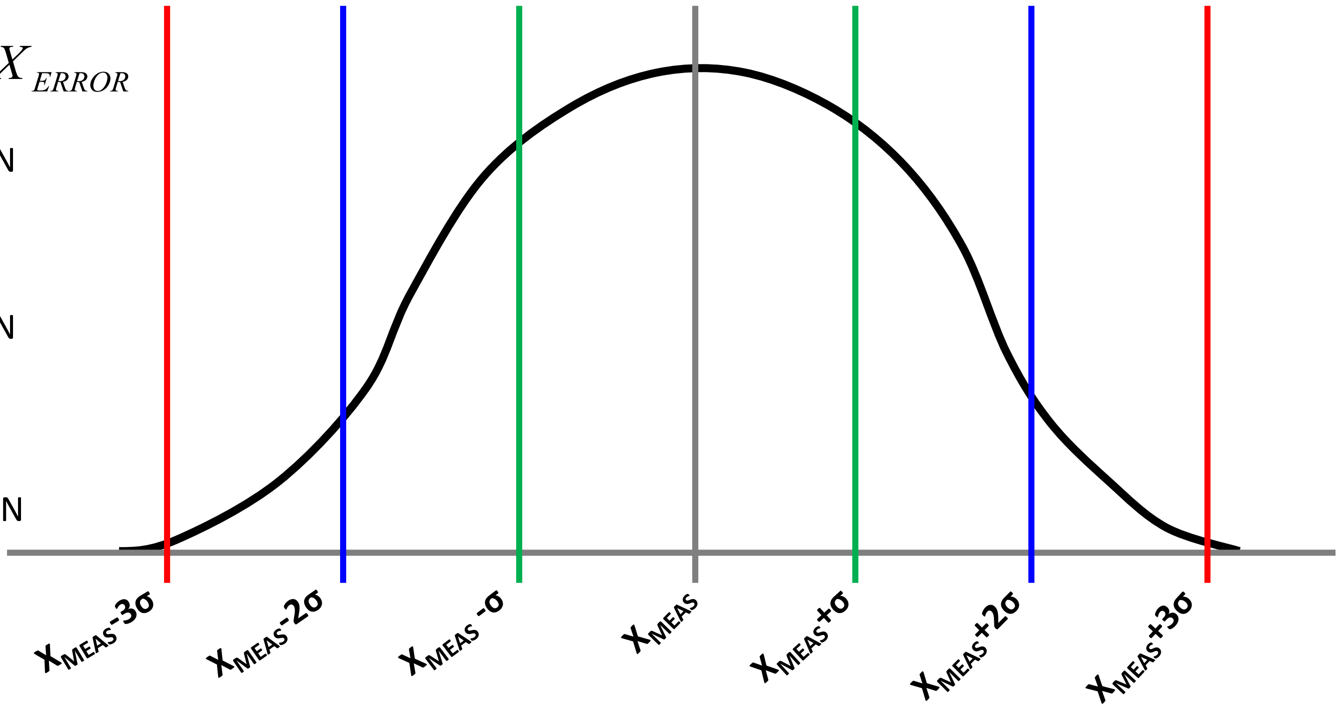
99.7% Confidence

X_{TRUE} FALLS BETWEEN (blue lines)

95.4% Confidence

X_{TRUE} FALLS BETWEEN (green lines)

68.3% Confidence



- The standard practice in reporting measurement uncertainty is to use the ±2σ or the 95% confidence interval (between the blue lines).

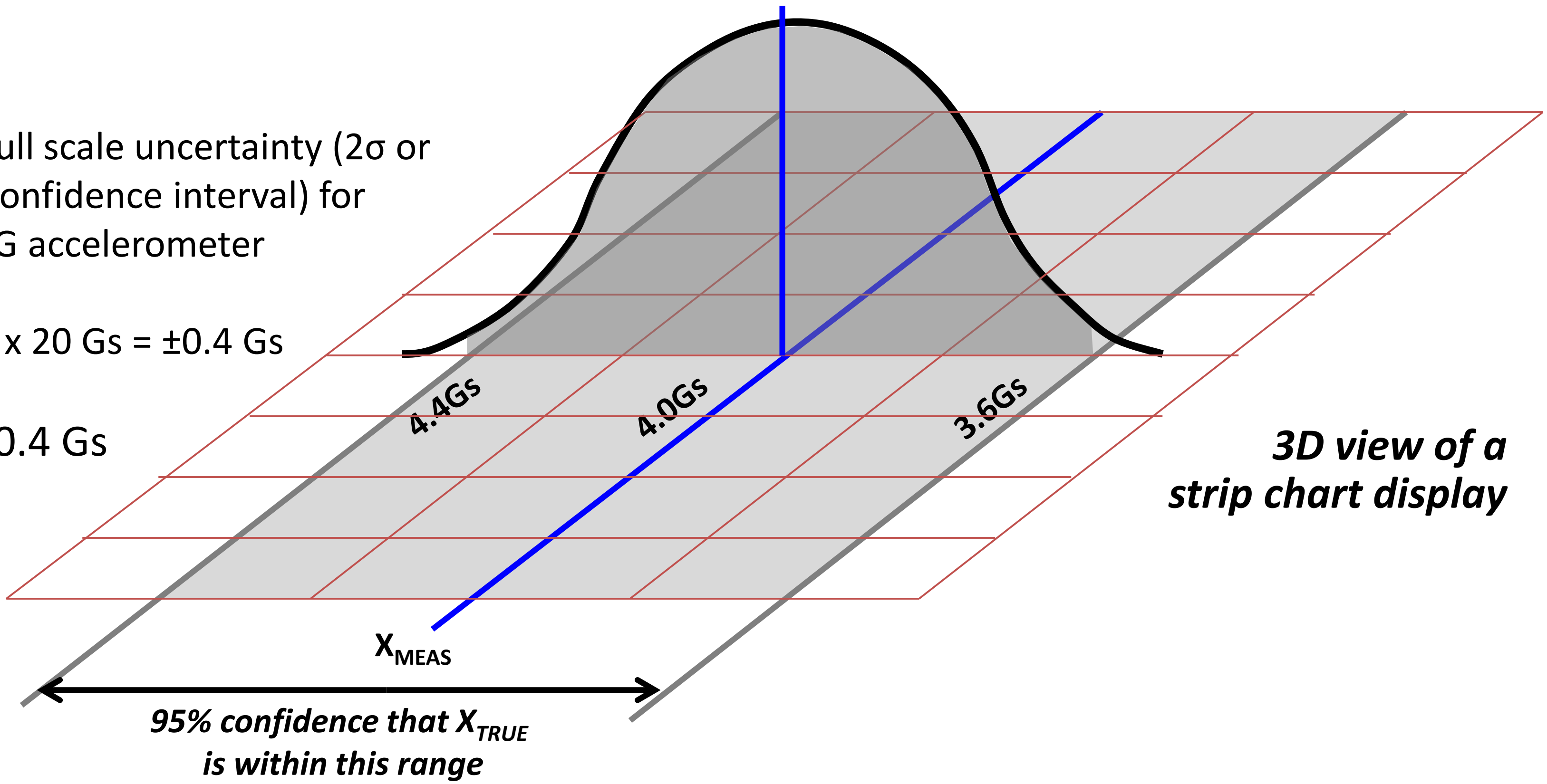
Measurement Uncertainty 95% (2σ)

- When looking at a strip chart, there is a normal distribution curve riding on the blue line that represents the measured value. The true value falls within the gray area (±2σ) around X_{MEAS}. Note that when reading strip charts, you do not see the gray area, only the blue line.

±2% full scale uncertainty (2σ or 95% confidence interval) for a ±10G accelerometer

±0.02 x 20 Gs = ±0.4 Gs

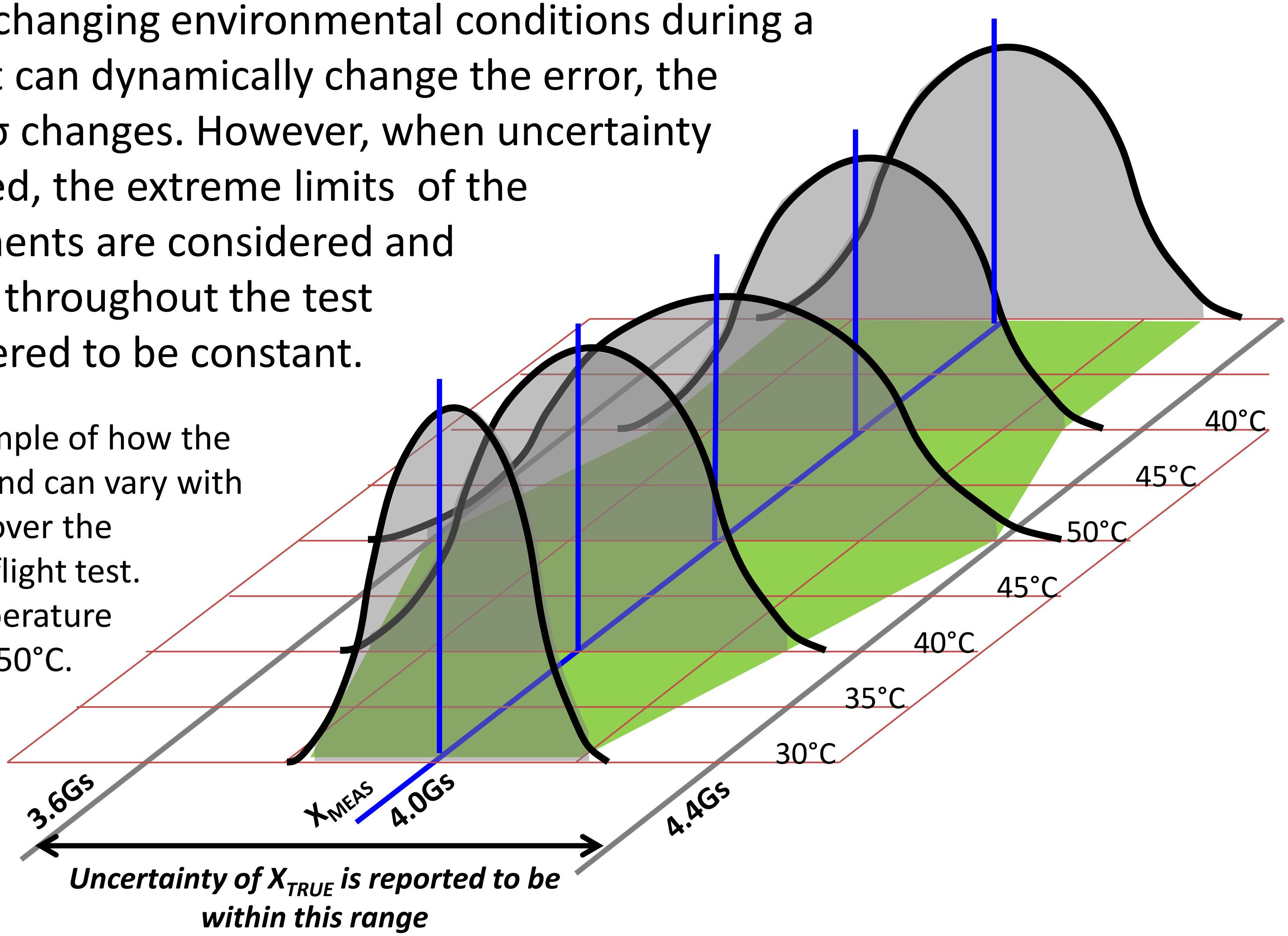
4.0 ± 0.4 Gs



Measurement Uncertainty 95% (2σ)

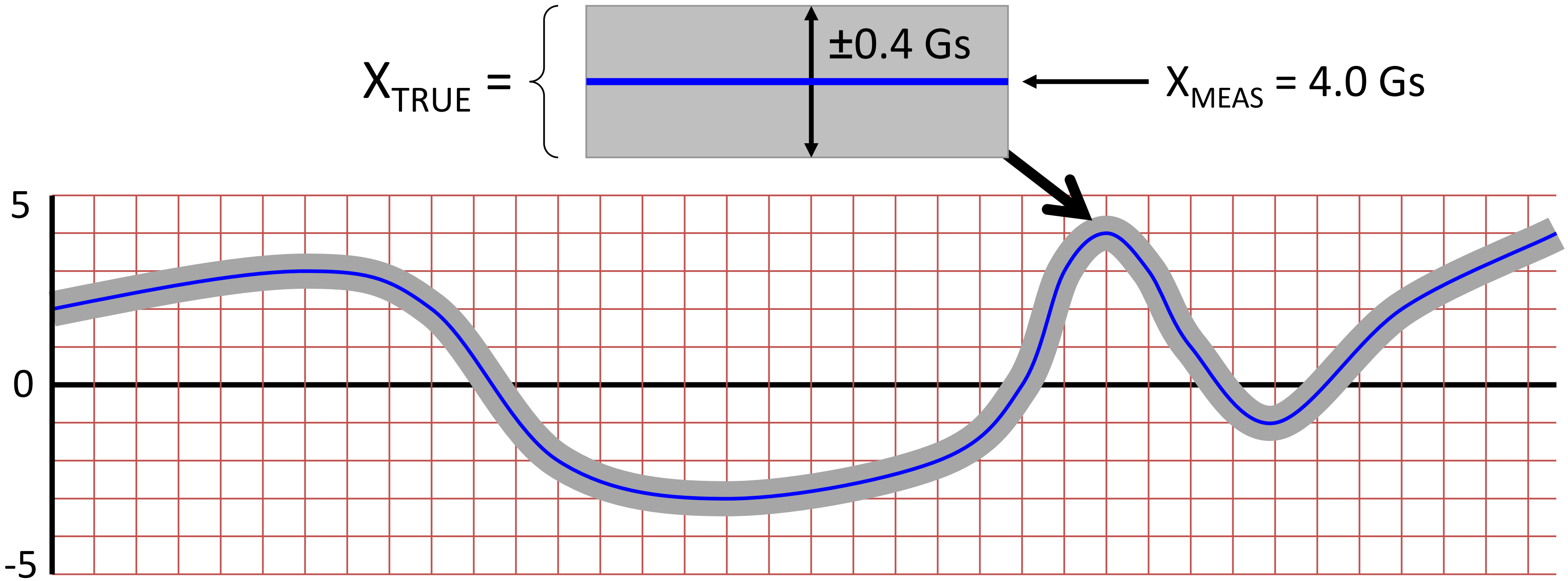
- Because changing environmental conditions during a flight test can dynamically change the error, the value of σ changes. However, when uncertainty is reported, the extreme limits of the environments are considered and the error throughout the test is considered to be constant.

This is an example of how the ±2σ error bound can vary with temperature over the duration of a flight test. The max temperature for the test is 50°C.



Measurement Uncertainty 95% (2σ)

$$X_{TRUE} = X_{MEAS} \pm X_{ERROR}$$



- The flight test engineer has to determine how wide the gray line can be and still be allowed to make quality decisions. In this example, you are 95% confident that the peak of the signal could be as high as 4.4 Gs or as low as 3.6 Gs.

Resolution of a Measurement

- A common misconception is that resolution is the same as accuracy. Resolution is a contribution to the overall system error, but it is not the error of the measurement.
- Resolution is the smallest quantity that can be measured by the data channel or the engineering unit weighting per count. For example, if a channel can display ±10 Gs over a 4000-count channel, then the resolution is:

$$\frac{20\ \text{Gs}}{4000\ \text{counts}} = 0.005\ {}^{\text{Gs}}\!/_{\text{count}}$$

- 0.005 Gs/count is not the accuracy. In designing an instrumentation system, you want the resolution to be smaller than the ±2σ uncertainty.
- This resolution is 80x smaller than the ±0.4G uncertainty in the example.

Engineering Units

- **Engineering Units** is self-explanatory. However, not getting it correct can be devastating.
- If out-of-the-ordinary units are requested (such as m/sec^2 instead of G's) it can be easily converted in the processing if it is a linear conversion. Conversion to something non-linear like dB which involves logarithms is more difficult.
- If there is data analysis software being used by your customer that reads the EU converted data, make sure that the units for the inputs to the software match the engineering units being measured.

Engineering Units

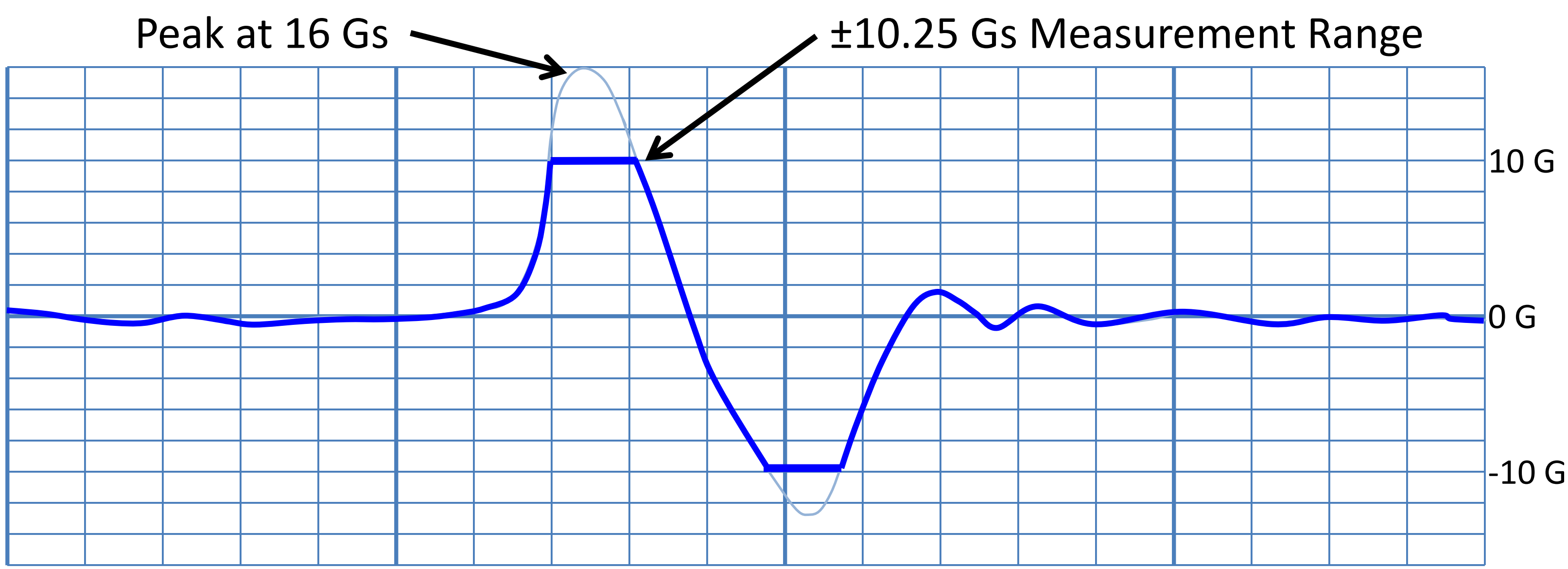
- Some notes on Engineering Units:
  - Make sure to note the type of pressure measurement in the correct units:
    - Absolute (PSIA)Pressure – referenced to a vacuum (0 PSI)
    - Differential (PSID) Pressure – referenced to some other defined pressure
    - Gage (PSIG) Pressure – referenced to atmospheric pressure
      - Example: an absolute pressure in PSI has units PSIA
  - Bus measurements have defined engineering units, but can be changed if requested.
    - For example, the heading on a 1553 parameter is in semicircles, but you need it in degrees. The conversion coefficient will need to be adjusted by a factor of 180.

Engineering Unit Range

- **Engineering Unit Range** is the maximum and minimum engineering unit value the flight test engineer wants to measure.
- This determines what model of transducer is needed and to what range it will be calibrated.
- Changes in the EU Range late in an instrumentation design could result in the following:
  - Purchase of a new transducer
  - Recalibration of the transducer
  - Increase in error when changing to a smaller EU range (using a ±100G accelerometer to measure ±30G). The error is based on the full scale range of the transducer, not the measurement range

Engineering Unit Range

- During testing, if the engineering unit range is too small you may see data that looks like this. Here the data exceeded the range and pegged the data channel. There is no way to measure the peak at this point.



Transducers and Specifications

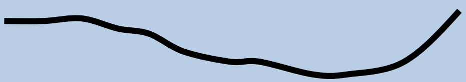
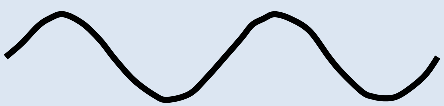
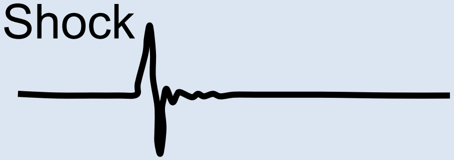
- Accelerometers
- Strain Gages
- Pressure Transducers
- Thermocouples
- Transducer Specifications

Transducers

- Transducers contain a sensing element that responds to a physical phenomena.
- Electronics within the transducer turns the sensing response to an electrical signal.
- The electrical signal may be conditioned within the transducer to a high-level voltage that can be measured by a data acquisition system.
- The transducer must survive and provide quality data in the harsh environment it will be subjected to.
- There are numerous types of transducers available. We will cover the most common types to get an appreciation of the various technologies used.

Accelerometers

- There are a wide range of accelerometers available
- The technology used in each depends upon the type of signal being measured.

Measurement Type	Time Domain	Freq Domain	Other
Simple Motion 	Time plot Maximum Value		
Periodic Vibration 	Peak Amplitude Average Value RMS	Discrete Line Frequency Spectrum	
Random Vibration 		Power Spectral Density	Amplitude Probability Distribution
Shock 	Peak Value Rise Time Duration		

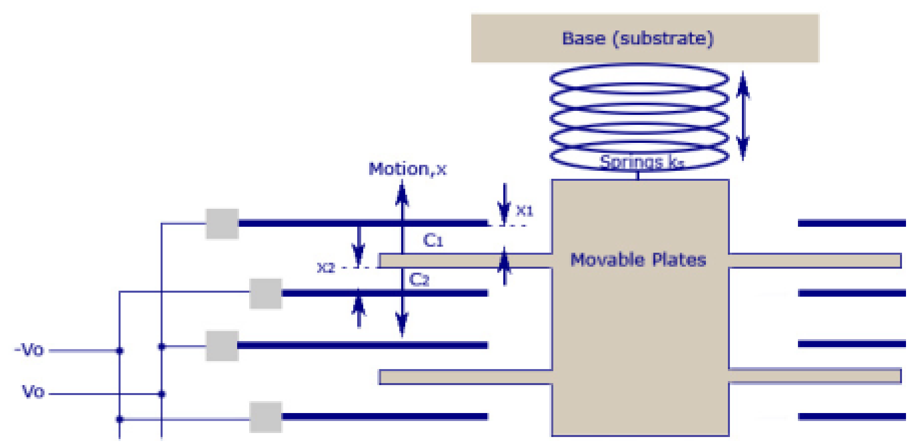
Accelerometers – Variable Capacitance

- Have a DC (steady state) response
- Have high sensitivities to measure small accelerations
- Have a lower frequency response
- Have good temperature stability
- Available in single or tri-axial models

- Variable capacitance accelerometers are good for measuring low frequency vibration, motion and steady state acceleration.

tri-axial

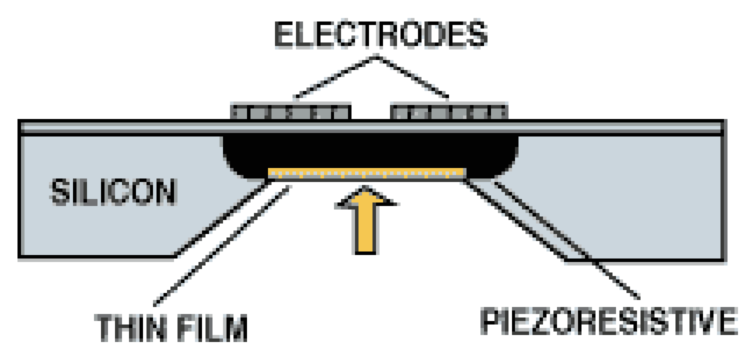
single axis



Accelerometers – Piezo-Resistive

- Have low sensitivity making them desirable for high-G shock measurements.
- Have a wide bandwidth and the frequency response goes down to zero frequency or steady state, so they can measure long duration transients.

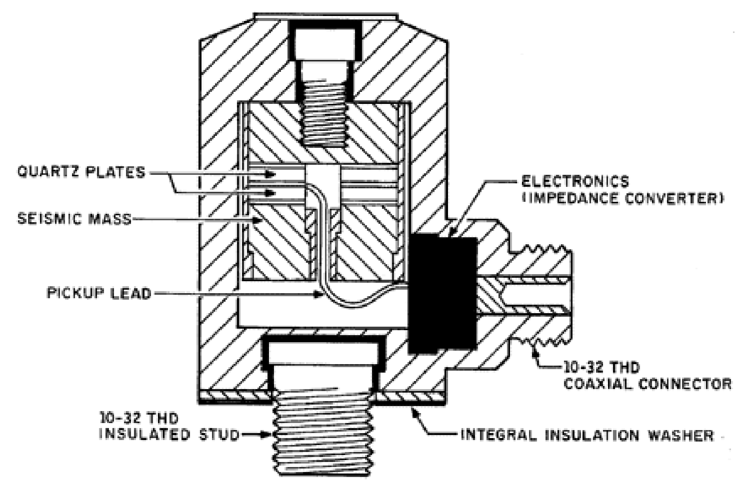
Piezo-resistive accelerometers are used extensively in transportation crash tests. Due to the low sensitivity, they are not used for vibration measurements.



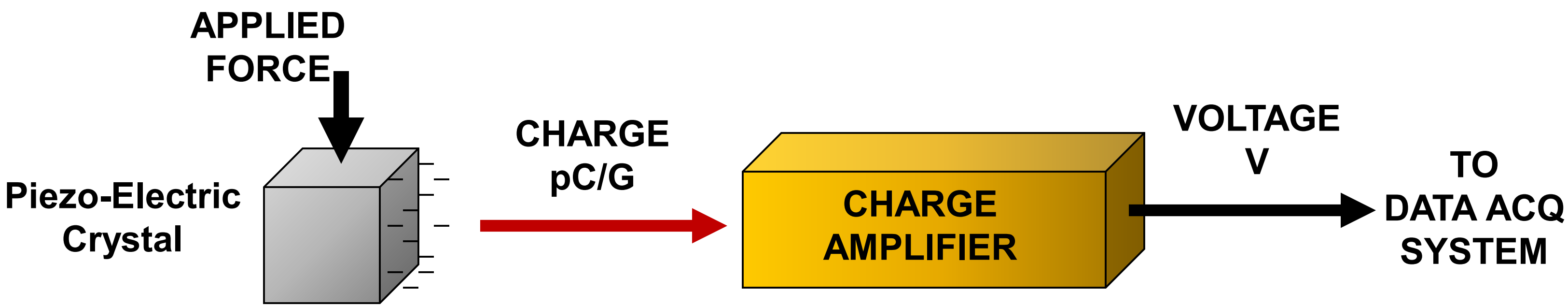
Accelerometers – Piezoelectric

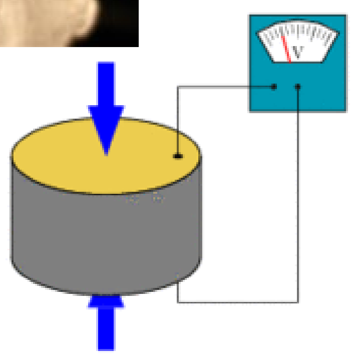
- Have a very wide measurement frequency range (a few Hz to 30 KHz).
- Can measure high G levels .
- Are available in a wide range of sensitivities, weights, sizes and shapes.
- Can be mounted in more volatile environments.

Piezo-electric accelerometers are the most widely used and should be considered for both shock and vibration measurements.



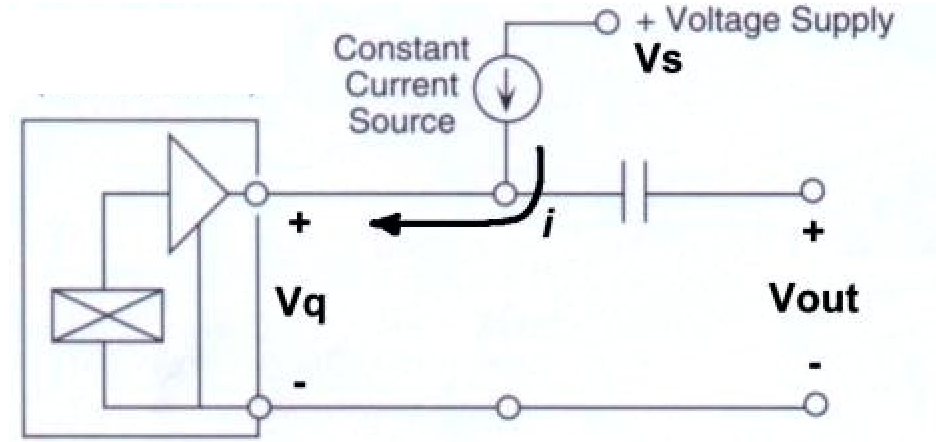
Accelerometers – Piezoelectric





- When a force is applied to the Piezo-electric crystal within the accelerometer, it produces a proportional charge.
- The cable between the accelerometer and charge amplifier is a special, low-capacitance cable.
- The charge amplifier converts the charge in pico-Coulombs (pC) to voltage (V).
- The voltage signal is then conditioned in the data acquisition system.

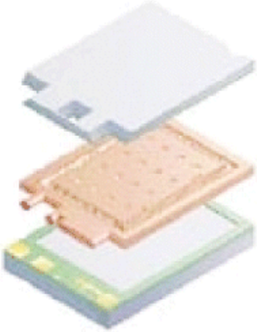
Accelerometers – Constant Current Piezoelectric



- Another piezoelectric type accelerometer for measuring vibration is powered with a constant current source.
- The voltage supply associated with the constant current source is known as the "compliance voltage".
- This accelerometer has internal electronics, so a charge amplifier is not needed.
- Uses only a shielded twisted pair cable for both signal and power.
- Because of the internal electronics the environment in which it is used must be not as volatile.

Accelerometers – MEMS

- Another source of acceleration measurements are IC packaged accelerometers. The devices come in both through-hole and surface mount packaging. Primarily used in the auto industry, these devices are something to keep in mind where the situation may warrant a small sensor.

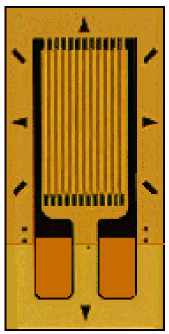


This unit, contains solid state devices measuring accelerations, angular rates, and attitudes which are output to RS-232.

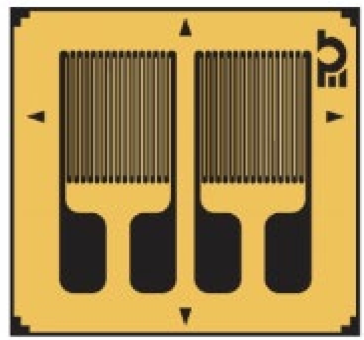
Strain Gages

- Strain gages come in many forms for the various strain and loads measurements being made.

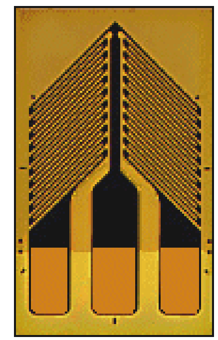
Uniaxial



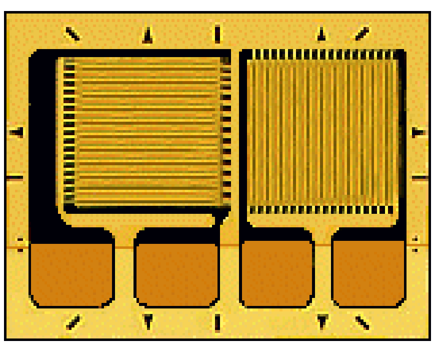
Bending Strain



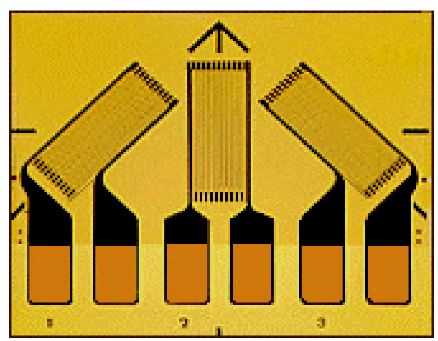
Shear/Torsion



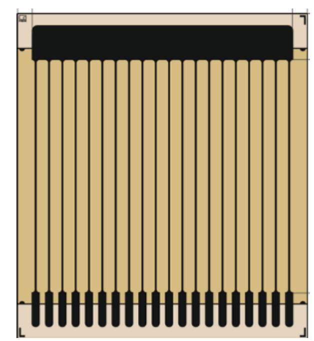
Biaxial Rosette



Three Element Rosette

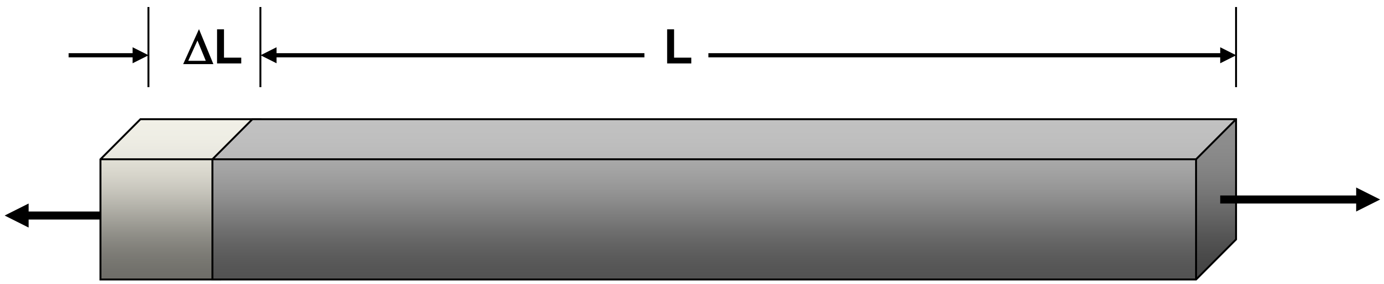


Crack Propagation



Strain Gages – What is Strain?

- Strain is defined as the amount of deformation per unit length (in / in, mm / mm) of an object when a load is applied. The quantity is dimensionless, but a unit of strain (Greek letter **ε**) is used. Because the change in length is so small, strain is usually expressed in micro strain (με) or one millionth (10^{-6}) ε.



$$\text{strain} = \left(\frac{\Delta L}{L}\right) \quad (\varepsilon) \quad = \left(\frac{\Delta L}{L}\right) \times 10^{6} \quad (\mu\varepsilon)$$

Strain Gages – What is Strain?

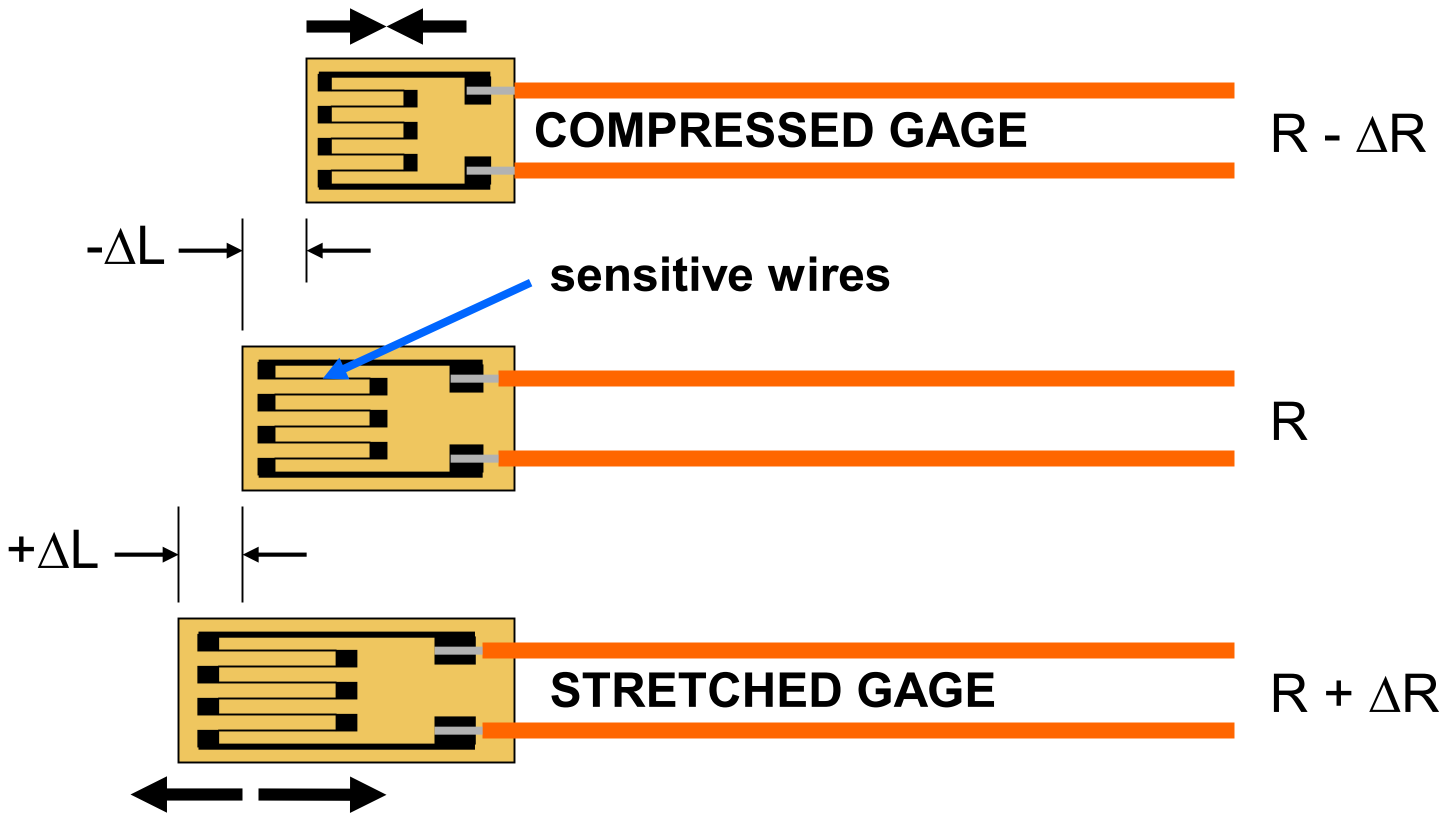
- If a metal rod is originally 3.0000 inches long and it is stretched to a length of 3.0012 inches, what is the amount of micro strains the rod experiences?

$$\text{strain} = \left(\frac{\Delta L}{L}\right) = \left(\frac{3.0012 - 3.0000}{3.0000}\right) = \left(\frac{0.0012}{3.0000}\right)$$

$$= 0.0004\varepsilon = 0.0004 \times 10^{6}\,\mu\varepsilon = 400\,\mu\varepsilon$$

Strain Gages

- To measure the strain, a strain gage is adhered to the surface. When a strain gage stretches or compresses, the small wires also stretch and compress, causing the resistance of the gage to change proportionally to the change in length.



Strain Gages – Gage Factor

- The relationship between the relative change in resistance and relative change in length is called the Gage Factor (GF). It can be thought of as the “sensitivity” of the gage.

$$GF = \left(\frac{\Delta R}{R}\right) / \left(\frac{\Delta L}{L}\right) = \left(\frac{\Delta R}{R}\right) / strain$$

Rearranging … $\Delta R = GF \times R \times strain$

Strain Gages – Gage Factor

- When a batch of strain gages is manufactured, a sample is taken to determine the Gage Factor. It is usually specified as some nominal value with a corresponding tolerance.

This example illustrates that this particular <u>model</u> of strain gage has a nominal Gage Factor of 2, but can vary as much as ±5% from all the batches of gages the vendor produces.

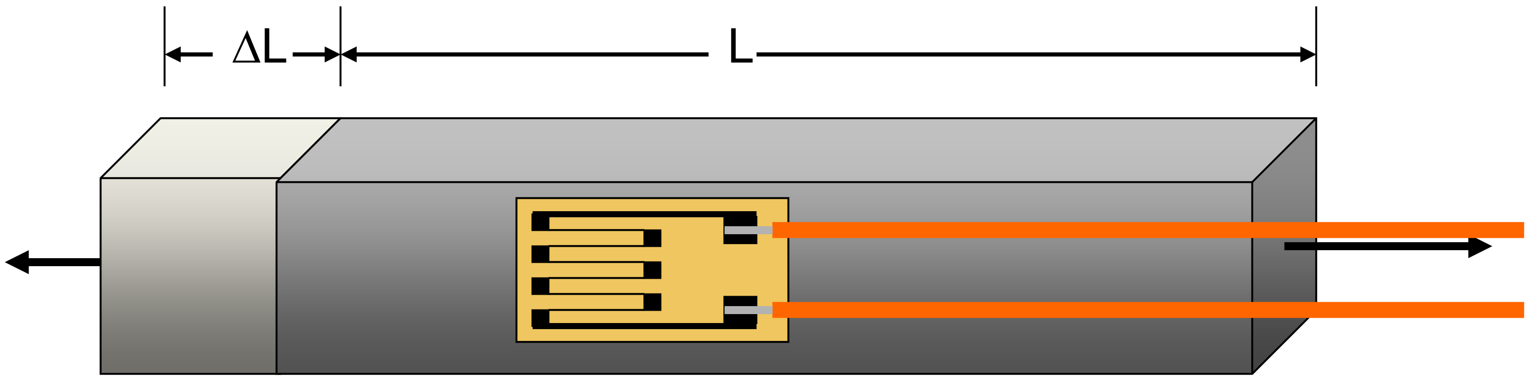
For an individual package from a known batch of gages, the Gage Factor will be specified on the package (2.005) and have a tolerance of only ±1%.

Gage Factor (Actual Value Printed on Each Package)	2.0 ±5%
Gage Factor Tolerance Per Package	1.00%

Think of the Gage Factor as being equivalent to the sensitivity of an accelerometer (mV/G) which is included in their calibration certificate.

Strain Gages – Resistance Change

- For the example we did earlier, we measured 400 $\mu\varepsilon$. The equivalent resistance change of a 350Ω gage with a vendor specified GF of 2.005 would then be:

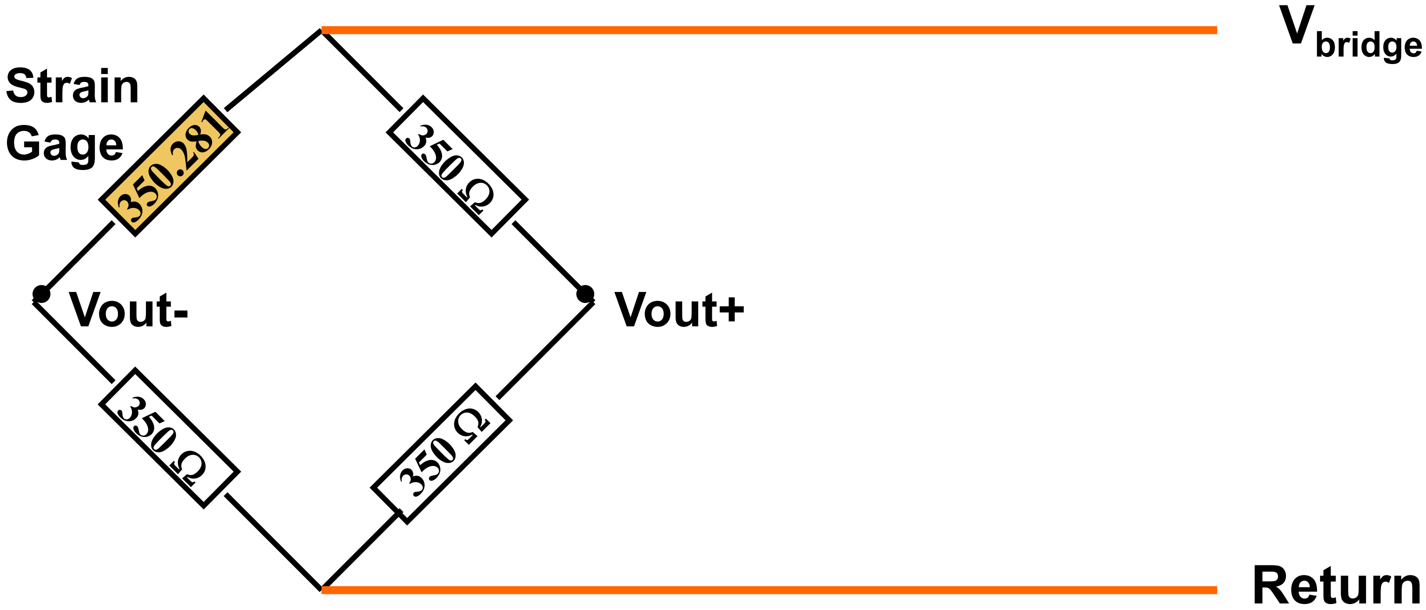


$$\Delta R = GF \times R \times strain$$
$$\Delta R = 2.005 \times 350\Omega \times 400\mu\epsilon$$
$$\Delta R = 0.281\Omega$$

We now have converted the micro strain quantity to its equivalent resistance change by knowing the gage factor for the strain gage.

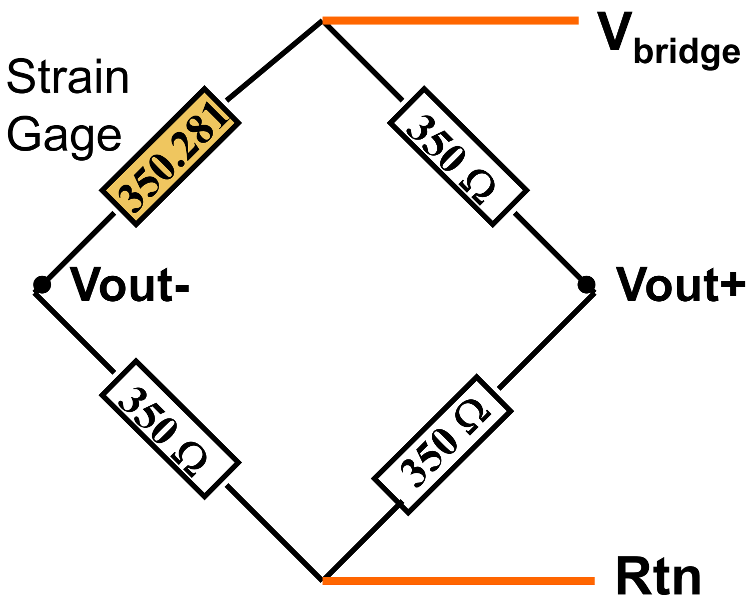
Strain Gages – Wheatstone Bridge

- Data acquisition systems measure a voltage, not a resistance. So using the gage as one of the arms of a Wheatstone bridge, we can now get a voltage proportional to the resistance change which is proportional to the micro strains.
- The configuration shown below only has one *active arm*, so the remaining three resistors are of a fixed value, equal to the nominal strain gage resistance of 350 Ω.



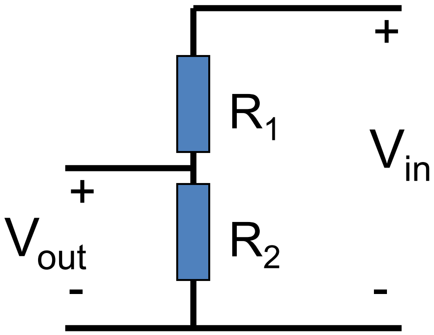
Strain Gages – Wheatstone Bridge Output

- Looking at the left and right pair of resistors as a voltage divider circuit, you can calculate Vout+ and Vout-.



Voltage Divider Law

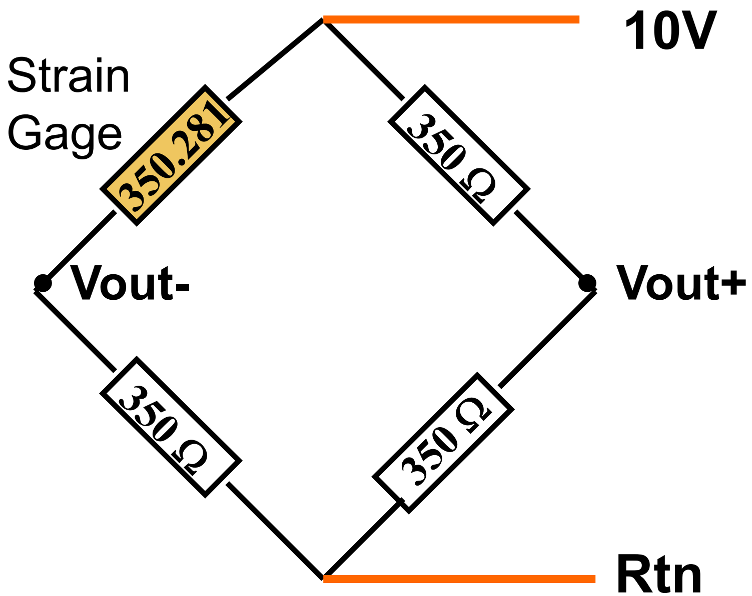
$$V_{out} = \left(\frac{R_2}{R_1 + R_2} \right) V_{in}$$



Strain Gages – Wheatstone Bridge Output

$$V_{out+} = \left(\frac{350}{350+350}\right)10vdc = \frac{1}{2}10vdc = 5.000vdc$$

$$V_{out-} = \left(\frac{350}{350.281+350}\right)10vdc = \frac{350}{700.281}10vdc = 4.998vdc$$



V_{out} is the difference of the voltages

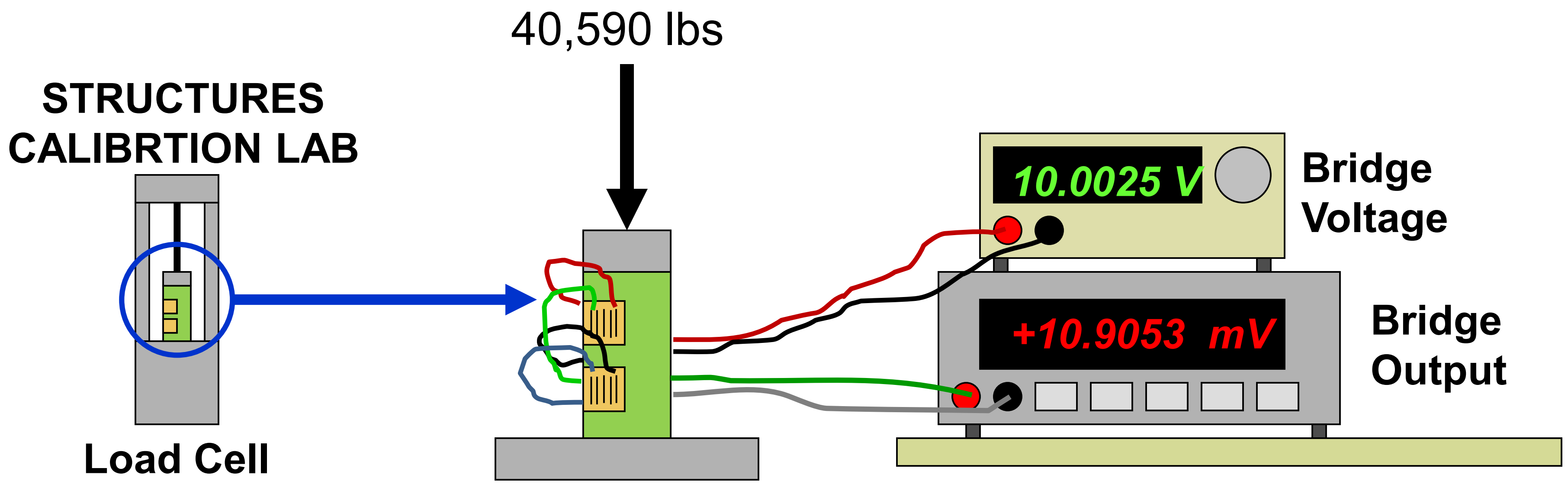
$V_{out} = V_{out+} - V_{out-}$

$V_{out} = 5.000 - 4.998$

$V_{out} = 0.002$ or 2mV

So 400 $\mu\varepsilon$ is equivalent to 2 mV

Strain Gages – Reading Force



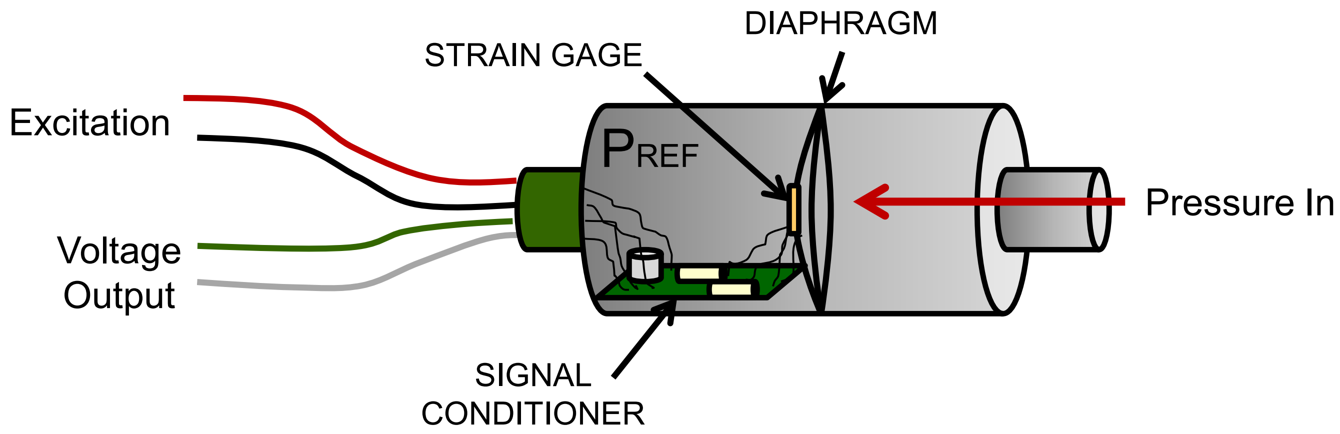
- When a force must be measured, the item with the strain gages installed must be calibrated to get a lbs to mV relationship.

40,590 lbs → +10.9053 mV

Otherwise without a calibration, we would only know $\mu\varepsilon$.

Pressure Transducers

- Pressure is measured by the movement of a sensing element (usually a diaphragm) when pressure is applied.
- The physical movement must be converted to electrical energy using a transducer (in some cases a strain gage).
- Signal conditioning is required to provide a high level voltage output.

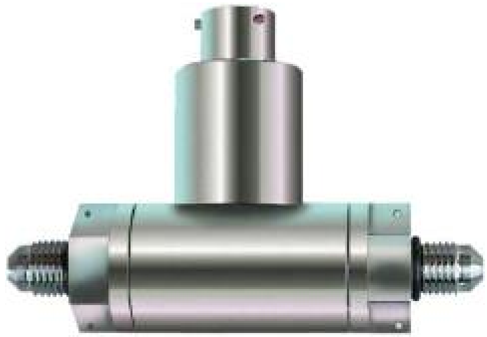


Pressure Transducers – Types of Pressure Measurements

- ***Absolute pressure*** is measured relative to a perfect vacuum (0 PSI). An example is atmospheric pressure. A common unit of measure is pounds per square inch, absolute (PSIA).
- ***Differential pressure*** is the difference in pressure between two points of measurement. This is commonly measured in units of pounds per square inch, differential (PSID).

Absolute Pressure Transducer

Has a single pressure port
The reference is 0 PSI



Differential Pressure Transducer

Has two pressure ports
Identify which port is the reference

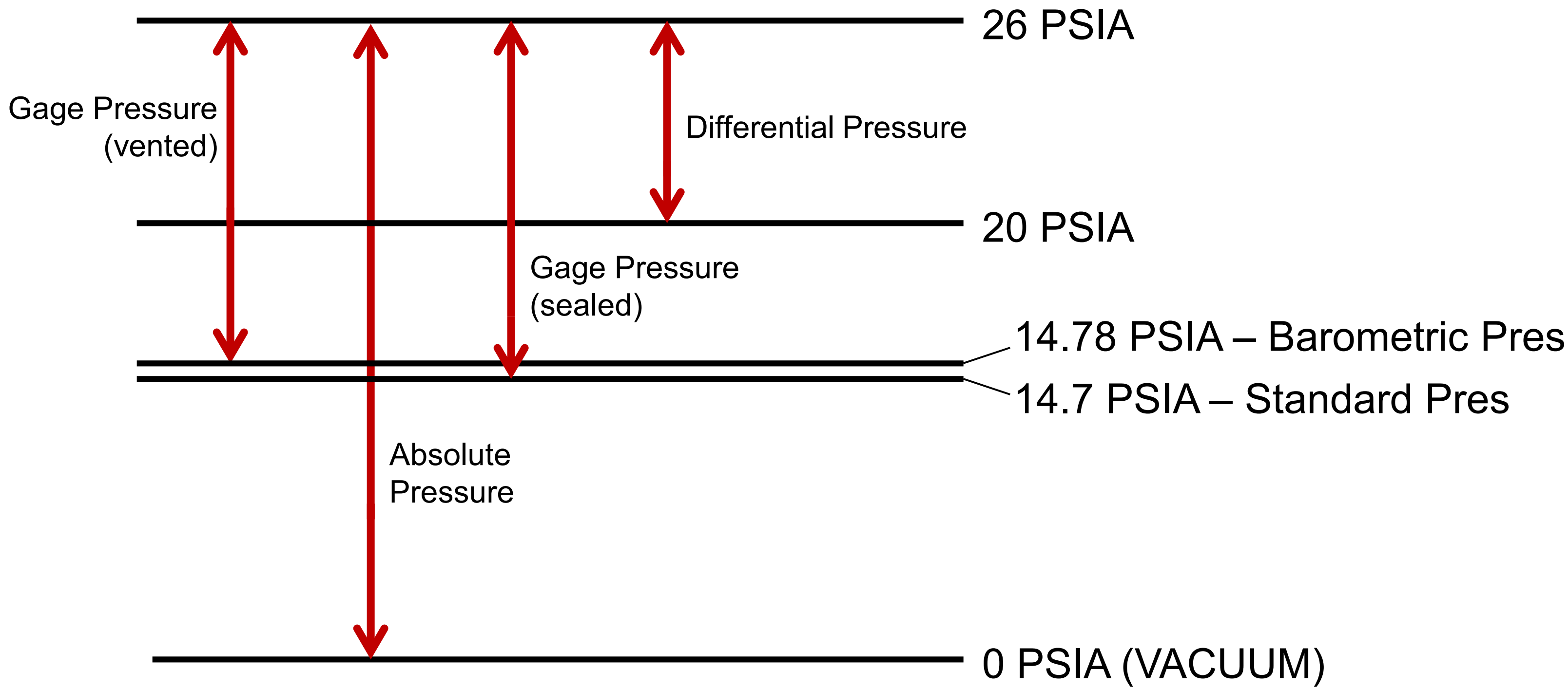
Pressure Transducers – Types of Pressure Measurements

- ***<u>Gauge pressure</u>*** is measured relative to ambient pressure. Common measurement units are pressure per square inch, gauge (PSIG).
    - **Sealed** gage pressure (PSISG) is measured relative to a sealed chamber, pressurized to a standard day pressure (14.7 PSI).
    - **Vented** Gage Pressure (PSIVG) is measured relative to the atmospheric pressure (vented to the outside atmosphere).
- Manufacturers do not always specify if a PSIG transducer is *sealed* or *vented*, so it is best to contact them to be sure.

Gage Pressure Transducer

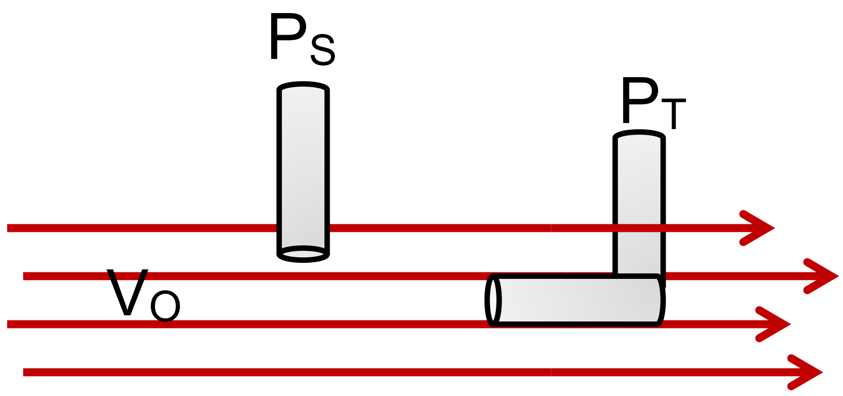
A vented gage pressure transducer can sometimes be identified by a small pin hole in the housing.

Pressure Transducers – Types of Pressure Measurements



Absolute Pressure:	26 PSIA
Gage Pressure (sealed):	11.3 PSISG
Gauge Pressure (vented):	11.22 PSIVG
Differential Pressure:	6 PSID

Pressure Transducers – Pitot-Static Pressure



- The tube facing the flow measures total pressure (P_T)
- The tube normal to the flow measures static pressure (P_S)
- This approach is used on aircraft to measure velocity
- To calculate the derived parameter flow velocity, you need to measure P_T and P_S and use those measurements in the following formula:

$$V_O = \sqrt{\frac{2(P_T - P_S)}{\rho}}$$

ρ = Fluid Density

Pressure Transducers – Pitot-Static Pressure

Static Pressure Port on the aircraft skin

Total Pressure probes on an aircraft

Pressure Transducers – Air Data Computer

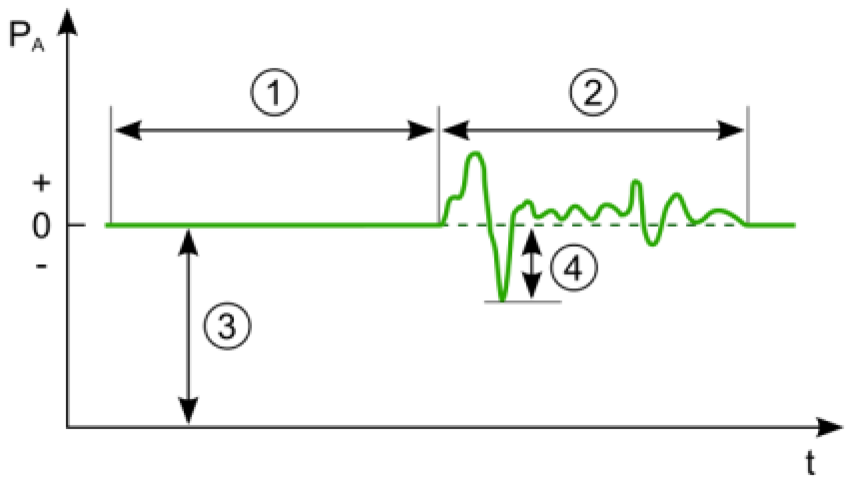
Wing Boom with a pitot-static probe that has both a total and static pressure ports.

The air data computer then calculates airspeed, altitude, and mach number from these pressures.

Total and Static pressure input ports on an Air Data Transducer

Pressure Transducers - Sound Pressure Level

Sound Pressure Level (SPL) or **sound level** is a logarithmic measure of the effective sound pressure of a sound relative to a reference value. It is measured in decibels (dB) above a standard reference level. The standard reference sound pressure in air or other gases is 20 µPa RMS.



1) Silence
2) Audible sound
3) Atmospheric pressure
4) Instantaneous sound pressure

$$SPL\ (dB) = 20 \log \frac{P}{P_{REF}}$$

P_{REF} = 20 µPa (RMS) or
2.9E-9 PSI (RMS)

This is the threshold of hearing at 1 KHz.

Pressure Transducers - Sound Pressure Level

- Sound Pressure Levels measured in dB can have deceiving magnitudes.
- The threshold of pain is at 140 dB.
- 170 dB is the equivalent of just under 1 PSIA RMS.
- Note that every 20 dB is a pressure factor of 10.

	dB	$PSIA_{(RMS)}$	$PSIA_{(PEAK)}$
	170	0.9171	1.297
	160	2.900E-1	4.101E-1
	150	9.171E-2	1.297E-1
Jet Engine @ 75ft	140	2.900E-2	4.101E-2
	130	9.171E-3	1.297E-2
	120	2.900E-3	4.101E-3
	110	9.171E-4	1.297E-3
Jackhammer	100	2.900E-4	4.101E-4
Average Street Traffic	90	9.171E-5	1.297E-4
	80	2.900E-5	4.101E-5
	70	9.171E-6	1.297E-5
	60	2.900E-6	4.101E-6
Conversational Speech	50	9.171E-7	1.297E-6

Pressure Transducers - Microphones

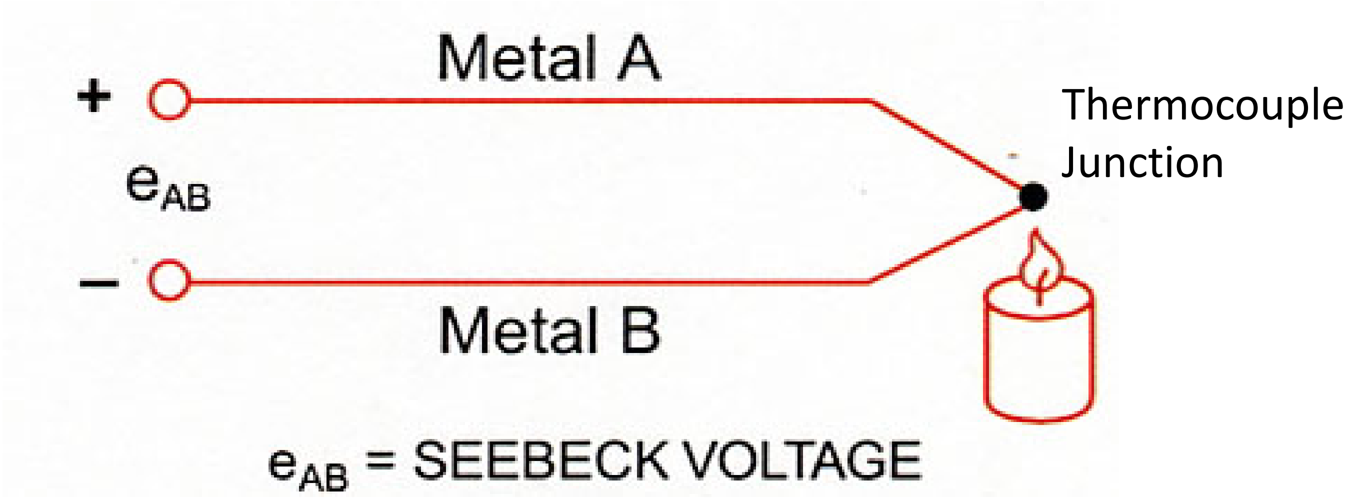
- A microphone is basically an absolute pressure transducer with EU ranges and frequency responses for audio or acoustic signals.

Pressure Transducers – Microphones

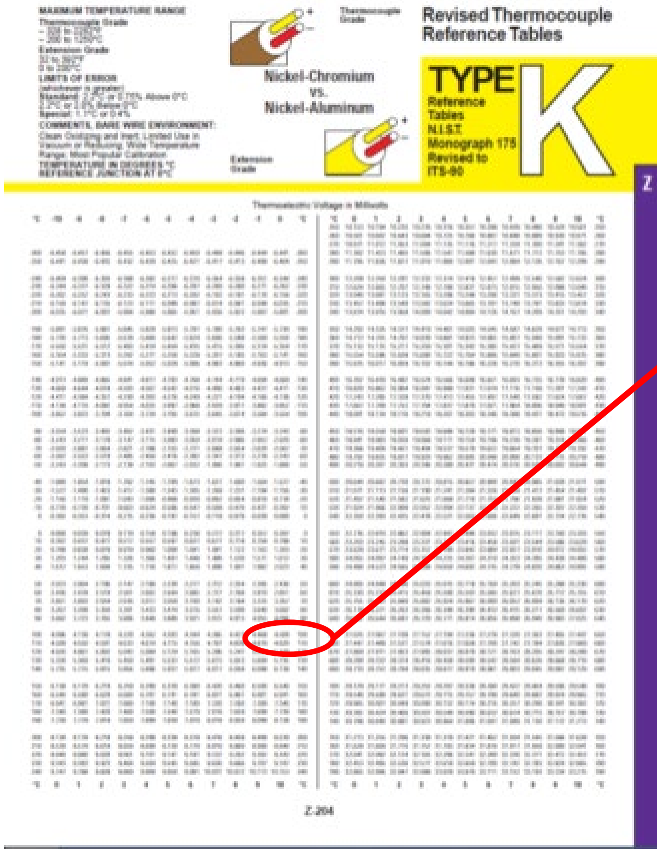
- Jet-Blast Deflector (JBD) testing collecting the sound pressure level (SPL) of the engine exhaust. The microphones are on the tripods on the right.

Thermocouples

- One of the most common ways to measure temperature is with a thermocouple.
- When two wires composed of dissimilar metals are joined at one end and heated as shown below, an open circuit voltage can be measured. This voltage is known as the Seebeck Voltage.
- The Seeback Voltage is 0 V at 32^{o}F or 0^{o}C



Thermocouples – Thermocouple Reference Table



4.509 mV = 100^{o}C

- Thermocouple Reference Tables give the mV Seebeck Voltages at various temperatures for a particular thermocouple type.
- The actual equation for this data is a fifth order equation.

TEMPERATURE CONVERSION EQUATION: $T = a_0 + a_1 x + a_2 x^2 + \ldots + a_n x^n$

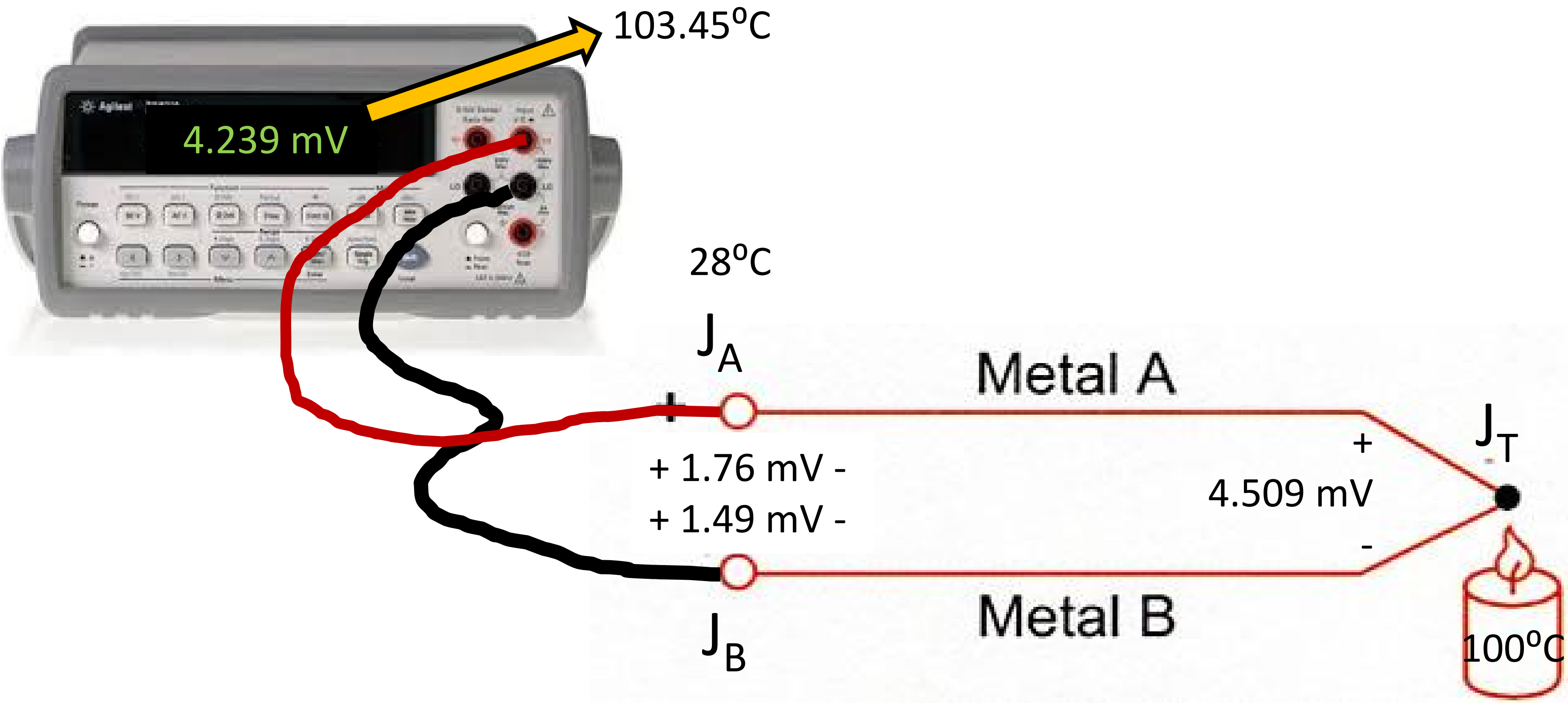
NESTED POLYNOMIAL FORM: $T = a_0 + x(a_1 + x(a_2 + x(a_3 + x(a_4 + a_5 x))))$ (5th order)

where x is in Volts, T is in °C

NBS POLYNOMIAL COEFFICIENTS

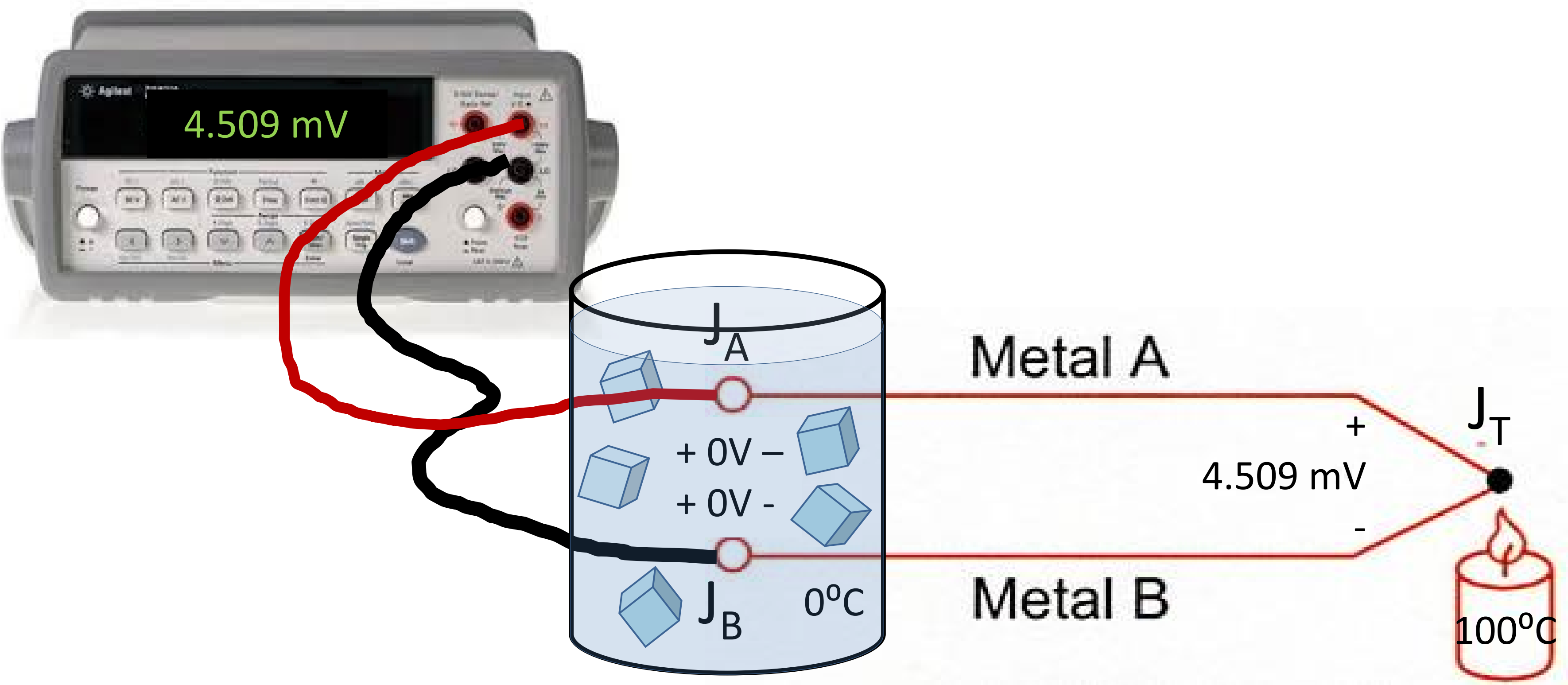
Thermocouples – Measuring the Voltage

- You cannot just measure this voltage with a multi-meter because two other thermocouple junctions are created (J_A and J_B) between the copper test leads and the Metal A and Metal B thermocouple wire.



Thermocouples – Measuring the Voltage

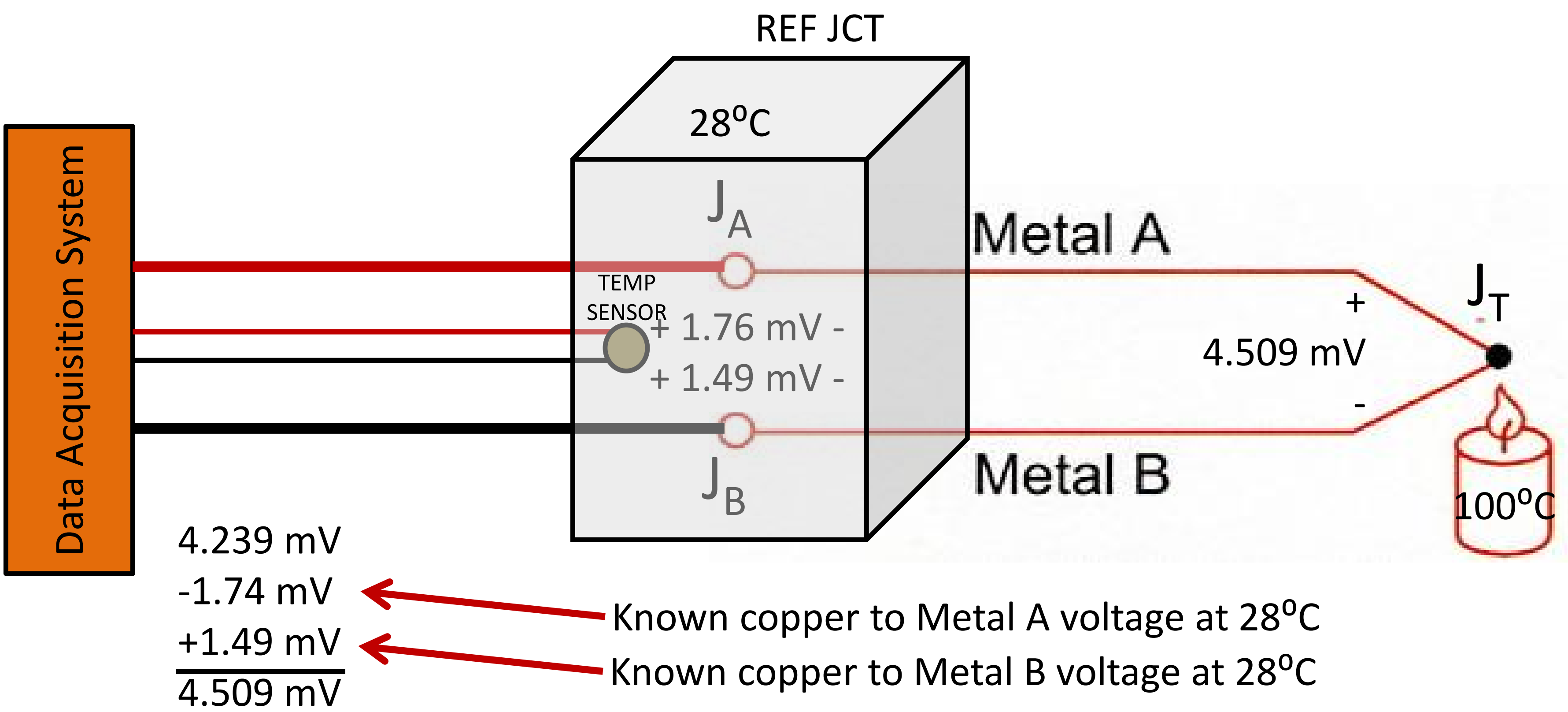
- One way to remove the voltages generated at J_A and J_B is to place it in an ice bath (at 32^{o}F or 0^{o}C). Now only the voltage generated at J_T are being measured.



Not very practical to have an ice bath on an aircraft

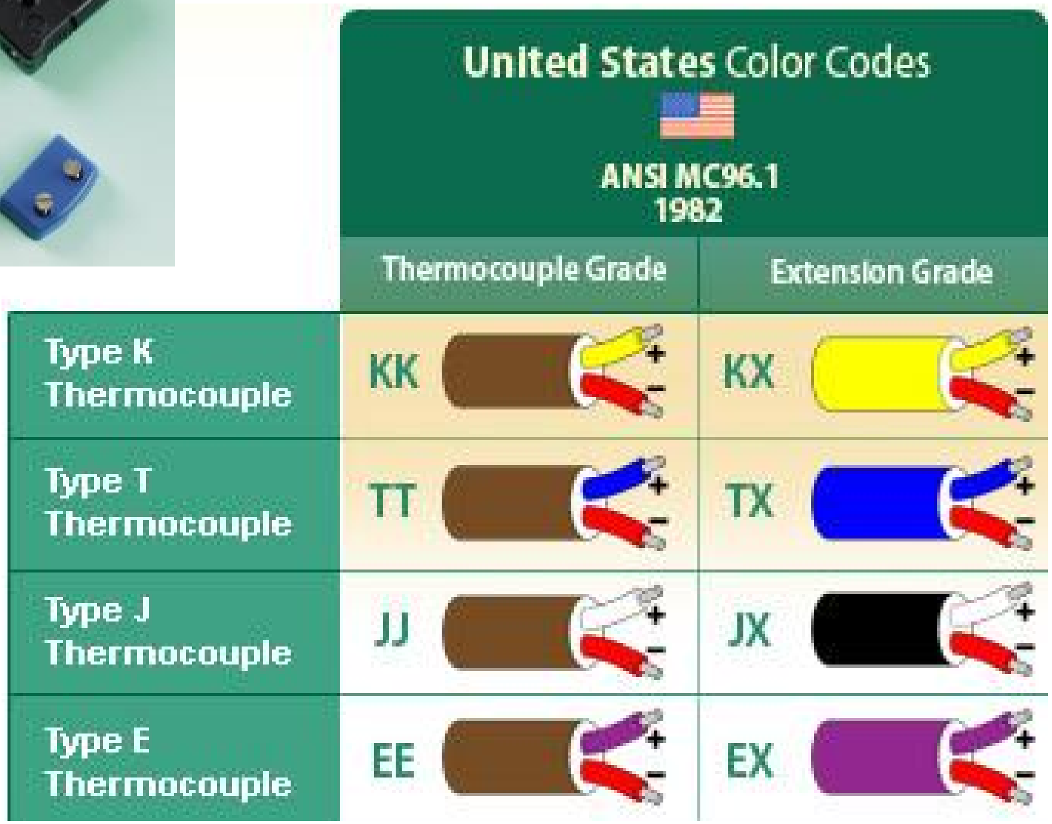
Thermocouples – Reference Junction

- A reference junction contains a temperature sensor to measure the temperature in a block of metal where the copper to Metal A/B junctions occur. The electronics within the data acquisition system subtracts out the voltages generated at J_A and J_B such that the correct voltage at J_T is being measured.



Thermocouples – Color Codes

Thermocouple connectors have pins of the same material as the wire. The casing has the same color as the thermocouple wire.



ALLOY

Chromel
Alumel

Copper
Constantan

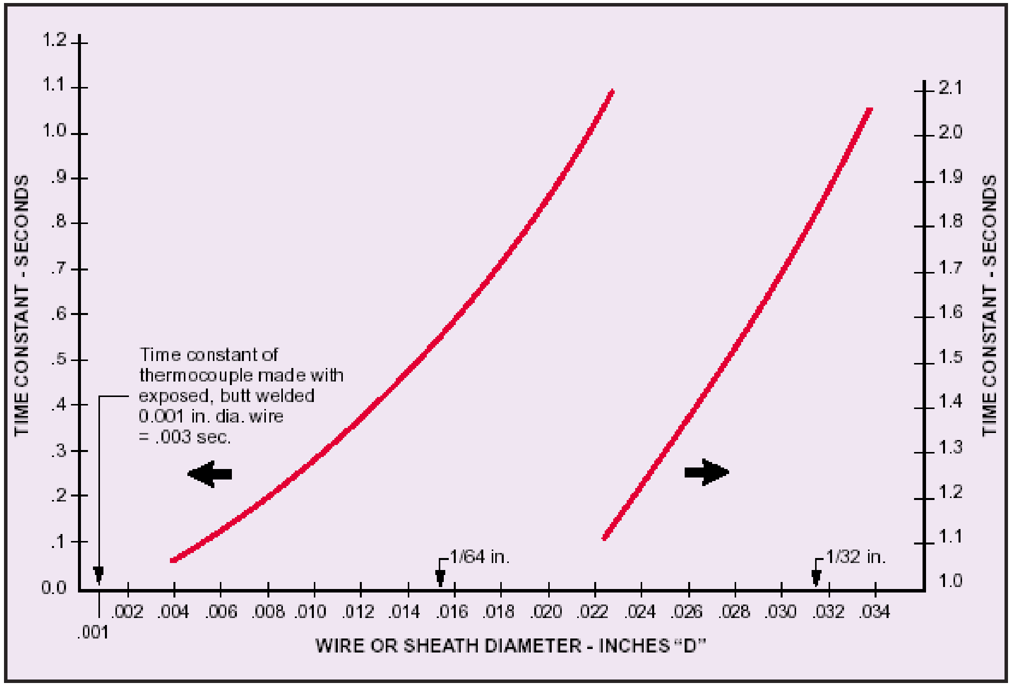
Iron
Constantan

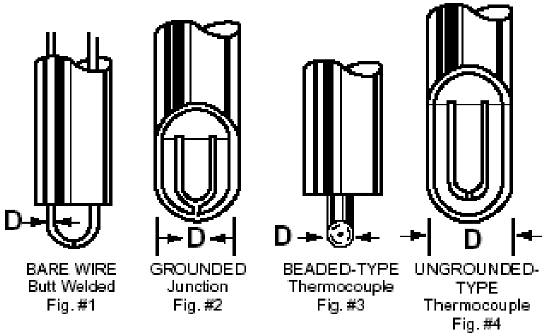
Chromel
Constantan

Note: Red is the negative lead.
There are other standards out there, so be aware.

Thermocouples – Response Time

- The response of a thermocouple (or other similar type transducers) is determined by its time constant. The time constant is the time it takes for the thermocouple to reach 63% of the temperature environment.
- The size and shielding type of the thermocouple wire at the junction determine the time constant.
- Manufacturers such as Omega Engineering have time constant curves which give the value for various thermocouple types and wire sizes.





Thermocouples – Response Time

- The increasing sensed temperature of a thermocouple follows the equation:

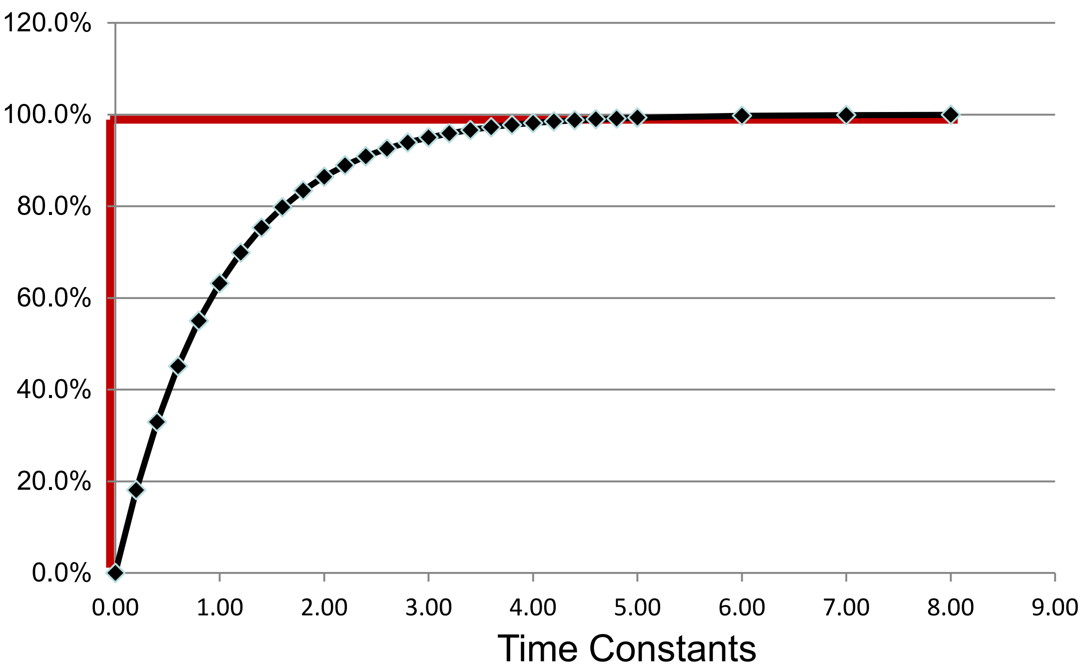
$$T = T_0\left(1 - e^{-t/\tau}\right)$$

T_0 is the environment temperature

t is the time

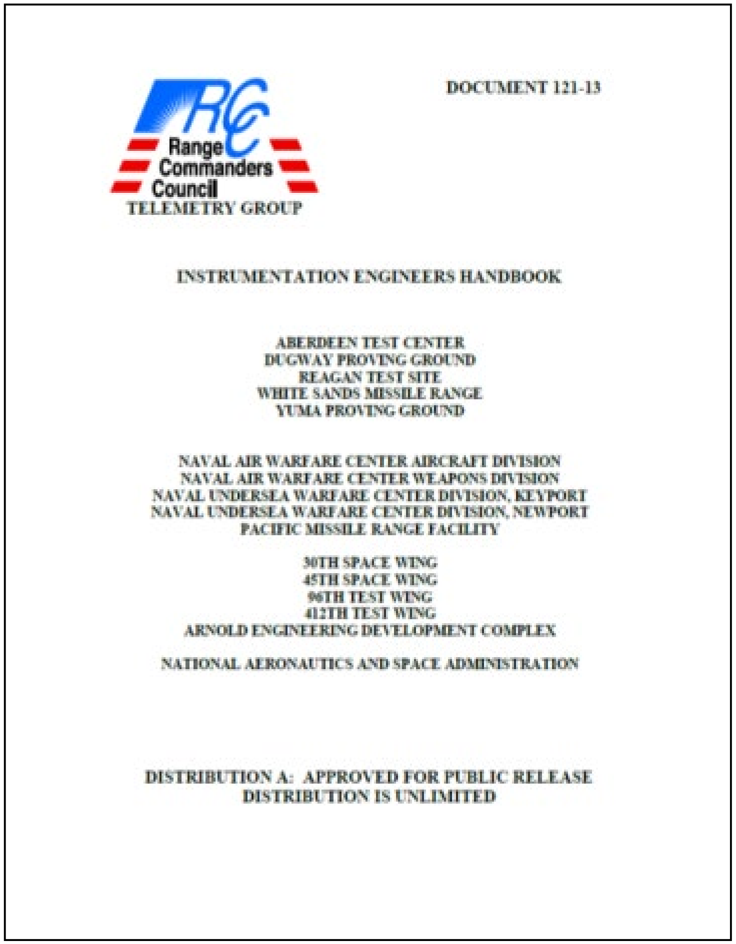
τ is the time constant of the thermocouple

Time	% Full Temp
0	0%
1τ	63.2%
2τ	86.5%
3τ	95.0%
4τ	98.2%
4.6τ	99%
5τ	99.3%



PART 2

Other Transducers


DOCUMENT 121-13

Range Commanders Council
TELEMETRY GROUP

INSTRUMENTATION ENGINEERS HANDBOOK

ABERDEEN TEST CENTER
DUGWAY PROVING GROUND
REAGAN TEST SITE
WHITE SANDS MISSILE RANGE
YUMA PROVING GROUND

NAVAL AIR WARFARE CENTER AIRCRAFT DIVISION
NAVAL AIR WARFARE CENTER WEAPONS DIVISION
NAVAL UNDERSEA WARFARE CENTER DIVISION, KEYPORT
NAVAL UNDERSEA WARFARE CENTER DIVISION, NEWPORT
PACIFIC MISSILE RANGE FACILITY

30TH SPACE WING
45TH SPACE WING
96TH TEST WING
412TH TEST WING
ARNOLD ENGINEERING DEVELOPMENT COMPLEX

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

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We do not have time to go through every transducer type. If there are other measurement types you need to make, please refer to IRIG-121 Instrumentation Engineers Handbook for additional information.

Transducer Specifications

When looking at transducer specifications, you have to know the requirements of the data, and the environment the transducer will be located in. There are many specifications listed, but these are the most common ones.

Electrical:
Power (voltage and current) Requirements
Transducer Sensitivity (output voltage)

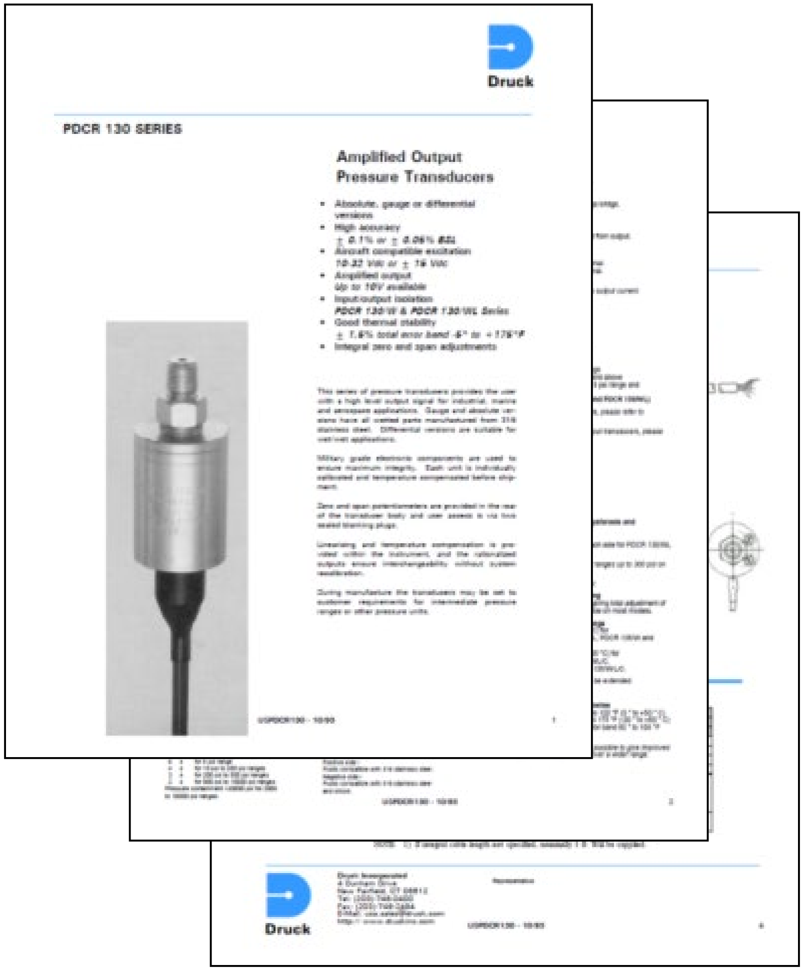
Data:
Frequency response
Engineering Unit Range

Environment:
Temperature, humidity, altitude
Fluid being measured (if a pressure transducer or flow meter)

Physical:
Size
Electrical and Mechanical Interfaces

Transducer Specifications

- For this example, we will look at a pressure transducer specification.



Druck

PDCR 130 SERIES

Amplified Output
Pressure Transducers

- Absolute, gauge or differential versions
- High accuracy ± 0.1% or ± 0.06% BSL
- Aircraft compatible excitation 18-32 Vdc or ± 15 Vdc
- Amplified output Up to 10V available
- Input/output isolation PDCR 130/W & PDCR 130/WL Series
- Good thermal stability ± 1.5% total error band -5° to +175°F
- Integral zero and span adjustments

Let's say we are making a pressure measurement on an engine.

- The EU range is 0 to 60 PSIA
- The frequency response is 0 – 100 Hz
- The medium being measured is air
- The temperature environment is up to 200^{o}F
- The burst pressure of the system can be up to 200 PSIA.

- Note that errors specified within a spec sheet are usually assumed to be 95% (2σ) uncertainty numbers.
- Always contact the manufacturer if you are unsure.

Transducer Specifications – Electrical

Power: 10VDC preferred or 28VDC

Supply Voltage

PDCR 130 Series
10-32V d.c. @20mA isolated from output.

A power source of 10 VDC at 40mA is available.

Why is "isolated from output" important to pay attention to?

Output Voltage: ±5 volt input range to analog to digital converter

Output Voltage
~~2.5V standard for 2.5 psi range~~
5V standard for 5 psi range and above
~~(10V maximum available for 5 psi range and above)~~
(Isolated on PDCR 130/W and PDCR 130/WL)

Bi-directional output available, please refer to manufacturer.

For alternative amplified output transducers, please refer to manufacturer.

0-5V is acceptable. With some gain and offset used, the full 4000-count range of a 12-bit data channel is used.

Gain = 2, Offset = -5V

Transducer Specifications – EU Range/Frequency Range

EU Range: 0 – 60 PSIA

Operating Pressure Ranges
PDCR 130/W and PDCR 135/W
2.5 psi gauge only
5, 10, 15, 20, 30, 50, 100, 150, 200, 300, 500, 900, 1000 psi gauge or absolute
2000, 3000, 5000, 7500, 10000 psi absolute or sealed gauge

Other pressure units may be specified, e.g. ins. H_2O, kPa, etc.

Must select the 100 PSIA range to meet the requirements. Note that errors are based on 100 not 60 PSIA.

Frequency Range of Interest: 0 – 100 Hz

Natural Frequency (Mechanical)
PDCR 130/W and PDCR 135/W,
PDCR 130/WL and PDCR 135/WL
10.5 kHz for 5 psi range increasing to 210 kHz for 500 psi range.

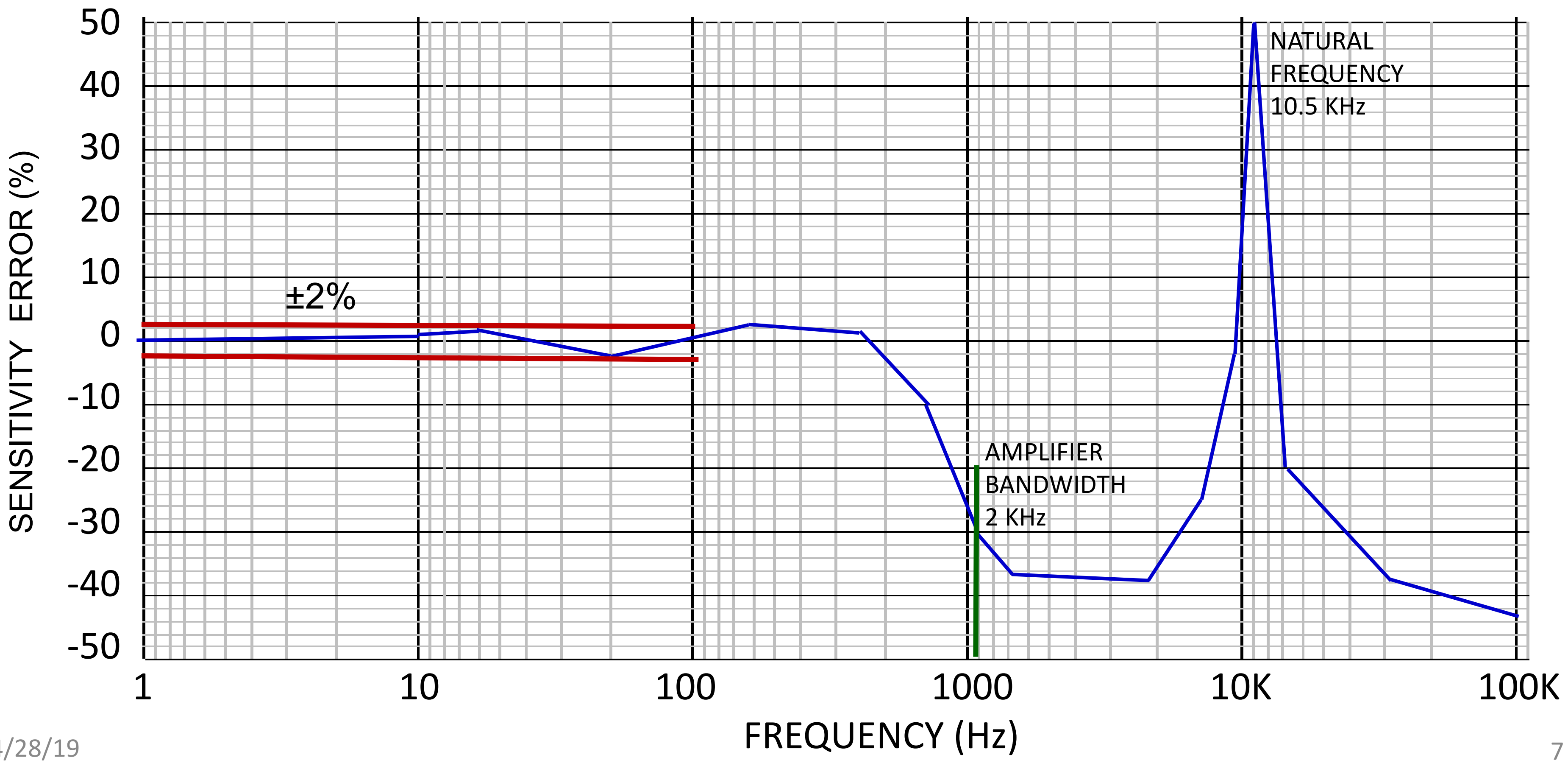
For more detailed information please refer to manufacturer.

Amplifier Bandwidth
-3dB at 2kHz nominal.

Need to contact the manufacturer for the specifics, but most likely this will satisfy the 100 Hz frequency response request.

Transducer Specifications – Frequency Range

- The frequency response as specified was ambiguous.
- If given a sensitivity frequency response graph, note the maximum error in the frequency of interest (0 – 100 Hz)
- For this example, the error of the sensitivity is within ±2%.



Transducer Specifications – Burst Pressure

Burst Pressure: 200 PSIA

PDCR 130/W and PDCR 135/W

10	x	for 2.5 psi range
6	x	for 5 psi range
4	x	for 10 psi to 200 psi ranges
3	x	for 200 psi to 500 psi ranges
2	x	for 900 psi to 10000 psi ranges

Pressure containment >20000 psi for 2000 to 10000 psi ranges.

For our 0-100 PSIA transducer range, that would result in a max pressure of 400 PSIA.

Exceeding Burst Pressure will damage the sensing element in the pressure transducer (such as the diaphragm).
It can also lead to a catastrophic failure (hydraulic fluid loss, leakage in pitot-static system).

Transducer Specifications – Temperature

Temperature Range: up to 200°F

Operating Temperature Range
-40° to +175°F (-40° to +80°C) for
PDCR 130/W, PDCR 130/WL, PDCR 135/W and
PDCR 135/WL
-40 ° to +250 °F (-40 ° to +125 °C) for
PDCR 130/W/C, PDCR 130/WL/C,
PDCR 135/W/C, and PDCR 135/W/L/C.

This temperature range can be extended.

Temperature Effects

PDCR 130 and PDCR 135 Series
± 0.5% total error band 32 ° to 122 °F (0 ° to +50 ° C)
± 1.5% total error band -5 ° to 175 °F (-20 ° to +80 ° C)
2.5 psi range, ±0.5% total error band 50 ° to 105 °F
(10° to 40 °C)

For special applications it is possible to give improved temperature compensation over a wider range.

The transducer will operate fine up to 250°F without being damaged.

The error is going to be greater than ±1.5% at 200°F.

We may want to take them up on their offer of a wider range.

Or it may have to be mounted remotely in a cooler area of the engine bay.

Transducer Specifications – Medium and Size

Medium: Air

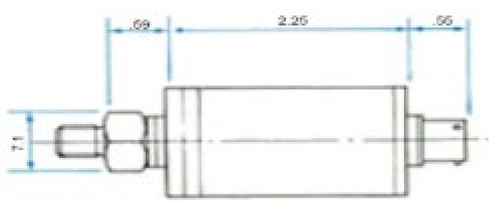
Pressure Media

PDCR 130/W and PDCR 135/ W
Fluids compatible with 316 stainless steel.

PDCR 130/WL and PDCR 135/WL
Positive side:-
Fluids compatible with 316 stainless steel.
Negative side:-
Fluids compatible with 316 stainless steel and silicon.

Air is compatible with stainless steel, so no issue exists.

Size Constraints:



PDCR 130/W/C & PDCR 135/W/C

Depending upon available mounting locations, this transducer may not fit in the area desired.

Transducer Specifications – Electrical and Pressure Interfaces

Electrical Connection

PDCR 130/W and PDCR 135/W
3 feet integral shielded/vented cable supplied.

PDCR 130/WL and PDCR 135/WL
3 feet teflon shielded cable supplied.
Longer lengths available on request.

Connector Versions

PDCR 130/W/C, PDCR 135/W/C,
PDCR 130/WL/C and PDCR 135/WL/C
6 pin Bayonet receptacle, PT1H-10-6P or equivalent (Hermetic stainless) to MIL-C-26482.
Mating electrical socket type PT06A-10-6S or equivalent available on request (P/N 163-009).

Verify that you have or can obtain the correct mating electrical connectors.

Pressure Connection

PDCR 130/WL, PDCR 135/WL,
PDCR 130/WL/C, and PDCR 135/WL/C
Positive Port: 1/4" NPT male or 7/16 UNF male (MS33656-4)
Negative Port: 1/4" NPT male or 7/16 UNF male (MS33656-4)

PDCR 130/W, PDCR 135/W,
PDCR 130/W/C and PDCR 135/W/C
Gauge, Absolute and Sealed Gauge: 1/4" NPT male or 7/16" UNF male (MS33656-4).
Other pressure connections available on request.

Verify that the pressure fittings are compatible to the tubing being used

Video

Video – Qualitative Images

- For qualitative information, a high-definition (1920x1080p at 25 or 30 frames per second (fps)) camera is used.

Camera shown without the lens

Video – Qualitative Images

- This is an HD video screenshot of the camera shown in the previous slide.
- Provides a sense of what is going on during the test. The distance from the basket to fuel probe cannot be determined from the image.

Note the time stamp on the video used to correlate the frame to any data that was being captured.

Video – Quantitative Images

- Because actual measurements are being extracted from the video images, there are additional steps that must take place.
  - Surveyed targets mounted on aircraft/store surfaces
  - Lenses on the cameras must be calibrated
  - Cameras must have synchronized shutters

Video – Surveyed Targets

- Surveyed target points on the aircraft and store are applied to the surfaces.
- These points are used as references when analyzing the images for the position of a store in relation to the aircraft.

Video – Lens Calibrations

- Because quantitative information is being gathered from these video images, the lens for each camera is calibrated. This photo shows a lens calibration being performed using a light board. The Light Emitting Diodes (LEDs) are arranged in three dimensions at known locations. Distortions in the lens can then be determined from the test image.

Video – Shutter Synchronization

- Because position of the store is changing with time, all the cameras must be taking a single image at the same instant.
- So there are signal pulses run to each camera to obtain that synchronization.

MIL-STD-1553 Bus

MIL-STD-1553

- MIL-STD-1553 is a military standard published by the United States Department of Defense that defines the mechanical, electrical, and functional characteristics of a serial data bus. It features a *dual redundant* balanced (differential) line, time division multiplexing, half-duplex command/response protocol, and up to 31 remote terminals.

- There are 2 versions of the standard: A and B.
  - MIL-STD-1553A was written in 1975
  - MIL-STD-1553B was written in 1978

MIL-STD-1553 Components

- **Bus Transmission Line**
  - Shielded twisted pair wire of a defined characteristic impedance, frequency response, and attenuation.

- **Bus Terminator**
  - Resistor which terminates the extreme ends of the bus.

- **Bus Coupler**
  - Transformer device which provides the means of connecting a Bus Controller, Bus Monitor, and Remote Terminals to the 1553 bus.
  - The coupler also contains isolation resistors.

MIL-STD-1553 Components

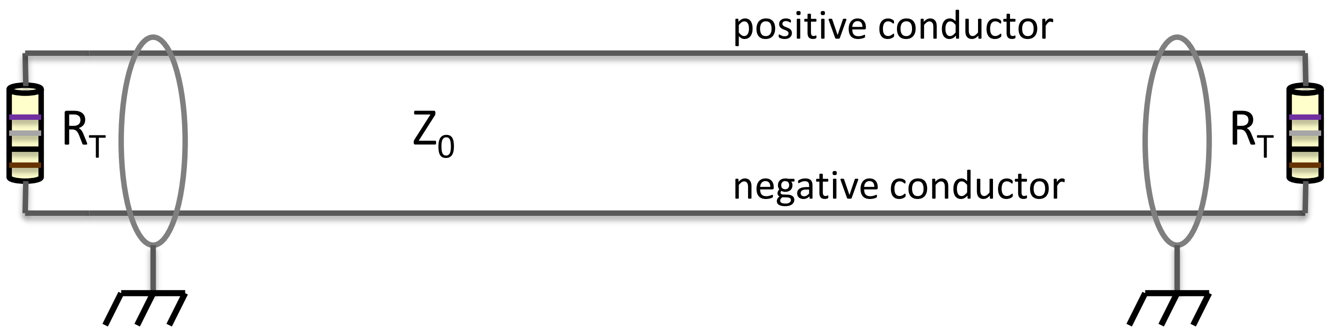
- **Bus Controller (BC)**
  - The terminal assigned the task of initiating information transfers on the data bus.
  - Is the “boss” of the bus (typically is the Mission Computer).

- **Bus Monitor (BM)**
  - Only listens and does not transmit on the bus.
  - Used within an instrumentation system.

- **Remote Terminal (RT)**
  - All terminals not operating as the bus controller or bus monitor.
  - RTs only respond when commanded.
  - Each RT is assigned an RT number or address.

MIL-STD-1553 Bus

- In its most simplistic form, the 1553 bus is a shielded pair of wires with terminating resistors on each end. The resistor values match the impedance of the bus. The shield is terminated to chassis ground at each end.



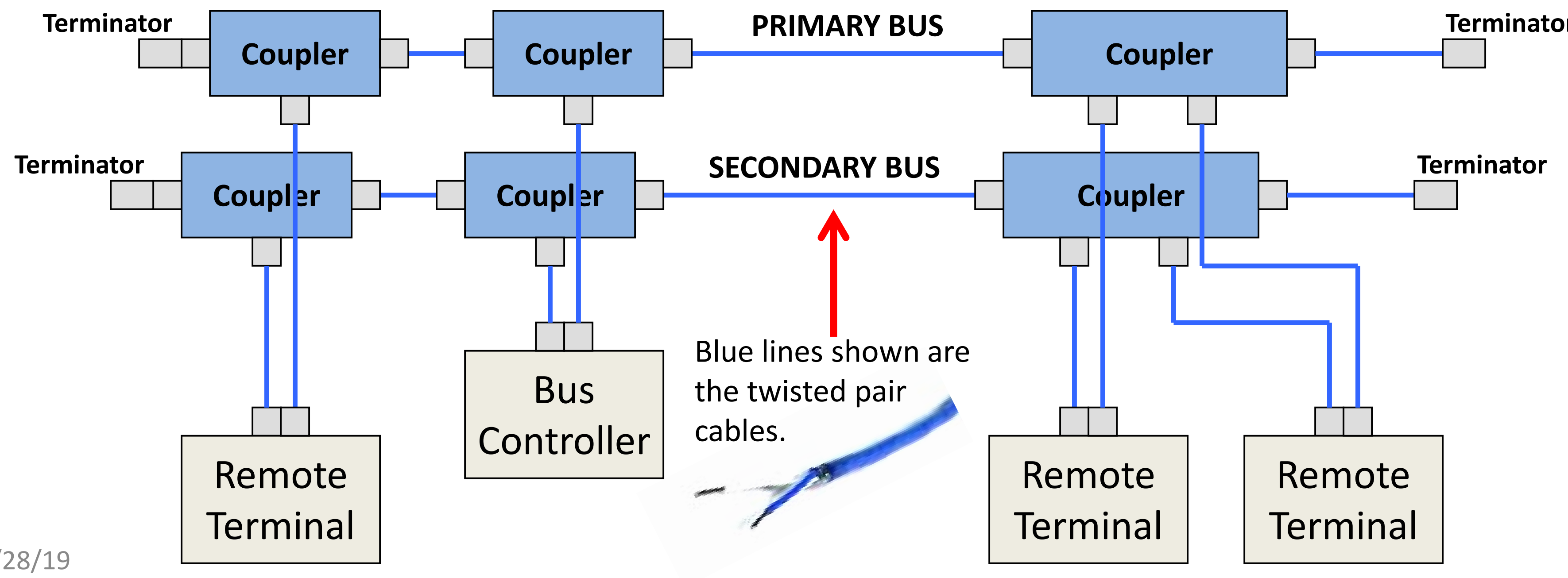
Terminator

For 1553A: $Z_0 = 70\ \Omega \pm 10\%$, $R_T = Z_0$

For 1553B: $Z_0 = 70\ \Omega$ to $85\ \Omega$, $R_T = Z_0 \pm 2\%$

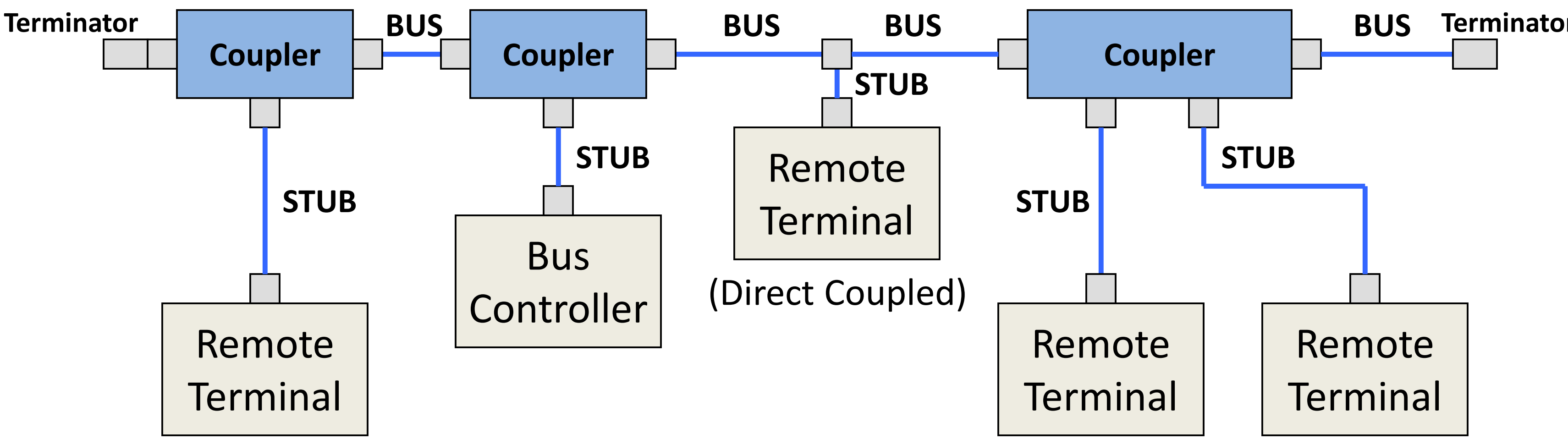
1553 Architecture and Dual Redundancy

- Bus controllers and remote terminals are the components that talk on the bus. This diagram shows the typical connections that need to be made to both the primary and secondary busses.
- A 1553 bus is actually made up of two busses, a primary and a secondary bus. 1553 messages are not transmitted on both busses simultaneously, but on either one or the other. So both busses must be monitored for data. Usually each bus is run physically apart from one another to avoid damage to both cables.
-



Bus Controller and Remote Terminal Connections to the 1553 Bus

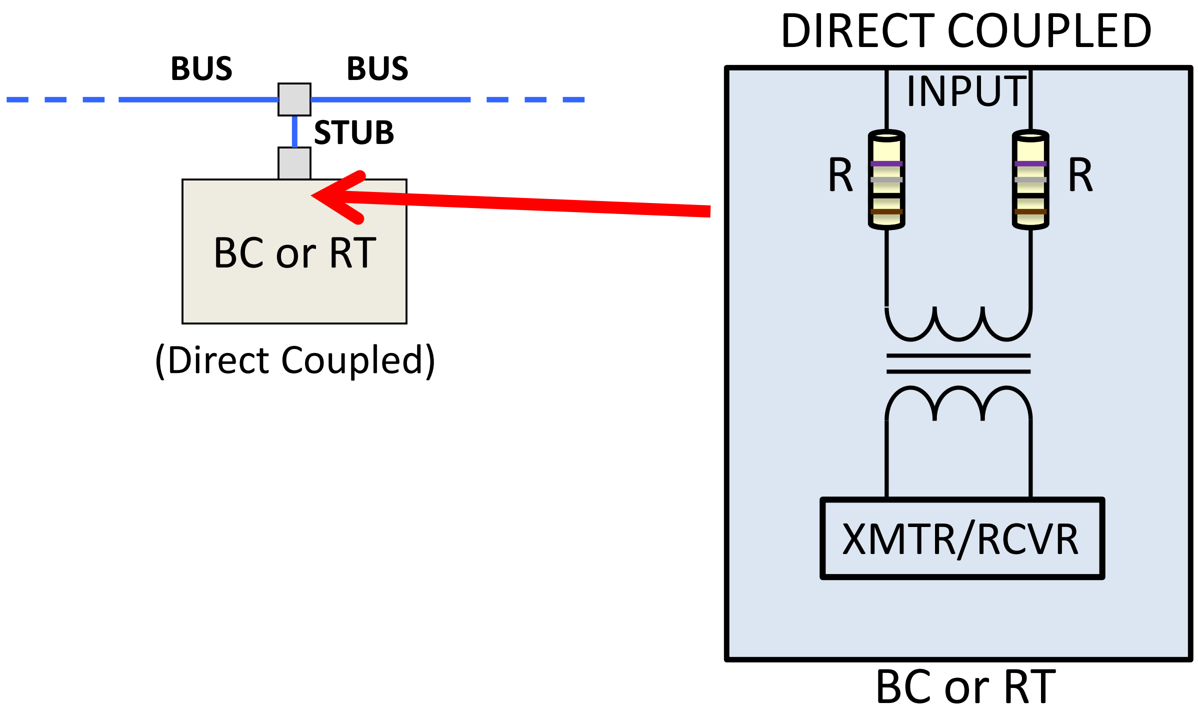
- Bus controllers and remote terminals connect to the bus via a stub connection. This is accomplished in one of two ways on the bus: direct coupled, or transformer coupled stub.



From now on through the training only the primary bus is shown. However, keep in mind that a second set of 1553 bus components are needed for the secondary bus.

Direct Coupled Stubs

- Direct coupled inputs on a BC or RT have isolation resistors and an isolation transformer on the input pins. The value of the isolation resistors depend upon the version of the 1553 bus.

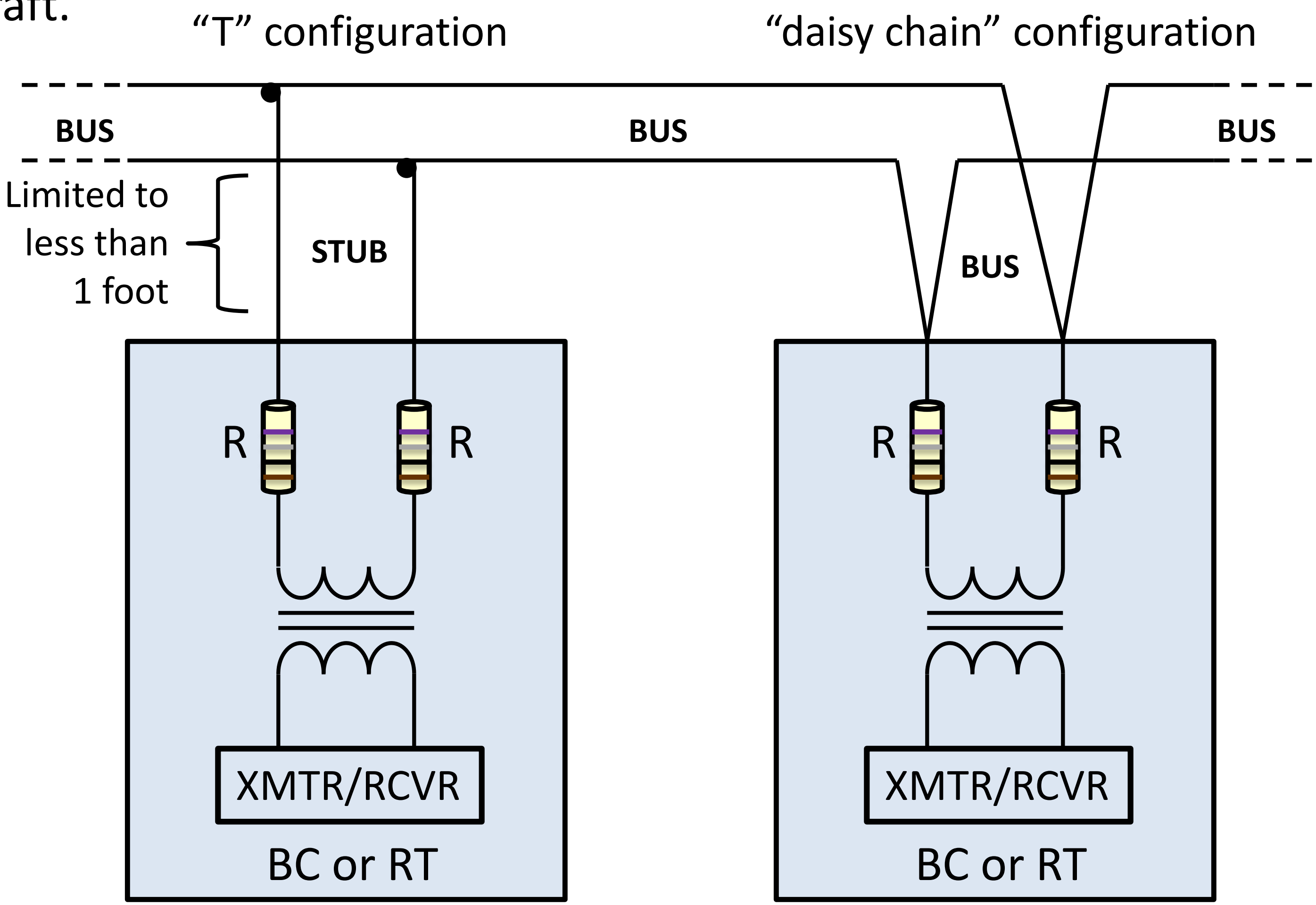


1553A:
$R = 0.75Z_0 \pm 5\%$

1553B
$R = 55\Omega \pm 2\%$

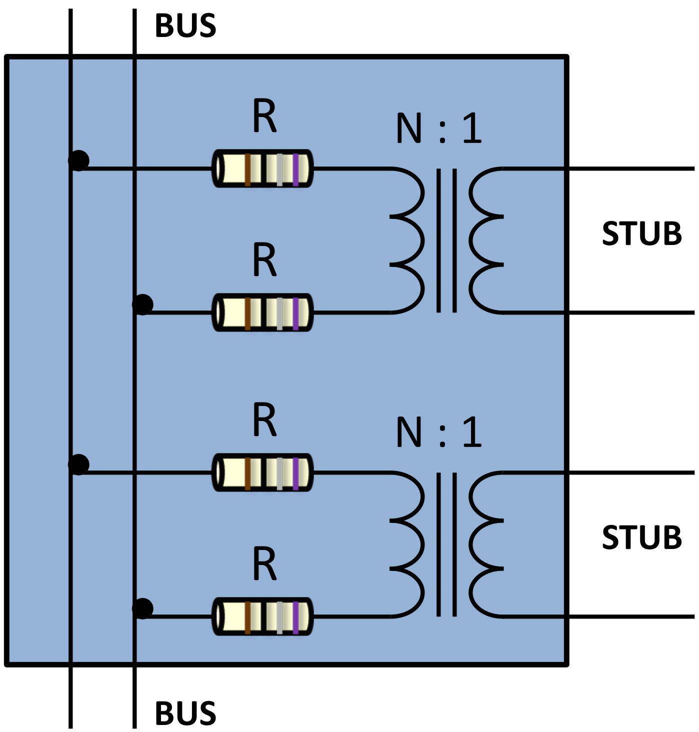
Direct Coupled Stubs

- For direct coupling, the bus is T'd or daisy chained to the input of the BC or RT. If it is T'd, its length is limited to a maximum of 1 foot. An easy way identify direct coupling is there are no external bus couplers mounted in the aircraft.



Bus Couplers

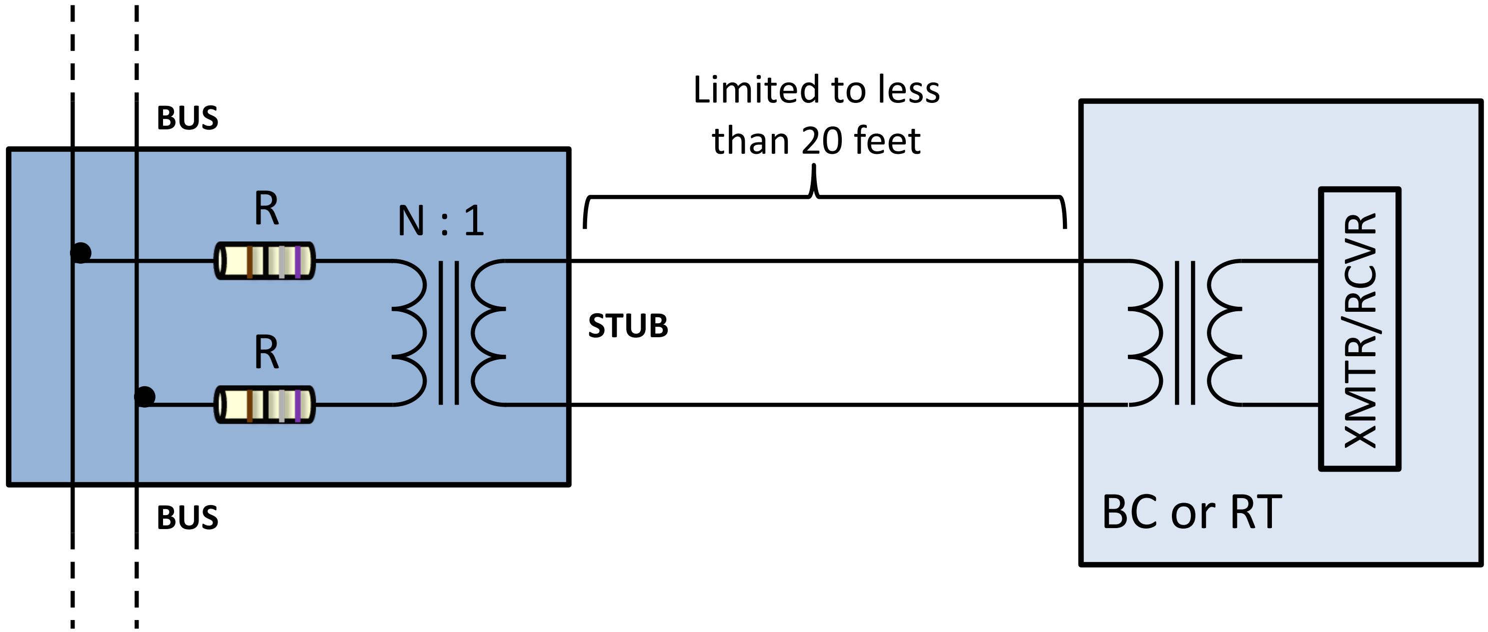
- Bus couplers have two bus connections and one or more stub connections. The isolation resistors and transformer are located within the coupler. Two separate bus couplers are needed, one for the primary and one for the secondary bus.



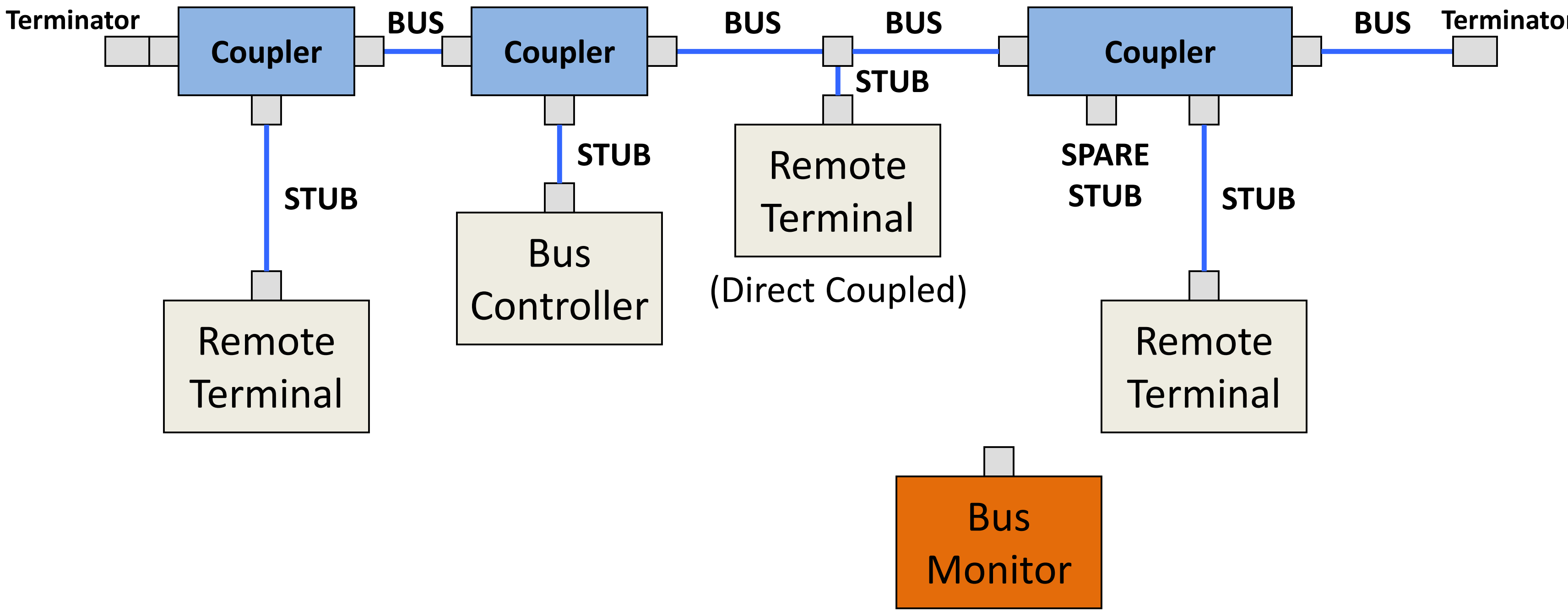
1553A:	1553B
$R = 0.75Z_0 \pm 5\%$	$R = 0.75Z_0 \pm 2\%$
$N = 1$	$N = 1.41 \pm 3\%$

Transformer Coupling to a 1553 Bus

- For transformer coupled bus taps, the stub can have a length of no more than 20 feet. This is the <u>preferred</u> method for an instrumentation bus monitor.

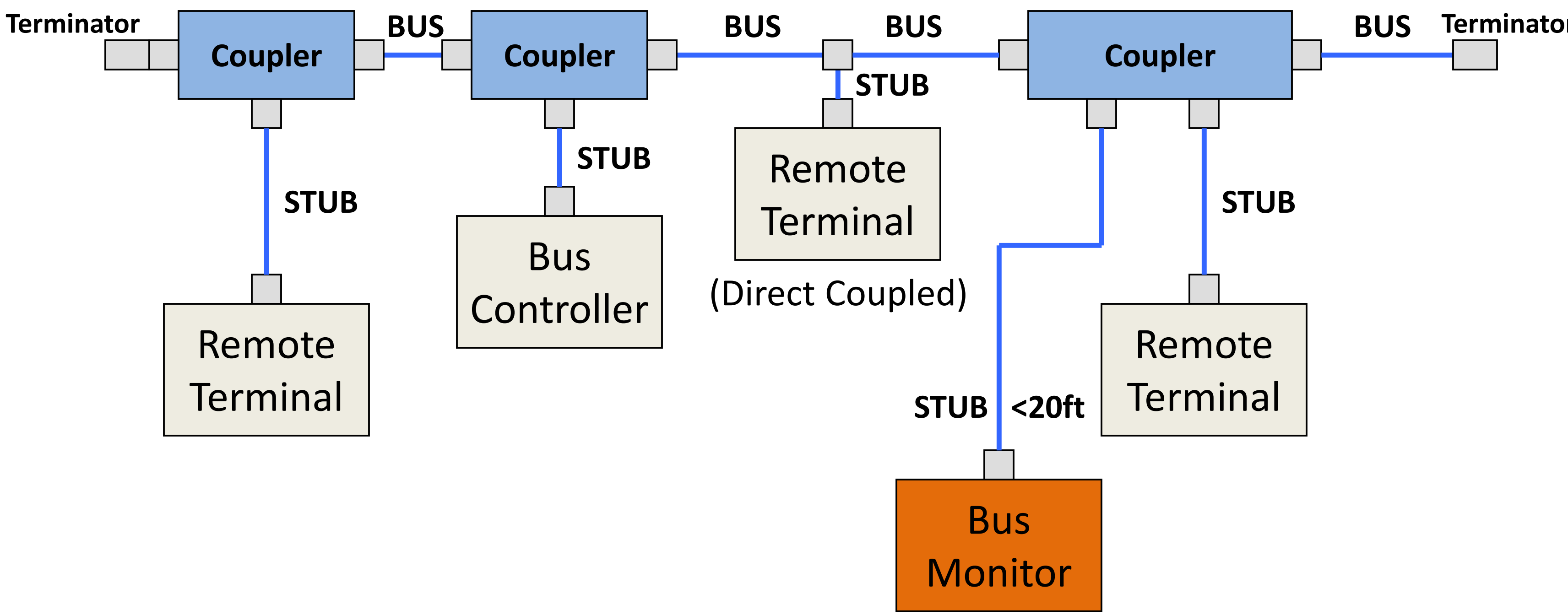


Connecting a Bus Monitor to the Bus - Aircraft with a Spare Stub

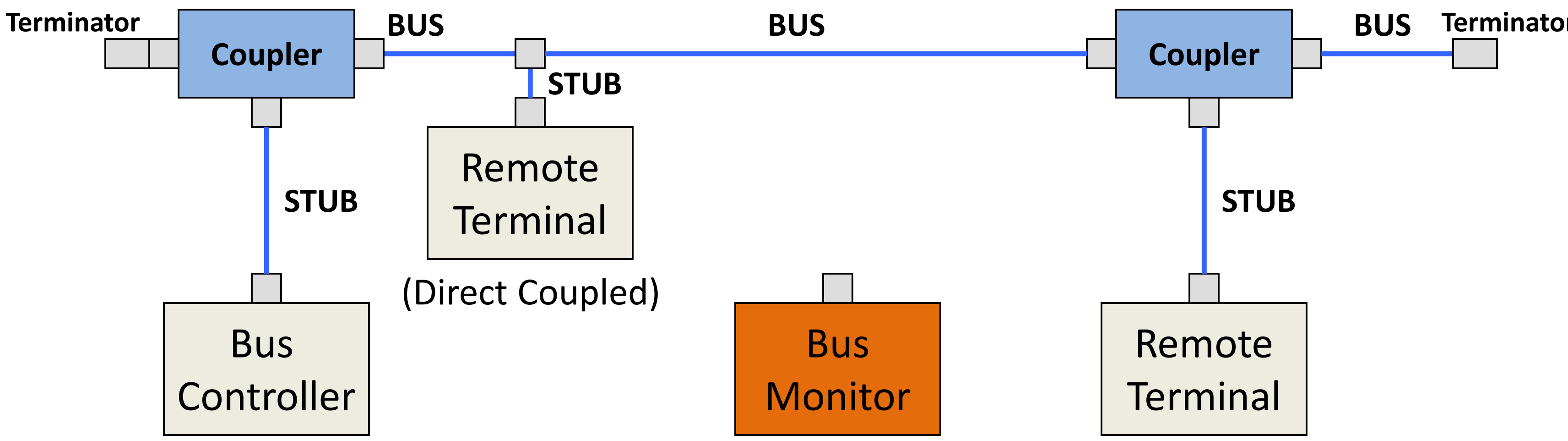


Connecting a Bus Monitor to the Bus - Aircraft with a Spare Stub

- This is the easiest way to connect to the 1553 bus. As long as the bus monitor's stub length is within 20 wire-feet, nothing additional need to be done.

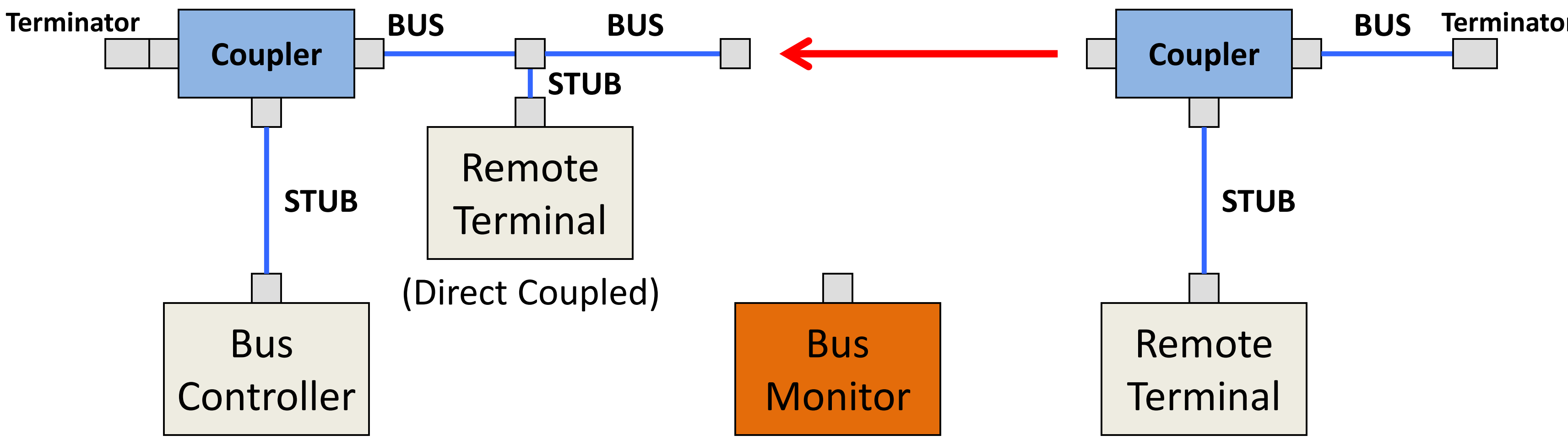


Connecting a Bus Monitor to the Bus
- Aircraft with No Spare Stubs



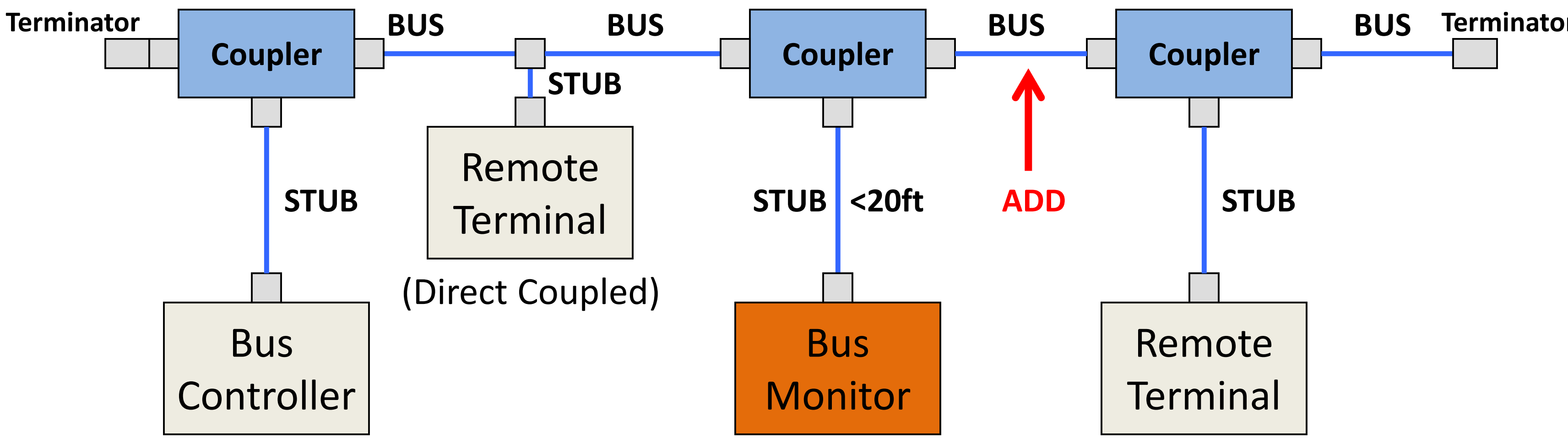
Connecting a Bus Monitor to the Bus - Aircraft with No Spare Stubs

- Disconnect the bus from the coupler that is closest to the instrumentation system.

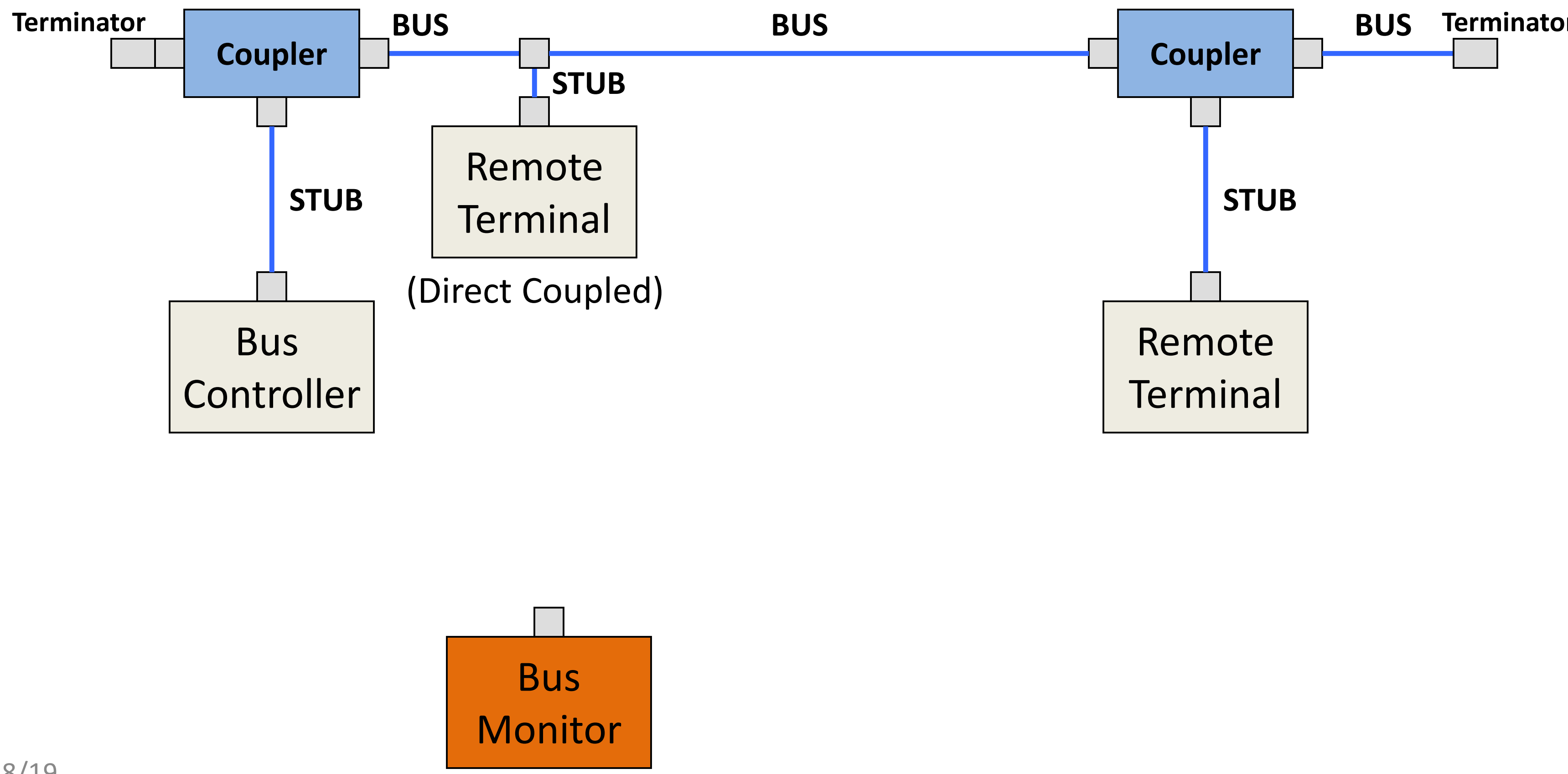


Connecting a Bus Monitor to the Bus
- Aircraft with No Spare Stubs

- Insert the instrumentation coupler and add an additional bus wire run to the next coupler.

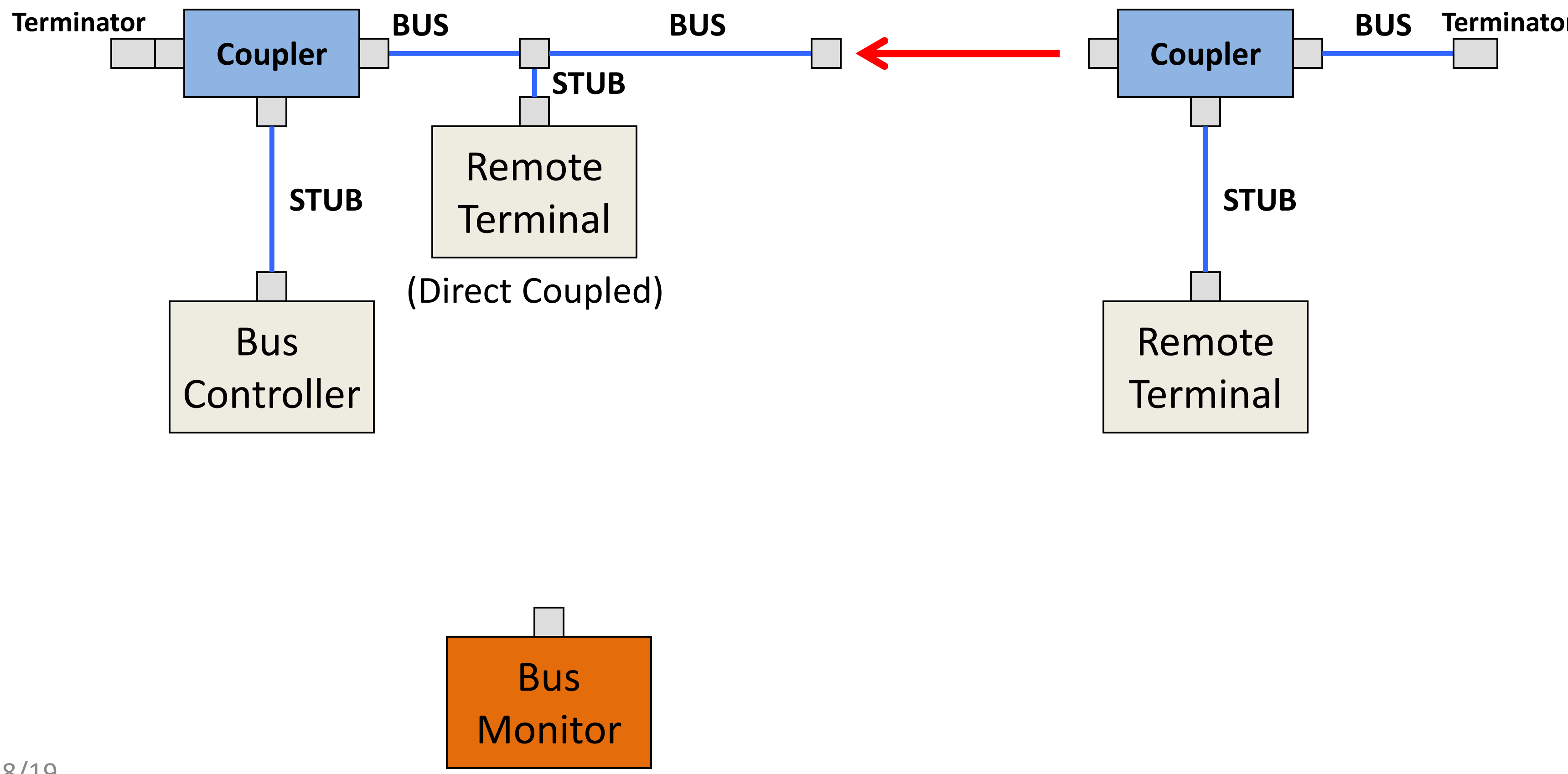


Connecting a Bus Monitor to the Bus
- Bus Monitor >20 feet from the Bus



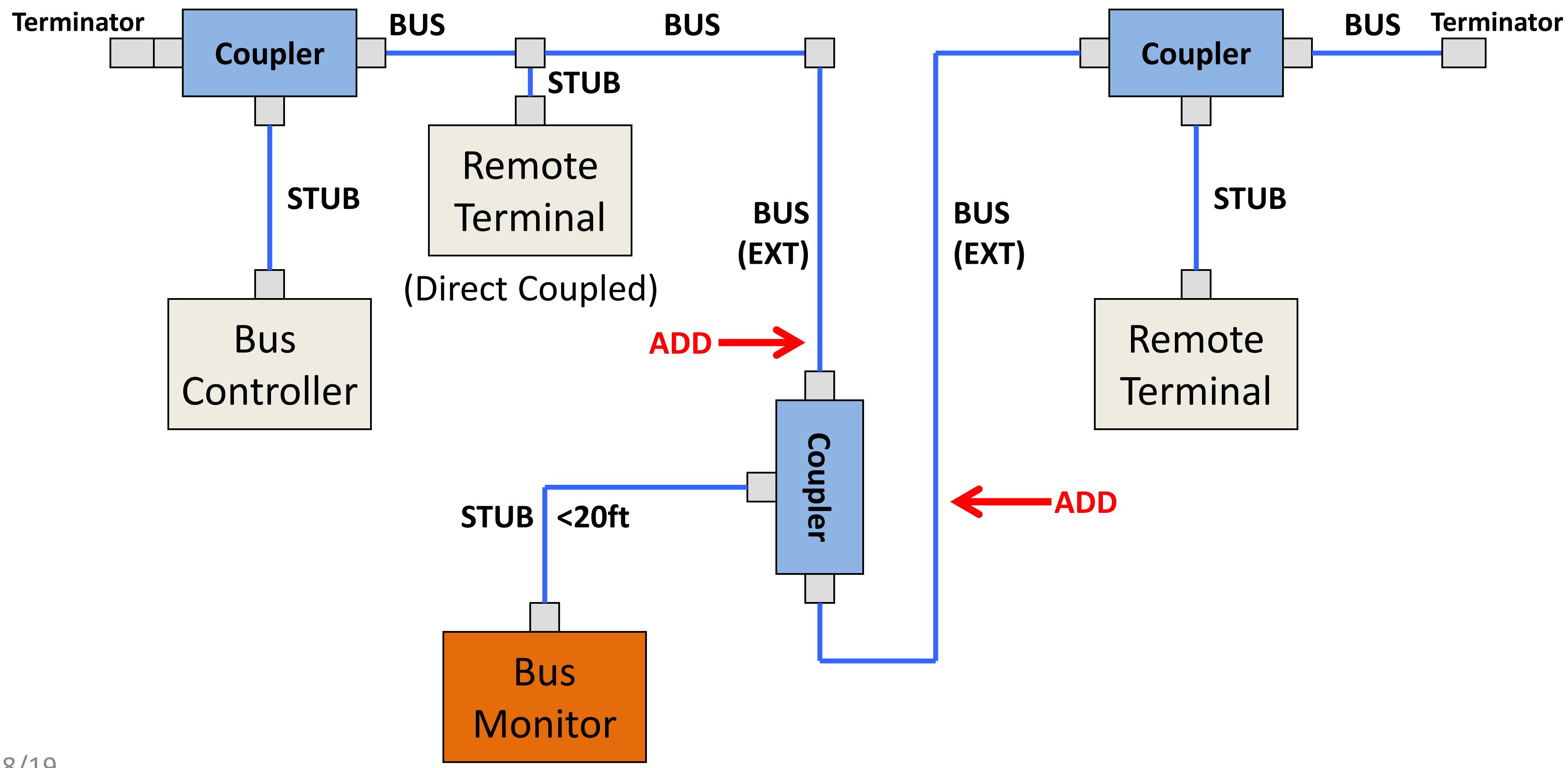
Connecting a Bus Monitor to the Bus
- Bus Monitor >20 feet from the Bus

- Remove the connector from the closest available coupler.



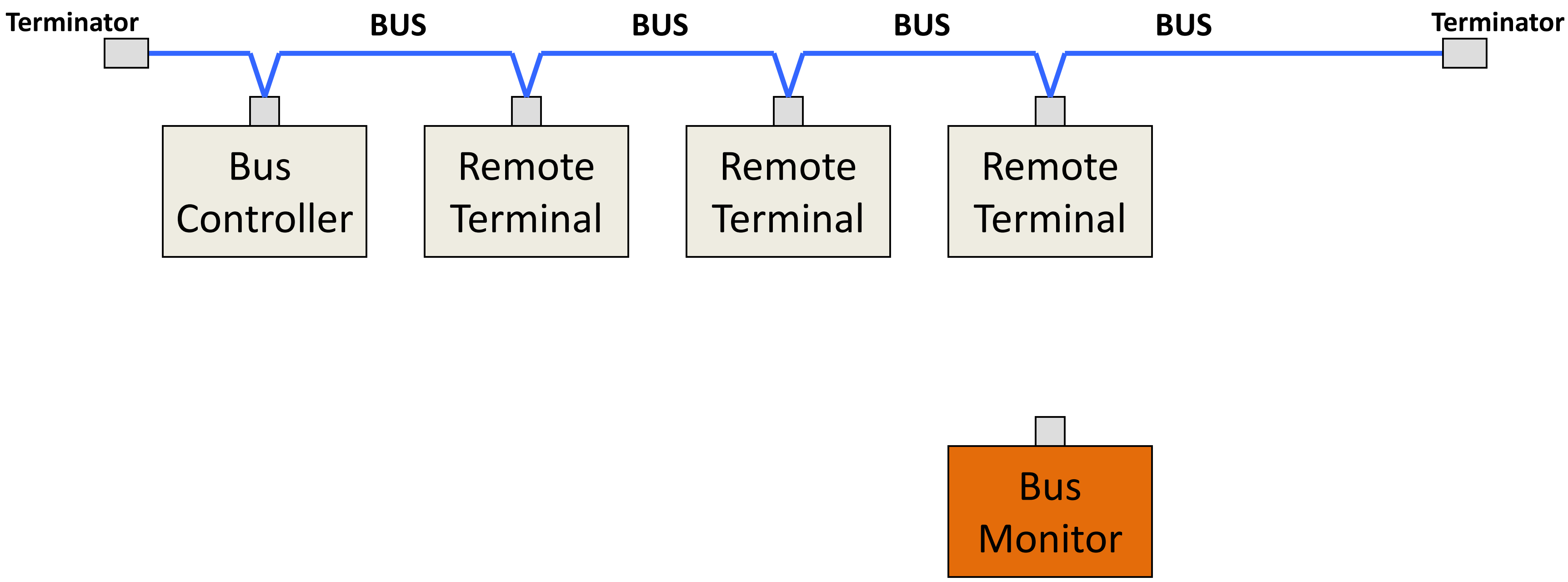
Connecting a Bus Monitor to the Bus
- Bus Monitor >20 feet from the Bus

- "Extend" the bus to the instrumentation coupler located within 20 feet of the bus monitor. As a rule of thumb, you can extend the bus by no more than 10-20% of its total length.



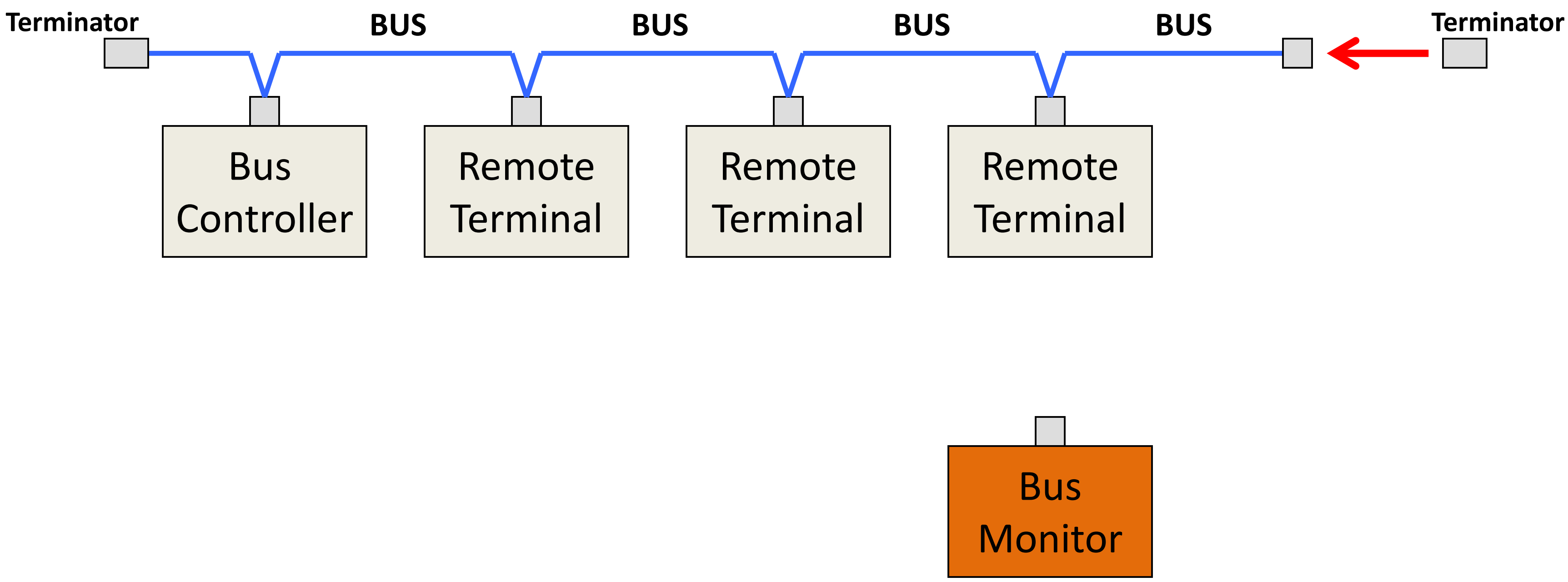
Connecting a Bus Monitor to the Bus
- Aircraft with Direct Coupling Only

- There are no bus couplers installed in the production configuration of the bus.
- All connections are direct coupled and daisy chained.



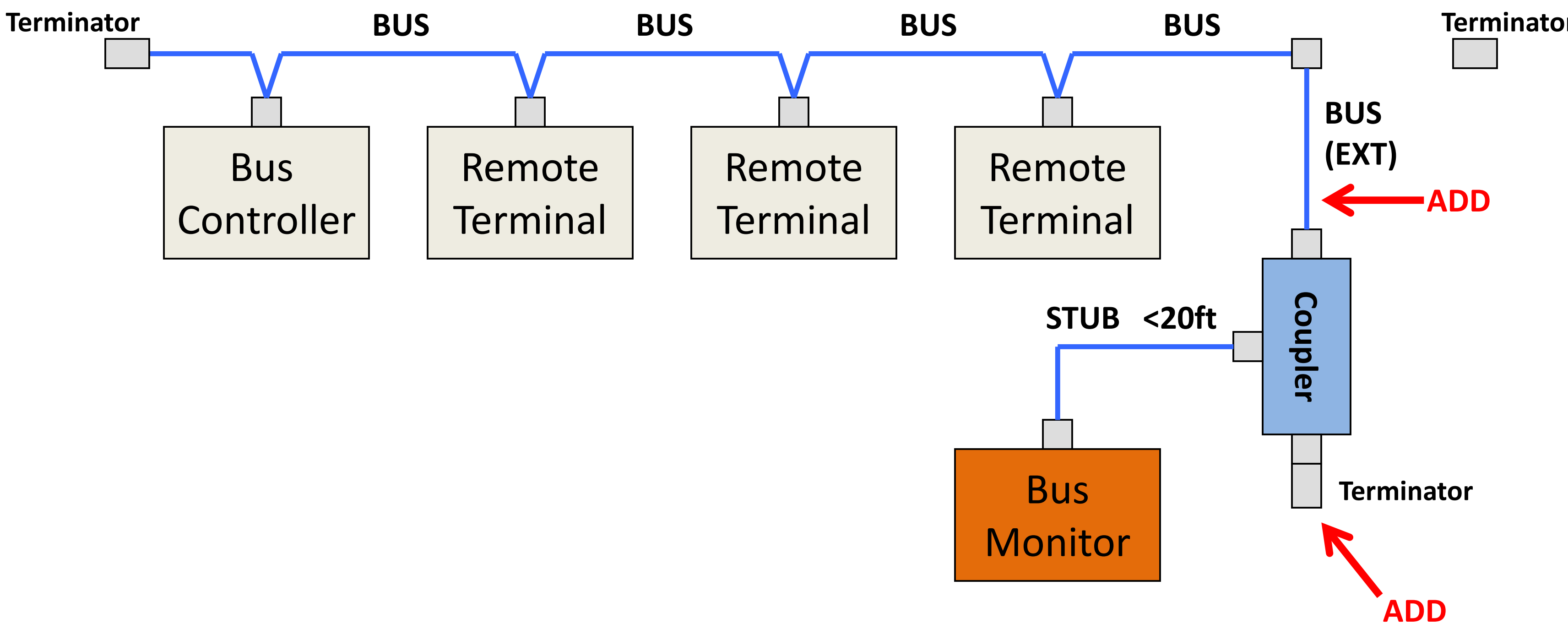
Connecting a Bus Monitor to the Bus - Aircraft with Direct Coupling Only

- Remove the bus from one of the terminators. This is one of only two locations where there is a connector that can be easily accessed.



Connecting a Bus Monitor to the Bus
- Aircraft with Direct Coupling Only

- Extend the bus to the instrumentation coupler and add a terminator to the other bus input of that coupler.



1553 Word Types

- The 1553 bus operates on a Command/Response protocol. Each word is 20 bit periods long and transmitted at a rate of 1 Mbps. There are only three word types defined in MIL-STD-1553:

- **Command Word** – can only be transmitted by the bus controller

- **Data Word** – can be transmitted by either the bus controller or a remote terminal

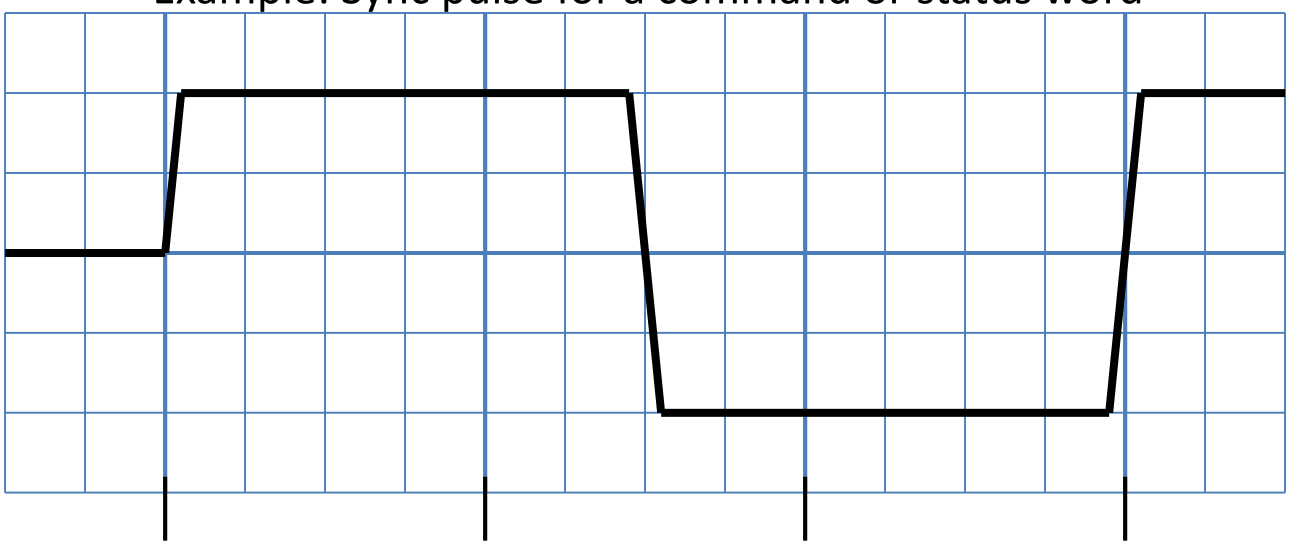
- **Status Word** – only transmitted by the remote terminal

We will now go over the structure of each of these word types.

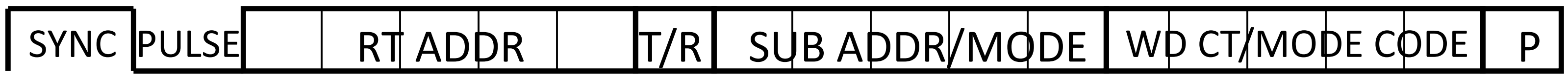
Sync Pulses

- In order for the components on the bus to recognize the beginning of words and to identify the type of word, a sync pulse is used at the beginning of every 1553 word. The sync pulse occupies the first three bit periods of the word (3µsec).

Example: Sync pulse for a command or status word



Command Word



The command word is always the first word of a message and transmitted by the bus controller.

SYNC PULSE – a pulse consisting of a "1" followed by a "0" which identifies the word as a command word.

RT ADDR – the address of the RT that is being commanded

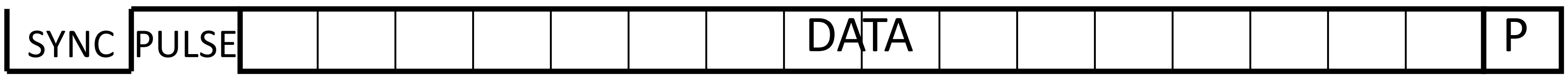
T/R – Transmit/Receive bit. Tells the specific RT whether to transmit data or receive data in a message.

SUB ADDR/MODE – the sub address (message number) or the use of a mode code.

WD CT/MODE CODE – the number of data words contained in the message, or the mode code value

P – odd parity bit

Data Word



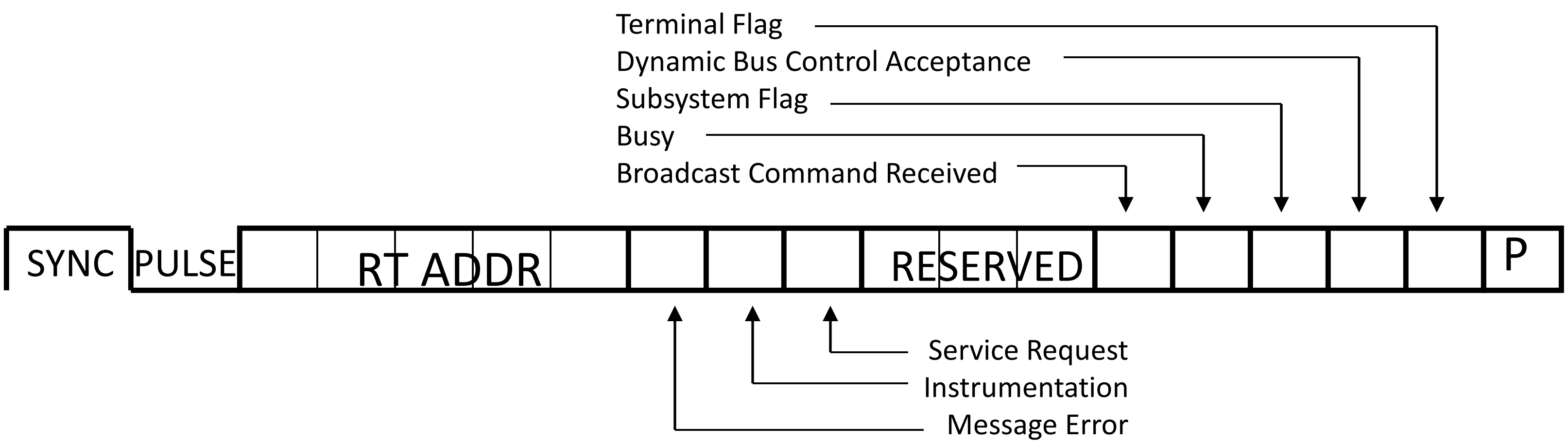
The data word contains the information being transmitted by the bus controller or the remote terminal.

SYNC PULSE – a pulse consisting of a “0” followed by a “1” which identifies the word as a data word.

DATA – 16 bits of information as defined in the bus catalog.

P – odd parity bit

Status Word



The status word is only transmitted by the remote terminal.

SYNC PULSE – a pulse consisting of a “1” followed by a “0” which identifies the word as a data word. It is distinguished from the command word because it is not the first word of the message.

RT ADDR – the address of the RT that sent the status word

FLAG and **STATUS BITS** – gives status feedback to bus controller

P – odd parity bit

1553 Messages

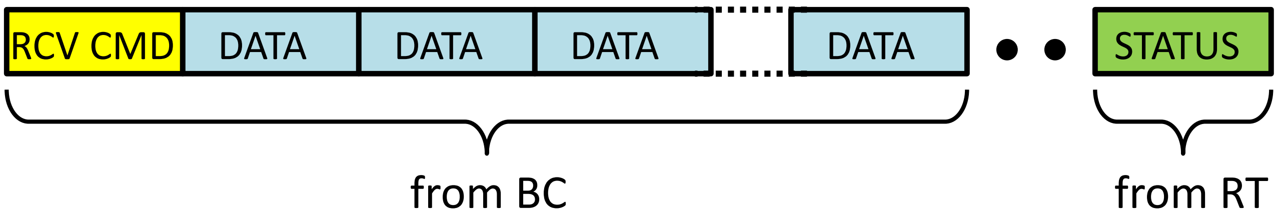
- 1553 messages are made up of command, data, and status words described earlier.

- There are three basic types of messages:
  - **BC to RT transfer**
  - **RT to BC transfer**
  - **RT to RT transfer**

A 1553 messages can contain:
1 or 2 command words,
between 1 and 32 data words,
and 1 or 2 status words depending upon the type of message.

Message Transfer – BC to RT

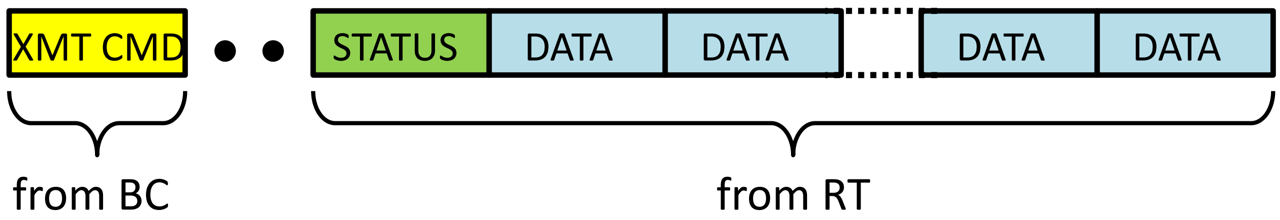
- The BC to RT transfer tells the selected RT to receive (T/R bit = 0) the allotted number of words. When the data is received, the RT responds with a status word.



"••" is the time that it takes the RT to respond with its status of receiving the command.

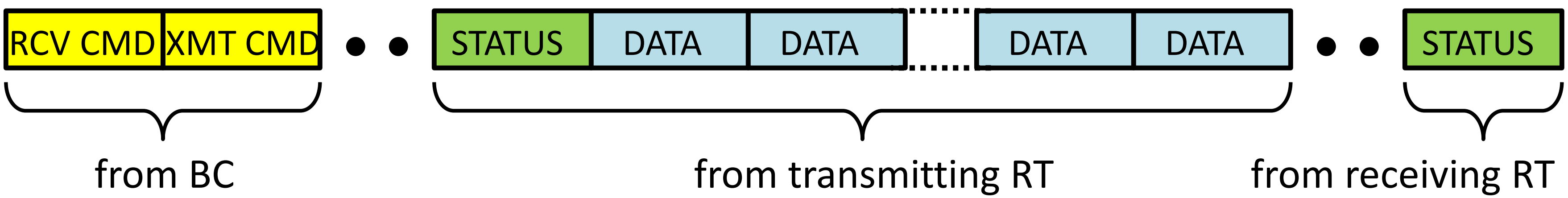
Message Transfer – RT to BC

- The RT to BC transfer tells the selected RT to transmit (T/R bit = 1) a message specified by the bus controller. After the command is received, the RT responds with a status word followed by the requested data.



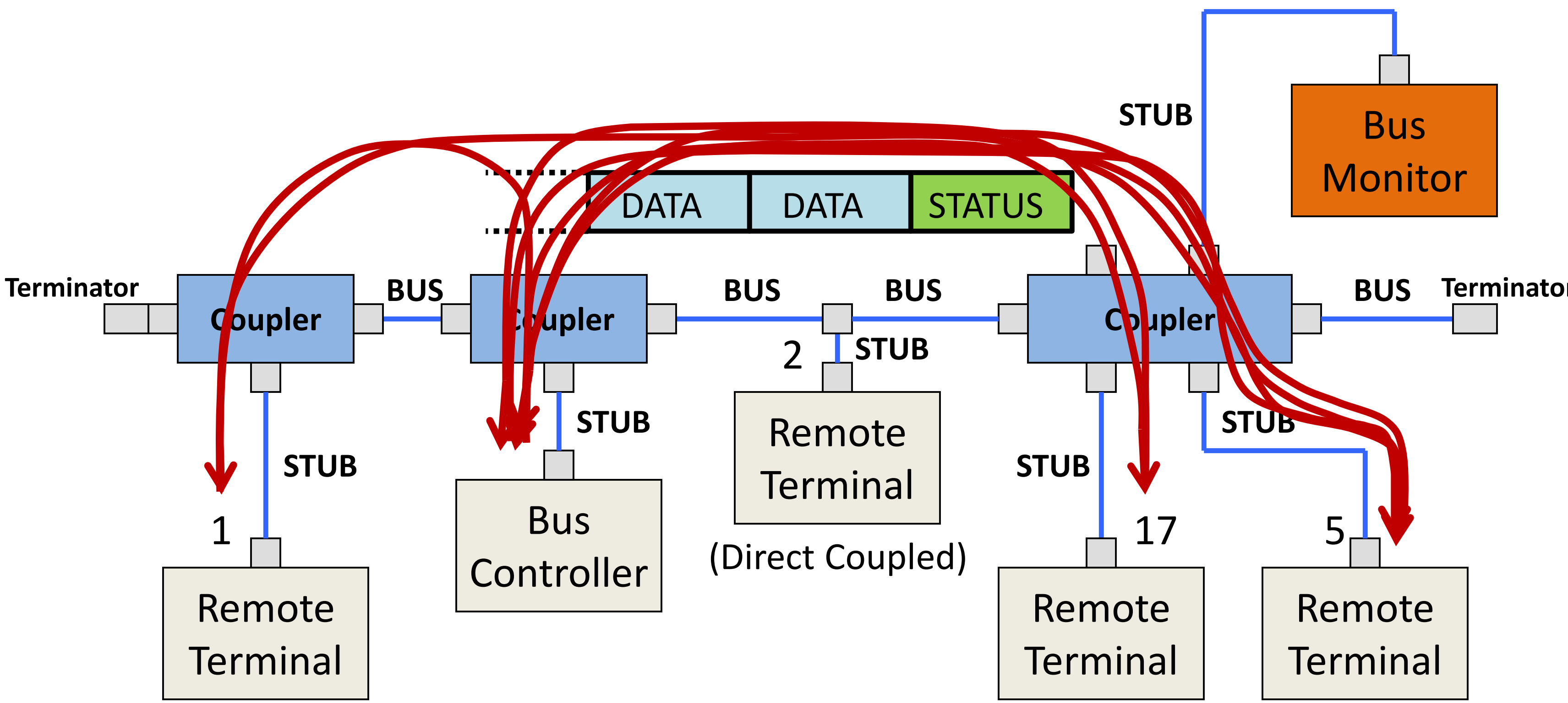
Message Transfer – RT to RT

- The RT to RT transfer allows data to be passed from one RT to another. The bus controller commands the receiving and transmitting RTs. The receive command always comes first.

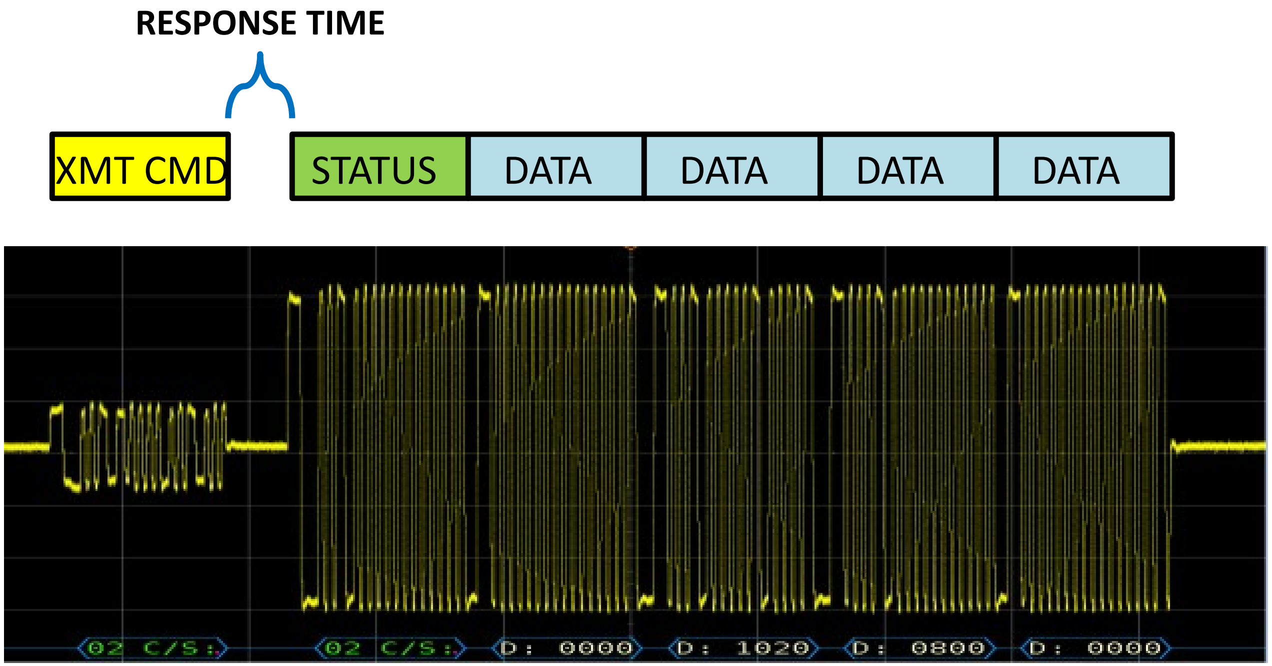


Bus Monitors and 1553 Messages

- As all the messages are being transmitted on the bus, the bus monitor is listening in. Depending upon the type of bus monitor, it may be only storing selected messages or all the messages.



Actual 1553 Waveform – RT to BC Transfer



Measured at the stub of the RT

1553 Bus Catalog

- The bus catalog is the decoder of all the messages and words being transmitted on the bus. Without it, the information will not have any meaning.

- Bus catalogs are generated by the aircraft manufacturer, the designer of the avionics or of a weapons system. Because there is no standard on how this information is conveyed, and it is provided by different sources, interpreting a bus catalog can be confusing.

- Sometimes you have to make a guess at what the information means. Therefore, the bus data must be verified at the aircraft to make sure your guess is correct.

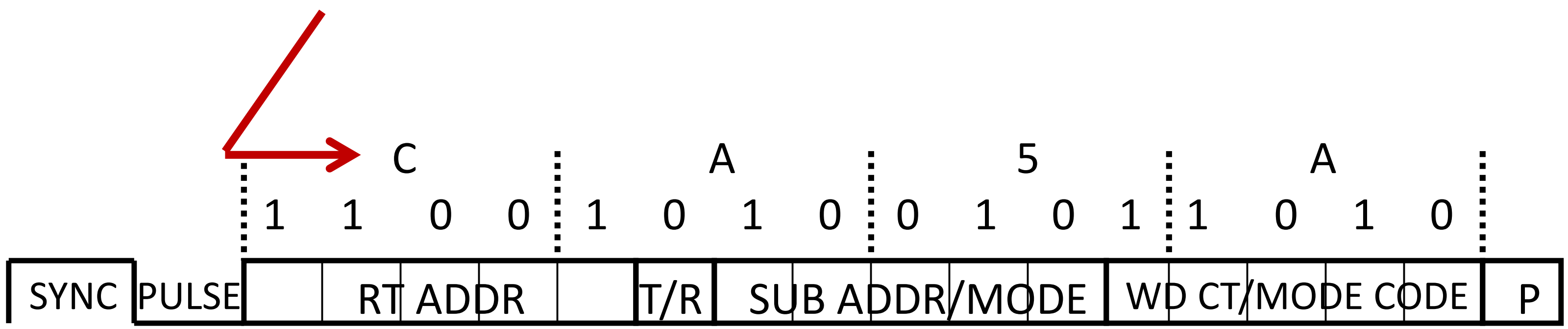
- The bus catalog must match the version of the software loaded in the aircraft. These loads are called Operational Flight Programs or OFPs.

- …and with any document, there can be errors in the information.

1553 Bus Catalog

- Information from the bus catalog is used to program the bus monitor of your data acquisition system.
- Bus monitors usually need the first command word information in order to identify the 1553 data word of interest.
- For this example, we want to capture the roll position 1553 word and convert to EUs.

BCWORD	RT NO	T/R	MSG NO	WD NO
CA5A	25	R	18	11



RT Number: 11001 = 25

T/R: 0 = receive command

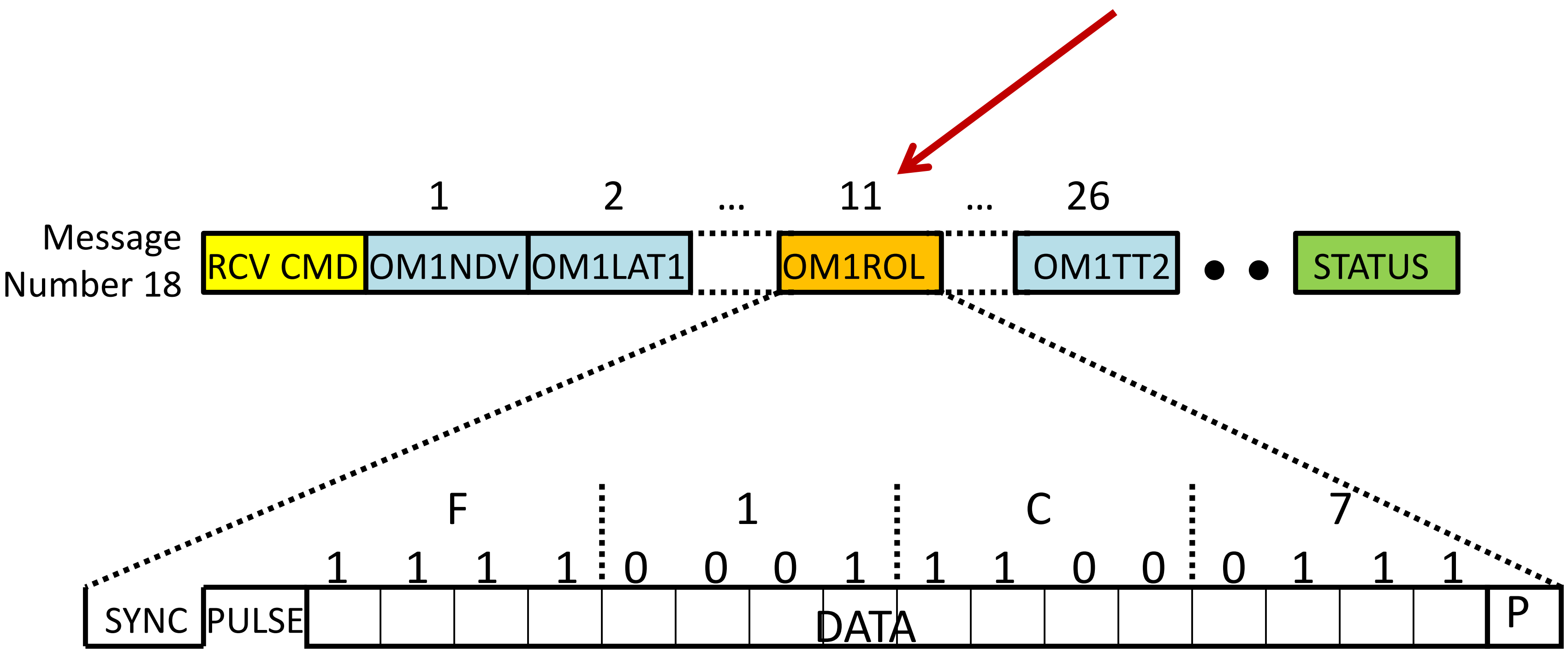
SUB ADDR (message number): 10010 = 18

Word Count: 11010 = 26

This information is used to program the bus monitor to capture the message.

1553 Bus Catalog

BCWORD	RT NO	T/R	MSG NO	WD NO
CA5A	25	R	18	11



1553 Bus Catalog

MSB	NO BITS	MSB VAL	CONV	EU	SRCE	DEST	RATE
00	16	180	2'S	DEG	MC	ALE-47	10

Using the above information, we can convert the data value of F1C7 in hexadecimal to the engineering unit value. This bus catalog specifies the MSB value. It is much easier if the LSB is given because that is equal to the C1 coefficient, but it can be calculated.

$$\mathrm{LSB} = \frac{\mathrm{MSB}}{2^{\mathrm{NOBITS\text{-}1}}} = \frac{180}{2^{16-1}} = \frac{180}{2^{15}} \frac{180}{32768} = 0.005493164 \text{ deg/count}$$

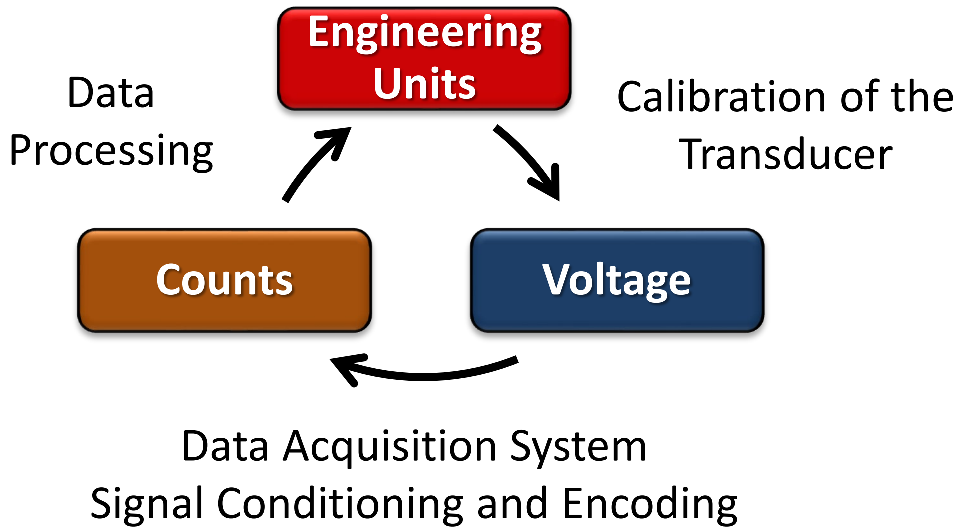
The data value is F1C7 for this example and has a two's complement conversion type.

F1C7 h = -3641 in decimal counts
EU = counts x C1
EU = -3641 counts x 0.005493164 deg/count = -20.00 degrees

Using Requirements to Configure an Analog Data Channel

Measurement Path

- Making a measurement on the aircraft and ultimately displaying the engineering unit result, follows path shown below. The diagram shows how the signal will transform from a physical measurement, to an analog voltage, digitized to a count value, then processed back into the resulting engineering units.



Measurement Example - Accelerometer

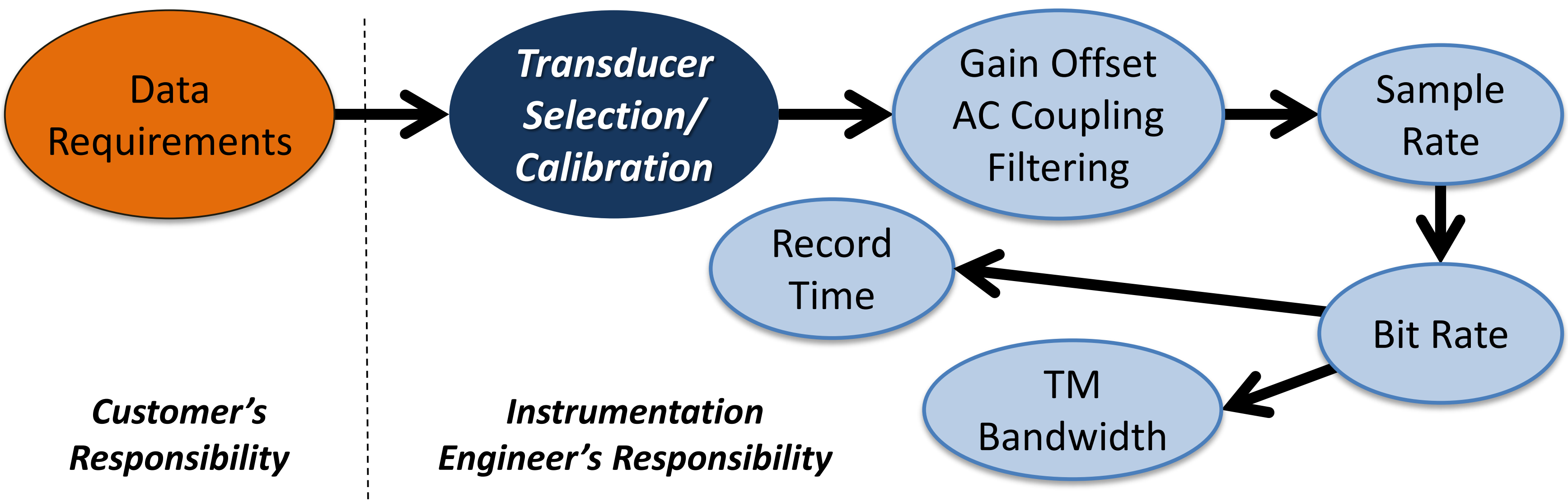
- To illustrate how the measurement requirements establish the design of a data channel in an instrumentation system, we will use an example of an acceleration measurement. This type of measurement covers many of the decisions made in a typical instrumentation system design.

Wing Brace Normal Acceleration
EU Range +/- 30 Gs
Frequency Range: 0 – 300 Hz
Required Measurement Uncertainty: ±3%

The data will be transmitted to a ground station and recorded onboard for up to 4-hours.

Transducer Selection

- From the description, the transducer type for this measurement is an accelerometer. The accelerometer type must have a range of ±30Gs, and have a flat frequency response that exceeds 300 Hz.



Transducer Selection

- Because of the relatively low G-level and frequency, a variable capacitance type accelerometer will be a good choice for this measurement.

Dynamic characteristics	Units	7290A-2	-10	-30	-50	-100	-150
Range [1]	g	±2	±10	±30	±50	±100	±150
Sensitivity	mV/g	1000 ±50	200 ±10	66 ±4	40 ±2	20 ±1	3.2 ±0.66
Frequency response (± 5%) [2]	Hz	0 to 15	0 to 500	0 to 800	0 to 1000	0 to 1000	0 to 1000
Mounted resonance frequency	Hz	1300	3000	5500	6000	6000	6000
Non-linearity and hysteresis	% FSO typ (max)	±0.20 (±0.50)	±0.20 (±0.50)	±0.20 (±0.50)	±0.20 (±0.50)	±1 (±2)	±1 (±2)
Transverse sensitivity [3]	% (max)	2	2	2	2	2	2
Zero measurand output	mV	±50	±50	±50	±50	±50	±50
Damping ratio		4.0	0.7	0.7	0.6	0.6	0.6
Damping ratio change							
From -65°F to +250°F (-55°C to +121°C)	%/°C	+0.08	+0.08	+0.08	+0.08	+0.08	+0.08
Thermal zero shift (max)							
From 32°F to 122°F (0°C to 50°C)	% FSO [4]	±1.0	±1.0	±1.0	±1.0	±1.0	±1.0
From -13°F to +167°F (-25°C to +75°C)	% FSO	±2.0	±2.0	±2.0	±2.0	±2.0	±2.0
Thermal sensitivity shift (max)							
From 32°F to 122°F (0°C to +50°C)	%	±2.0	±2.0	±2.0	±2.0	±2.0	±2.0
From -13°F to +167°F (-25°C to +75°C)	%	±3.0	±3.0	±3.0	±3.0	±3.0	±3.0
Thermal transient error per ISA RP 37.2	Equiv. g/°C	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001
Overrange (determined by electrical clipping or mechanical stops, whichever is smaller.)							
Electrical clipping	g	-3.5/+3.8	-18/+19	-53/+57	-87/+95	-175/+190	-265/+288
Mechanical stops, typical	g	±4	±30	±90	±90	±150	±300
Recovery time	μs	< 10	< 10	< 10	< 10	< 10	< 10
Threshold (resolution) [5]	Equiv. g's	0.0005	0.0025	0.0075	0.013	0.013	0.013
Base strain sensitivity, max	Equiv. g's	0.01	0.01	0.01	0.01	0.01	0.01
Magnetic susceptibility (@ 100 gauss, 60 Hz)	Equiv. g's	< 0.1	< 0.1	< 0.1	< 0.1	< 0.1	< 0.1
Warm-up time (to within 1%)	ms	1	1	1	1	1	1

Transducer Specification

Dynamic characteristics	Units	-30
Range [1]	g	±30
Sensitivity	mV/g	66 ±4
Frequency response (± 5%) [2]	Hz	0 to 800
Mounted resonance frequency	Hz	5500
Non-linearity and hysteresis	% FSO typ (max)	±0.20 (±0.50)
Transverse sensitivity [3]	% (max)	2
Zero measurand output	mV	±50
Damping ratio		0.7
Damping ratio change		
From -65°F to +250°F (-55°C to +121°C)	%/°C	+0.08
Thermal zero shift (max)		
From 32°F to 122°F (0°C to 50°C)	% FSO [4]	±1.0
From -13°F to +167°F (-25°C to +75°C)	% FSO	±2.0
Thermal sensitivity shift (max)		
From 32°F to 122°F (0°C to +50°C)	%	±2.0
From -13°F to +167°F (-25°C to +75°C)	%	±3.0
Thermal transient error per ISA RP 37.2	Equiv. g/°C	‹ 0.001
Overrange (determined by electrical clipping or mechanical stops,		
Electrical clipping	g	-53/+57
Mechanical stops, typical	g	±90
Recovery time	µs	‹ 10
Threshold (resolution) [5]	Equiv. g's	0.0075
Base strain sensitivity, max	Equiv. g's	0.01
Magnetic susceptibility (@ 100 gauss, 60 Hz)	Equiv. g's	‹ 0.1
Warm-up time (to within 1%)	ms	1

Major considerations:

EU Range met

Sensitivity will determine the output voltage range

Frequency Response within ±5% error over the band from 0 to 800 Hz – need to verify via calibration what it is between 0 to 300 Hz.

Temperature specs need to be reviewed as this is the bulk of the error from this accelerometer. If mounted externally on an aircraft, it will experience a wide temperature range.

Transducer Calibration

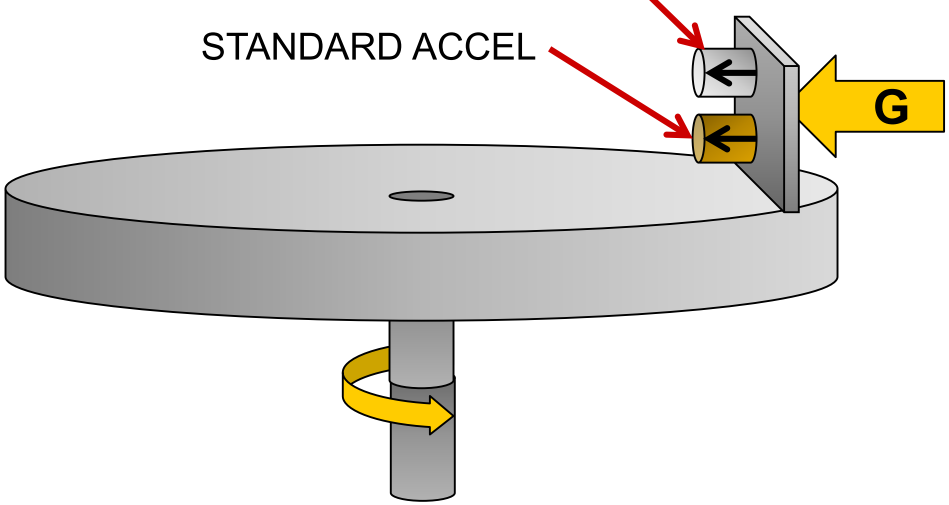
- The transducer is then sent to a calibration lab to verify that it meets the vendor's specifications, to better define its frequency response in the frequency range of interest, and to generate point pairs (G level, voltage output) so the data channel on the instrumentation system can be calibrated.
- This cannot be done until the requirements of the measurement are well defined.

Centrifuge

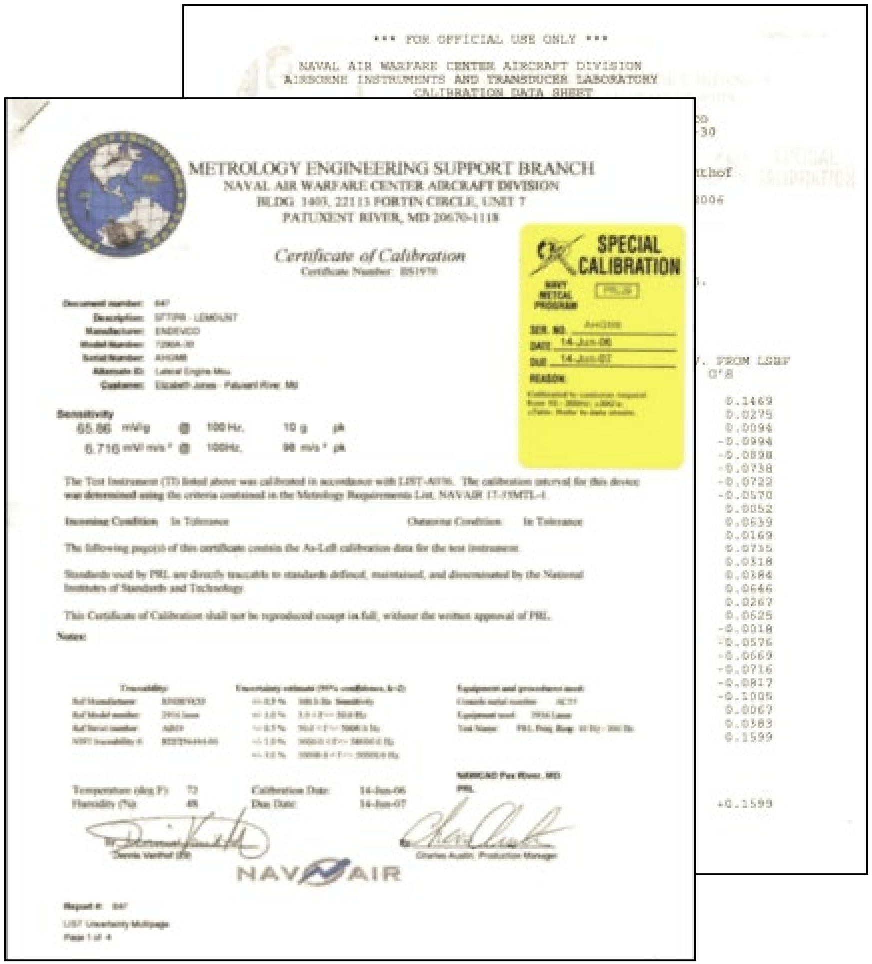
Shaker

Transducer Calibration

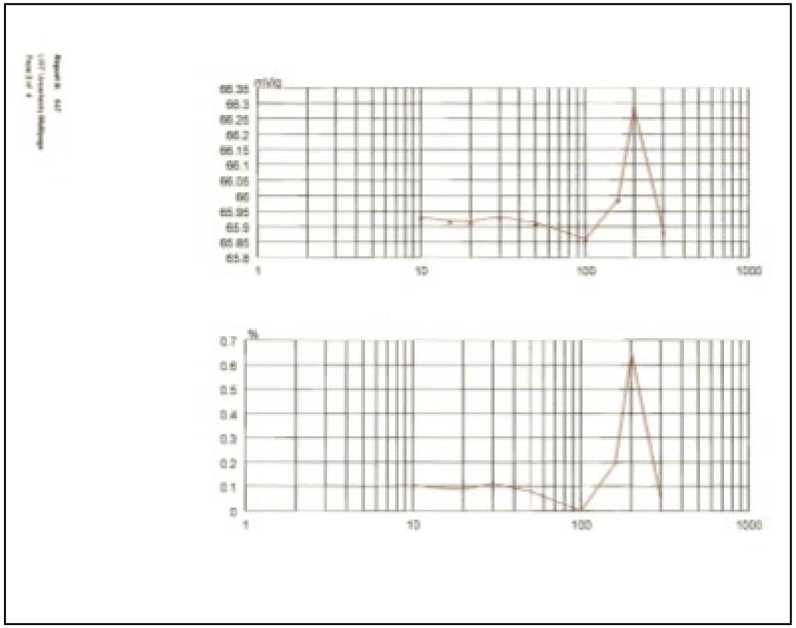
- The accelerometer is calibrated by placing it in a centrifuge. The centrifuge spins at different speeds until the desired G-level is achieved. The standard accelerometer provides the actual G-level being produced. The standard is many times more accurate than the accelerometer under calibration and is calibrated at NIST (National Institute of Standards and Technology).



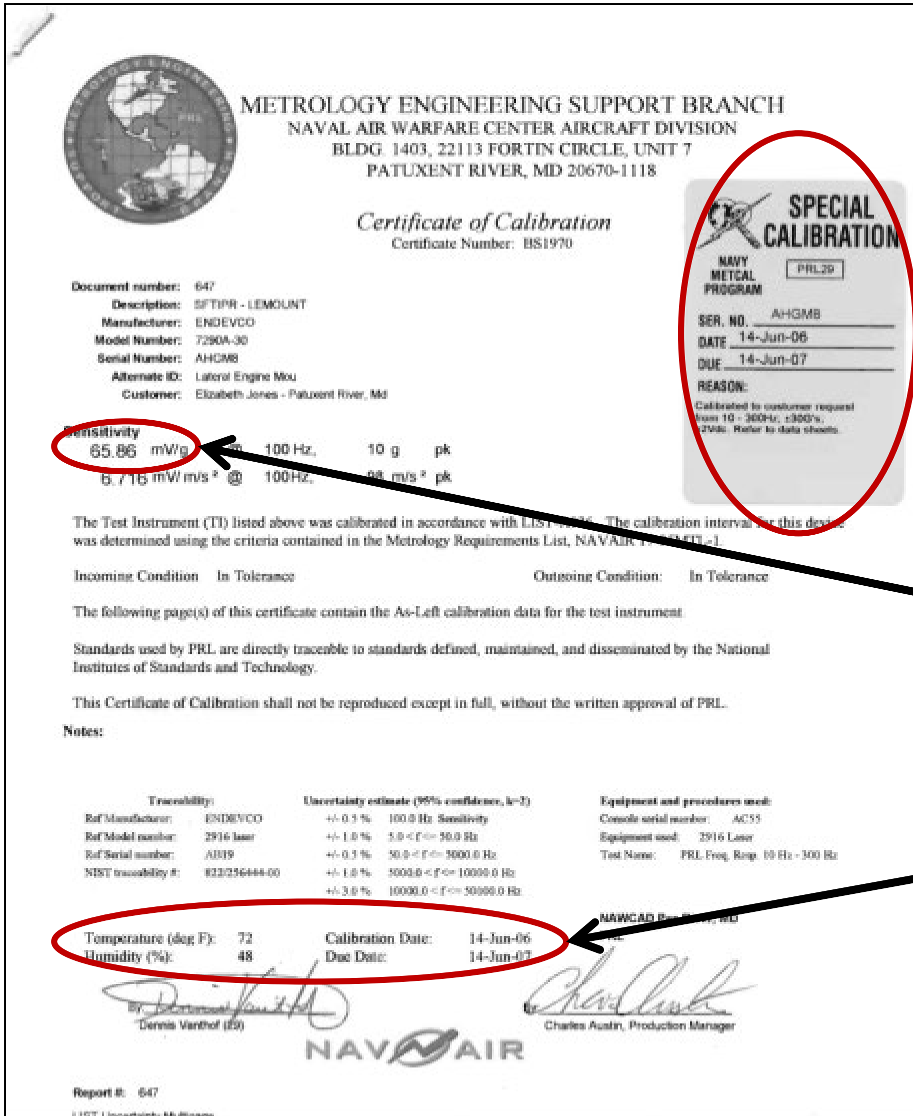
Transducer Certificate of Calibration



- A Certificate of Calibration should be provided with each transducer. This paperwork will be used later on in the process when the data channel is calibrated on the aircraft.



Transducer Certificate of Calibration



METROLOGY ENGINEERING SUPPORT BRANCH
NAVAL AIR WARFARE CENTER AIRCRAFT DIVISION
BLDG. 1403, 22113 FORTIN CIRCLE, UNIT 7
PATUXENT RIVER, MD 20670-1118

Certificate of Calibration
Certificate Number: BS1970

SPECIAL CALIBRATION
NAVY METCAL PROGRAM
PRL29
SER. NO. AHGM8
DATE 14-Jun-06
DUE 14-Jun-07
REASON:
Calibrated to customer request from 10 - 300Hz, ±300's, 12Vdc. Refer to data sheets.

Document number: 647
Description: SFTIPR - LEMOUNT
Manufacturer: ENDEVCO
Model Number: 7290A-30
Serial Number: AHGM8
Alternate ID: Lateral Engine Mou
Customer: Elizabeth Jones - Patuxent River, Md

Sensitivity
65.86 mV/g @ 100 Hz, 10 g pk
6.716 mV/ m/s² @ 100Hz, 98 m/s² pk

The Test Instrument (TI) listed above was calibrated in accordance with LIST-... The calibration interval for this device was determined using the criteria contained in the Metrology Requirements List, NAVAIR 17-...MTL-1.

Incoming Condition In Tolerance Outgoing Condition: In Tolerance

The following page(s) of this certificate contain the As-Left calibration data for the test instrument.

Standards used by PRL are directly traceable to standards defined, maintained, and disseminated by the National Institutes of Standards and Technology.

This Certificate of Calibration shall not be reproduced except in full, without the written approval of PRL.

Notes:

Traceability:		Uncertainty estimate (95% confidence, k=2)		Equipment and procedures used:	
Ref Manufacturer:	ENDEVCO	+/- 0.5 %	100.0 Hz Sensitivity	Console serial number:	AC55
Ref Model number:	2916 laser	+/- 1.0 %	5.0 < f <= 50.0 Hz	Equipment used:	2916 Laser
Ref Serial number:	AB19	+/- 0.5 %	50.0 < f <= 5000.0 Hz	Test Name:	PRL Freq. Resp. 10 Hz - 300 Hz
NIST traceability #:	822/256444-00	+/- 1.0 %	5000.0 < f <= 10000.0 Hz		
		+/- 3.0 %	10000.0 < f <= 50000.0 Hz		

Temperature (deg F): 72 Calibration Date: 14-Jun-06
Humidity (%): 48 Due Date: 14-Jun-07

NAWCAD Pax River, MD

By: Dennis Vanthof (E9)

Charles Austin, Production Manager

NAVAIR

Report #: 647
LIST Uncertainty Multipage

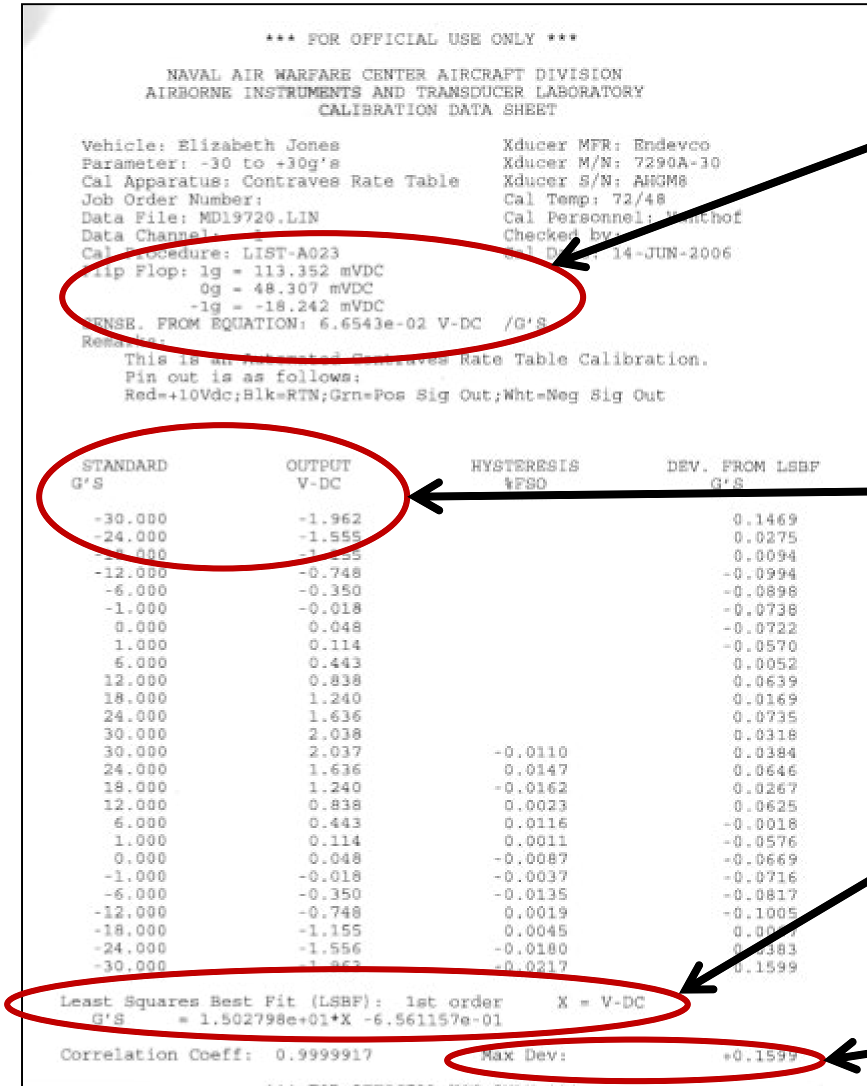
Some things to note on the certificate of calibration:

This was a special calibration because only 0-300 Hz of the bandwidth was checked (instead of the full 500 Hz).

Sensitivity
65.86 mV/g @ 100 Hz, 10 g pk

Temperature (deg F):	72	Calibration Date:	14-Jun-06
Humidity (%):	48	Due Date:	14-Jun-07

Transducer Certificate of Calibration



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NAVAL AIR WARFARE CENTER AIRCRAFT DIVISION
AIRBORNE INSTRUMENTS AND TRANSDUCER LABORATORY
CALIBRATION DATA SHEET

Vehicle: Elizabeth Jones
Parameter: -30 to +30g's
Cal Apparatus: Contraves Rate Table
Job Order Number:
Data File: MD19720.LIN
Data Channel: 1
Cal Procedure: LIST-A023
Flip Flop: 1g = 113.352 mVDC
0g = 48.307 mVDC
-1g = -18.242 mVDC
SENSE. FROM EQUATION: 6.6543e-02 V-DC /G'S
Remarks:
This is an Automated Contraves Rate Table Calibration.
Pin out is as follows:
Red=+10Vdc;Blk=RTN;Grn=Pos Sig Out;Wht=Neg Sig Out

Xducer MFR: Endevco
Xducer M/N: 7290A-30
Xducer S/N: AHGM8
Cal Temp: 72/48
Cal Personnel: Wanthof
Checked by:
Cal Date: 14-JUN-2006

STANDARD G'S	OUTPUT V-DC	HYSTERESIS %FSO	DEV. FROM LSBF G'S
-30.000	-1.962		0.1469
-24.000	-1.555		0.0275
-18.000	-1.155		0.0094
-12.000	-0.748		-0.0994
-6.000	-0.350		-0.0898
-1.000	-0.018		-0.0738
0.000	0.048		-0.0722
1.000	0.114		-0.0570
6.000	0.443		0.0052
12.000	0.838		0.0639
18.000	1.240		0.0169
24.000	1.636		0.0735
30.000	2.038		0.0318
30.000	2.037	-0.0110	0.0384
24.000	1.636	0.0147	0.0646
18.000	1.240	-0.0162	0.0267
12.000	0.838	0.0023	0.0625
6.000	0.443	0.0116	-0.0018
1.000	0.114	0.0011	-0.0576
0.000	0.048	-0.0087	-0.0669
-1.000	-0.018	-0.0037	-0.0716
-6.000	-0.350	-0.0135	-0.0817
-12.000	-0.748	0.0019	-0.1005
-18.000	-1.155	0.0045	[illegible]
-24.000	-1.556	-0.0180	0.0383
-30.000	-1.963	-0.0217	0.1599

Least Squares Best Fit (LSBF): 1st order X = V-DC
G'S = 1.502798e+01*X -6.561157e-01

Correlation Coeff: 0.9999917 Max Dev: +0.1599

*** FOR OFFICIAL USE ONLY ***

Flip Flop: 1g = 113.352 mVDC
0g = 48.307 mVDC
-1g = -18.242 mVDC
SENSE. FROM EQUATION: 6.6543e-02 V-DC /G'S
Remarks:

STANDARD G'S	OUTPUT V-DC
-30.000	-1.962
-24.000	-1.555
-18.000	-1.155
-12.000	-0.748
-6.000	-0.350
-1.000	-0.018
0.000	0.048

Least Squares Best Fit (LSBF): 1st order X = V-DC
G'S = 1.502798e+01*X -6.561157e-01

Max Dev: +0.1599

Transducer Certificate of Calibration

*** FOR OFFICIAL USE ONLY ***

NAVAL AIR WARFARE CENTER AIRCRAFT DIVISION
AIRBORNE INSTRUMENTS AND TRANSDUCER LABORATORY
CALIBRATION DATA SHEET

Vehicle: Elizabeth Jones
Parameter: -30 to +30g's
Cal Apparatus: Contraves Rate Table
Job Order Number:
Data File: MD19720.LIN
Data Channel: 1
Cal Procedure: LIST-A023
Flip Flop: 1g = 113.352 mVDC
0g = 48.307 mVDC
-1g = -18.242 mVDC
SENSE. FROM EQUATION: 6.6543e-02 V-DC /G'S

Xducer MFR: Endevco
Xducer M/N: 7290A-30
Xducer S/N: AHGM8
Cal Temp: 72/48
Cal Personnel: Vanthof
Checked by:
Cal Date: 14-JUN-2006

Remarks:
This is an Automated Contraves Rate Table Calibration.
Pin out is as follows:
Red=+10Vdc;Blk=RTN;Grn=Pos Sig Out;Wht=Neg Sig Out

STANDARD G'S	OUTPUT V-DC	HYSTERESIS %FSO	DEV. FROM LSBF G'S
-30.000	-1.962		0.1469
-24.000	-1.555		0.0275
-18.000	-1.155		0.0094
-12.000	-0.748		-0.0994
-6.000	-0.350		-0.0898
-1.000	-0.018		-0.0738
0.000	0.048		-0.0722
1.000	0.114		-0.0570
6.000	0.443		0.0052
12.000	0.838		0.0639
18.000	1.240		0.0169
24.000	1.636		0.0735
30.000	2.038		0.0318
30.000	2.037	-0.0110	0.0384
24.000	1.636	0.0147	0.0646
18.000	1.240	-0.0162	0.0267
12.000	0.838	0.0023	0.0625
6.000	0.443	0.0116	-0.0018
1.000	0.114	0.0011	-0.0576
0.000	0.048	-0.0087	-0.0669
-1.000	-0.018	-0.0037	-0.0716
-6.000	-0.350	-0.0135	-0.0817
-12.000	-0.748	0.0019	-0.1005
-18.000	-1.155	0.0045	0.0067
-24.000	-1.556	-0.0180	0.0383
-30.000	-1.963	-0.0217	0.1599

Least Squares Best Fit (LSBF): 1st order X = V-DC
G'S = 1.502798e+01*X -6.561157e-01

Correlation Coeff: 0.9999917 Max Dev: +0.1599

*** FOR OFFICIAL USE ONLY ***

DEV. FROM LSBF G'S
0.1469
0.0275
0.0094
-0.0994
-0.0898
-0.0738
-0.0722
-0.0570
0.0052
0.0639
0.0169

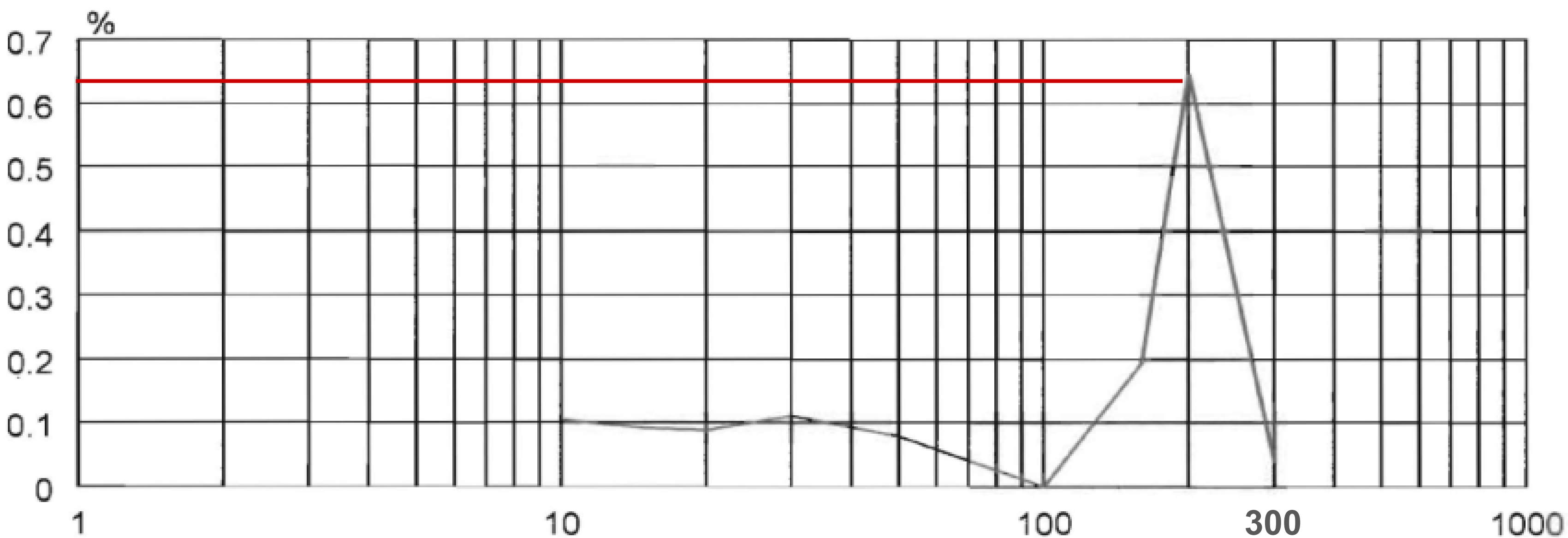
HYSTERESIS %FSO
-0.0110
0.0147
-0.0162
0.0023
0.0116
0.0011
-0.0087
-0.0037
-0.0135
0.0019
0.0045
-0.0180
-0.0217

Transducer Certificate of Calibration

- Frequency sweep from 10 to 300 Hz

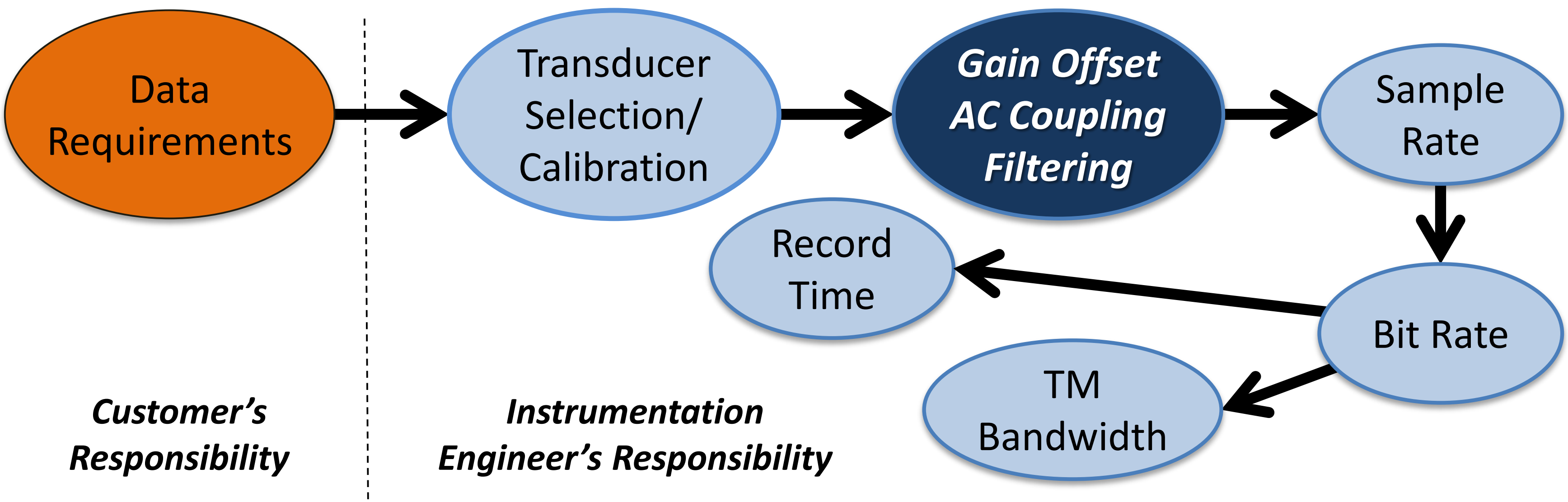
Frequency (Hz)	Applied Acceleration (pk g)	Sensitivity (pk mV/ pk g)	Sensitivity ($mV/m/sec^2$)	Deviation (%)	Actual Uncertainty (%)	Expected Uncertainty (%)
10	2.016945	65.9282	6.72281	0.10	0.03	1
15	3.025343	65.9196	6.72193	0.09	0.07	1
20	8.018447	65.9177	6.72174	0.09	0.12	1
30	9.982308	65.9324	6.72324	0.11	0.03	1
50	10.01372	65.9115	6.72110	0.08	0.11	0.5
100	10.02237	65.8595	6.71580	0.00	0.42	0.5
159	9.903729	65.9872	6.72882	0.19	0.37	0.5
200	9.988359	66.2860	6.75929	0.65	0.30	0.5
300	9.951986	65.8852	6.71842	0.04	0.06	0.5

Error in the sensitivity (referenced to the response @100 Hz) which illustrates the frequency response – max error is approximately 0.63% at 200 Hz.
Note this is well within the 5% specified from 0 to 500 Hz.



Gain, Offset, AC Coupling, and Filtering

- Next the analog signal from the transducer must be conditioned before it is sampled and digitized in the analog to digital converter (ADC). These settings are dependent upon the measurement requirements.



Gain and Offset

- The voltage output from the transducer is indicated in the Certificate of Calibration point pairs. The maximum and minimum voltages are noted to the right.

STANDARD G'S	OUTPUT V-DC
-30.000	-1.962
-24.000	-1.555
-18.000	-1.155
-12.000	-0.748
-6.000	-0.350
-1.000	-0.018
0.000	0.048
1.000	0.114
6.000	0.443
12.000	0.838
18.000	1.240
24.000	1.636
30.000	2.038
30.000	2.037
24.000	1.636
18.000	1.240
12.000	0.838
6.000	0.443
1.000	0.114
0.000	0.048
-1.000	-0.018
-6.000	-0.350
-12.000	-0.748
-18.000	-1.155
-24.000	-1.556
-30.000	-1.963

max voltage = 2.038v

min voltage = -1.963v

Gain

- Usually you have multiple transducers of a single type, and it is good practice to keep the gains consistent across the channels.
- If we have multiple transducers of similar type calibrations, the input voltage range may be set to -2.1v to +2.1v to cover all of the calibration voltage ranges. This will include our calibration voltage range of -1.963v to 2.038v.
- The input to the data system's analog to digital converter (ADC) is ±5v. The required gain can be calculated to be:

$$Gain = \frac{V_{OutputRange}}{V_{InputRange}} = \frac{5V - (-5V)}{2.1V - (-2.1V)} = \frac{10V}{4.2V} = 2.38$$

- The reason for the consistency is to notice when a gain is incorrect. It is easier to spot a gain that is not 2.38 when the gains are all the same. This is just an engineering tradeoff for the small decrease in channel resolution.

Offset

- The offset for the calibration is:

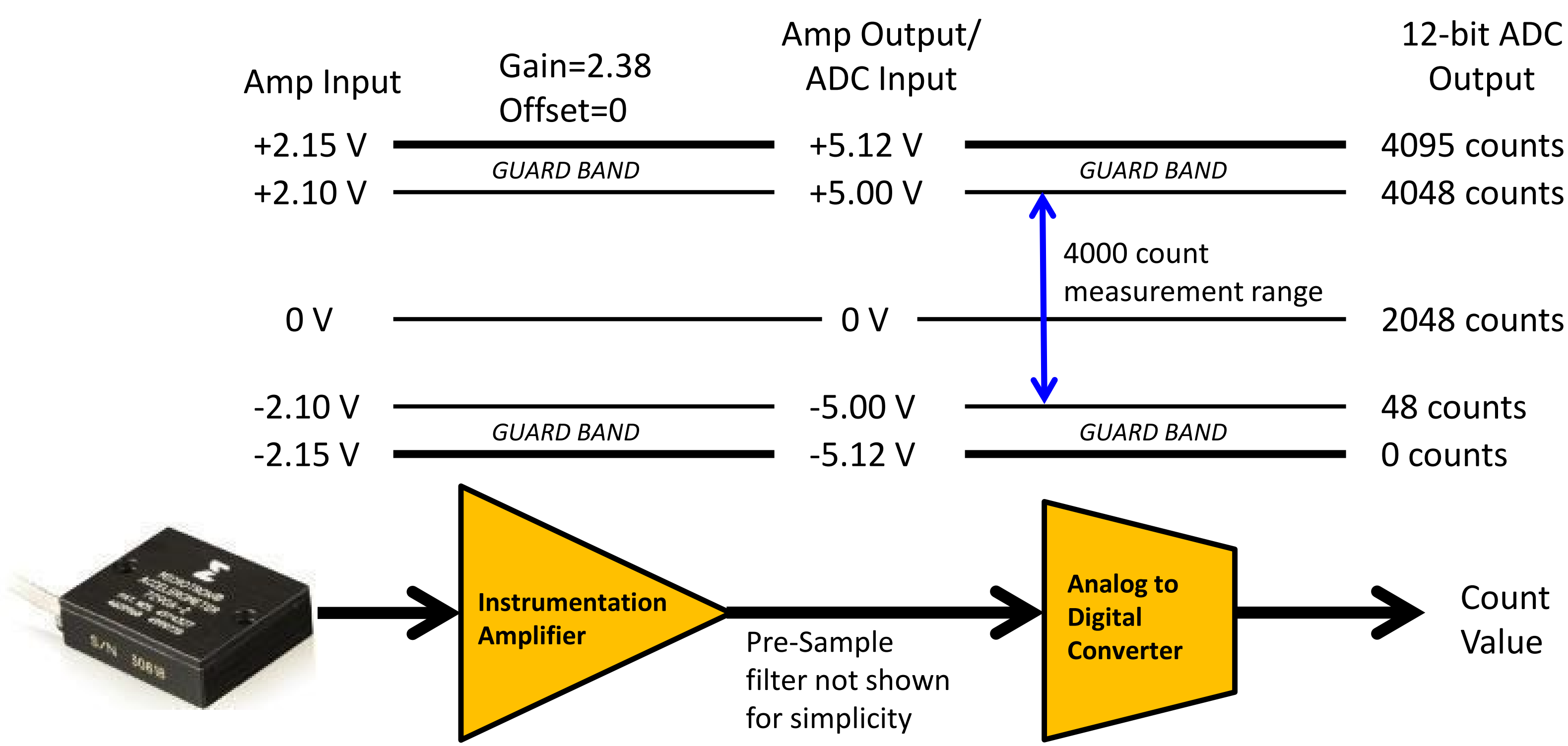
$$V_{offset} = \frac{1}{2}\left(V_{upper} + V_{lower}\right)$$

$$V_{offset} = \frac{1}{2}\left(2.038V + (-1.963V)\right) = \frac{1}{2}(0.075V) = 0.0375V$$

- Again, to stay consistent in our offset settings across multiple data channels, we will use a 0V offset.
- Most offsets of these types of accelerometers will be within ±50mV according to the specification sheets.

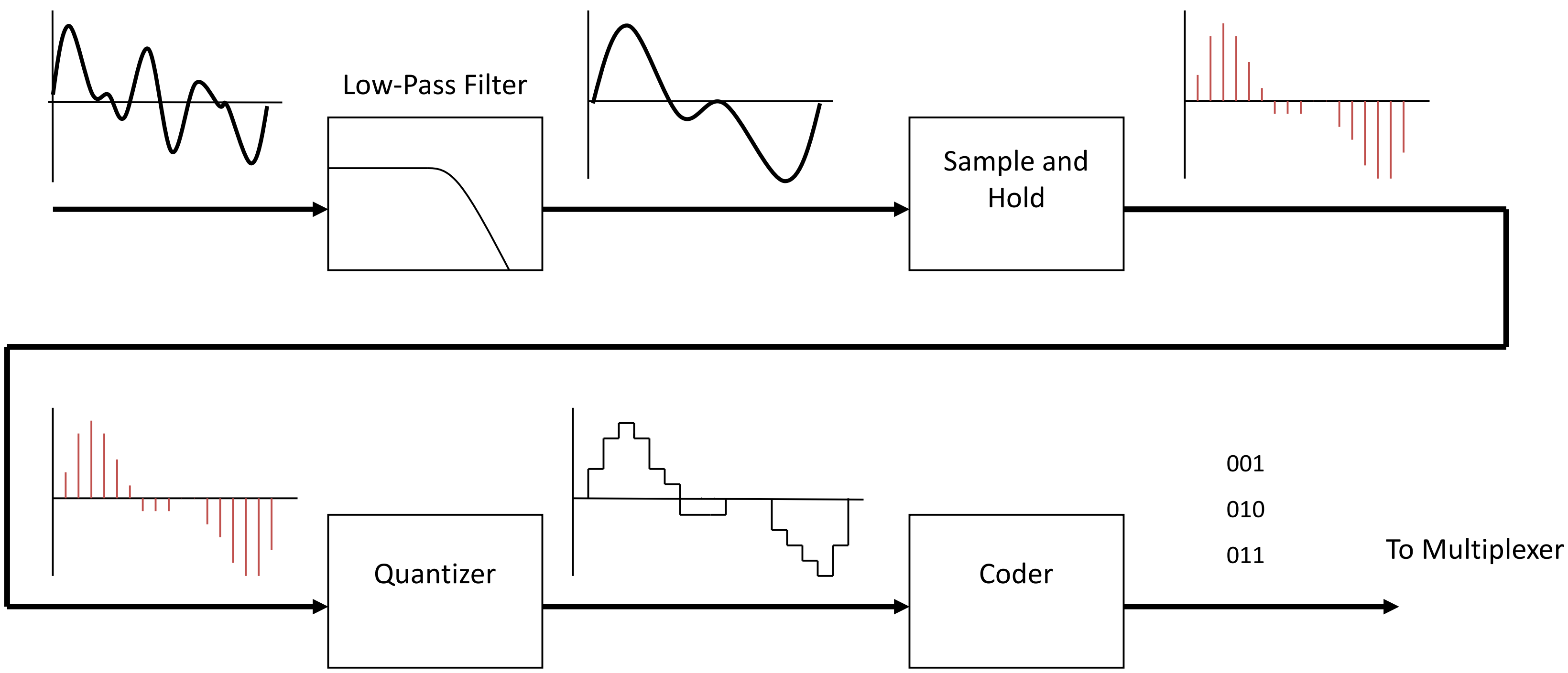
Gain and Offset

- When the ADC digitizes the ±5 V range, it allows for another 0.05 V of room (guard band) in the encoding range. This is to ensure that if the measurement does exceed the maximum value by a small amount, the data is not lost. Count values of 0 and 4095 do not convey any information other than you are outside of the measurement range.



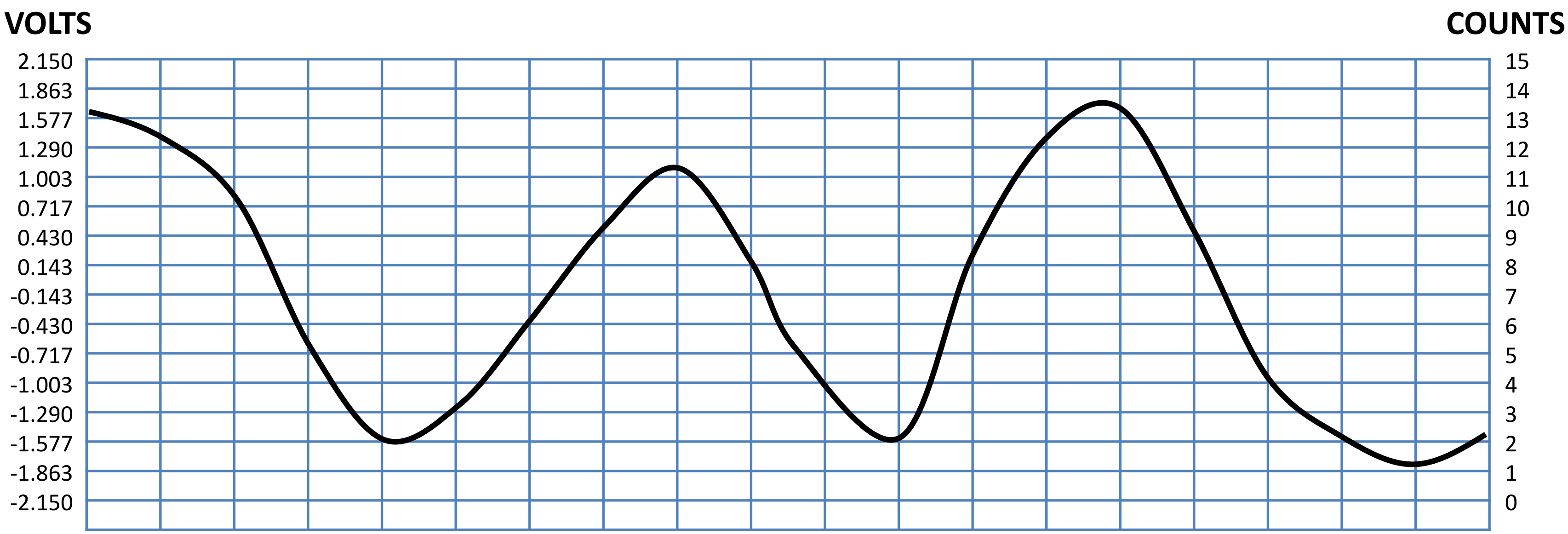
Sampling and Digitizing Process

- This next section describes the process of how the measurement's signal is digitized.
- This illustrates the sampling that was just described which results in the count values in the calibration process. The low-pass filter will be discussed later.



Encoding Voltages to Counts in the ADC

- Below is an illustration of how the voltage from the accelerometer is encoded in the ADC. For simplicity, we will use a 4-bit ADC, which covers count values from 0 to 15.



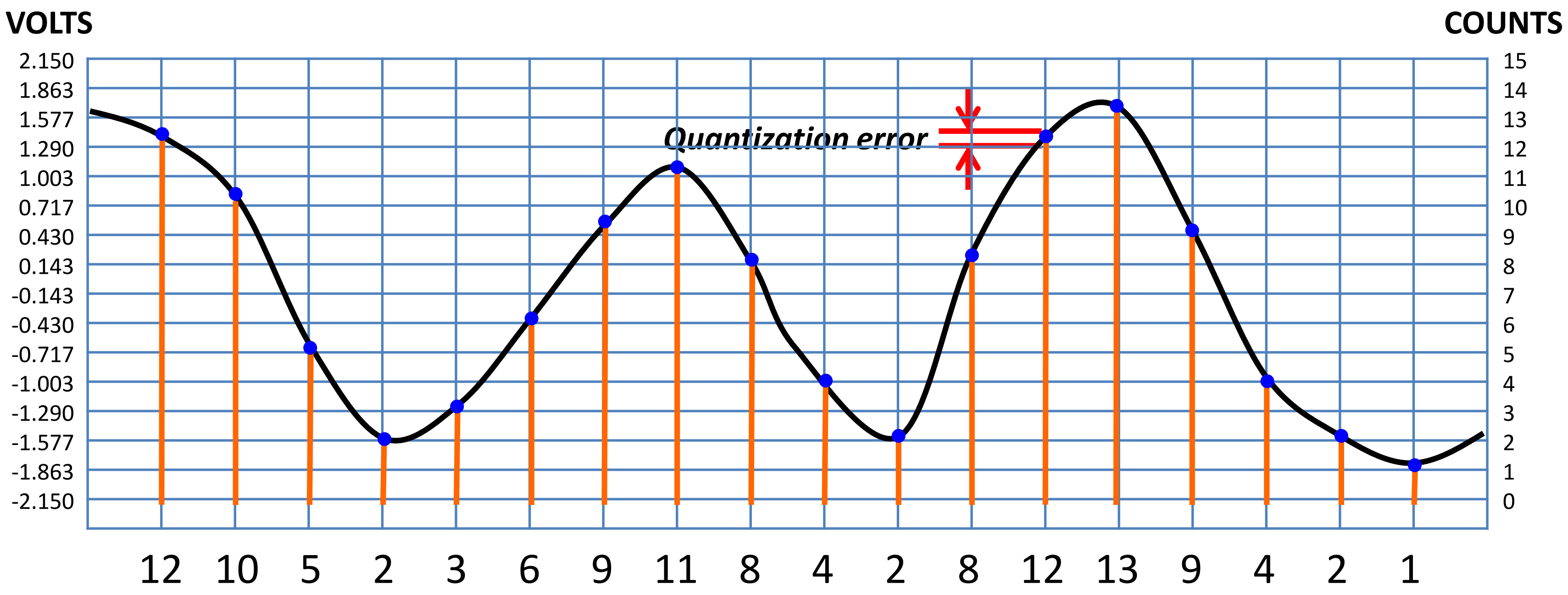
The voltage resolution is determined

$$Resolution = \frac{voltage\ range}{count\ range} = \frac{2.15 - (-2.15)\ volts}{15\ counts} = 0.287\frac{volts}{count}$$

For a 12-bit ADC (0 to 4095 counts), the resolution is approximately 0.001 V/count

Encoding Voltages to Counts in the ADC

- When the signal is sampled, each sample is given the count value of the threshold that is exceeded. As you can see, there is an error that can be as high as the resolution of the channel called the quantization error. This error contributes to the overall error of the system.

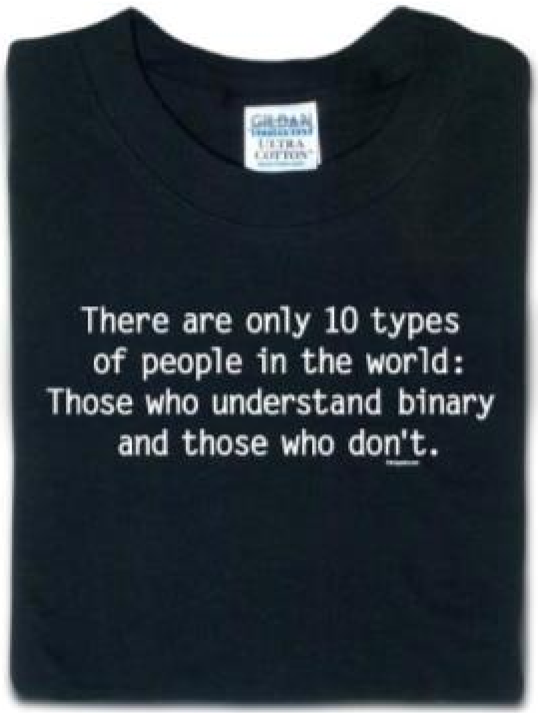


This is where the term Pulse Code Modulation comes from.
The pulses shown in orange are coded to a count value

Numbering Systems – Binary, 2's Complement, and Hexadecimal

- In order for the count values to be transmitted and stored onto a solid state media, they are converted into a pattern of ones and zeros. There are several numbering systems used to do this, but binary and 2's complement are the systems used most often. Many 1553 parameters are encoded in 2's complement.

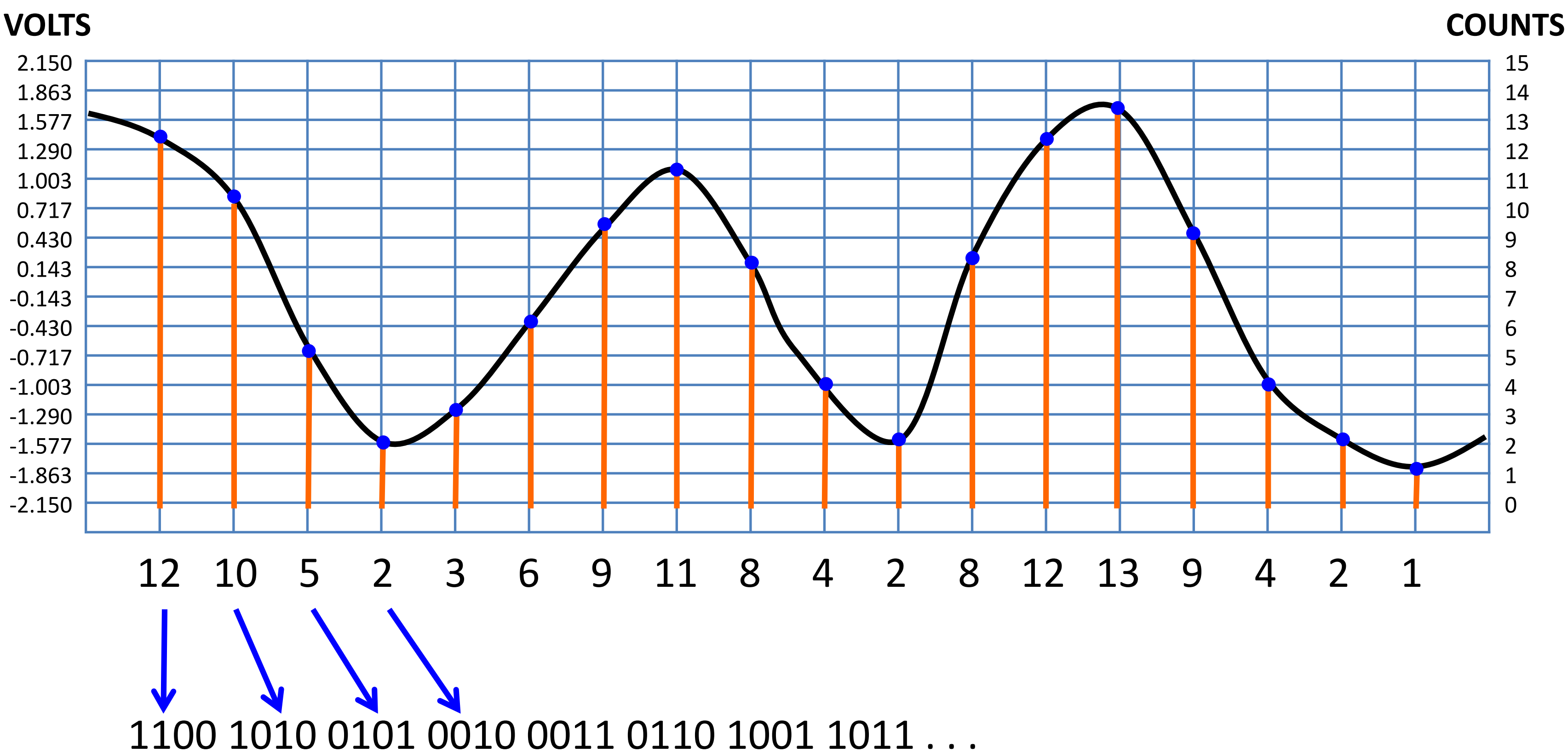
Decimal	Binary	Hex
15	1111	F
14	1110	E
13	1101	D
12	1100	C
11	1011	B
10	1010	A
9	1001	9
8	1000	8
7	0111	7
6	0110	6
5	0101	5
4	0100	4
3	0011	3
2	0010	2
1	0001	1
0	0000	0



Decimal	2's Comp	Hex
7	0111	7
6	0110	6
5	0101	5
4	0100	4
3	0011	3
2	0010	2
1	0001	1
0	0000	0
-1	1111	F
-2	1110	E
-3	1101	D
-4	1100	C
-5	1011	B
-6	1010	A
-7	1001	9
-8	1000	8

Converting Decimal Counts to Binary

- Each of the count values are then encoded to the appropriate numbering scheme. For a majority of analog measurements, binary is used.



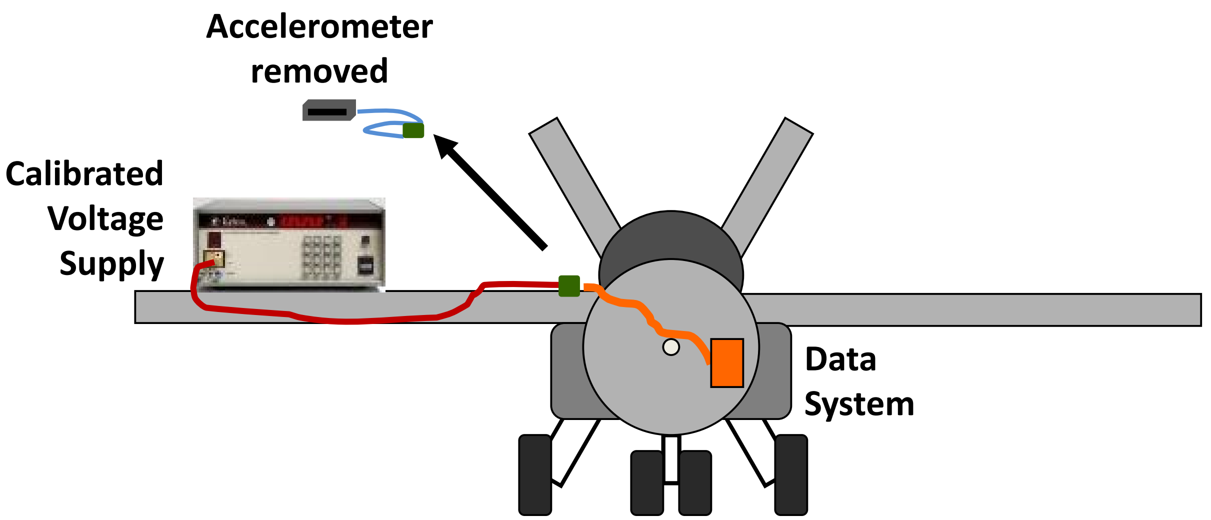
Obtaining the Counts to EU Relationship

- To obtain the counts to engineering unit relationship, an end-to end calibration is performed to the data channel on the aircraft.

- There are three types of end-to-end calibrations:
  - Exciting the transducer
  - Simulating an engineering unit
  - Voltage substitution

Obtaining the Counts to EU Relationship

- To obtain the engineering unit to count relationship for the accelerometer, a voltage substitution calibration is done to the data channel. This end-to-end calibration is done on the aircraft. A calibrated voltage supply is used to simulate the G-level of the accelerometer

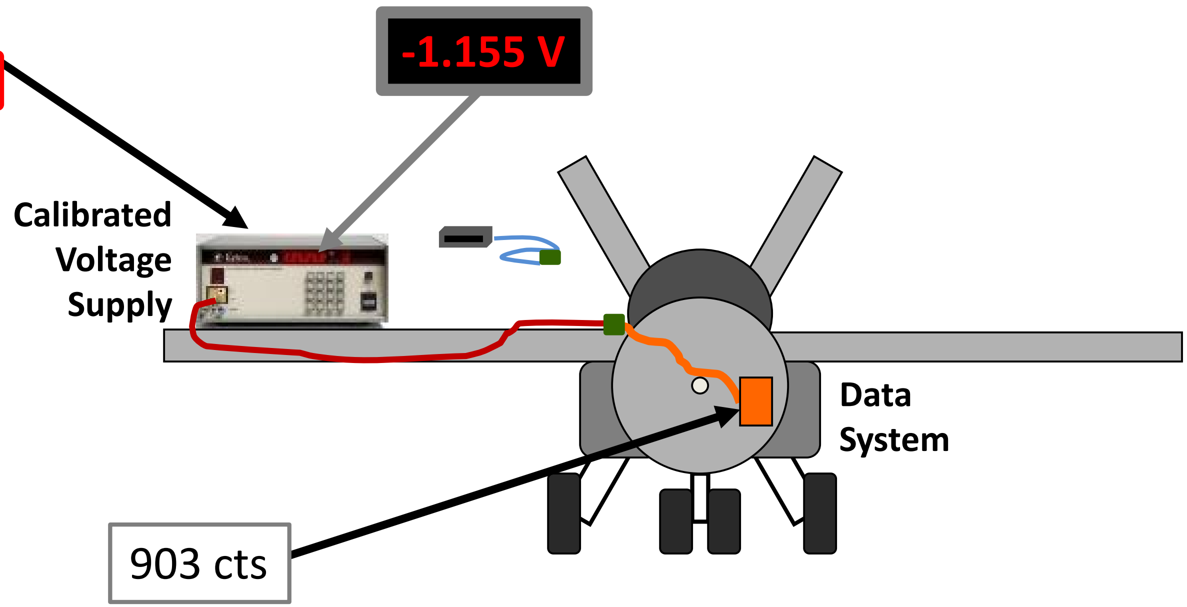


Obtaining the Counts to EU Relationship

- Each voltage from the calibrated G level from the lab calibration sheet is simulated through the wiring and data acquisition system. Up to 1000 samples are averaged and paired to the associated acceleration. This produces an (EU, count) point pair. This example shows (-18G, 903 counts).

STANDARD G'S	OUTPUT V-DC
-30.000	-1.962
-24.000	-1.555
-18.000	-1.155
[illegible]	[illegible]
-6.000	-0.350
-1.000	-0.018
0.000	0.048
1.000	0.114
6.000	0.443
12.000	0.838
18.000	1.240
24.000	1.636
30.000	2.038

-18G corresponds to 903 counts



Obtaining the Counts to EU Relationship

- This image shows position calibration of the collective stick on a helicopter. Counts are being related to percent full throw in the calibration.

Obtaining the Counts to EU Relationship

- For the calibration of the lateral stick position on the helicopter, a calibrated inclinometer is placed on the stick. Note the yellow calibration sticker which is confirmed to be valid before performing the calibration.

Obtaining the Counts to EU Relationship

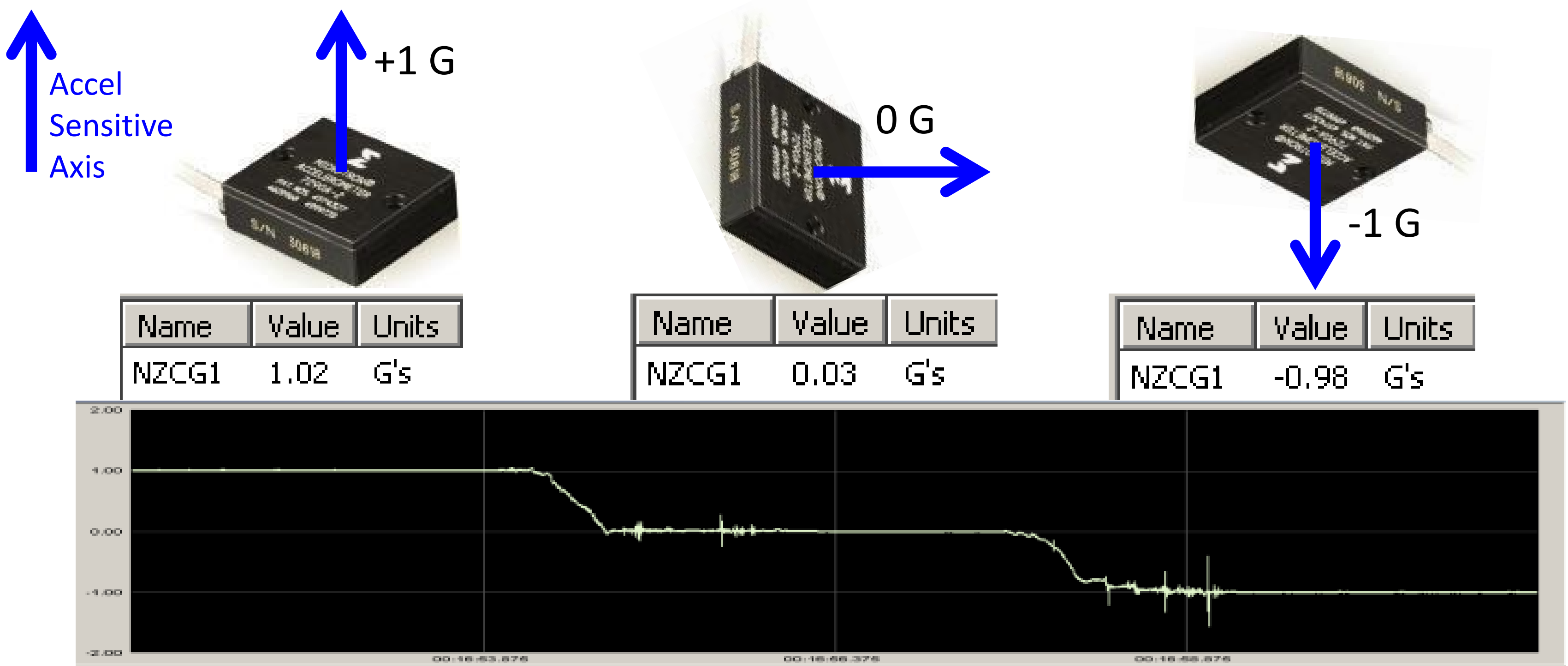
- After collecting all the point pairs for the accelerometer, they are reviewed for any anomalies by observing the statistical data collected. The standard deviation is an indication on how noisy the channel is, or if the voltage drifted during the capturing of the count samples.

Point Pair Values

N	Sub	EU	COUNTS	AC Type	Std Dev	Weighting
1	-1.9340000	-30.000000	130	N/A	1.4893680	0.4508120
2	-1.5390000	-24.000000	522	N/A	1.4268970	0.4911500
3	-1.1550000	-18.000000	903	N/A	1.4553760	0.4721170
4	-0.8000000	-12.000000	1255	N/A	1.4940660	0.4479820
5	-0.4016000	-6.0000000	1650	N/A	1.4342440	0.4861310
6	-0.1990000	-3.0000000	1850	N/A	1.4380780	0.4835430
7	0.0140000	0.0000000	2034	N/A	1.4588110	0.4698970
8	0.1960000	3.0000000	2242	N/A	1.4096050	0.5032750
9	0.4230000	6.0000000	2467	N/A	1.4598390	0.4692340
10	0.8080000	12.000000	2849	N/A	1.4085400	0.5040360
11	1.1720000	18.000000	3210	N/A	1.5044150	0.4418400
12	1.5970000	24.000000	3631	N/A	1.4846560	0.4536780

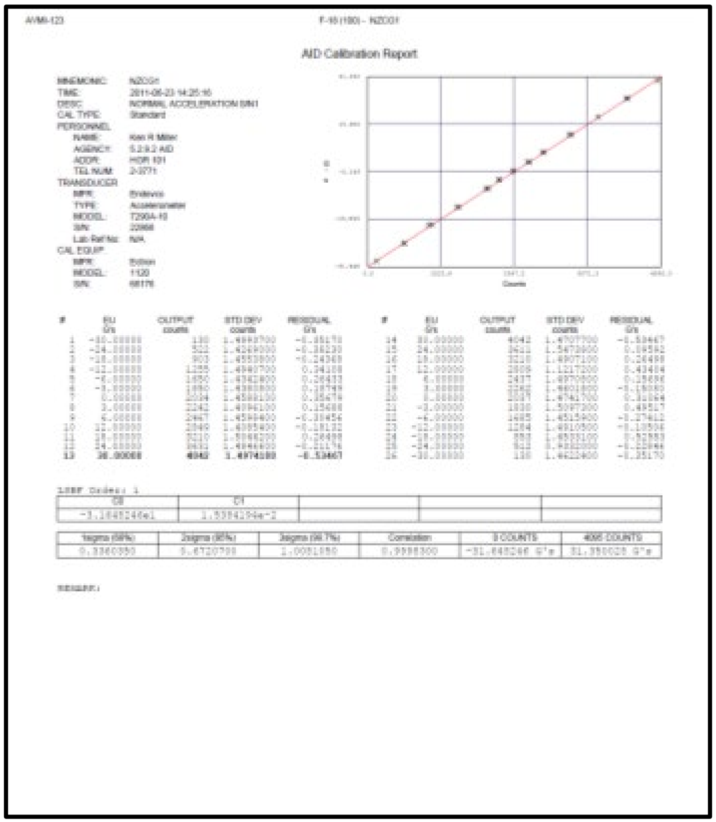
Validating the Counts to EU Relationship

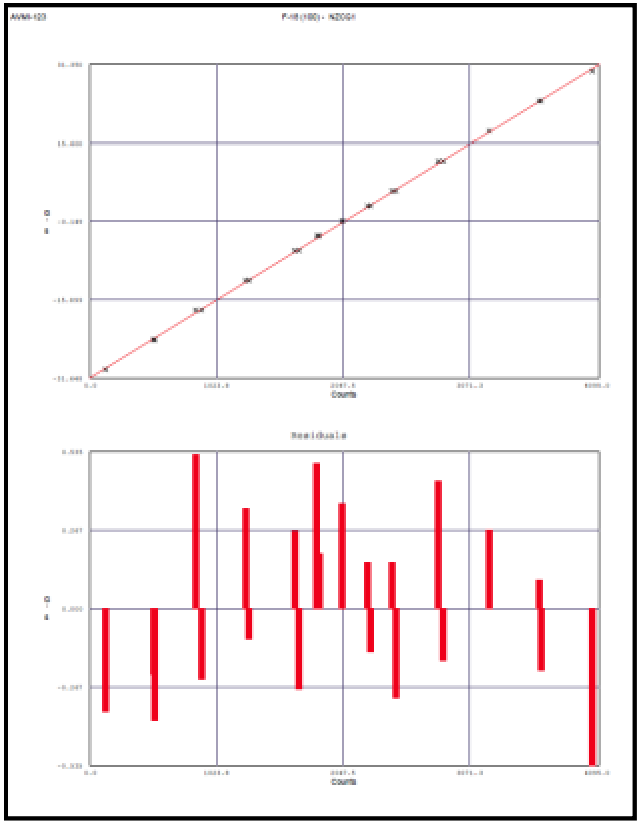
- To validate the measurement after calibration, one or more EU values are simulated. For an accelerometer, the best way to validate the measurement is to do a "flip-flop". The accelerometer is reconnected to the data system and the results should be within the 3σ number indicated on the calibration sheet. For example, 3σ = 1.0081050.



Measurement Calibration Certificate

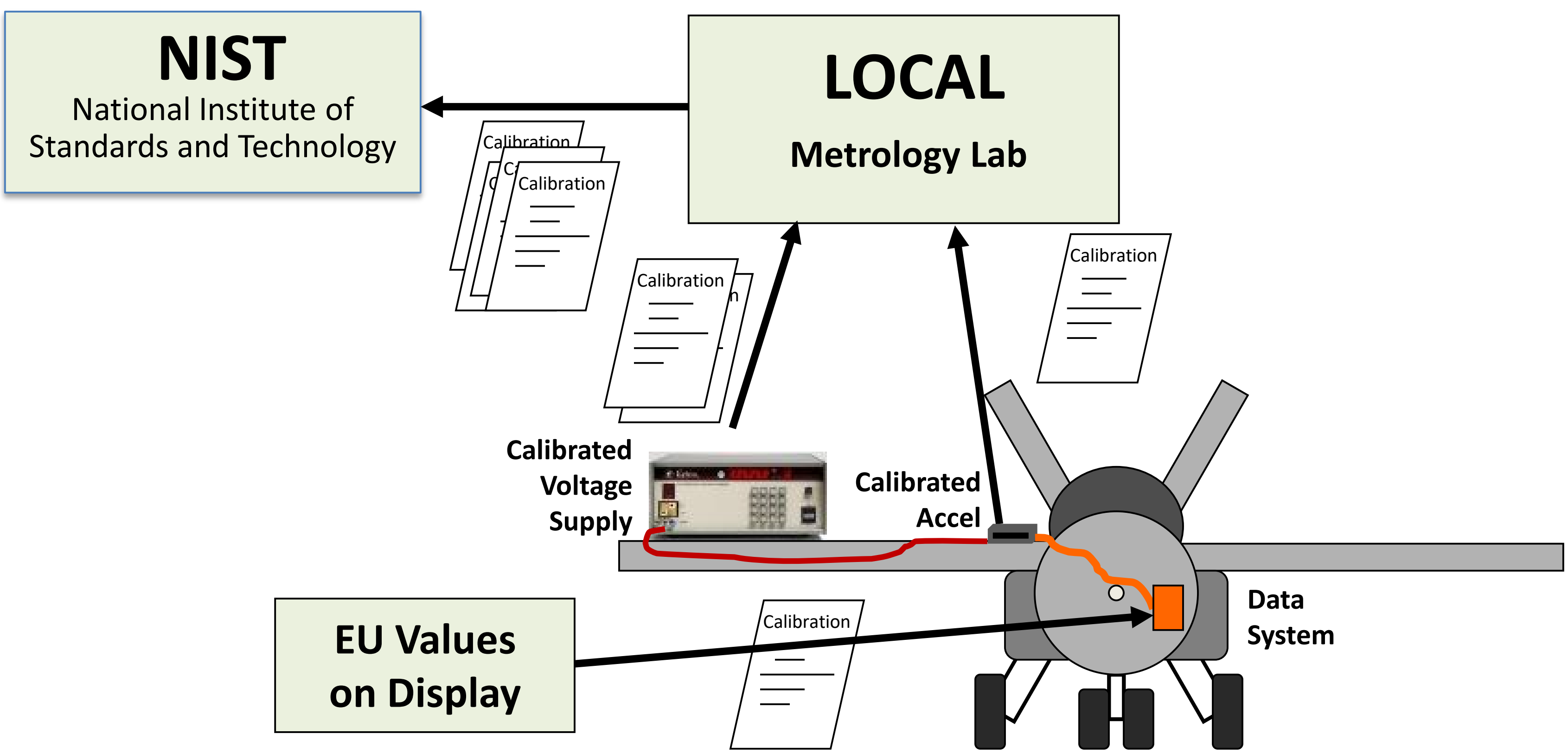
- Once validated, a calibration certificate for the measurement data channel must be created. It becomes part of the paperwork trail that will trace the data back to a standards laboratory.





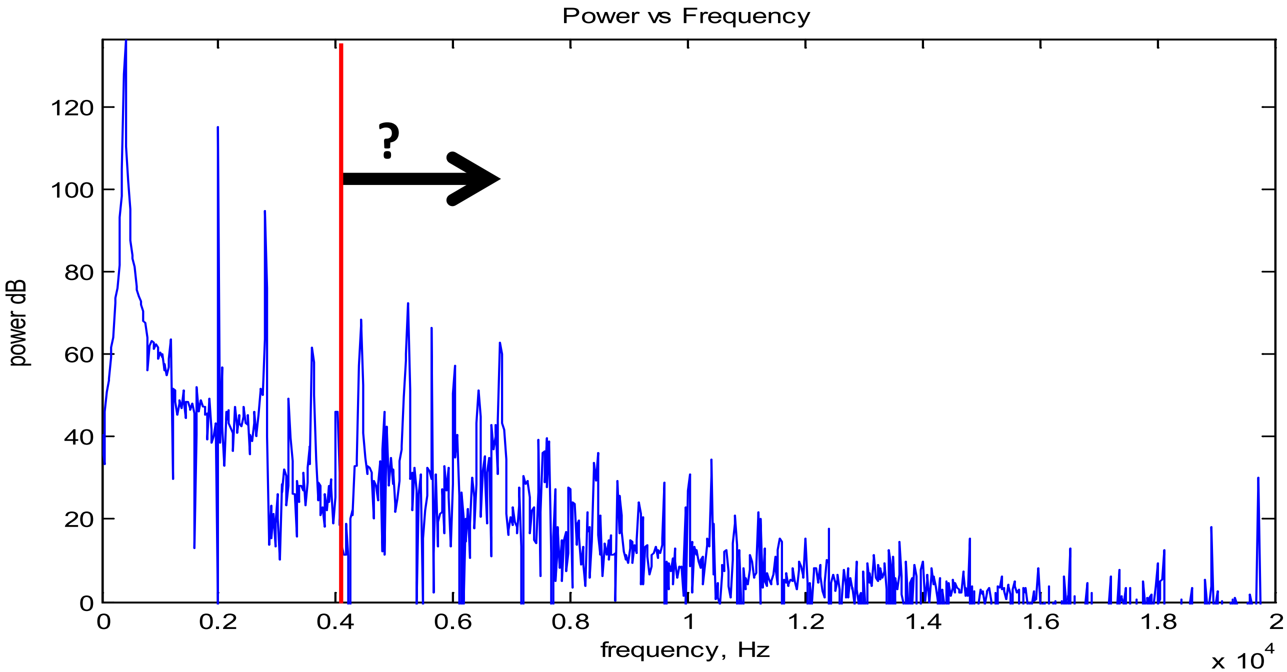
Traceability of the Engineering Units to a Standard

- In order for you to be able to trace the EU values back to a standards laboratory, all the paperwork shown below must be in place. A break in the chain, nullifies that traceability.



Pre Sample Filtering

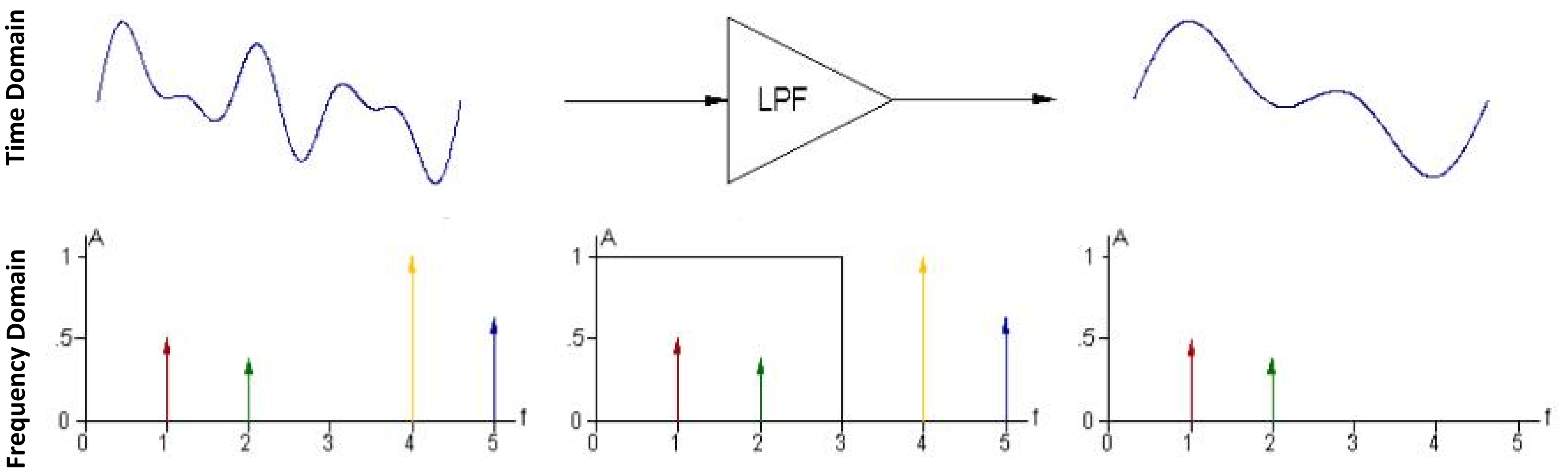
- An analog signal cannot be sampled unless it is first band-limited – meaning that there is a definable maximum frequency that exists.



If you only are interested in frequencies below 4 KHz, can it be guaranteed that no frequencies exist above 4KHz? To be sure, you must band limit the signal.

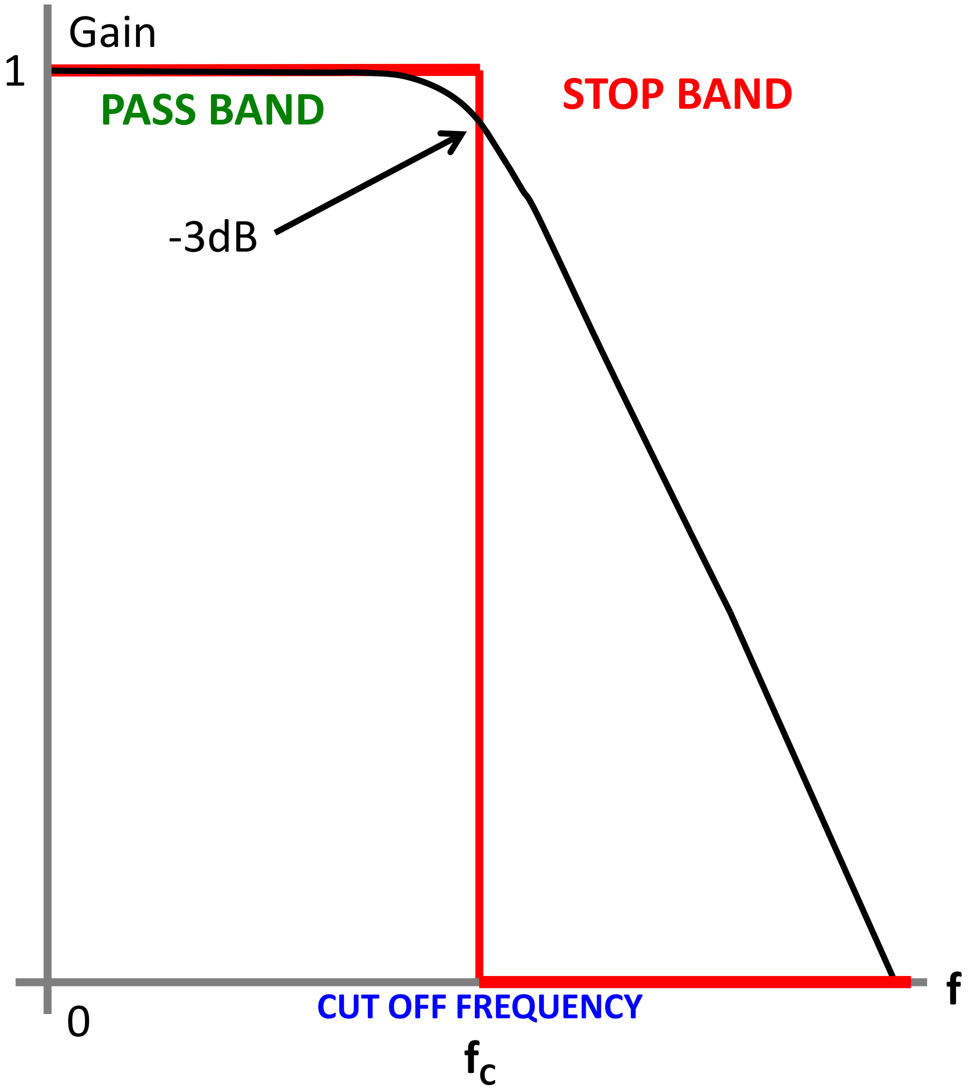
Pre Sample Filtering

- To band limit the signal, a low-pass filter is used. A low-pass filter passes low frequencies and rejects high frequencies. The diagram below shows an ideal filter's affect on a signal containing four frequencies of 1, 2, 4, and 5 Hz.



This example shows a signal band-limited to 2 Hz. No frequencies exist above 2 Hz after filtering the signal. ***The object of pre-sample filtering is to attenuate unwanted frequency components such that they no longer contribute to the signal.***

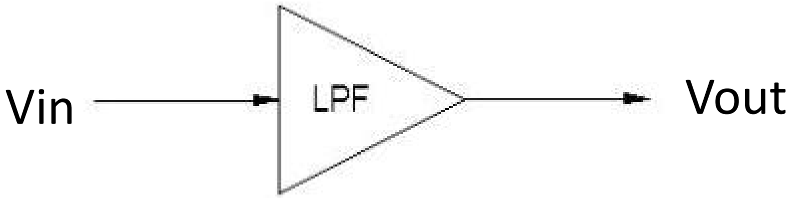
Pre Sample Filtering



- Unfortunately, filters are not ideal (shown as the red line).
- Realized filters (black line) do not have a flat response in the pass band and do not have a vertical drop at the cut off frequency, where the gain is always -3dB (70.7%).
- Because the data is located in the pass band, we are careful that the data is not affected by the changing gain.

Filter Gain

- Filter gains are normally expressed in decibels (dB), it also can be expressed as a percentage when relating it to error in a measurement.



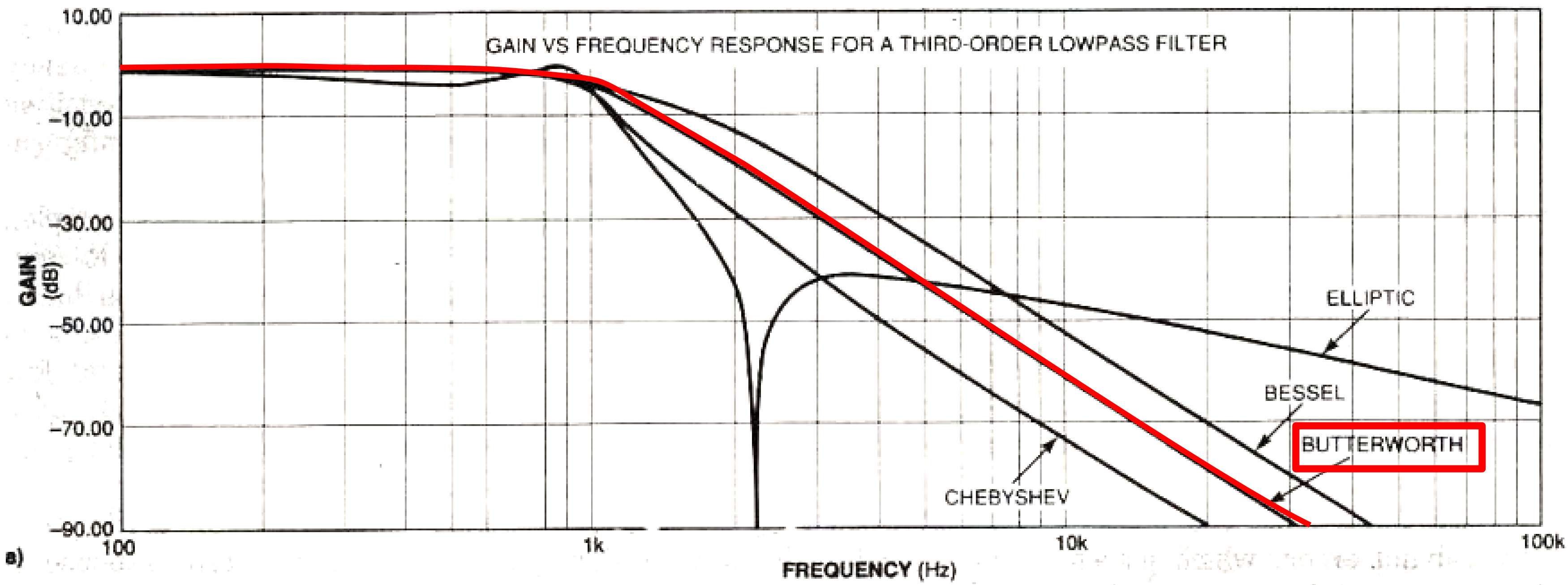
$$dB = 20log\left(\frac{Vout}{Vin}\right)$$

$$\% = 100\left(\frac{Vout}{Vin}\right)$$

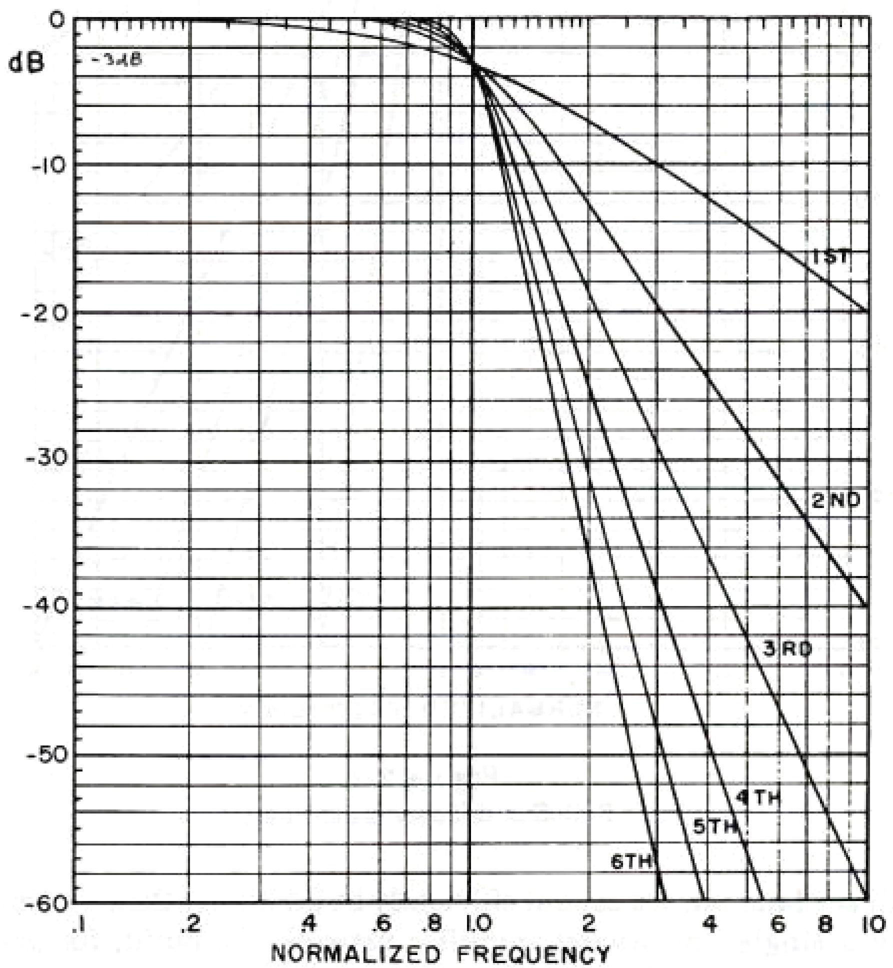
Later in the training when we discuss losses in power of telemetry systems, you will see a slightly different equation. We will discuss the differences then.

Pre Sample Filtering

- The Butterworth implementation of a low-pass filter has the best characteristics for filtering data over other filter types.
  - Maximally flat in the pass band
  - Closely approximates an ideal filter
  - Introduces lower phase distortion



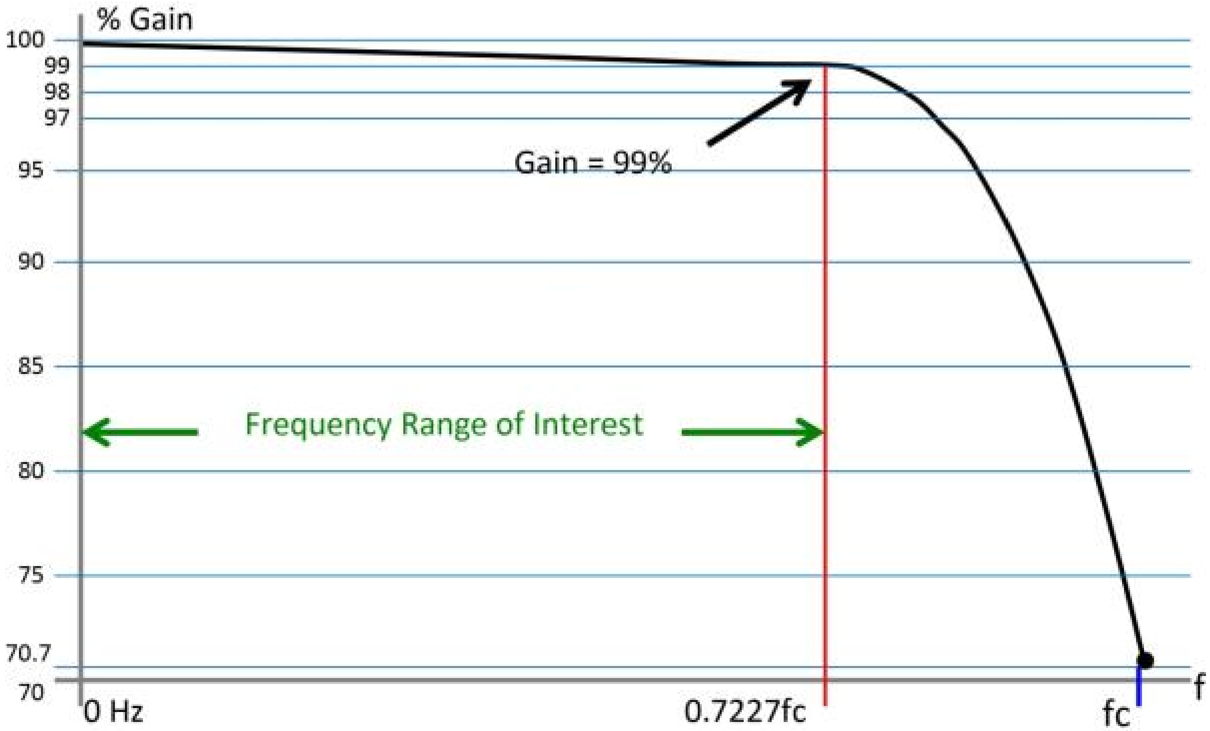
Pre Sample Filtering



- The more poles a filter has, the steeper the transition is from the pass band to stop band. It also looks more like an ideal filter.
- The cost of having more poles in the filter is the amount of components on the signal. conditioning cards in the data acquisition system. This limits the amount of channels per card.
- We will now focus on the band from ***0 to the cutoff frequency*** of the filter which is where the measurement data resides.

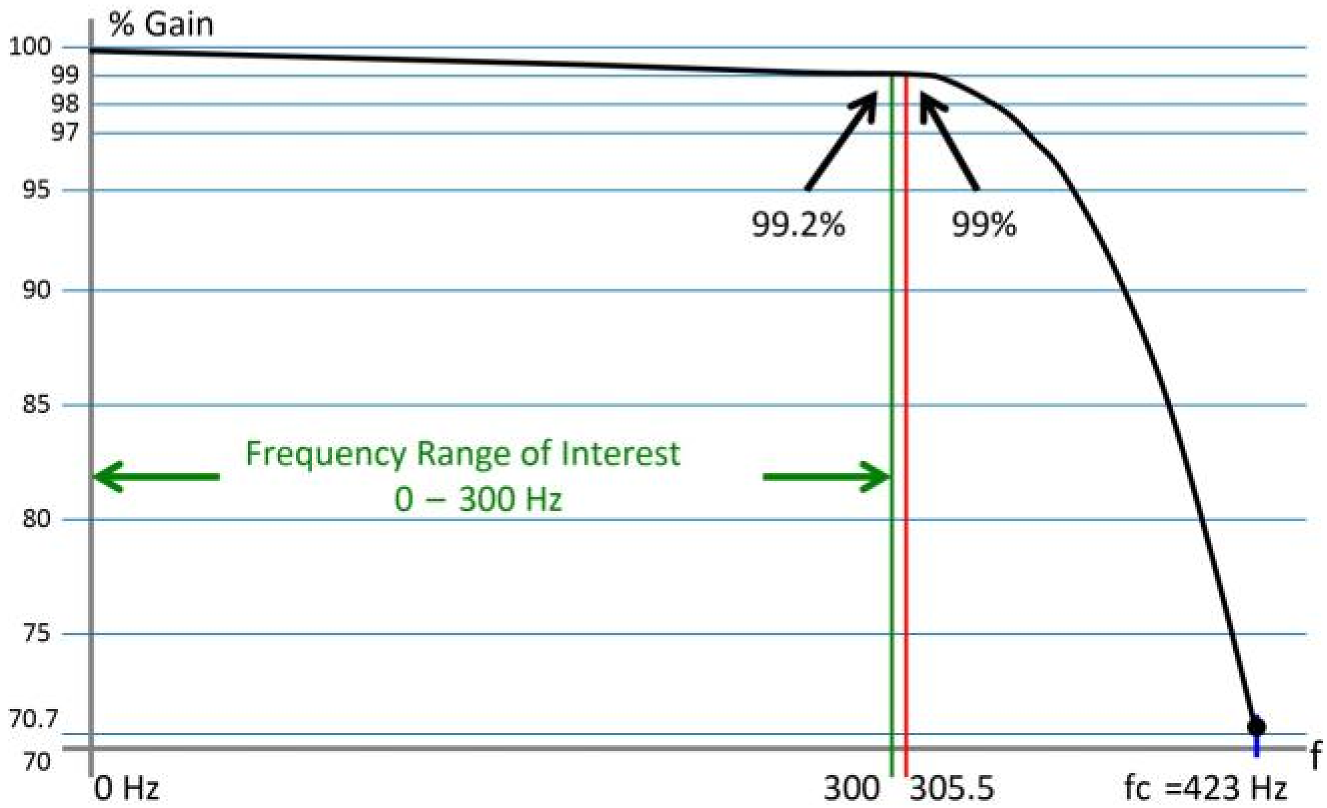
Pre Sample Filtering

- At 0 Hz (DC) the Butterworth filter has a gain of 100%, but falls towards 70.7% (-3 dB) as the frequency increases towards the cutoff frequency (fc). The cutoff frequency is selected such that the frequency range of interest does not have a filter gain less than 99%.
- This illustration is only valid for a 6-pole Butterworth filter.



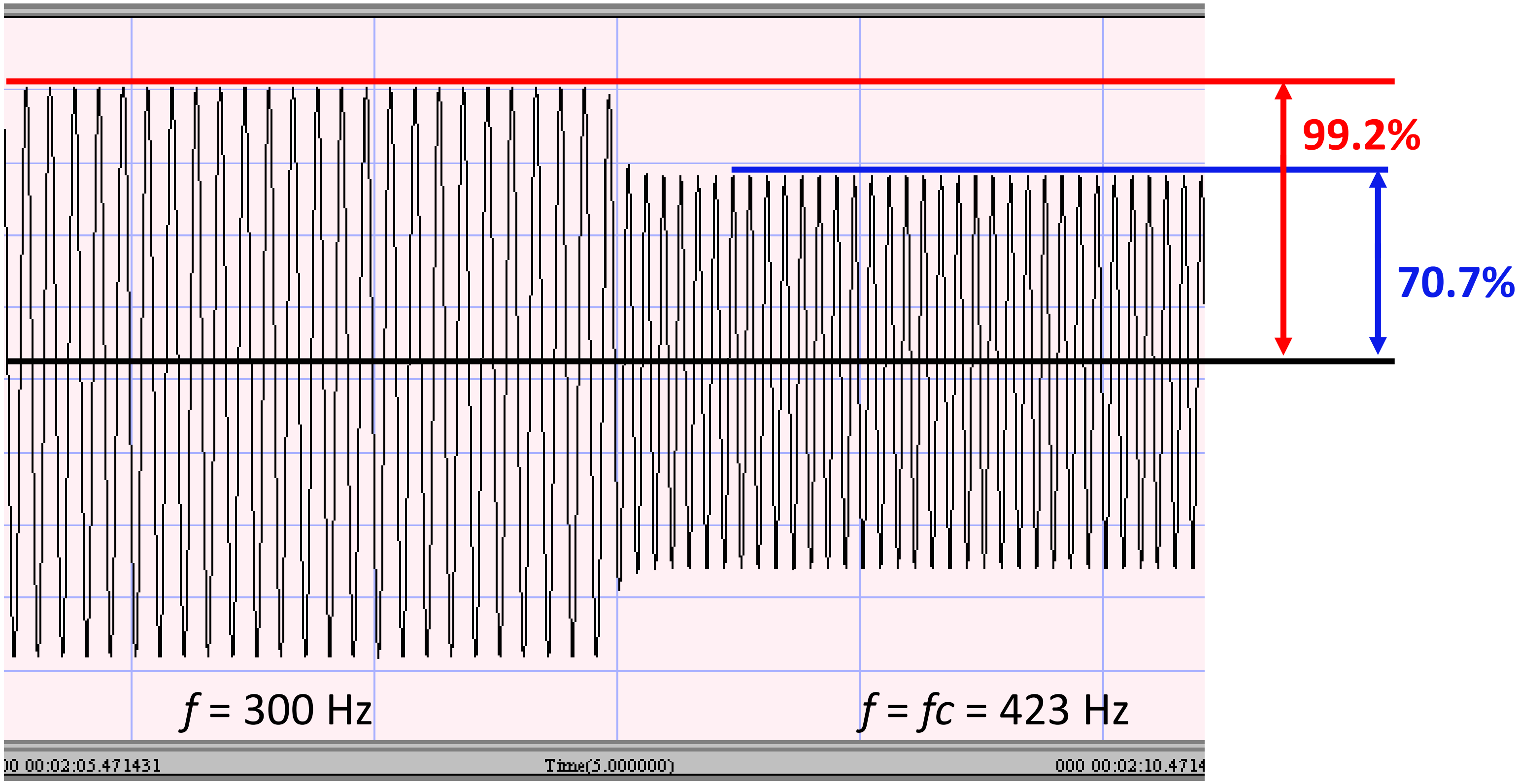
Pre Sample Filtering

- The frequency range of interest for the accelerometer measurement is 300Hz. The cutoff frequency should be at least 415.11 Hz for a 6-pole Butterworth filter. The next highest cutoff frequency available in the data acquisition system is 423 Hz.



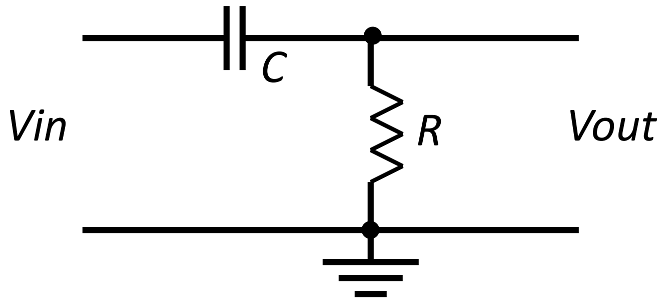
Pre Sample Filtering

- Here is the result of filtering on a sine wave. The cutoff frequency of the filter is set to 423 Hz. The change in amplitude can be seen as the frequency of the signal changes from 300 to 423 Hz – attenuating the amplitude to 70%.



AC-Coupling

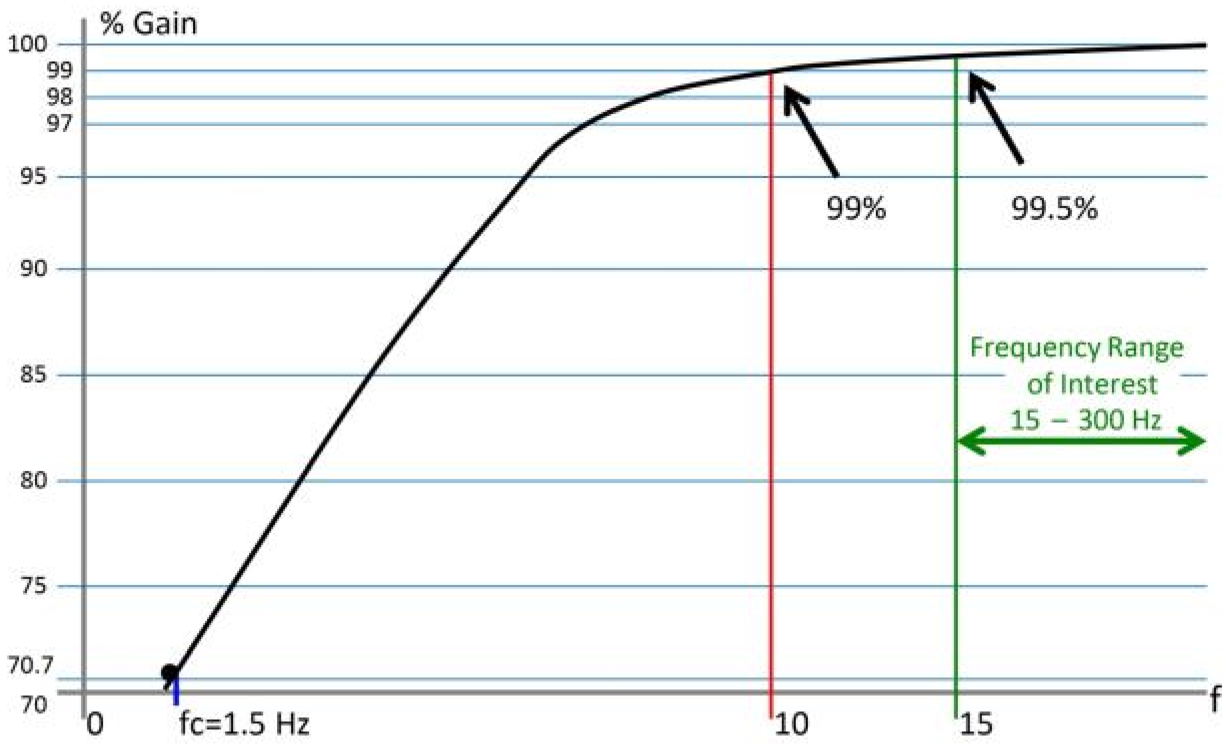
- Because the frequency range of interest was requested as 300 Hz, it is assumed that both the AC and DC components of the signal are desired.
- If the frequency range of interest was 15 – 300 Hz, then it is known that the DC component is not desired and AC-coupling is used to eliminate it.
- In this example, no AC-coupling is needed, but this is a good opportunity to cover it.
- If the frequency range of interest was 15 – 300 Hz, this is how AC-coupling would affect the signal.



Depending upon the data acquisition system, AC-coupling is accomplished using a single-pole, high-pass, passive filter (no active components such as an amplifier). For this example, we will assume there is a fixed cutoff frequency of 1.5 Hz.

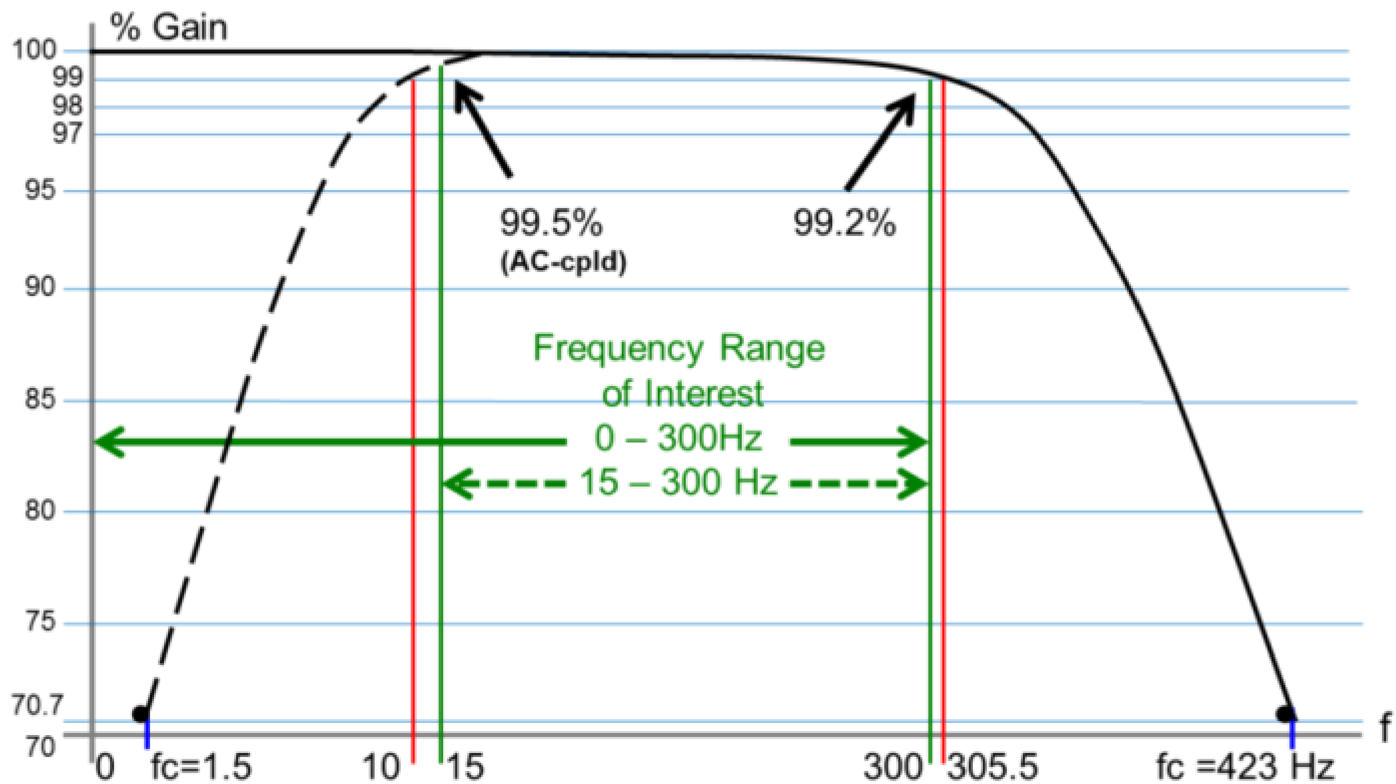
AC-Coupling

- Below is the frequency response of the AC-coupling. The one-pole filter has a slow transition, so the ≥99% gain is at 10 Hz and above.

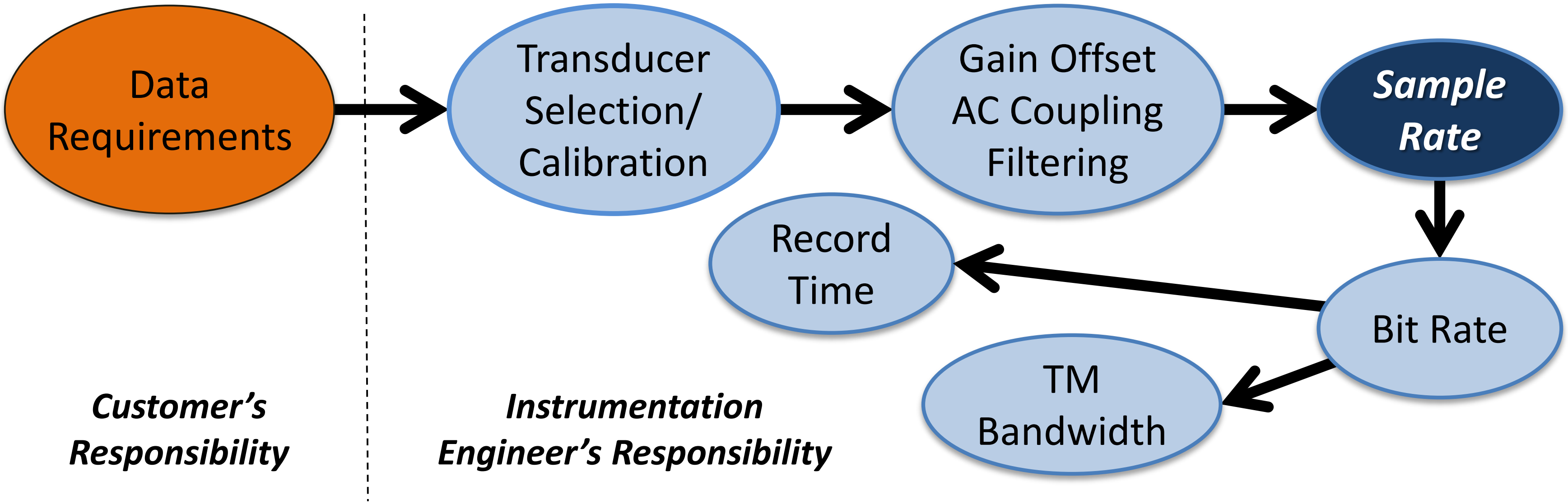


Overall Frequency Response of AC-Coupling and Pre Sample Filtering

- This would be the frequency response of the data channel. The dashed line shows the response with AC-coupling applied if it was needed. The frequency range of interest does not have any filter gain below 99%.



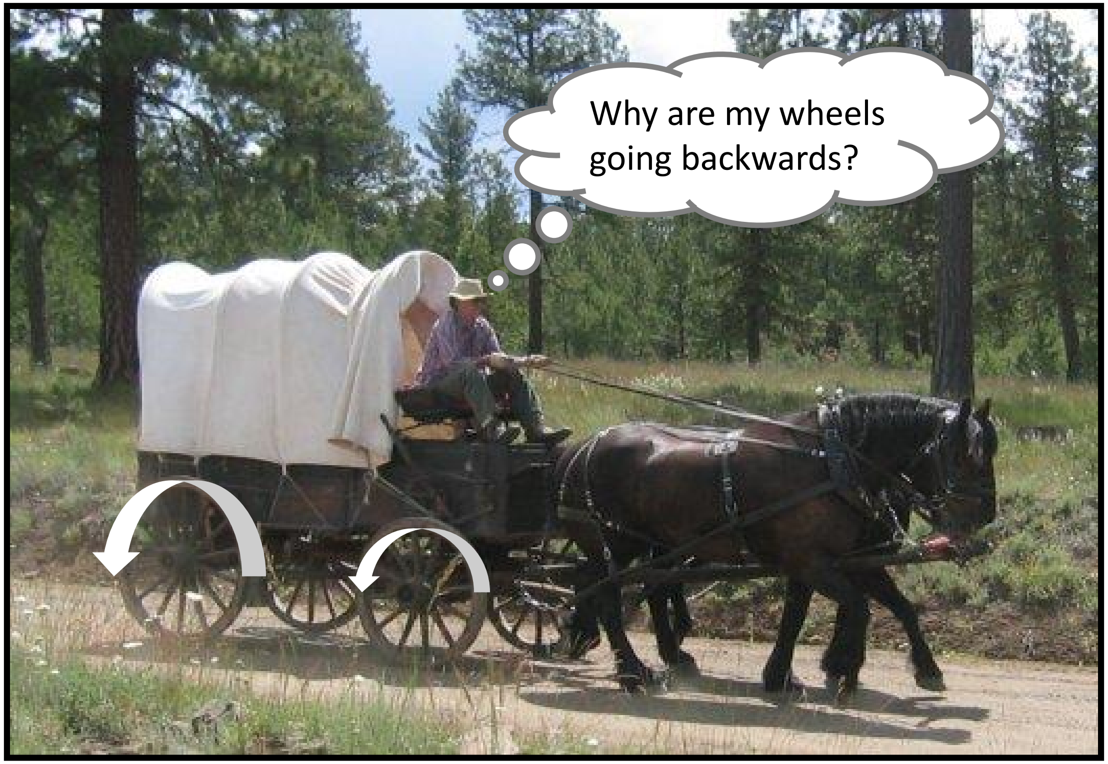
Sample Rate



- Next the minimum sample rate is determined.
- Sampling properly will address two issues:
  - Guaranteeing there are no aliased frequency components in the frequency range of interest (where the data resides).
  - Capturing the peaks of the signal within a defined error bound.

Aliasing

- Aliasing occurs when a signal is not adequately sampled, and a high frequency component of the signal takes on the identity (alias) of a lower frequency.
- The classic example of this is the wagon wheel moving backwards in a movie.

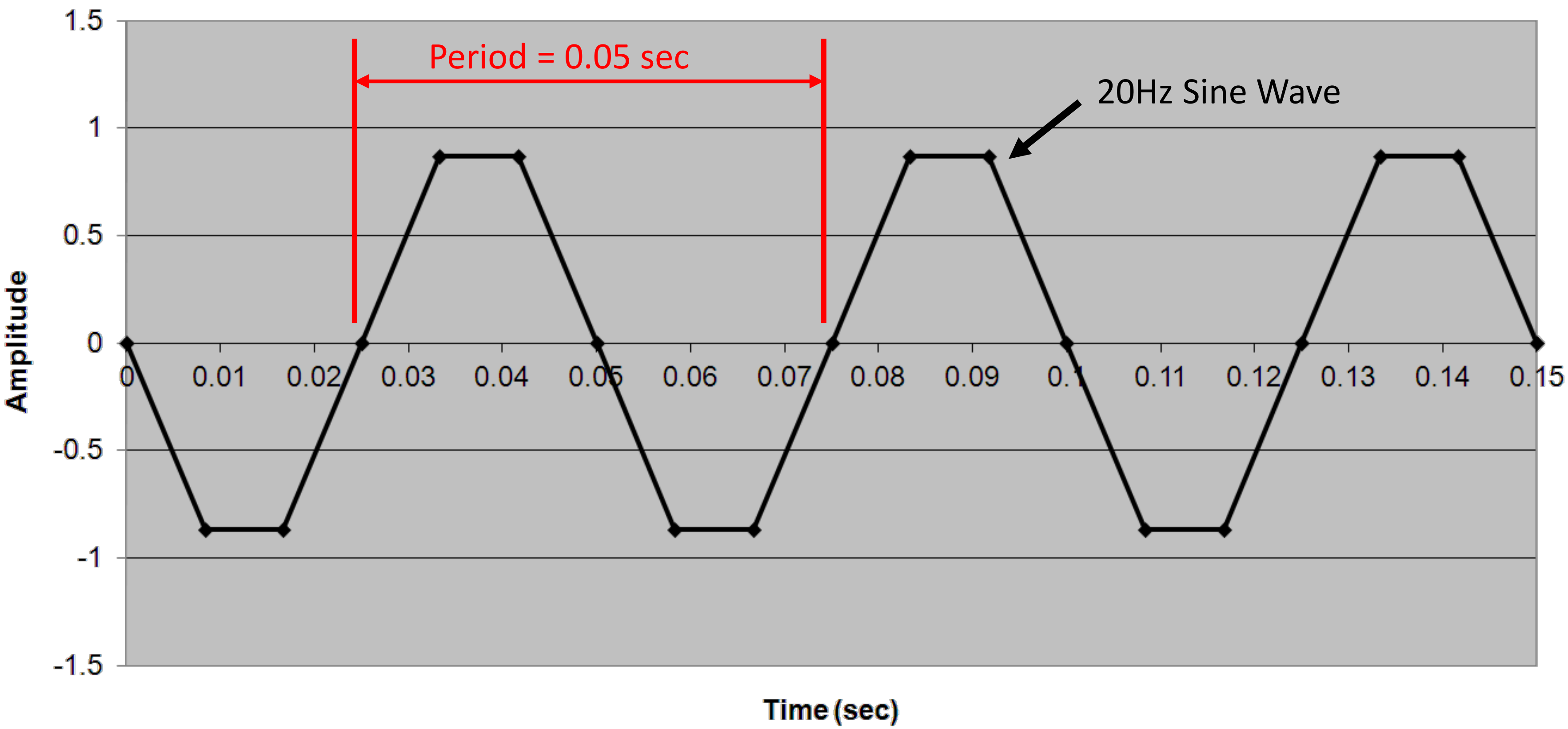


Aliasing

When a measurement isn't properly sampled, the result cannot be trusted. This video illustrates the rotating helicopter blades aliasing as 0 RPM.

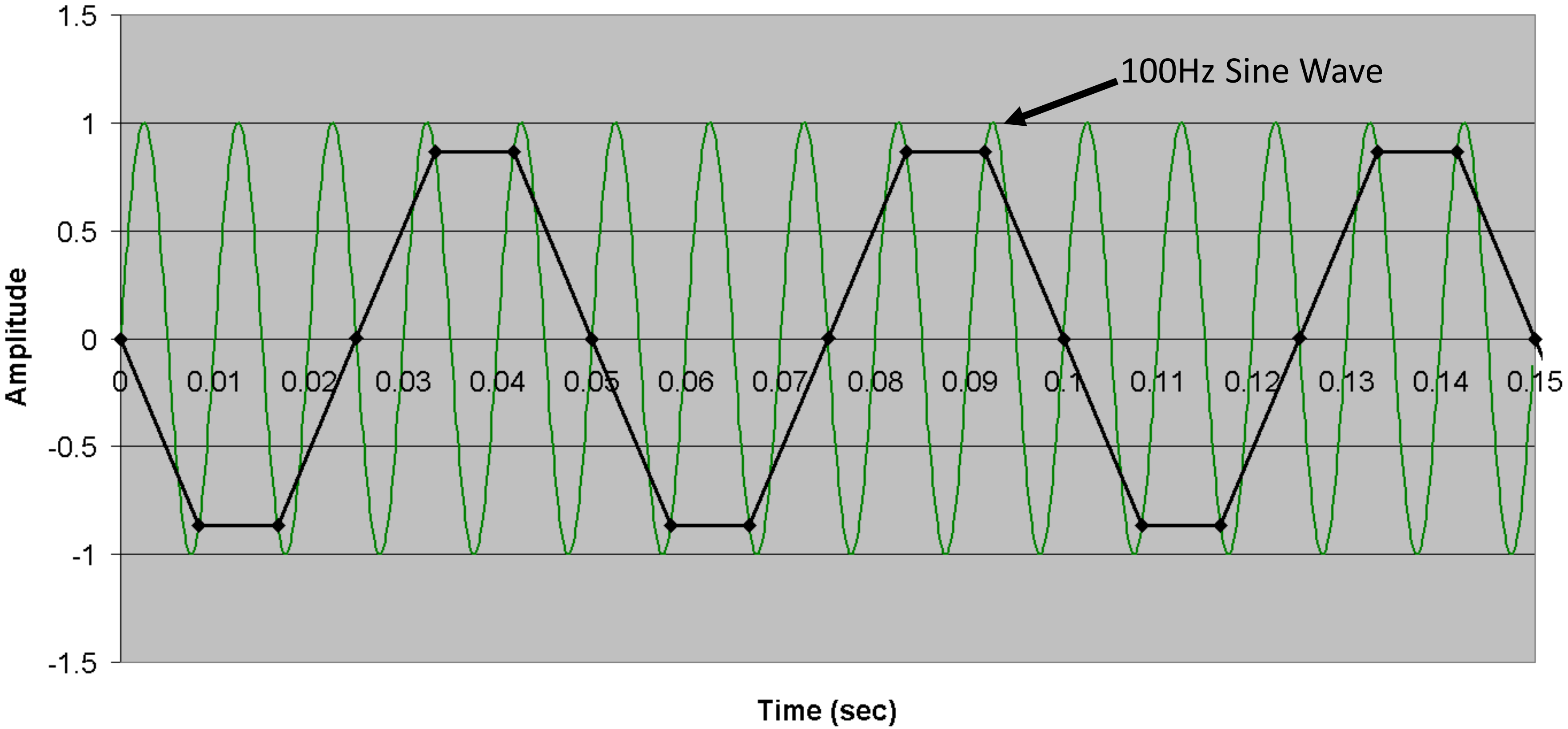
Aliasing in the Time Domain

- Here is an example of a sampled 20 Hz sine wave that you may see on a strip chart during a flight test. The sample rate of this data is 120 samples/sec. Can you trust this data if has not been band limited before sampling?



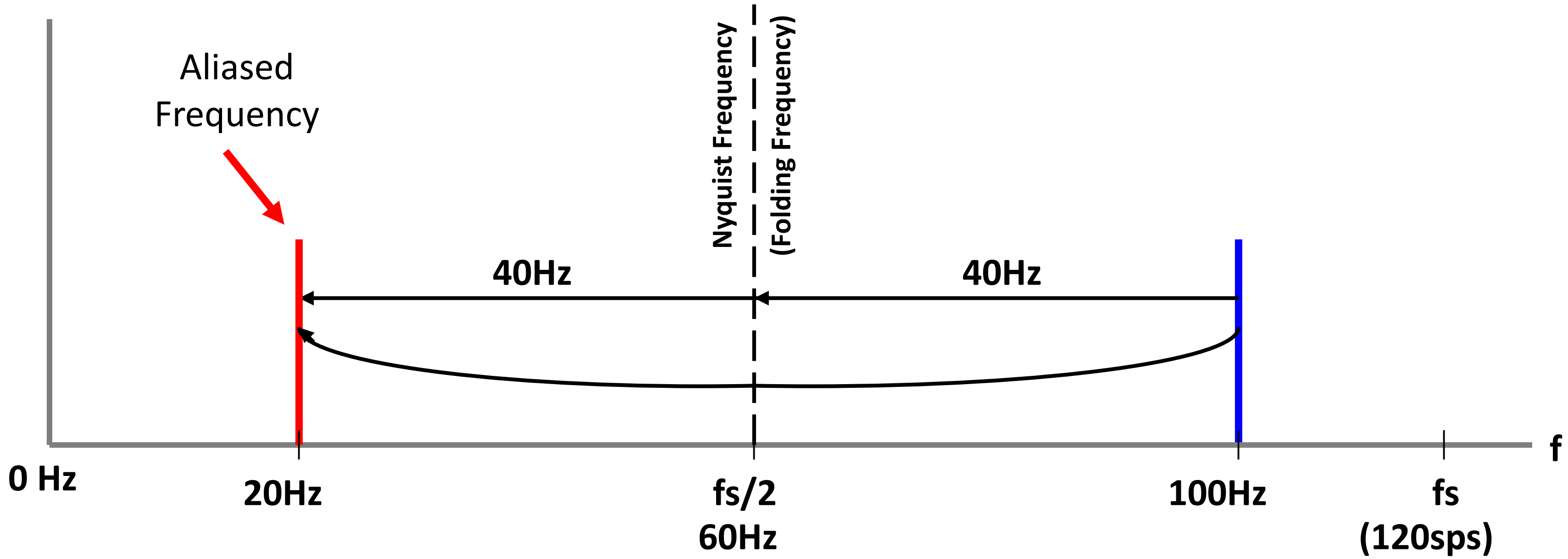
Aliasing in the Time Domain

- No, the original signal before sampling was actually a 100Hz sine wave. Because of inadequate sampling, it aliased as a 20 Hz sine wave. Data not properly band limited or sampled ***cannot*** be trusted.



Aliasing in the Frequency Domain

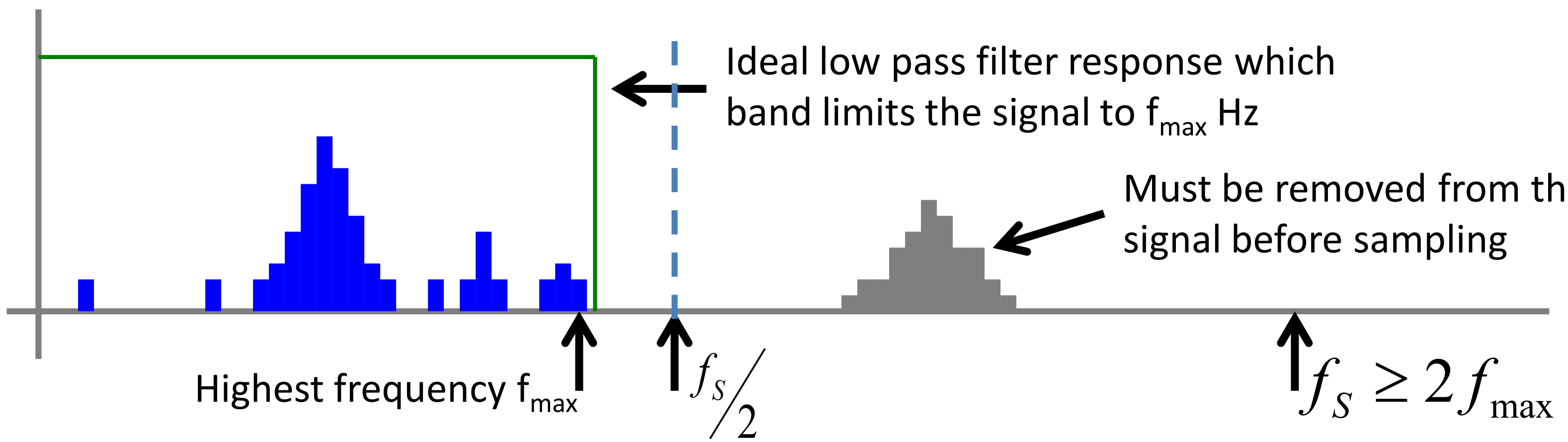
- This is what occurred in the frequency domain. Frequencies above half the sample rate “fold” about the frequency fs/2. This frequency is known as the Nyquist or folding frequency. If you folded the diagram at 60 Hz, the 100 Hz component appears to be at 20 Hz.



- The Nyquist Theory states that you must sample ***at least*** twice the highest frequency of your signal in order to avoid aliasing.

Pre Sample Filtering to Avoid Aliasing

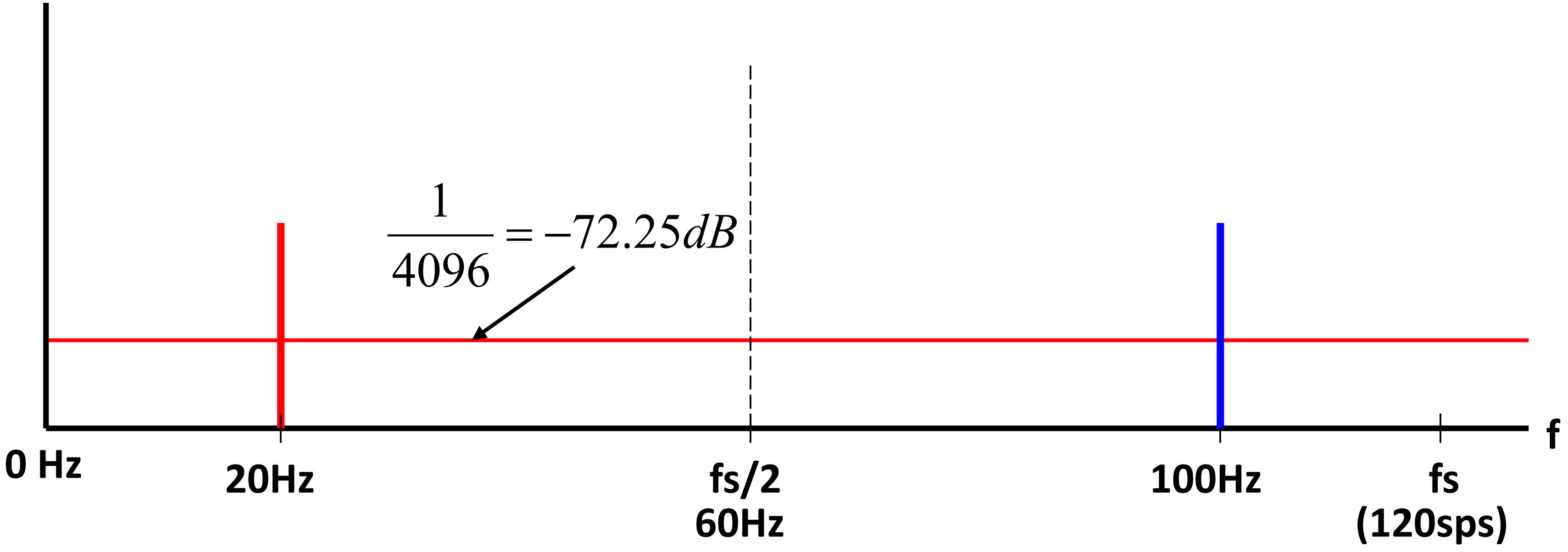
- Aliased data…
  - appears to be actual data and therefore cannot be detected
  - ***cannot*** be “fixed”, the result is ***irreversible***
- Once there is a suspicion of aliasing in the data, the data becomes worthless. To provide decision quality data, the signal must be first band limited such that there is no possibility of aliasing. This is accomplished with the pre-sample filter discussed earlier.



- Remember that pre-sample Butterworth filters are not ideal filters, and it will be seen that 2x is not adequate.

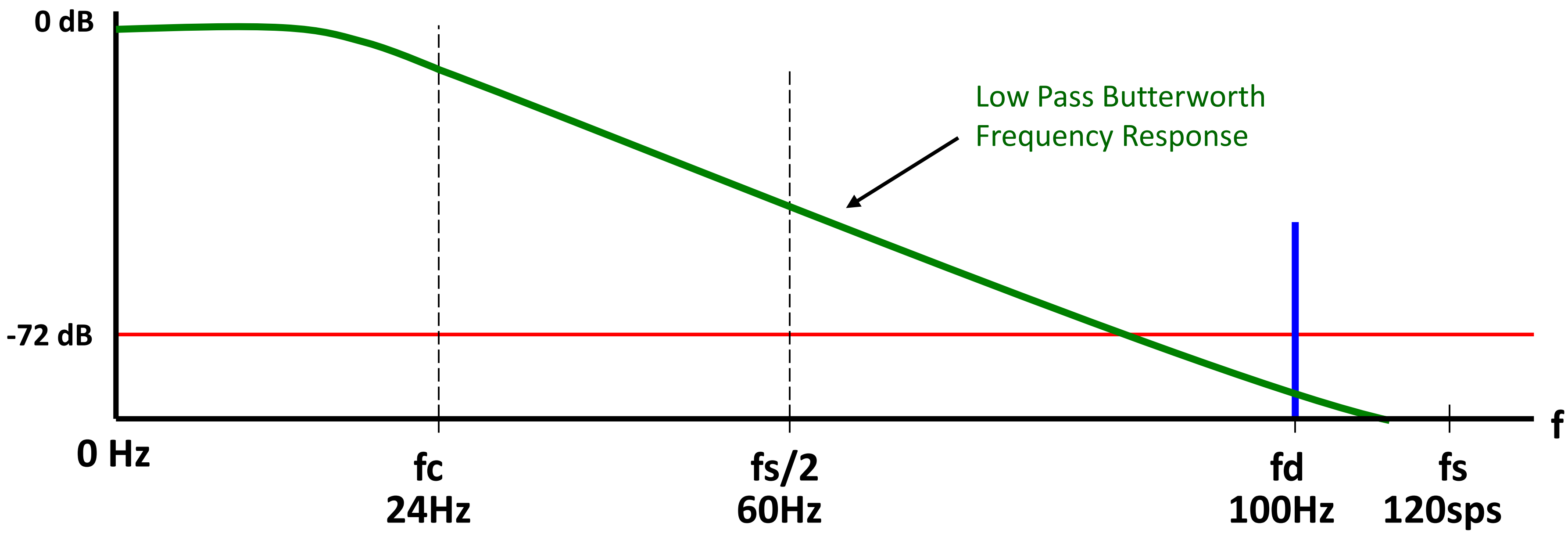
Pre Sample Filtering to Avoid Aliasing

- To adequately remove the 100 Hz component, we would have to attenuate the 100 Hz component such that it does not toggle a bit in the analog to digital converter (ADC). For a 12-bit ADC, that threshold is $1/2^{12}$ or 1/4096. Signals lower than this threshold are not detected by the ADC.



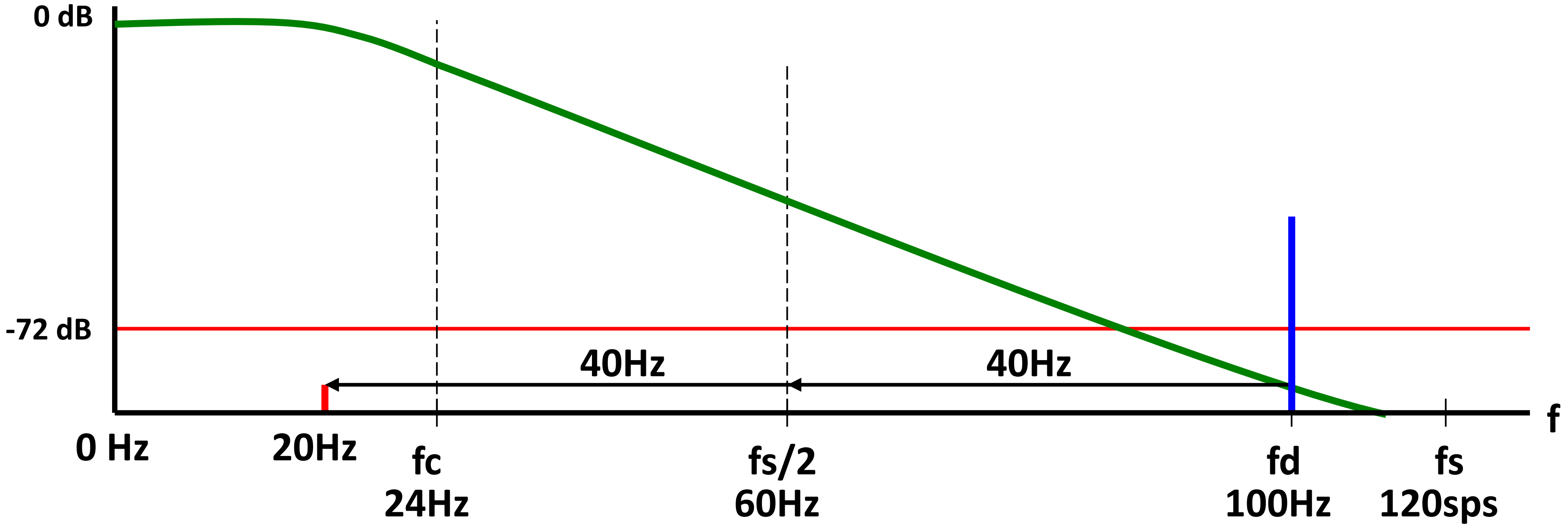
Pre Sample Filtering to Avoid Aliasing

- For this example, a 6-pole Butterworth filter with a cutoff frequency of 24 Hz is used to attenuate the 100 Hz signal.



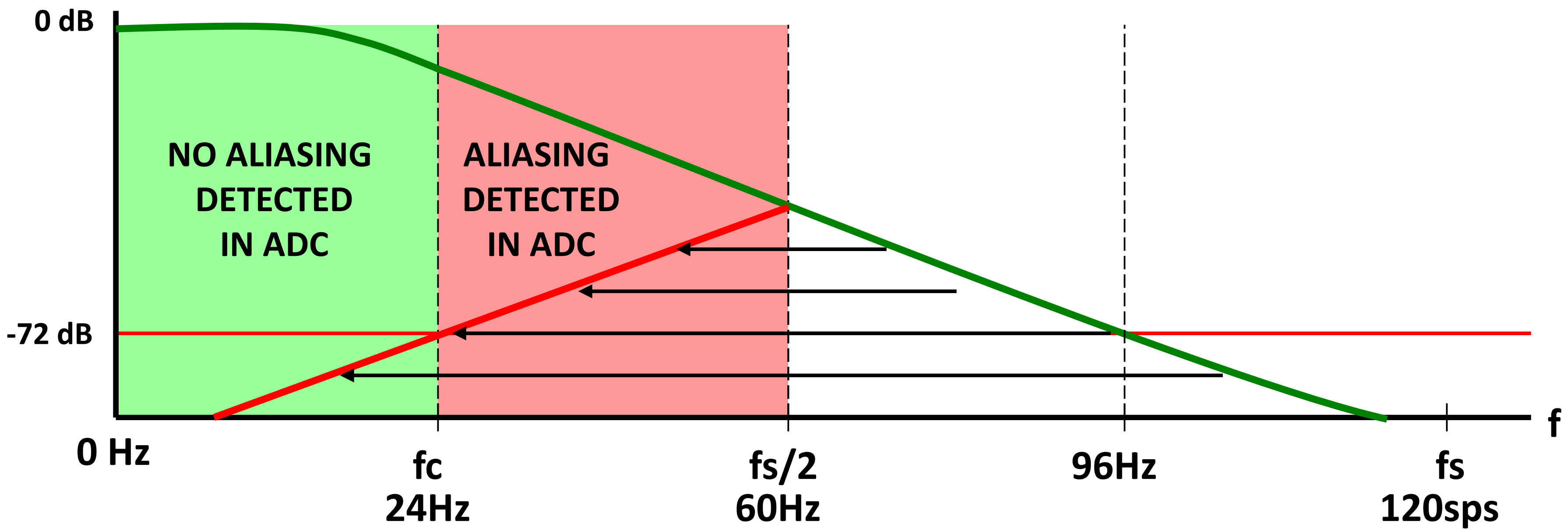
Pre Sample Filtering to Avoid Aliasing

- The 100 Hz signal is still is aliased as a 20 Hz signal, however the filter attenuates it such that it is below the 1/4096 or -72.25 dB threshold. The 20 Hz aliased signal is never seen in the data.



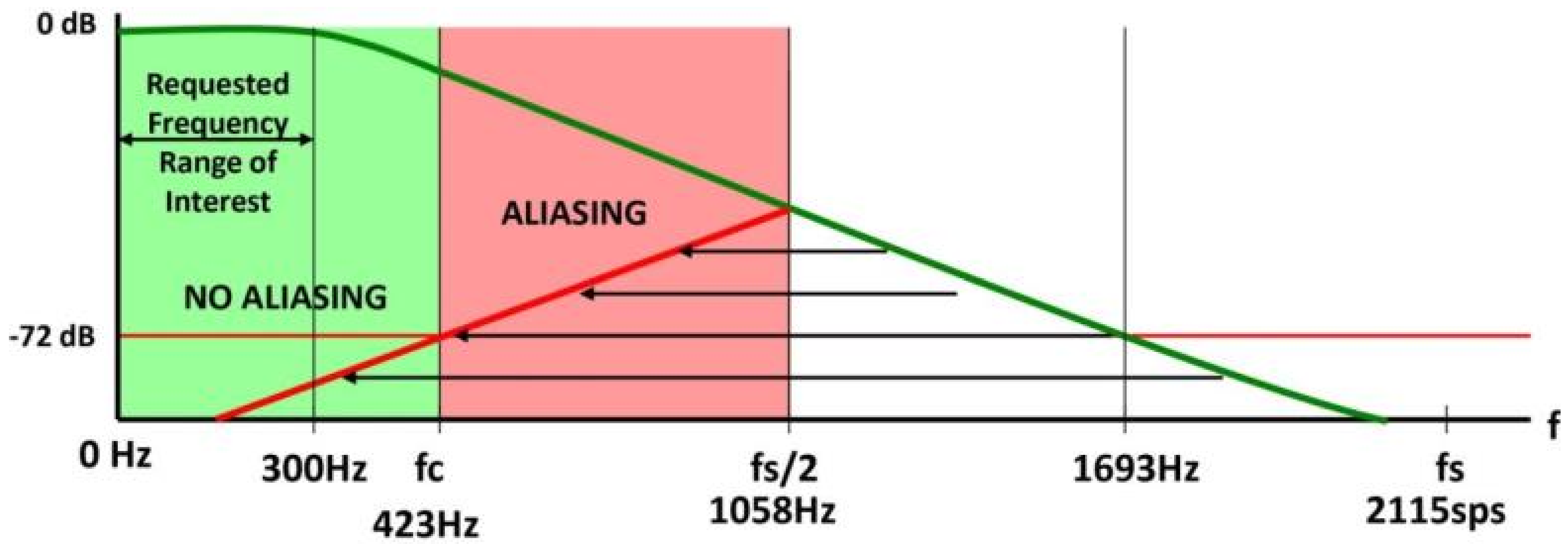
Pre Sample Filtering to Avoid Aliasing

- In fact, all frequency components above 96 Hz will be below -72.25 dB. When folded about the Nyquist frequency of fs/2 = 60 Hz, they will not be detected by the ADC in the frequency band of 0 to fc = 24 Hz.



Pre Sample Filtering to Avoid Aliasing

- For the accelerometer measurement, filtered at 423 Hz, the sample rate must be at least 2115 sps to guarantee that no aliasing occurs in the band from 0 Hz to 423 Hz. Also note that to avoid aliasing, we are actually sampling 7x our highest frequency of interest (not 2x). This is because the Butterworth filter is ***not an ideal filter.***



- If this sampling philosophy is not followed, the data is suspect of containing aliased data.

Minimum Sample Rate Determination

- The generic equation for determining the sample rate from the filter's cutoff frequency is:

$$f_S \geq \left(2^{n/p} + 1\right) f_C$$

Where, f_s is the minimum sample rate
n is the number of bits in the ADC
p is the number of poles in the Butterworth filter
f_c is the cutoff frequency of the Butterworth filter

Example: minimum sampling rate for a 4-pole Butterworth and 12-bit ADC.

$$f_S \geq \left(2^{12/4} + 1\right) f_C$$

$$f_S \geq \left(2^{3} + 1\right) f_C$$

$$f_S \geq \left(8 + 1\right) f_C$$

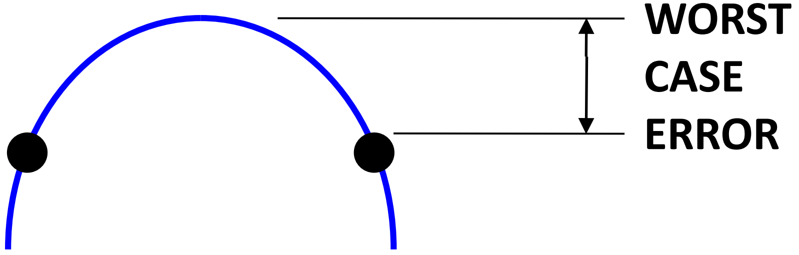
$$f_S \geq 9 f_C$$

Sample Rate

- To determine the proper sample rate of the accelerometer, there are many characteristics (cutoff frequency and number of poles in the filter and the number of bits in the ADC) that need to be known about the data acquisition system. **This is why you should not accept sample rates as a requirement from your customer. Always insist on a frequency range of interest.**
- To avoid any confusion, remember that frequency is measured in Hz (1/sec), and sample rate in units of samples per second (sps).

Peak Sampling

- Now that there is confidence that no aliasing exists in the data, the next item to consider is the capturing of peaks in the data.



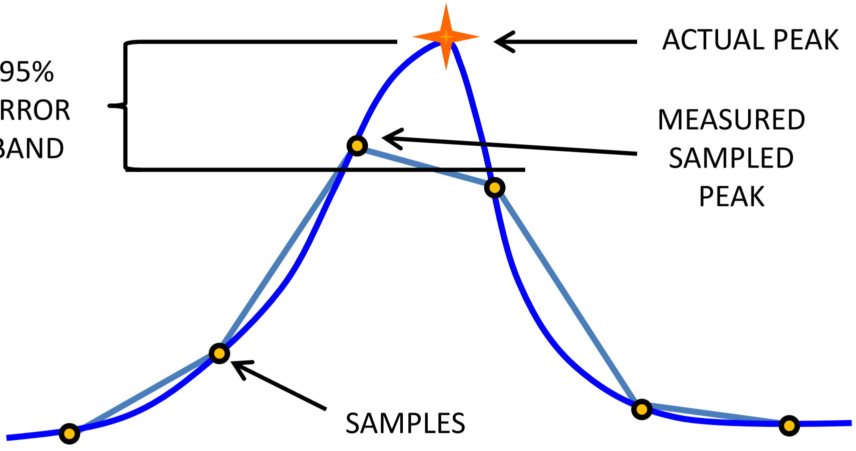
- When attempting to capture the amplitude of a signal, there will always be some maximum error directly related to the sample rate. The maximum error occurs when two consecutive samples are equidistant from the peak of the signal. Because errors are bounded by an uncertainty figure.
- A more realistic approach is shown on the next slide.

Peak Sampling

- The error in peak detection is described as: 95% of the time, the measured peak will fall within a defined error band as shown in the table below. As the sample rate is increased, the error band gets smaller. The remaining 5% of the measured peaks will fall outside that error band. The error is only in reference to f_{max}, lower frequencies will have smaller error bands.

$n = f_S/f_{max}$	95% error band
7	6.5%
10	3.6%
15	1.7%
20	1.0%
25	0.7%

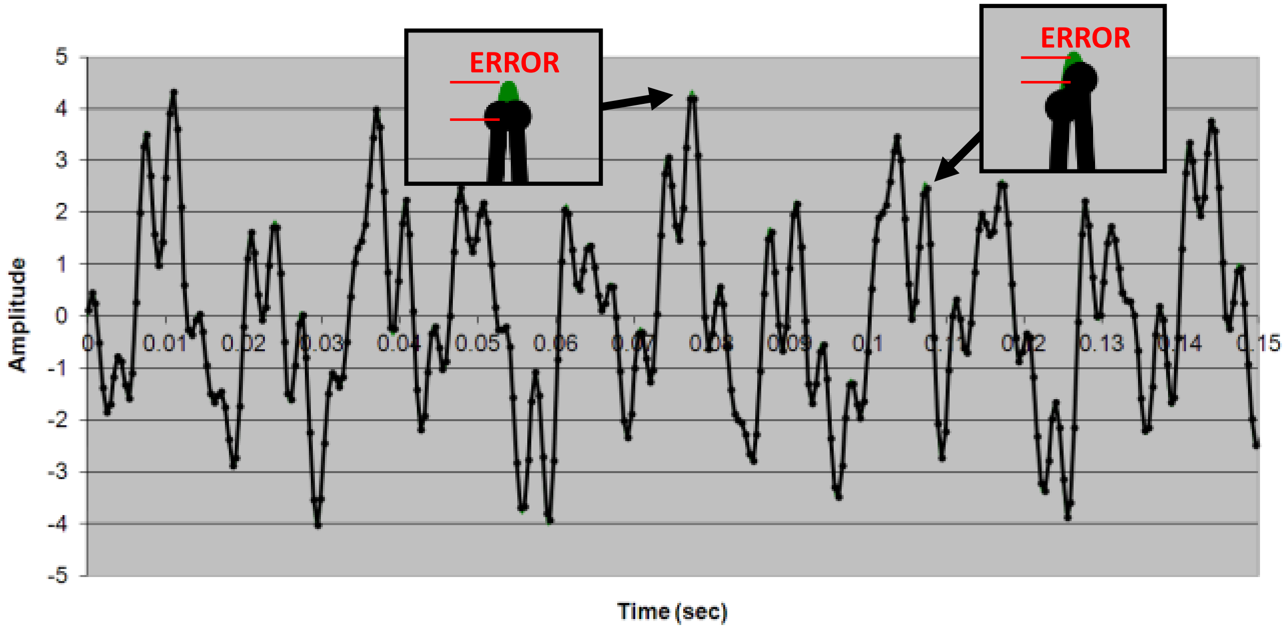
note f_{max} not f_C used in calculating n



- The amount of error acceptable has to be determined by the person requesting the data.

Peak Sampling

- Illustration of the example accelerometer measurement with a frequency range of interest of 300 Hz, filtered at 423 Hz, and sampled at 2115 sps.



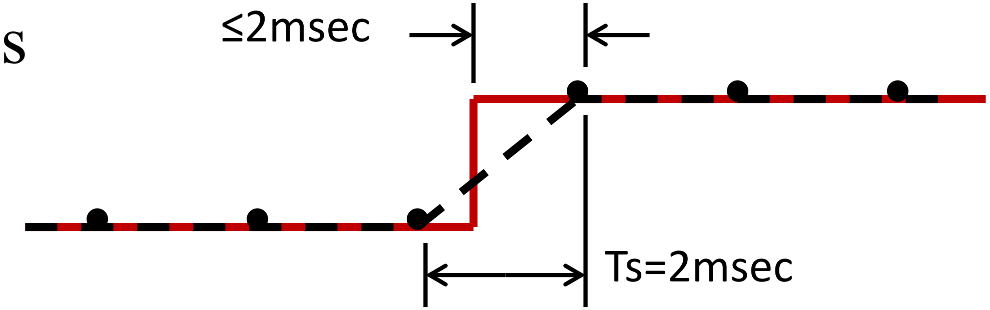
- There are 82 peaks appearing in the display. Because we are sampling just above 7X the max frequency of 300 Hz, 78 of those peaks (95%) are captured to within 6.5% of the actual peak of the original signal (shown in green).

Sample Rates for Non-Periodic Signals – Level Change Detection

- Previously we addressed sinusoidal signals when discussing sampling. The rules do change a bit when sampling other signal types.
- Level Change Detection:
  - When sampling level changes to within a certain time period (T), you just have to sample at the inverse of the time period. If you want to know when the aircraft hits the deck to within 2 ms, you would sample WOW (weight on wheels) at 500 sps.

$$f_S = \frac{1}{T} = \frac{1}{2\ \text{msec}} = 500\ \text{sps}$$

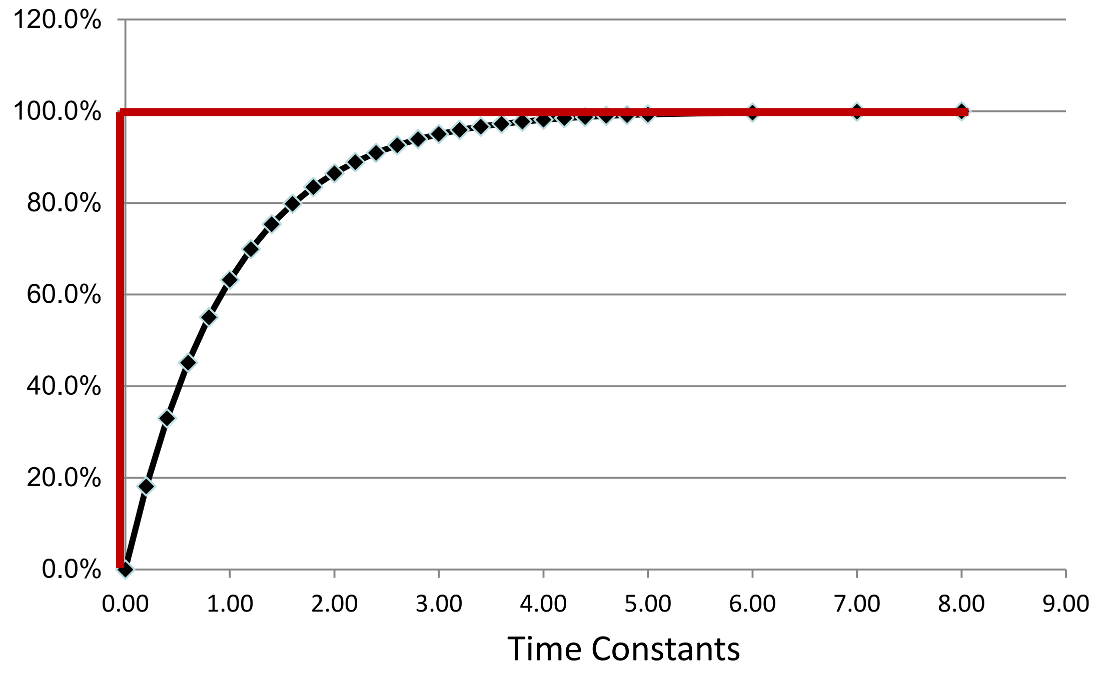
$$T_s = \frac{1}{f_S} = 2\ \text{msec}$$



Sample Rates for Non-Periodic Signals – Signals with a Time Constant Response

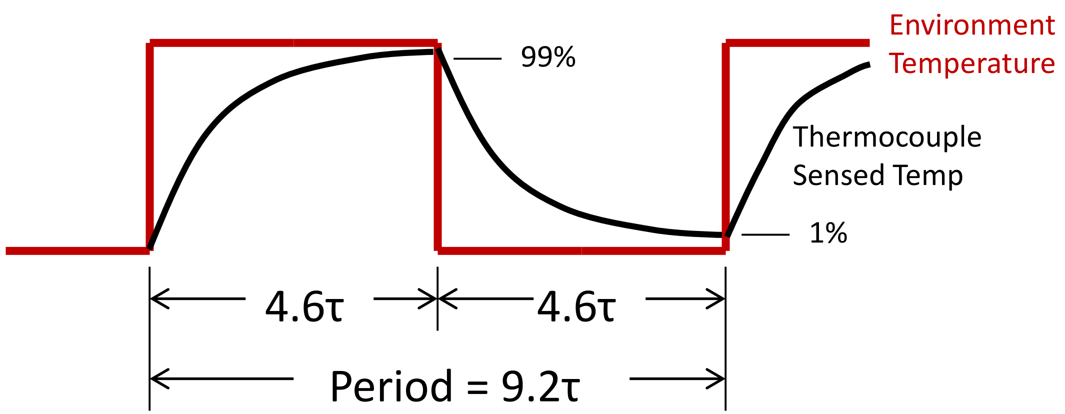
- Signals with a time constant response:
  - Signals such as thermocouples respond to the environment at a certain time constant (τ). This gives them a limited bandwidth, so the max frequency is known.

Time	% Full Temp
0	0%
1τ	63.2%
2τ	86.5%
3τ	95.0%
4τ	98.2%
4.6τ	99%
5τ	99.3%



Sample Rates for Non-Periodic Signals – Signals with a Time Constant Response

- Should a temperature environment cycle at worst case between two temperatures, the thermocouple will take a known amount of time to get within 99% of the max temperature. The shortest time period that can be captured within 99% is 9.2 time constants.



$$f_{max} = \frac{1}{9.2\tau}$$

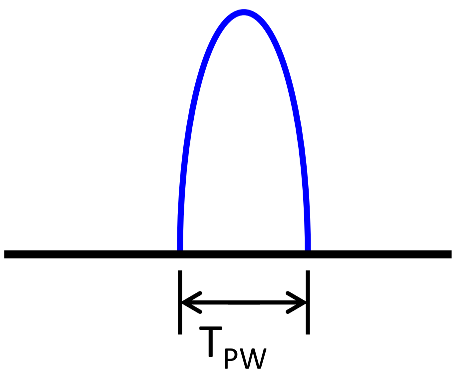
maximum response of the thermocouple

$$f_S \geq 20 f_{max}$$

- To have a 95% confidence that the maximum sensed temperature is measured to 99% of the maximum we sample at least 20x the highest sensed frequency, f_{max}. This was determined from the chart on peak sampling.

Sample Rates for Non-Periodic Signals – Shock Pulses

- Shock pulses are modeled by a half-sine waveform, with a certain pulse width, T_{PW}. The instrumentation engineer would have to be given T_{PW} and how much error in capturing the peak is acceptable.



If the T_{PW} is 40msec, and the peak needs to be captured to within 5%, then the minimum sample rate needed would be:

$$f_{\max} = \frac{1}{2T_{PW}} = \frac{1}{2(40m\sec)} = \frac{1}{80m\sec} = 12.5Hz$$

For a 95% confidence in capturing the peak to within 5%

$$n = {f_S}/{f_{\max}} = 8.5$$

$$f_S = 8.5 f_{\max} = 8.5(12.5) = 106.25 sps$$

PART 3

NAVAIR Public Release 2016-780
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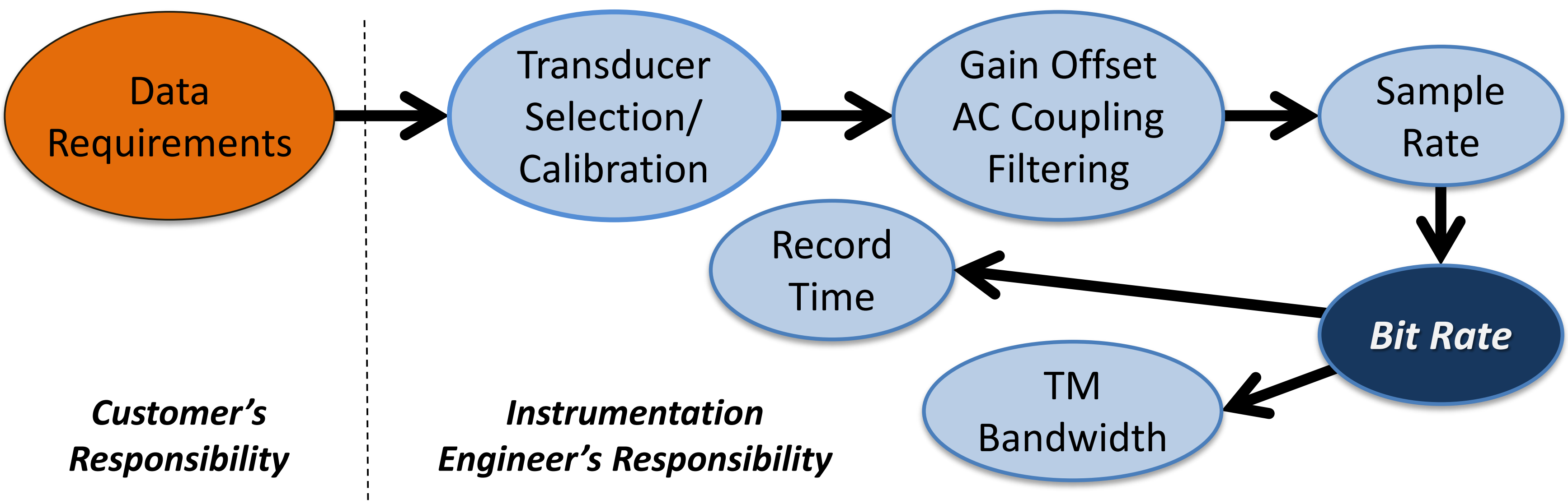
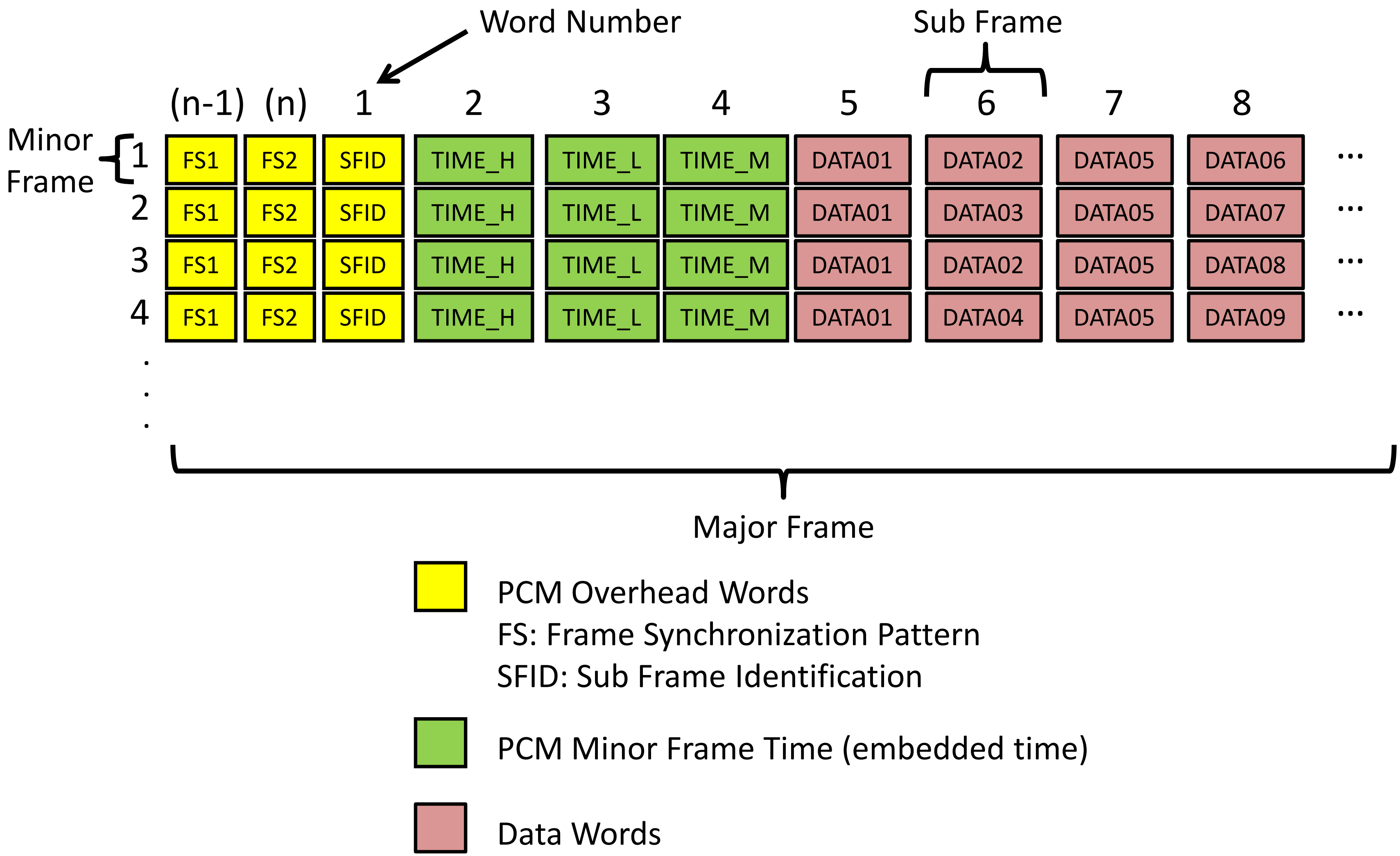
Creating a PCM Map to Obtain a Sample Rate

Bit Rate

- After the sample rates of all the measurements are determined, a grid called a PCM map is constructed. The PCM map is basically a schedule of when measurements are sampled. When many different sample rates are required, constructing the map can be a difficult task.
- **Chapter 4** of the IRIG-106 describes the structure of the PCM map such that data can be processed at any DoD range ground station. The resultant PCM bit stream is called a Chapter 4 PCM stream.



PCM Map Structure



PCM Map Structure

	1	2	3	4	5	6	7	8	9	
1	SFID	DATA01	DATA06	DATA02	DATA03	DATA01	DATA04	DATA05	DATA08	…
2	SFID	DATA01	DATA07	DATA02	DATA03	DATA01	DATA04	DATA05	DATA09	…
3	SFID	DATA01	DATA06	DATA02	DATA03	DATA01	DATA04	DATA05	DATA10	…
4	SFID	DATA01	DATA07	DATA02	DATA03	DATA01	DATA04	DATA05	DATA11	…

In order to obtain various sample rates, words are placed in the map at different intervals. There are three different types of words within the PCM map to accomplish this. All words must be evenly spaced within the map to obtain periodic sampling.

Super Commutated Word (DATA01)
Occurs more than once in each minor frame

Minor Frame Word (DATA02, DATA03, DATA04, DATA05)
Occurs only once in each minor frame

Sub Commutated Word (DATA06, DATA07, DATA08, DATA09, DATA10, DATA11)
Does not occur in every minor frame – only a sub multiple of the sub frame depth

Time words not shown due to space limitations on the slide.

PCM Map Structure

- The PCM map is a schedule of when the measurements are sampled. The structure of the map is designed to meet the minimum sampling requirements. The measurements are sampled sequentially beginning at word 1-1 and ending at 12-24. Then the sampling repeats back to word 1-1

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24
1	SFID	A1	A2	A3	V	S1	S2	A1	A2	A3	P1	P2	P3	A1	A2	A3	V	T1	T2	A1	A2	A3	FS1	FS2
2	SFID	A1	A2	A3	V	S3	S4	A1	A2	A3	P1	P2	P3	A1	A2	A3	V	T3	T4	A1	A2	A3	FS1	FS2
3	SFID	A1	A2	A3	V	S5	S6	A1	A2	A3	P1	P2	P3	A1	A2	A3	V	T5	T6	A1	A2	A3	FS1	FS2
4	SFID	A1	A2	A3	V	S7	S8	A1	A2	A3	P1	P2	P3	A1	A2	A3	V	T7	T8	A1	A2	A3	FS1	FS2
5	SFID	A1	A2	A3	V	S9	S10	A1	A2	A3	P1	P2	P3	A1	A2	A3	V			A1	A2	A3	FS1	FS2
6	SFID	A1	A2	A3	V			A1	A2	A3	P1	P2	P3	A1	A2	A3	V			A1	A2	A3	FS1	FS2
7	SFID	A1	A2	A3	V	S1	S2	A1	A2	A3	P1	P2	P3	A1	A2	A3	V	T9	T10	A1	A2	A3	FS1	FS2
8	SFID	A1	A2	A3	V	S3	S4	A1	A2	A3	P1	P2	P3	A1	A2	A3	V	T11	T12	A1	A2	A3	FS1	FS2
9	SFID	A1	A2	A3	V	S5	S6	A1	A2	A3	P1	P2	P3	A1	A2	A3	V	T13	T14	A1	A2	A3	FS1	FS2
10	SFID	A1	A2	A3	V	S7	S8	A1	A2	A3	P1	P2	P3	A1	A2	A3	V	T15		A1	A2	A3	FS1	FS2
11	SFID	A1	A2	A3	V	S9	S10	A1	A2	A3	P1	P2	P3	A1	A2	A3	V			A1	A2	A3	FS1	FS2
12	SFID	A1	A2	A3	V			A1	A2	A3	P1	P2	P3	A1	A2	A3	V			A1	A2	A3	FS1	FS2

A: accelerometer
S: strain gage
T: Temperature
V: pilot audio
P: pressure

Time words not shown due to space limitations on the slide.

PCM Map Structure and Sample Rate

- Let's say that parameter **A3** is our accelerometer measurement. It is placed in the map 48 times *in even intervals*. How many frames per second is needed to meet the minimum sample rate of 2115 sps?

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24
1	SFID	A1	A2	**A3**	V	S1	S2	A1	A2	**A3**	P1	P2	P3	A1	A2	**A3**	V	T1	T2	A1	A2	**A3**	FS1	FS2
2	SFID	A1	A2	**A3**	V	S3	S4	A1	A2	**A3**	P1	P2	P3	A1	A2	**A3**	V	T3	T4	A1	A2	**A3**	FS1	FS2
3	SFID	A1	A2	**A3**	V	S5	S6	A1	A2	**A3**	P1	P2	P3	A1	A2	**A3**	V	T5	T6	A1	A2	**A3**	FS1	FS2
4	SFID	A1	A2	**A3**	V	S7	S8	A1	A2	**A3**	P1	P2	P3	A1	A2	**A3**	V	T7	T8	A1	A2	**A3**	FS1	FS2
5	SFID	A1	A2	**A3**	V	S9	S10	A1	A2	**A3**	P1	P2	P3	A1	A2	**A3**	V			A1	A2	**A3**	FS1	FS2
6	SFID	A1	A2	**A3**	V			A1	A2	**A3**	P1	P2	P3	A1	A2	**A3**	V			A1	A2	**A3**	FS1	FS2
7	SFID	A1	A2	**A3**	V	S1	S2	A1	A2	**A3**	P1	P2	P3	A1	A2	**A3**	V	T9	T10	A1	A2	**A3**	FS1	FS2
8	SFID	A1	A2	**A3**	V	S3	S4	A1	A2	**A3**	P1	P2	P3	A1	A2	**A3**	V	T11	T12	A1	A2	**A3**	FS1	FS2
9	SFID	A1	A2	**A3**	V	S5	S6	A1	A2	**A3**	P1	P2	P3	A1	A2	**A3**	V	T13	T14	A1	A2	**A3**	FS1	FS2
10	SFID	A1	A2	**A3**	V	S7	S8	A1	A2	**A3**	P1	P2	P3	A1	A2	**A3**	V	T15		A1	A2	**A3**	FS1	FS2
11	SFID	A1	A2	**A3**	V	S9	S10	A1	A2	**A3**	P1	P2	P3	A1	A2	**A3**	V			A1	A2	**A3**	FS1	FS2
12	SFID	A1	A2	**A3**	V			A1	A2	**A3**	P1	P2	P3	A1	A2	**A3**	V			A1	A2	**A3**	FS1	FS2

$$2115\,\frac{samples}{second} \times \frac{major\ frame}{48\ samples} = 44.0625\,\frac{major\ frames}{second}$$

PCM Map Structure and Sample Rate

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24
1	SFID	A1	A2	**A3**	V	S1	S2	A1	A2	**A3**	P1	P2	P3	A1	A2	**A3**	V	T1	T2	A1	A2	**A3**	FS1	FS2
2	SFID	A1	A2	**A3**	V	S3	S4	A1	A2	**A3**	P1	P2	P3	A1	A2	**A3**	V	T3	T4	A1	A2	**A3**	FS1	FS2
3	SFID	A1	A2	**A3**	V	S5	S6	A1	A2	**A3**	P1	P2	P3	A1	A2	**A3**	V	T5	T6	A1	A2	**A3**	FS1	FS2
4	SFID	A1	A2	**A3**	V	S7	S8	A1	A2	**A3**	P1	P2	P3	A1	A2	**A3**	V	T7	T8	A1	A2	**A3**	FS1	FS2
5	SFID	A1	A2	**A3**	V	S9	S10	A1	A2	**A3**	P1	P2	P3	A1	A2	**A3**	V			A1	A2	**A3**	FS1	FS2
6	SFID	A1	A2	**A3**	V			A1	A2	**A3**	P1	P2	P3	A1	A2	**A3**	V			A1	A2	**A3**	FS1	FS2
7	SFID	A1	A2	**A3**	V	S1	S2	A1	A2	**A3**	P1	P2	P3	A1	A2	**A3**	V	T9	T10	A1	A2	**A3**	FS1	FS2
8	SFID	A1	A2	**A3**	V	S3	S4	A1	A2	**A3**	P1	P2	P3	A1	A2	**A3**	V	T11	T12	A1	A2	**A3**	FS1	FS2
9	SFID	A1	A2	**A3**	V	S5	S6	A1	A2	**A3**	P1	P2	P3	A1	A2	**A3**	V	T13	T14	A1	A2	**A3**	FS1	FS2
10	SFID	A1	A2	**A3**	V	S7	S8	A1	A2	**A3**	P1	P2	P3	A1	A2	**A3**	V	T15		A1	A2	**A3**	FS1	FS2
11	SFID	A1	A2	**A3**	V	S9	S10	A1	A2	**A3**	P1	P2	P3	A1	A2	**A3**	V			A1	A2	**A3**	FS1	FS2
12	SFID	A1	A2	**A3**	V			A1	A2	**A3**	P1	P2	P3	A1	A2	**A3**	V			A1	A2	**A3**	FS1	FS2

- Let's set a major frame rate of 45 mjfr/sec (above the required minimum 44.0625 mjfr/sec). This will result in a sample rate for our accelerometer to be:

$$48\frac{\text{samples}}{\text{major fr}} \times 45\frac{\text{major fr}}{\text{sec}} = 2160\frac{\text{samples}}{\text{sec}}$$

This meets the minimum sample rate defined earlier of 2115 sps and guarantees the data is not aliased.

PCM Map Structure and Sample Rate

- By placing parameters in the map in different quanitities, you get different sample rates. Remember, they must be evenly spaced within the map.

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24
1	SFID	A1	A2	**A3**	V	**S1**	S2	A1	A2	**A3**	**P1**	P2	P3	A1	A2	**A3**	V	**T1**	T2	A1	A2	**A3**	FS1	FS2
2	SFID	A1	A2	**A3**	V	S3	S4	A1	A2	**A3**	**P1**	P2	P3	A1	A2	**A3**	V	T3	T4	A1	A2	**A3**	FS1	FS2
3	SFID	A1	A2	**A3**	V	S5	S6	A1	A2	**A3**	**P1**	P2	P3	A1	A2	**A3**	V	T5	T6	A1	A2	**A3**	FS1	FS2
4	SFID	A1	A2	**A3**	V	S7	S8	A1	A2	**A3**	**P1**	P2	P3	A1	A2	**A3**	V	T7	T8	A1	A2	**A3**	FS1	FS2
5	SFID	A1	A2	**A3**	V	S9	S10	A1	A2	**A3**	**P1**	P2	P3	A1	A2	**A3**	V			A1	A2	**A3**	FS1	FS2
6	SFID	A1	A2	**A3**	V			A1	A2	**A3**	**P1**	P2	P3	A1	A2	**A3**	V			A1	A2	**A3**	FS1	FS2
7	SFID	A1	A2	**A3**	V	**S1**	S2	A1	A2	**A3**	**P1**	P2	P3	A1	A2	**A3**	V	T9	T10	A1	A2	**A3**	FS1	FS2
8	SFID	A1	A2	**A3**	V	S3	S4	A1	A2	**A3**	**P1**	P2	P3	A1	A2	**A3**	V	T11	T12	A1	A2	**A3**	FS1	FS2
9	SFID	A1	A2	**A3**	V	S5	S6	A1	A2	**A3**	**P1**	P2	P3	A1	A2	**A3**	V	T13	T14	A1	A2	**A3**	FS1	FS2
10	SFID	A1	A2	**A3**	V	S7	S8	A1	A2	**A3**	**P1**	P2	P3	A1	A2	**A3**	V	T15		A1	A2	**A3**	FS1	FS2
11	SFID	A1	A2	**A3**	V	S9	S10	A1	A2	**A3**	**P1**	P2	P3	A1	A2	**A3**	V			A1	A2	**A3**	FS1	FS2
12	SFID	A1	A2	**A3**	V			A1	A2	**A3**	**P1**	P2	P3	A1	A2	**A3**	V			A1	A2	**A3**	FS1	FS2

Pressure **P1**: $$12\,\frac{\text{samples}}{\text{major fr}} \times 45\,\frac{\text{major fr}}{\text{sec}} = 540\,\frac{\text{samples}}{\text{sec}}$$

Strain Gage **S1**: $$2\,\frac{\text{samples}}{\text{major fr}} \times 45\,\frac{\text{major fr}}{\text{sec}} = 90\,\frac{\text{samples}}{\text{sec}}$$

Temperature **T1**: $$1\,\frac{\text{samples}}{\text{major fr}} \times 45\,\frac{\text{major fr}}{\text{sec}} = 45\,\frac{\text{samples}}{\text{sec}}$$

Bit Rate

- The minimum bit rate is determined by how many bits are output in a second. It is calculated in the following way:

$$45\frac{\text{majorfr}}{\text{sec}} \times 12\frac{\text{minorfr}}{\text{majorfr}} \times 24\frac{\text{words}}{\text{minorfr}} \times 12\frac{\text{bits}}{\text{word}} = 155{,}520\frac{\text{bits}}{\text{sec}}$$

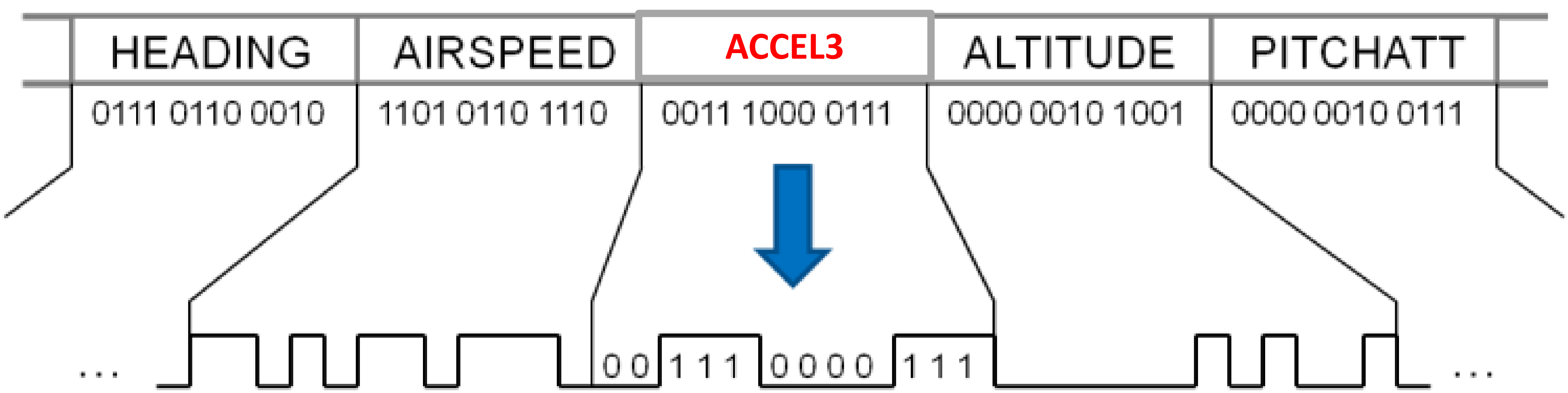
- The next highest bit rate selection is then chosen in the data system. For this example, that bit rate would be **160 Kbps**. This will increase the accelerometer's sample rate slightly from 2,160 to 2,222.2 sps.

$$\frac{160{,}000\frac{\text{bits}}{\text{sec}} \times 48\frac{\text{samples}}{\text{major fr}}}{12\frac{\text{bits}}{\text{word}} \times 24\frac{\text{words}}{\text{minor fr}} \times 12\frac{\text{minor fr}}{\text{major fr}}} = 2{,}222.2\frac{\text{samples}}{\text{sec}}$$

*Because the PCM map was intentionally made small to fit on the slide, the resulting 160 Kbps bit rate was a low bit rate. You will find that your actual bit rates will be much higher. To make it more realistic, the example will continue with a bit rate of **1.6 Mbps**.*

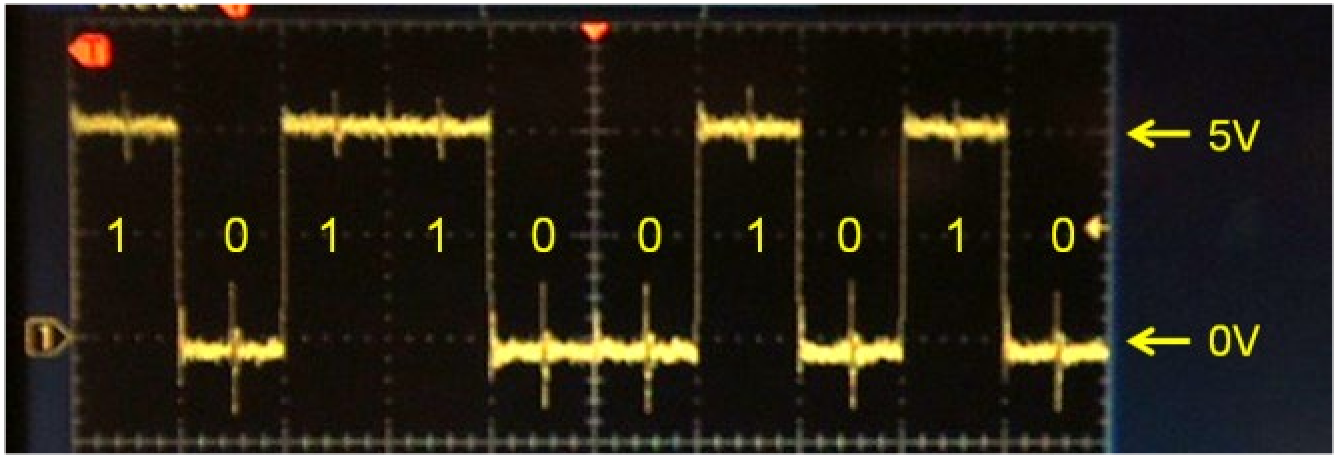
Data Within the PCM Signal

- If the accelerometer is sensing -18 Gs, the encoder converts the associated voltage to a count value. In this case it is 903 counts, which is converted to 0011 1000 0111 in binary. As the words in the PCM map are sampled, the 12-bit, binary encoded count value is multiplexed with all the other measurements into a serial bit stream of ones and zeros as shown below.



PCM Signal

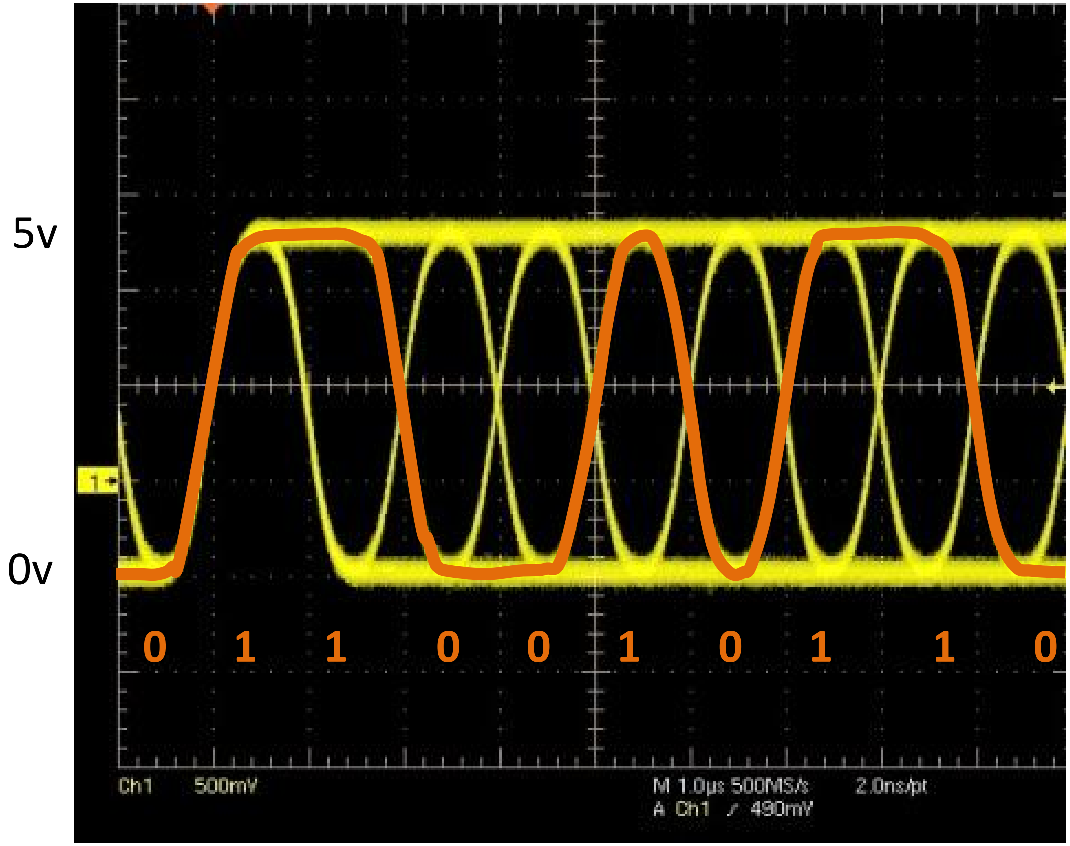
- Here is a screen shot of a PCM signal. This binary code representation is called NRZ-L which stands for “Non-Return to Zero Level” because the voltage of the bit stays high and does not return to 0V for each bit period.



- A “1” is represented by 5V, and a “0” is represented by 0V.
  - There will be 1.6 million 1’s and 0’s output in every second from the data system.

PCM Signal – Eye Pattern

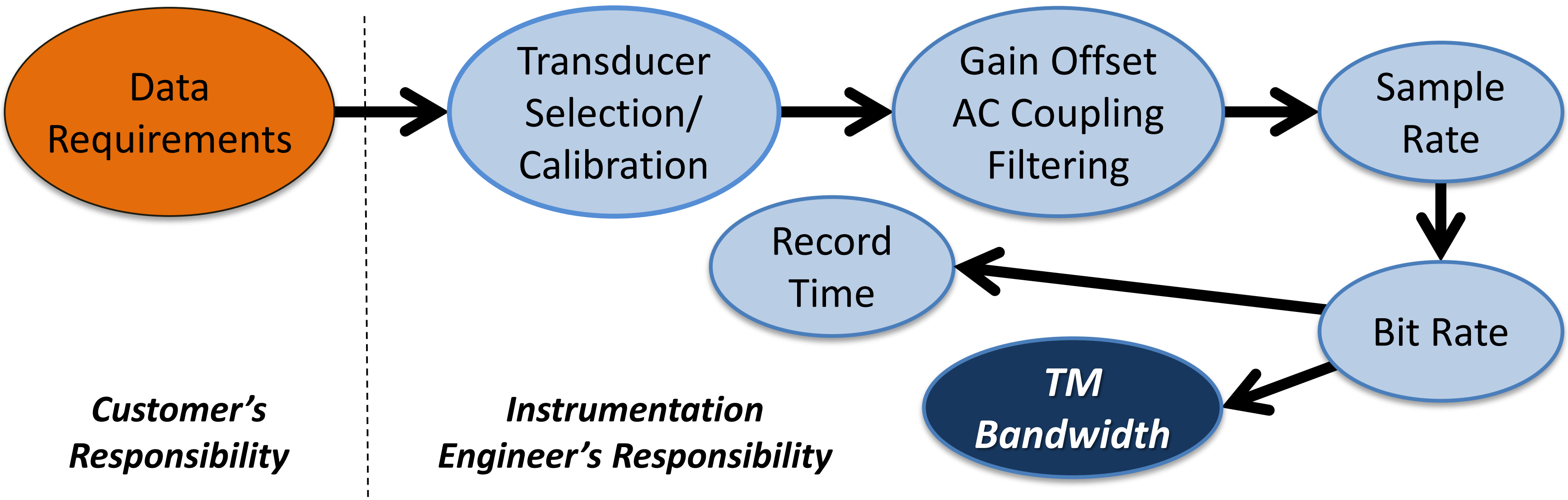
The signal below is also a PCM signal. It has what is called an eye pattern because of the openings in the signal. It is just a filtered version of what was shown earlier. The signal is over-laid on top of itself, which is why you see both 5v and 0v at the same instant in time. The orange trace would be one of the traces of the PCM.



Telemetry Bandwidth

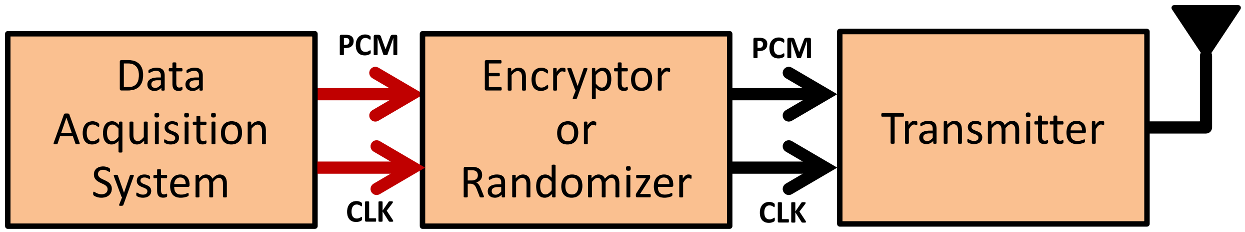
Telemetry Bandwidth

- Telemetry Bandwidth is finite. Therefore it must be used optimally such that the maximum amount of aircraft can fly simultaneously.
- A lot goes into optimizing the TM systems to reduce drop-outs in the data during the test.
- In the IRIG-106 Telemetry Standards document, **Chapter 2** describes transmitter and receiver systems, and frequency considerations are discussed in **Appendix A.**

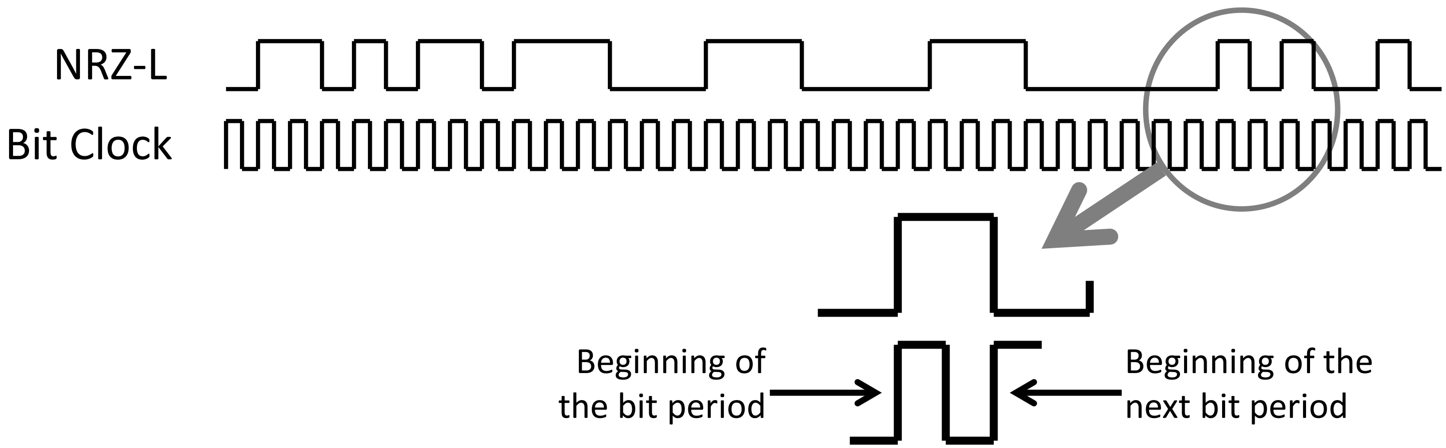


Typical Telemetry System - PCM

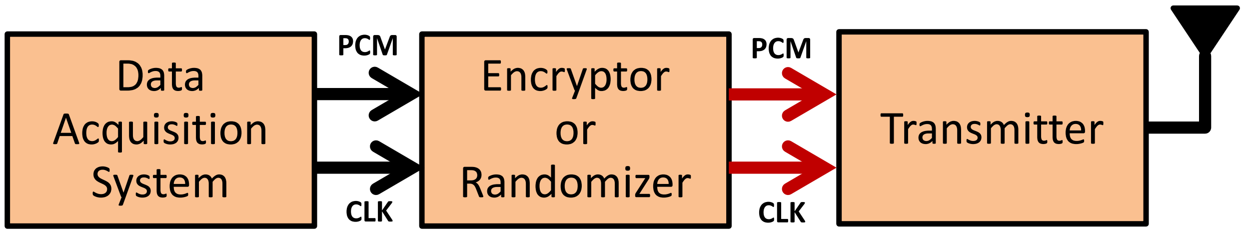
- A typical telemetry system will look like this

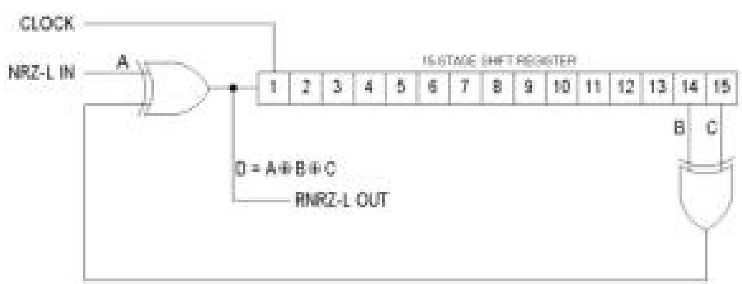


- The input to the encryptor or randomizer is the serial PCM stream of ones and zeros generated by the data acquisition system. Accompanying the PCM stream is a bit clock which defines the beginning and end of a bit period. The clock is required by the encryptor or randomizer.

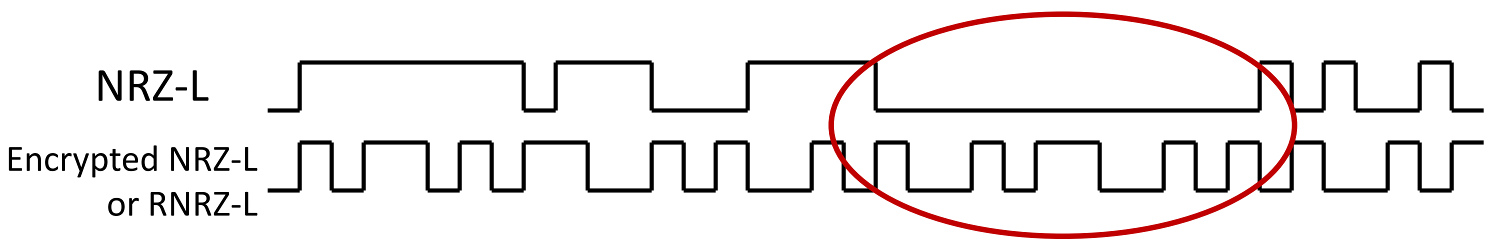


Typical Telemetry System – Randomized or Encrypted PCM

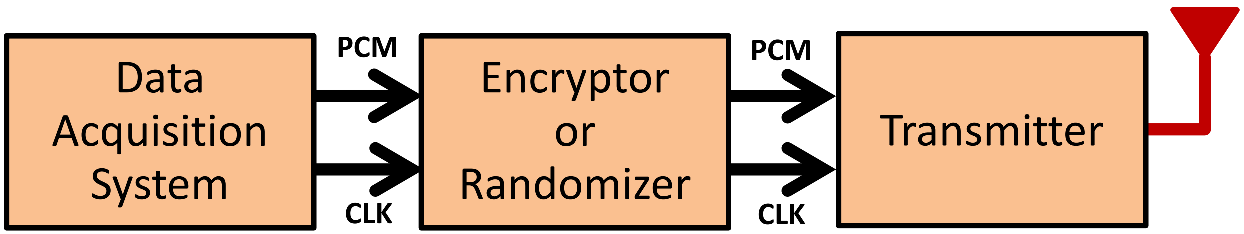




- If the data is classified, the bits must be scrambled such that without the decryption key, it cannot be decoded.
- If the data is not classified, the data is still scrambled using a PRN-15 code that is well known to everyone. This process is called randomization and is done to eliminate long strings of 1's and 0's that can cause TM spectrum issues from the transmitter.



Typical Telemetry System – Modulation Schemes

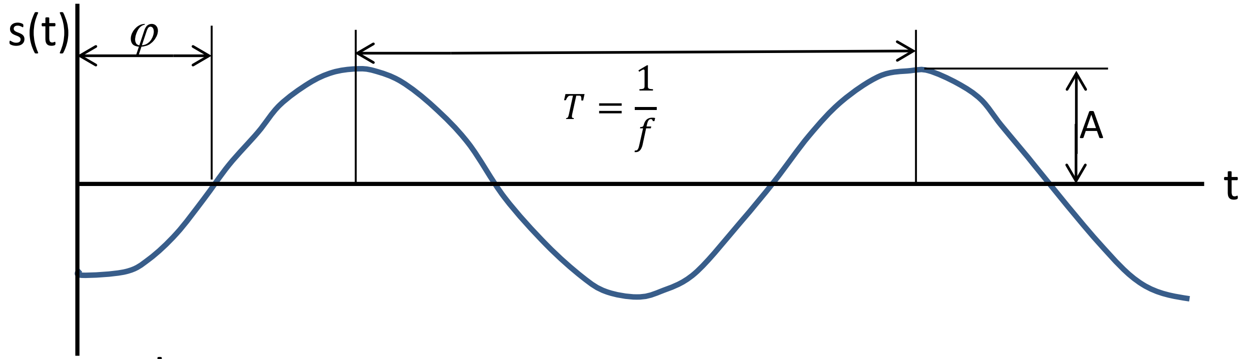


- The next step of the process is to transmit the data by modulating an RF (radio frequency) signal. There are several modulation schemes to accomplish this.
- Under the ARTM (Advanced Range Telemetry) program:
  - Teir 0: **PCM/FM** – PCM frequency modulating an RF carrier signal
  - Teir 1: **SOQPSK-TG** – Shaped Offset Quadrature Phase Shift Keying (Telemetry Group version)
  - Teir 2: **CPM** – Continuous Phase Modulation
- These modulation schemes are described in **Chapter 2** and **Appendix A** of the IRIG-106 Telemetry Standards.

Properties of a Sine Wave That Can Be Varied

$$s(t) = A sin(2\pi f t + \varphi)$$

amplitude frequency phase



where:

s(t) is the instantaneous amplitude of the RF signal at time t in seconds

A is the amplitude

f is the frequency in Hertz

2 π is the number of radians in a period, T, where π = 3.1416

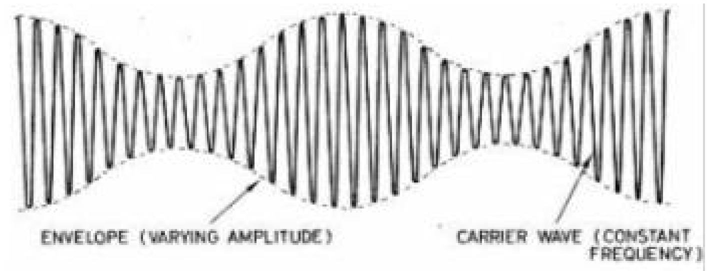
T is the period in seconds and is equal to 1/ f

ϕ is the phase in radians

Modulation Types

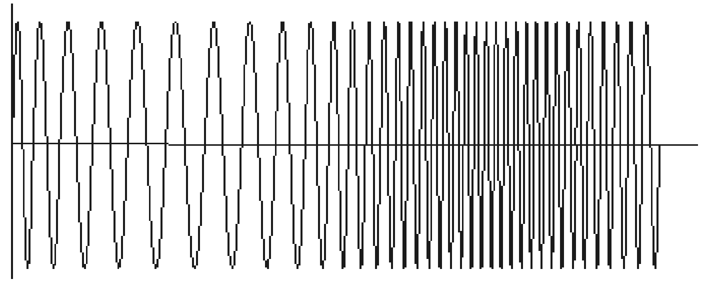
Amplitude Modulation (AM):
the amplitude of the signal varies with time.

$$s(t) = A(t)sin(2\pi ft + \varphi)$$



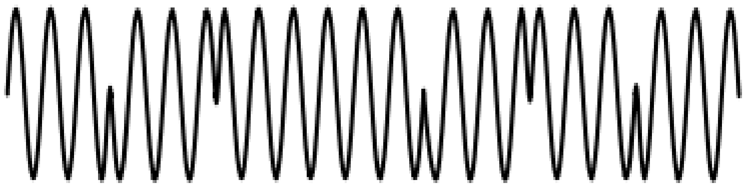
Frequency Modulation (FM):
the frequency of the signal varies with time.

$$s(t) = Asin(2\pi f(t)t + \varphi)$$



Phase Modulation (PM):
the phase of the signal varies with time. In this illustration, the phase jumps between 0° and 180°.

$$s(t) = Asin(2\pi ft + \varphi(t))$$



Telemetry Bands

$$s(t) = A\sin(2\pi f_c t + \varphi)$$

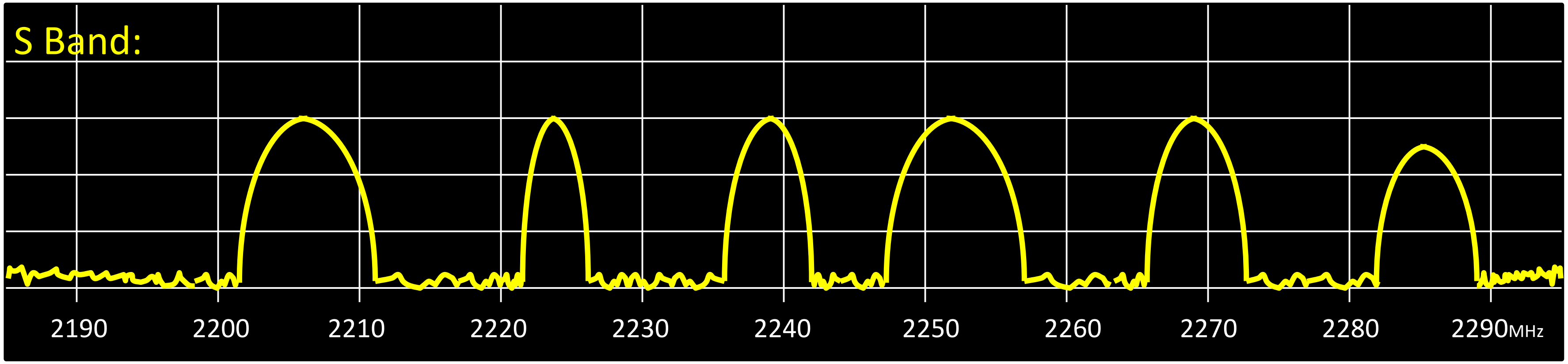
The signal s(t) is the waveform that is output from the transmitter in the telemetry system. The frequency of the signal is the carrier frequency (or center frequency) of the transmission. The allowable values of f_c are defined in the IRIG-106 Telemetry Standards and are assigned by the frequency coordinator of the Test Range.

BAND	Lower Freq (MHz)	Upper Freq (MHz)
Lower L	1435	1525
Lower S +	2200	2290
Upper S	2360	2395
Lower C	4400	4940
Middle C *	5091	5150
Upper C *	5925	6700

+ telemetry restrictions present within the band
* in the process of being approved for TM use (IRIG-106-17)

Telemetry Bands

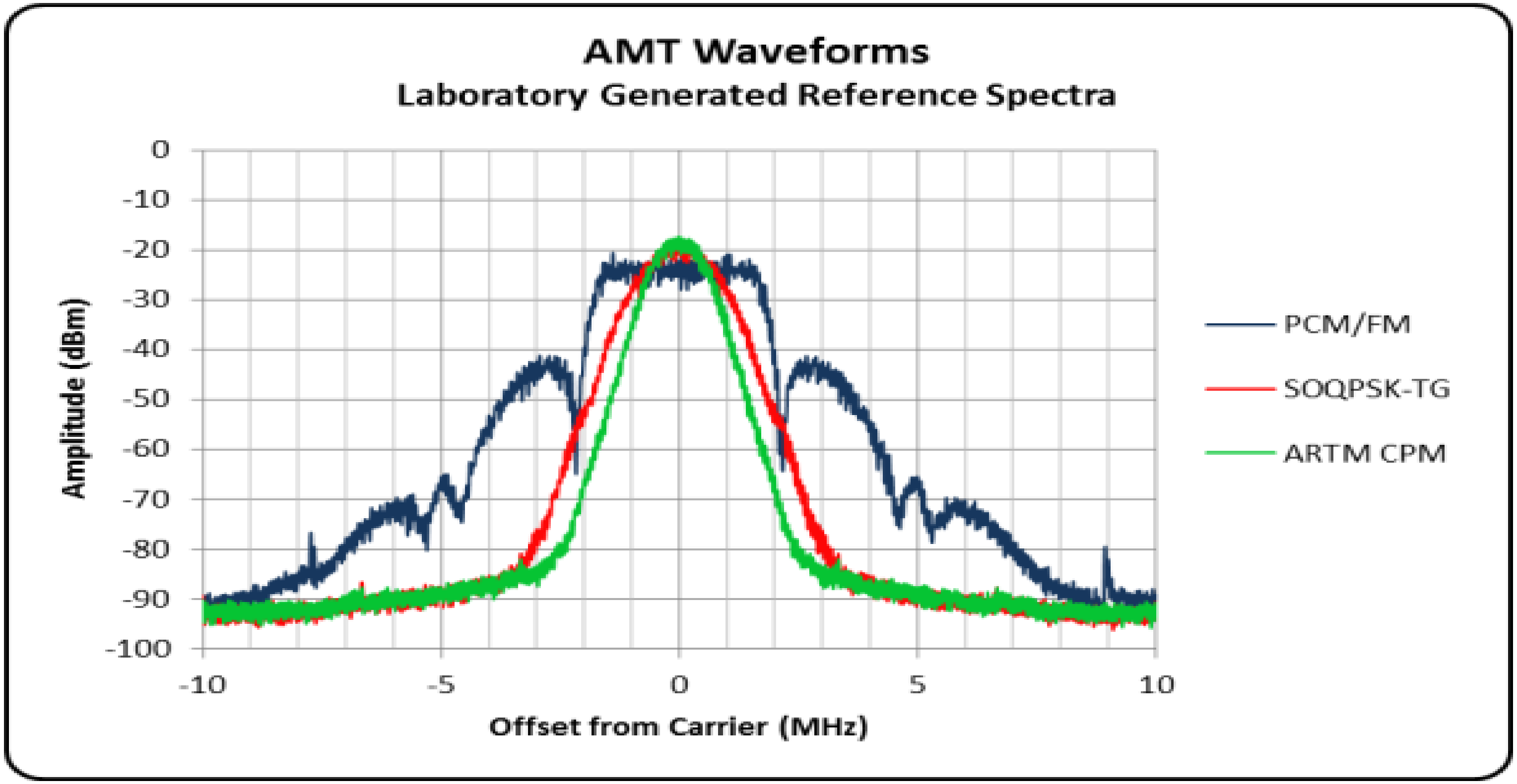
- The frequency coordinator at the Test Range assigns center frequencies of the TM spectrums of all the transmitting flight tests on the range such that they do not interfere with one another.



- In order to do this, Chapter 2 and Appendix A of the IRIG-106 Telemetry Standards provides guidance for the most effective use of the telemetry bands based upon the bit rate of the transmitted PCM stream.

Modulation Scheme RF Spectrum Comparison

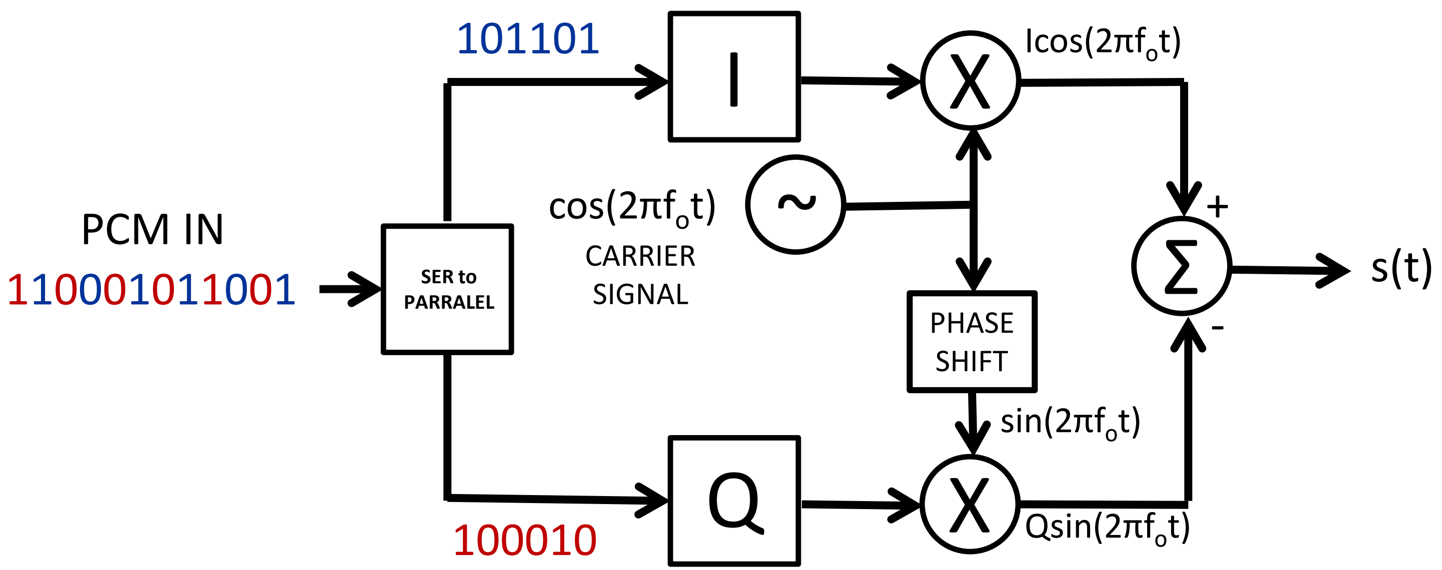
- To conserve bandwidth, SOQPSK-TG is used over the traditional PCM/FM used in the past for telemetry. CPM is not widely utilized at this point in time. The comparative bandwidths are shown below.



SOQPSK-TG utilizes 2/3 of the 99% power bandwidth as **PCM/FM**, which is why it's not used as often.

SOQPSK-TG Modulation Block Diagram

- SOQPSK is described in the IRIG-106 Standard in **Chapter 2** and **Appendix A**. This specific variation of SOQPSK is developed by the Telemetry Group of the Range Commander's Council (RCC) and is designated as SOQPSK-TG. SOQPSK is a form of phase modulation.

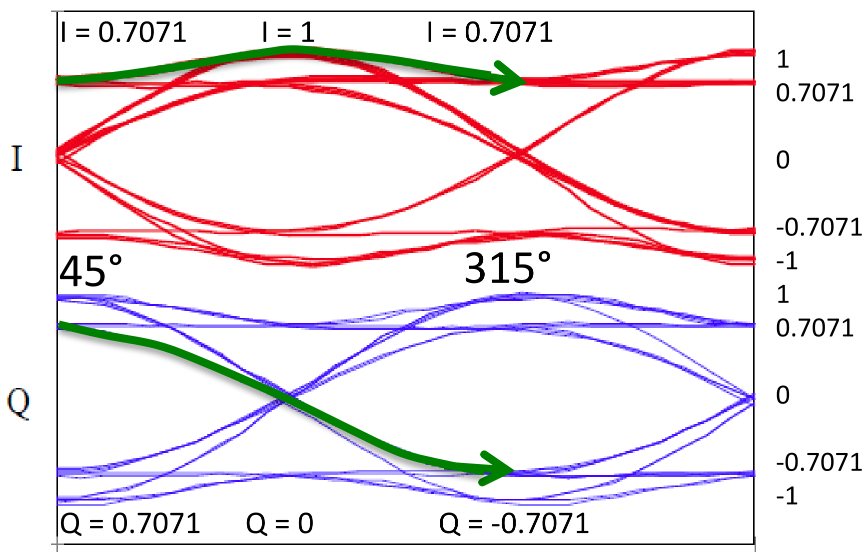


$$s(t) = Icos(2\pi f_o t) - Qsin(2\pi f_o t) = \sqrt{I^2 + Q^2}\, cos\left(2\pi f_o t + \tan^{-1}\frac{Q}{I}\right)$$

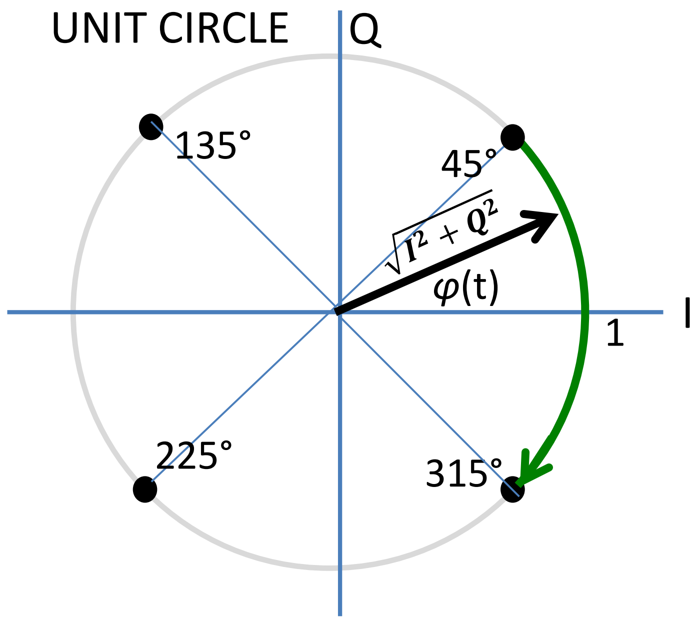
amplitude frequency phase

SOQPSK-TG - Controlling the Phase Shift of the RF Carrier

- In-phase (I) and quadrature (Q) signals are used to control the phase shift φ(t) of the modulated TM signal. This example shows a phase shift from 45° to 315°.



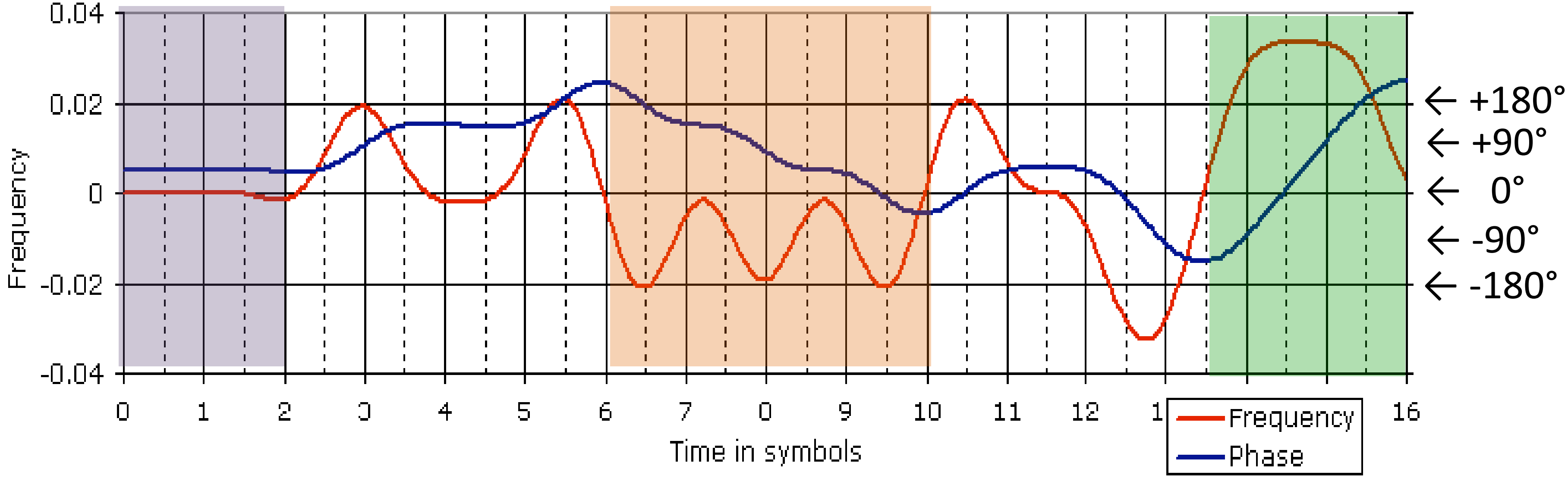
Eye patterns of the In-phase and quadrature channels in the time domain.



Magnitude = $\sqrt{I^2 + Q^2} = 1$

φ(t) = $\tan^{-1} \frac{Q}{I}$

SOQPSK-TG - Phase Shifting the Frequency of the RF Carrier

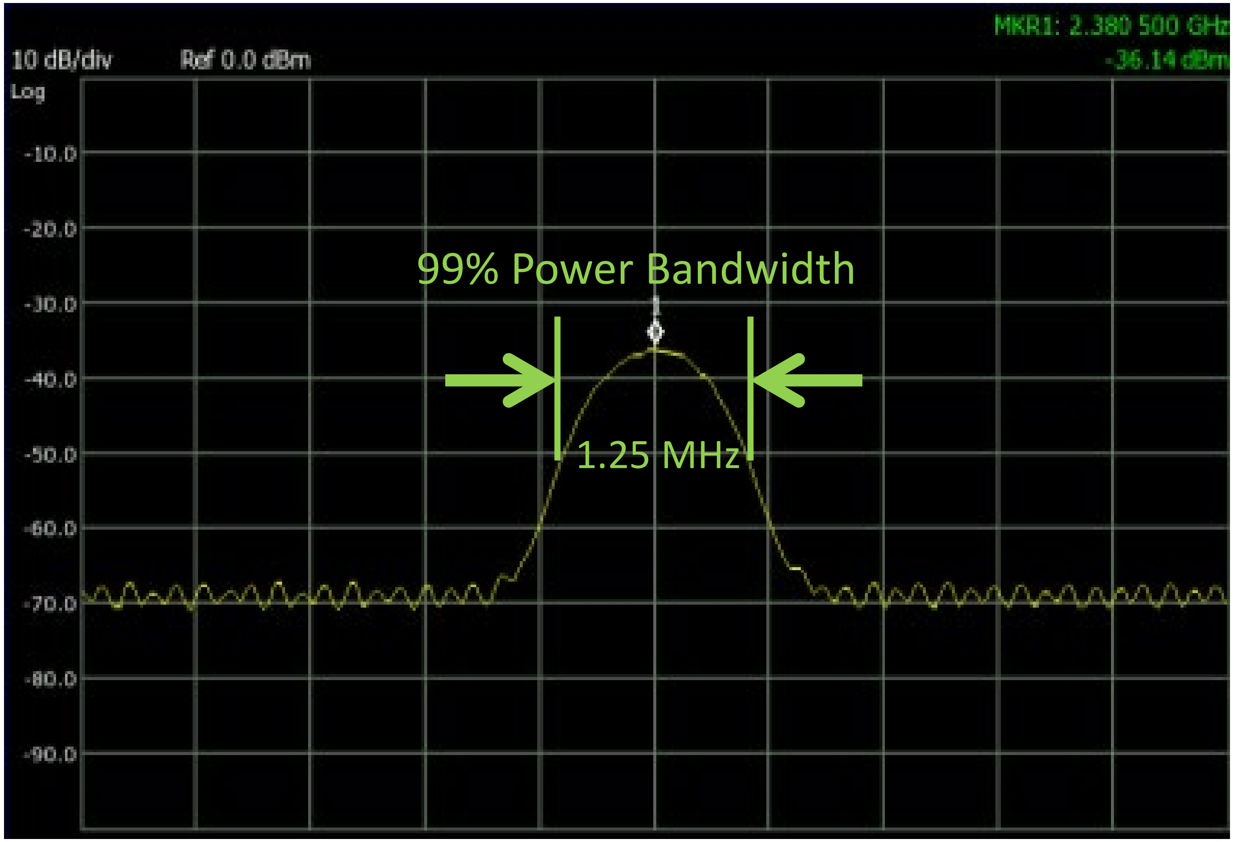


As I and Q modulates the phase, note that the frequency of the carrier is also changing.

Frequency is the time derivative of phase: $f(t) = \frac{d}{dt}\emptyset(t)$

and you can see this in the shaded areas of the graph. When the phase is increasing (green) the frequency shift has a positive value, when the phase is decreasing (orange), the frequency shift has a negative value, and no phase change (purple) has a zero frequency shift.
Conversely, phase is the integral of frequency: $\emptyset(t) = \int f(t)dt$

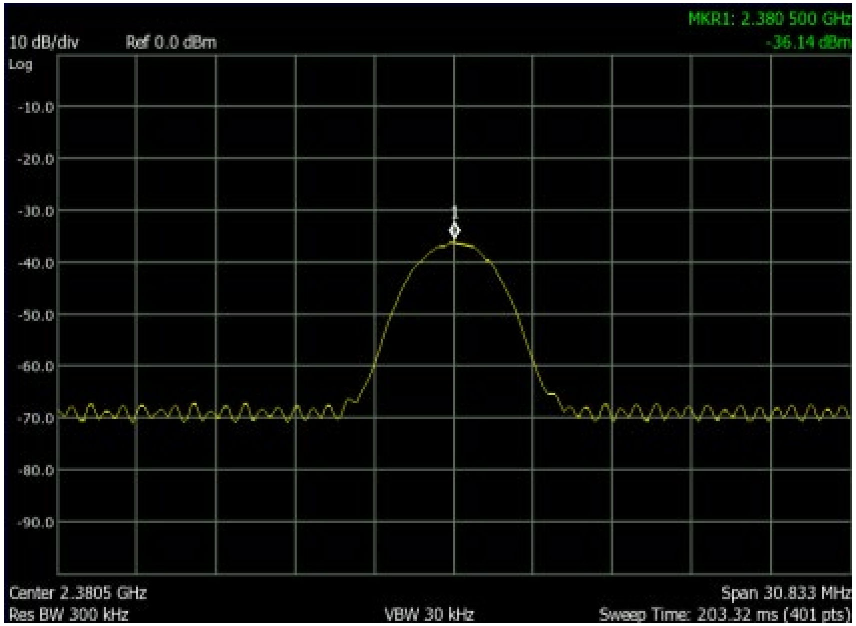
Telemetry Spectrum – 99% Power Bandwidth



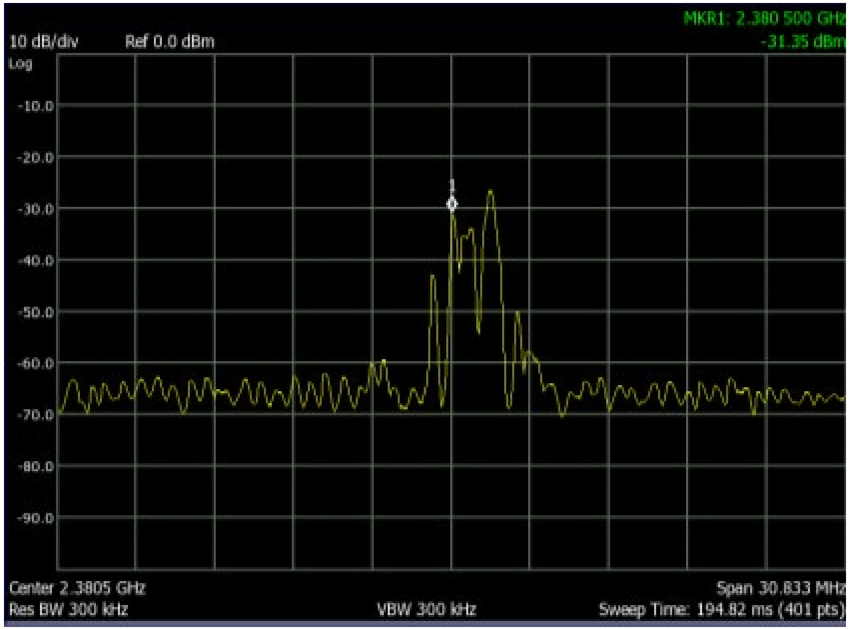
When the phase is modulated, it creates a frequency spectrum as shown above. 99% of the power of an SOQPSK spectrum falls within a bandwidth of 0.78 x Bit Rate. For our example of 1.6 Mbps, the 99% power bandwidth is 1.25 MHz. With PCM/FM the bandwidth would be 1.9 MHz (1.16 x Bit Rate).

Telemetry Spectrum – Proper and Improper SOQPSK Spectrums

- The SOQPSK-TG spectrum shown in the frequency domain. The spectrum on the right illustrates an improperly modulated due to a non-randomized NRZ-L.



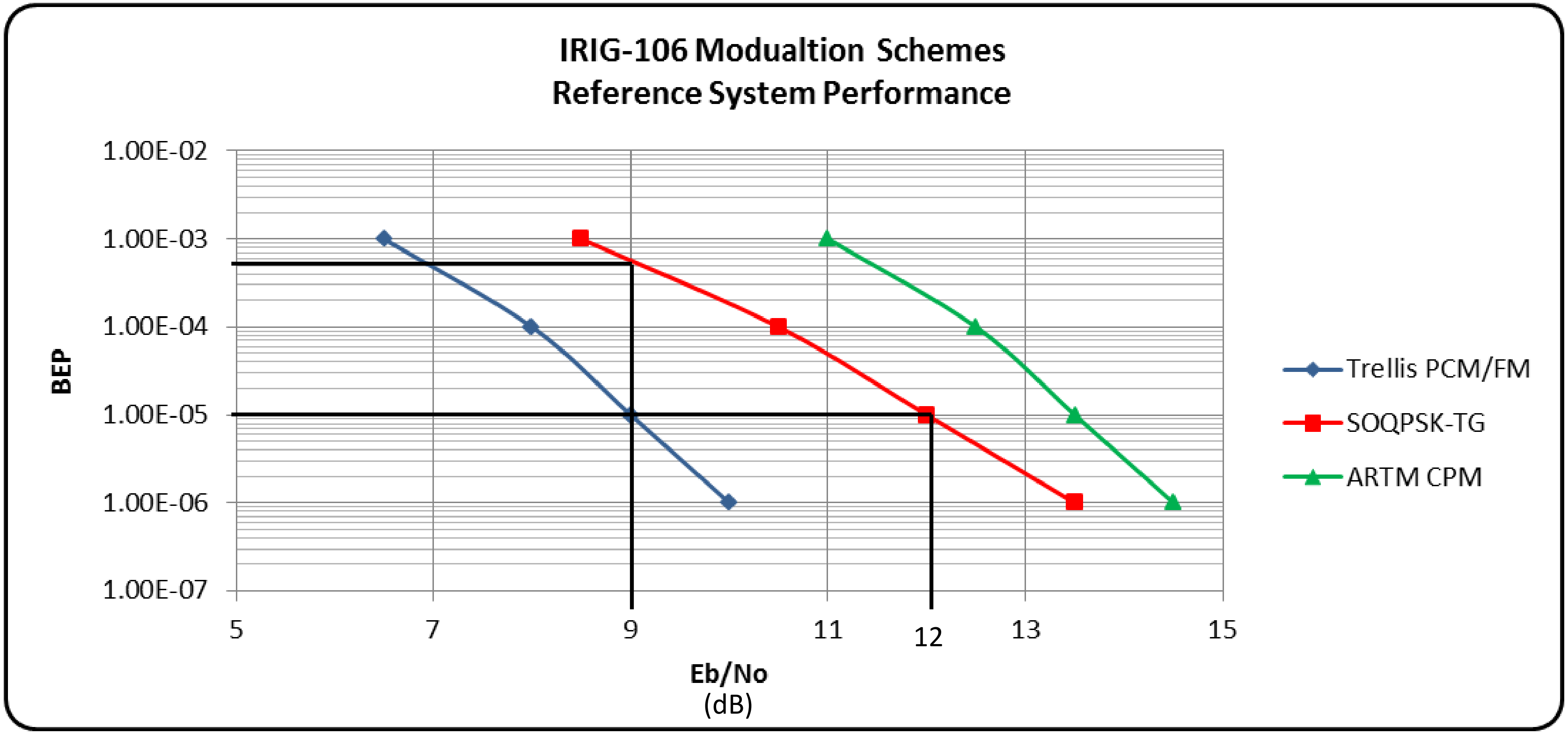
Good spectrum shape, no dips or spikes in the spectrum.



Bad SOQPSK spectrum – transmitter modulated with a non-randomized NRZ-L PCM stream resulting in long strings of 1s and 0s.

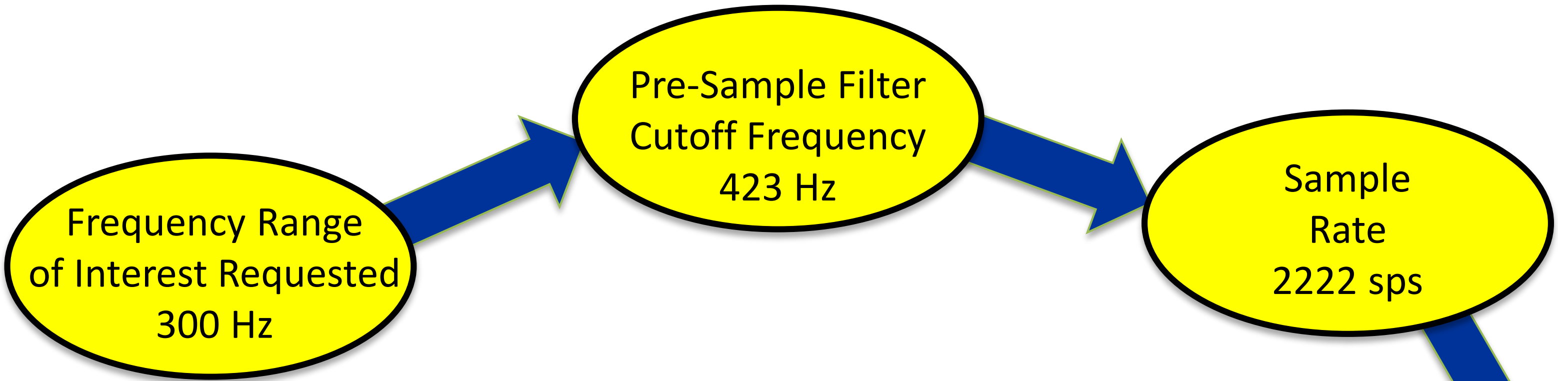
Saving Bandwidth at the Cost of Detection Efficiency

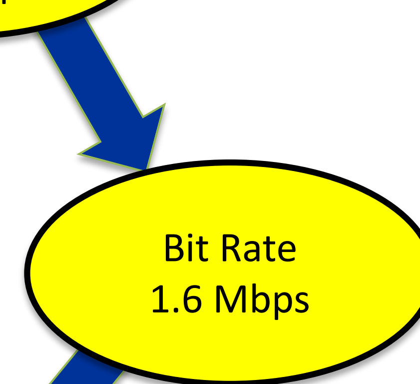
- The increased efficiency in bandwidth for SOQPSK over PCM/FM comes at a cost of detection efficiency. The result is more bit errors or a shorter transmitting range.



As an example, for a signal to noise ratio (Eb/No) of 9 dB, PCM/FM will have 10 bit errors per million bits, where SOQPSK-TG will have 550. For SOQPSK-TG to have the same bit error rate, the signal to noise ratio would have to be raised to 12 dB. For CPM it is even higher.

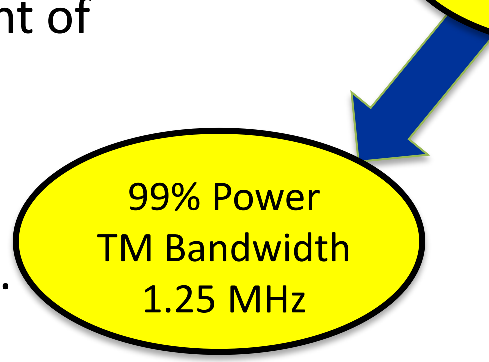
Telemetry Bandwidth Relation to the Frequency Range of Interest





Think back to the requirements and where the design process started. You can see where the decisions made when filling out the requirements for the frequency range of interest directly affects the resulting amount of bandwidth being utilized.

This is why the Frequency Range of Interest entry is the *most important* data requirement.



Telemetry System

- At frequencies in the GHz range, it is important to match all the components. The RF cable, splitter, relay, terminator, and antennas must all be designed for the frequency band being used.


Transmitter

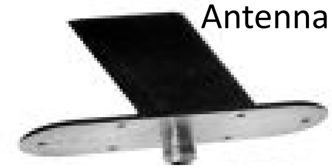

Power Splitter


Terminator


Relay

BAND	Lower Freq (MHz)	Upper Freq (MHz)
Lower L	1435	1525
Lower S +	2200	2290
Upper S	2360	2395
Lower C	4400	4940
Middle C *	5091	5150
Upper C *	5925	6700


RF Cables


Antenna

+ telemetry restrictions present within the band
* in the process of being approved for TM use (IRIG-106-15)

The decibel

- Spectrum analyzers use the **decibel (dB)** as the units of the vertical axis.

- The **decibel** (**dB**) is a logarithmic unit of measurement that expresses the magnitude of a physical quantity (usually power) relative to a specified or implied reference level. A factor of 10 results in the prefix of *deci* in decibel.

- A simpler explanation is that a dB is a unit of power gain.

- The equation for determining decibels is: $$dB = 10\log\left(\frac{P_{MEAS}}{P_{REF}}\right)$$

- Spectrum analyzers also have a reference level in units of dBm. The equation is the same as with dB, but P_{REF} is 1 mW.

Why was the gain of the pre-sample filter $dB = 20log\left(\frac{Vout}{Vin}\right)$?

The decibel

- At the very minimum, you should understand that negative dB's are factors less than one (attenuation) and positive dB's are factors greater than one (gain).

If you are at a meeting and hear dB levels thrown about, keep these relationships in your head:

- Every 10 dB is a factor of 10 in gain, every -10 dB, 1/10.

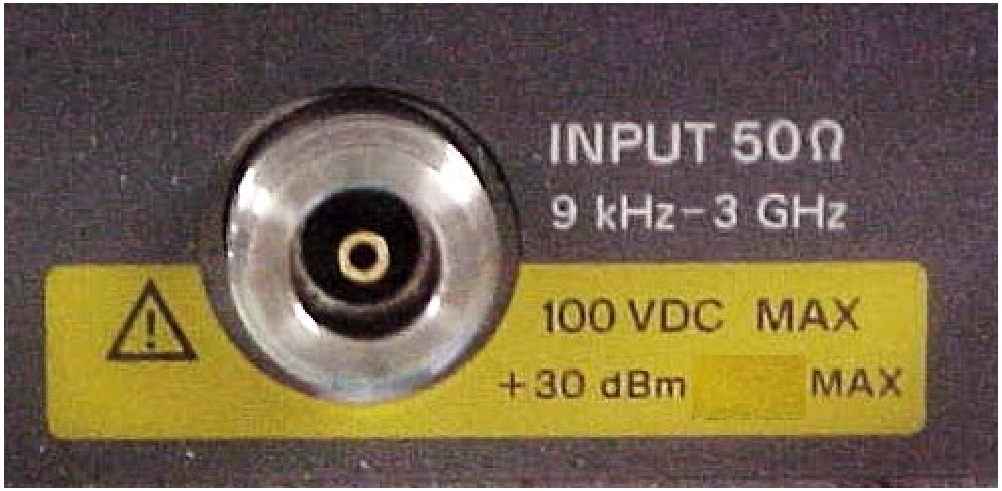
0 dB = a factor of 1	
10 dB = a factor of 10	-10 dB = a factor of 1/10
20 dB = a factor of 100	-20 dB = a factor of 1/100
30 dB = a factor of 1000	-30 dB = a factor of 1/1000

- Every 3 dB *approximately* doubles the output, every -3dB *approximately* halves the output.

0 dB = a factor of 1	
3 dB ≈ a factor of 2	-3 dB ≈ a factor of ½
6 dB ≈ a factor of 4	-6 dB ≈ a factor of ¼
9 dB ≈ a factor of 8	-9 dB ≈ a factor of ⅛

The decibel

Here is a warning on the RF input to a spectrum analyzer. The maximum power input is +30 dBm, how many Watts would that be?



Every 10 dB is a factor of 10. For 30 dB, that is three factors of 10 or 1000.

dBm is in reference to 1 mW. 1000 x 1 mW = 1 W

So you wouldn’t want to connect the output of a 10 W transmitter directly to this spectrum analyzer without attenuating the RF signal first.

RF Cable

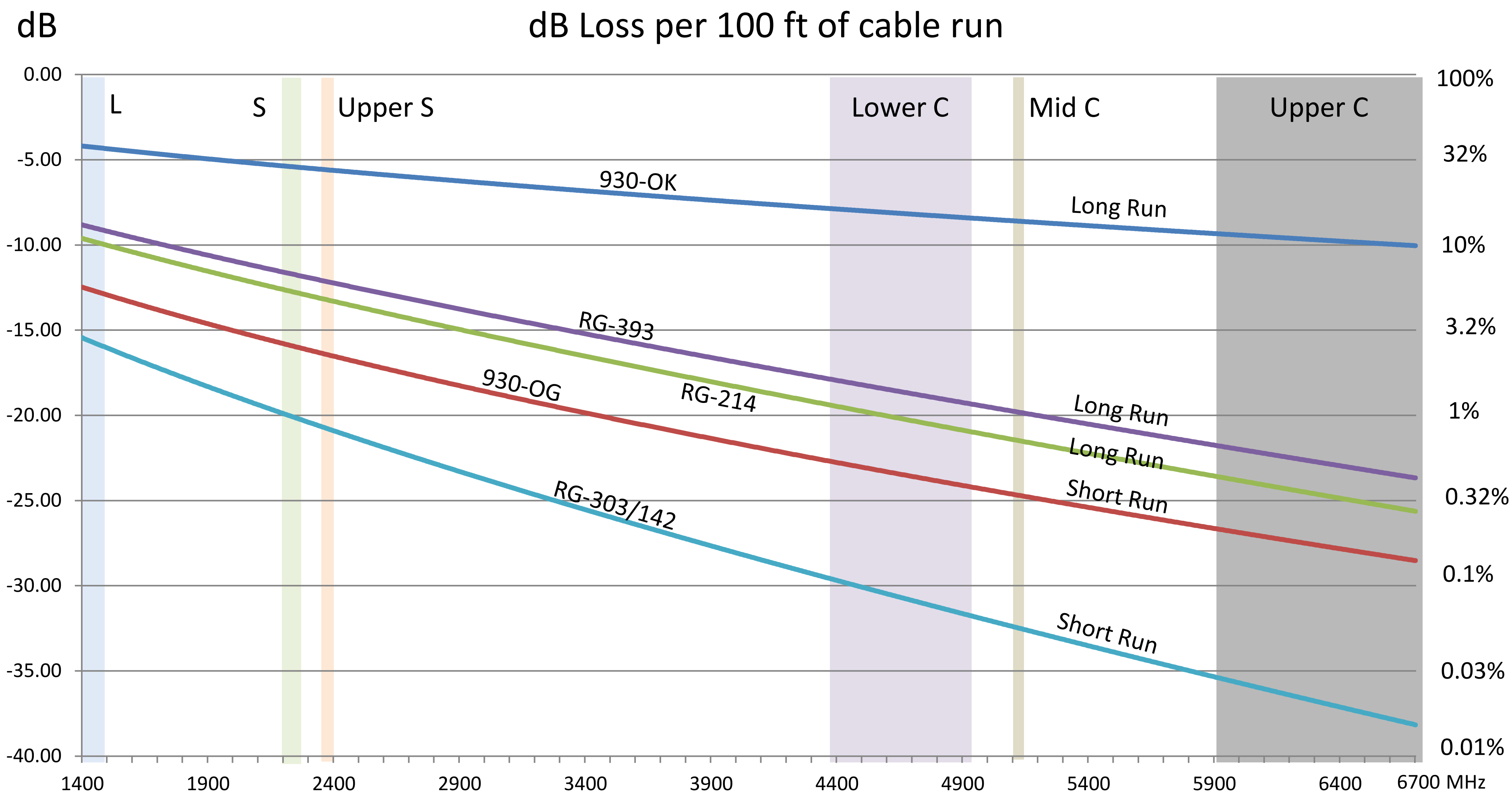
The attenuation of an RF cable at any frequency is determined by the equation:

$$\alpha = k_1\sqrt{f} + k_2 f$$

where…
α is the attenuation in dB/100ft
k_1, k_2 are the attenuation constants for a particular cable
f is the center frequency in MHz

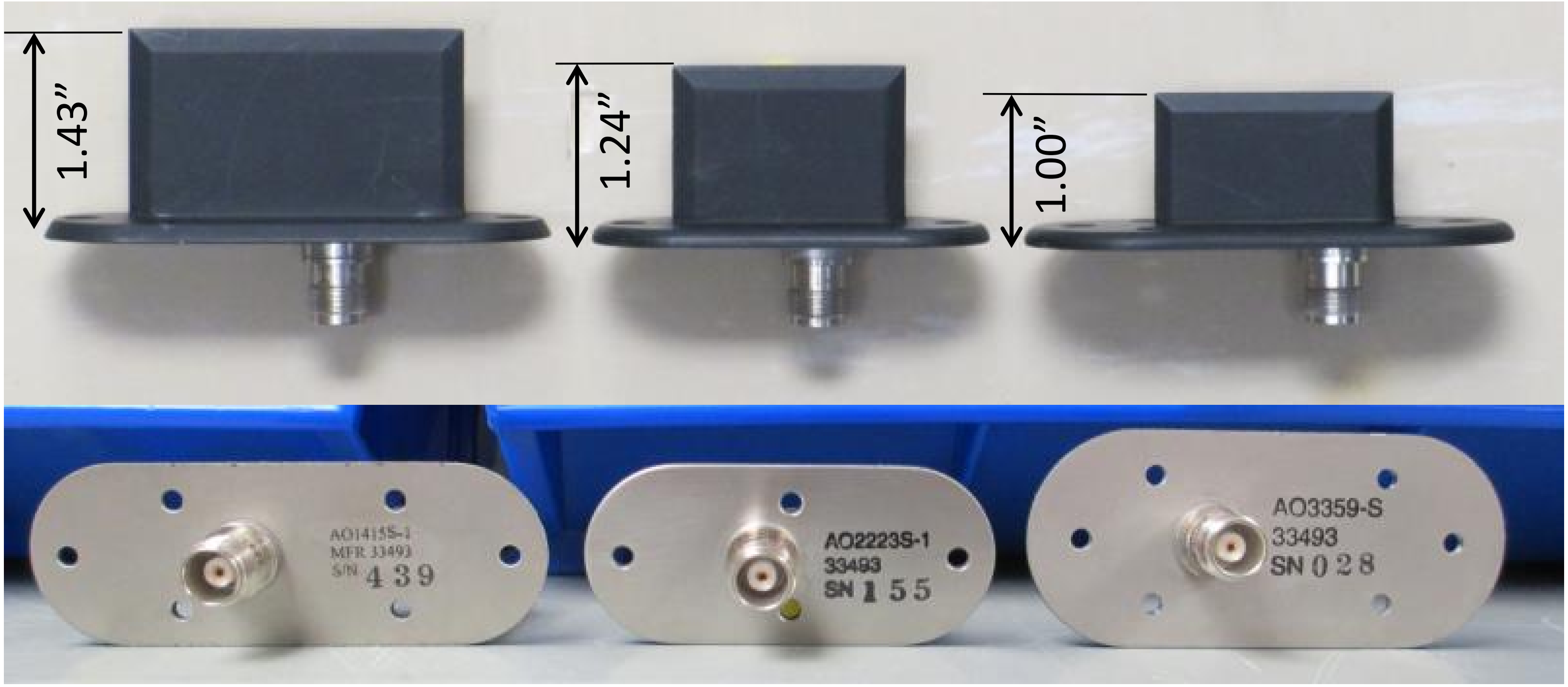
Cable Type	k1	k2
RG-303/142	0.368	0.0012
RG-393	0.191	0.0012
RG-214	0.210	0.00126
930-OG	0.321	0.000336
930-OK	0.103102	0.000239

RF Cable Frequency Response



The graph shows the dB loss per 100ft for each of the RF cable types in each of the telemetry bands. Larger diameter cable also has lower losses than the thinner cable which is why they are used for longer runs in the aircraft.

Antennas



L-Band Antenna
1.35 - 1.9 GHz

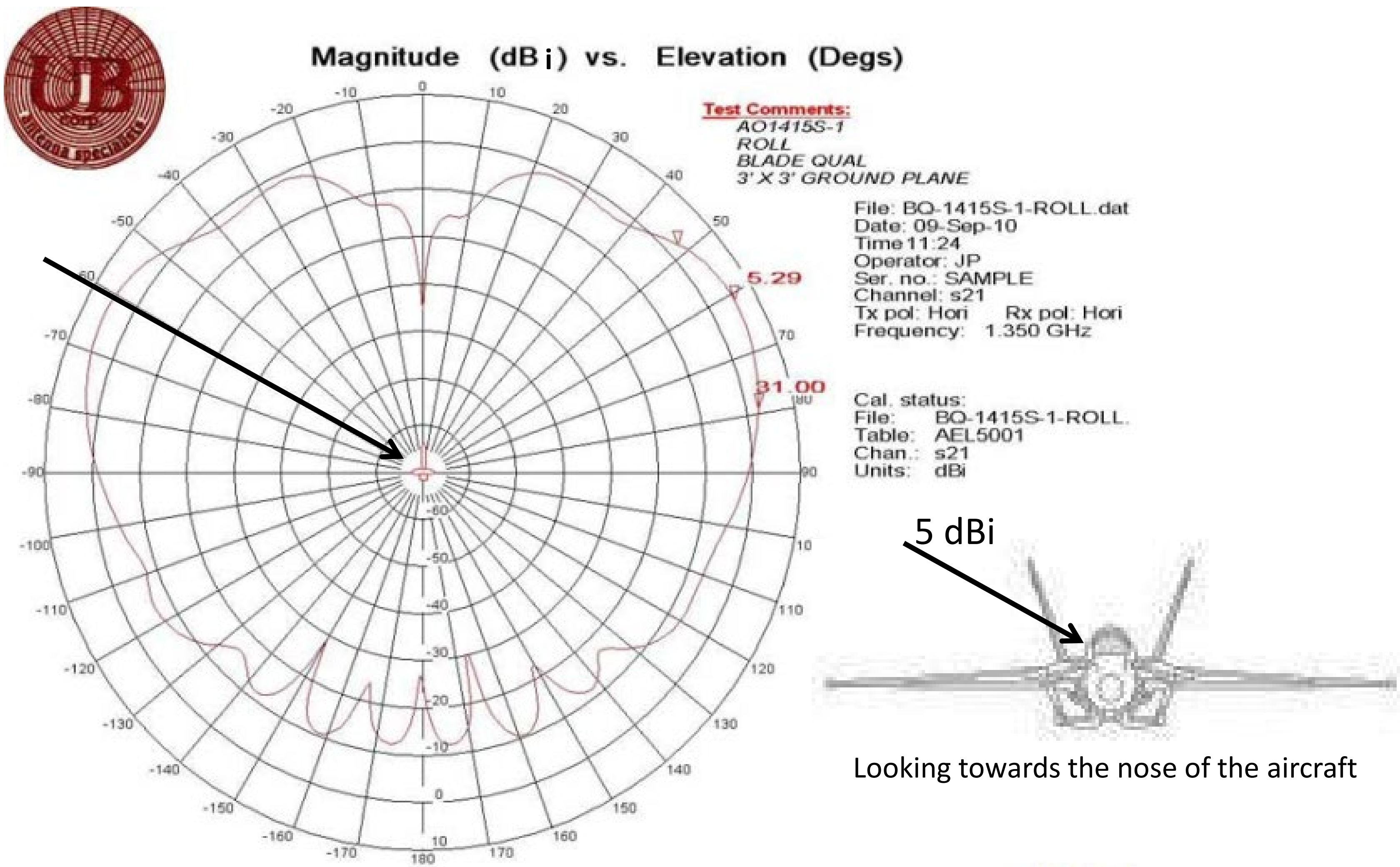
S-Band Antenna
2.2 - 2.4 GHz

C-Band Antenna
3.0 – 6.0 GHz

Higher frequencies have shorter wavelengths, which result in shorter antenna heights. Make sure the appropriate antenna is used for the frequency band used.

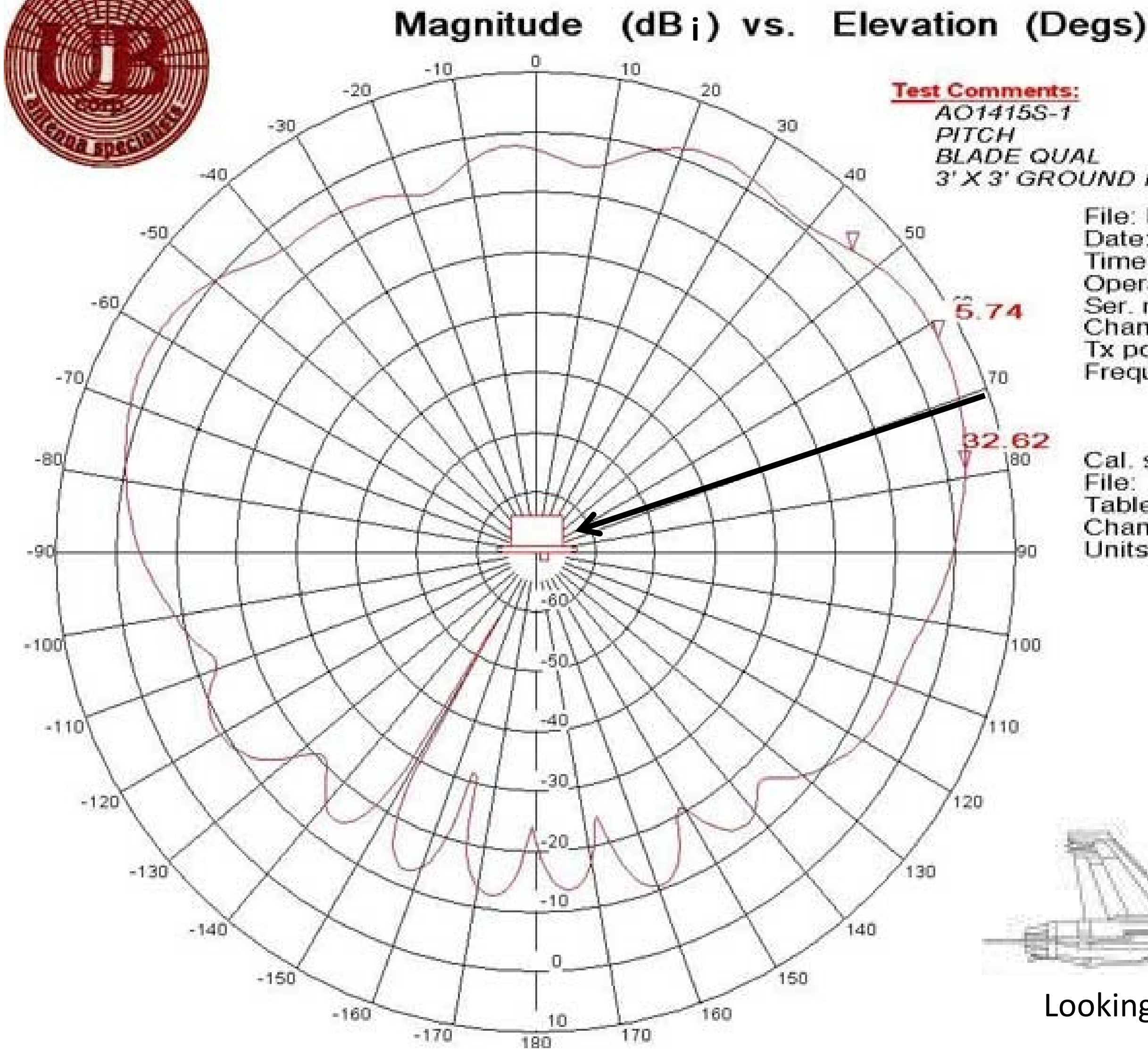
Antenna Patterns

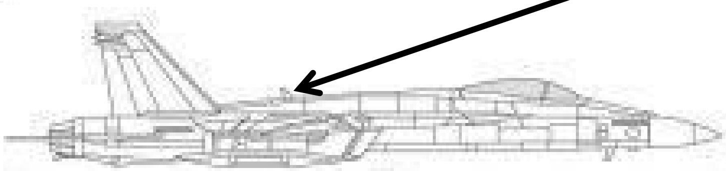
This and the following slide shows the antenna patterns for the AO1415S-1 (L-band antenna). The antenna gain is shown in both the ROLL and PITCH elevations. The units dBi refer to an isotropic (or point) source.



Looking towards the nose of the aircraft

Antenna Patterns

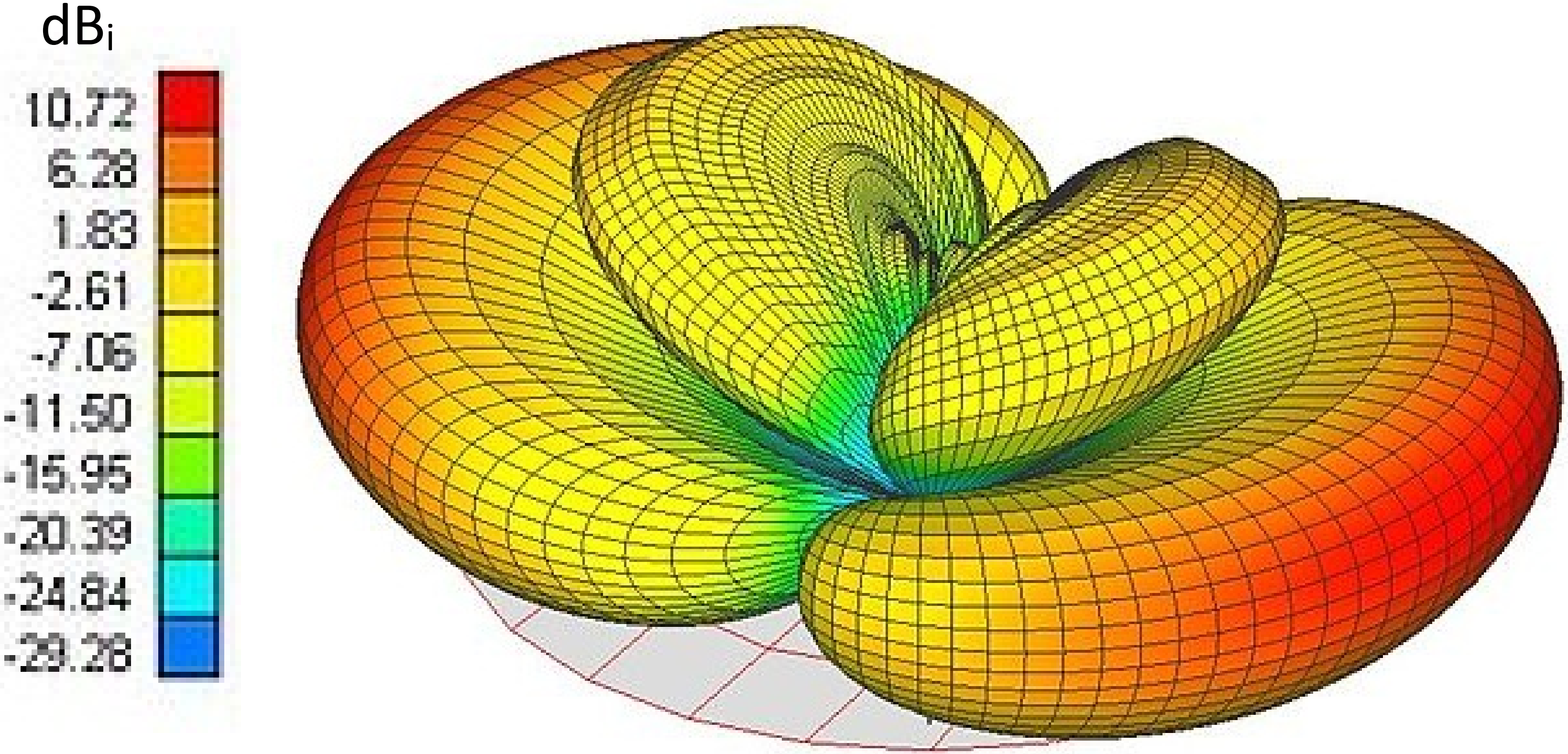




Looking towards the side of the aircraft

Antenna Patterns

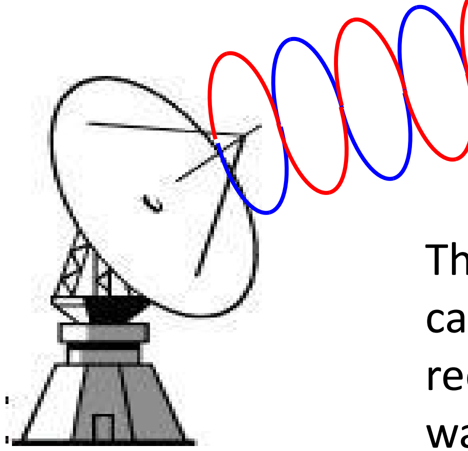
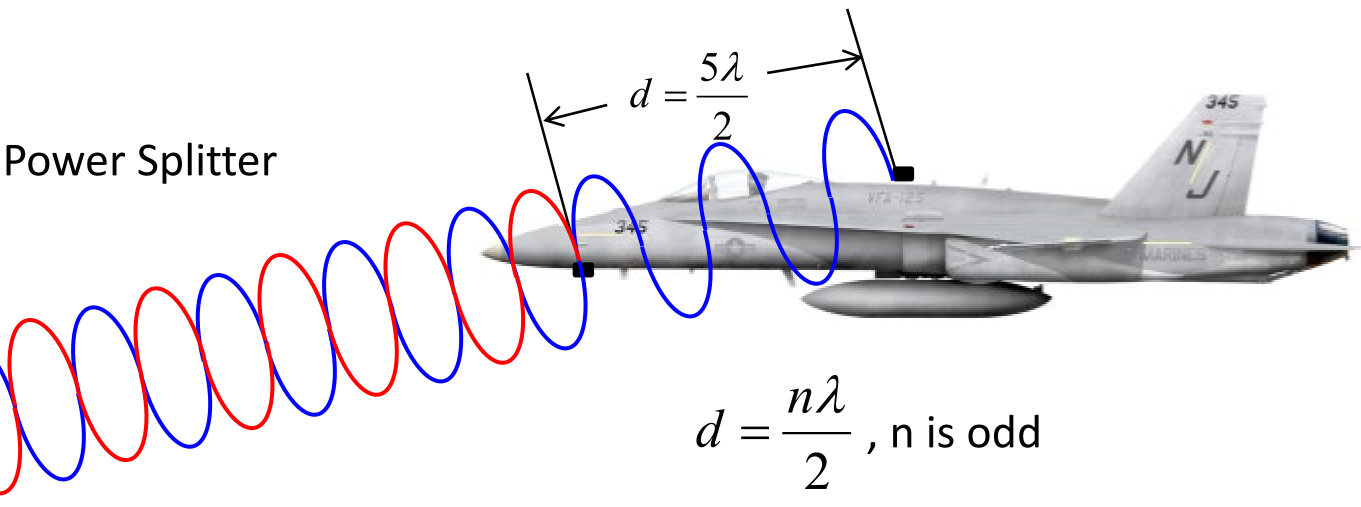
Sometimes it is difficult to visualize the antenna strength from two dimensional plots. This plot shows an antenna pattern in three dimensions.



Antenna Pattern Interference

When two (or more) antennas are located in close proximity to one another, their antenna patterns will interfere. 50/50 splitters, which evenly divide the power between the top and bottom antennas are not recommended due to the possible interfering affects of the signals.

Power Splitter

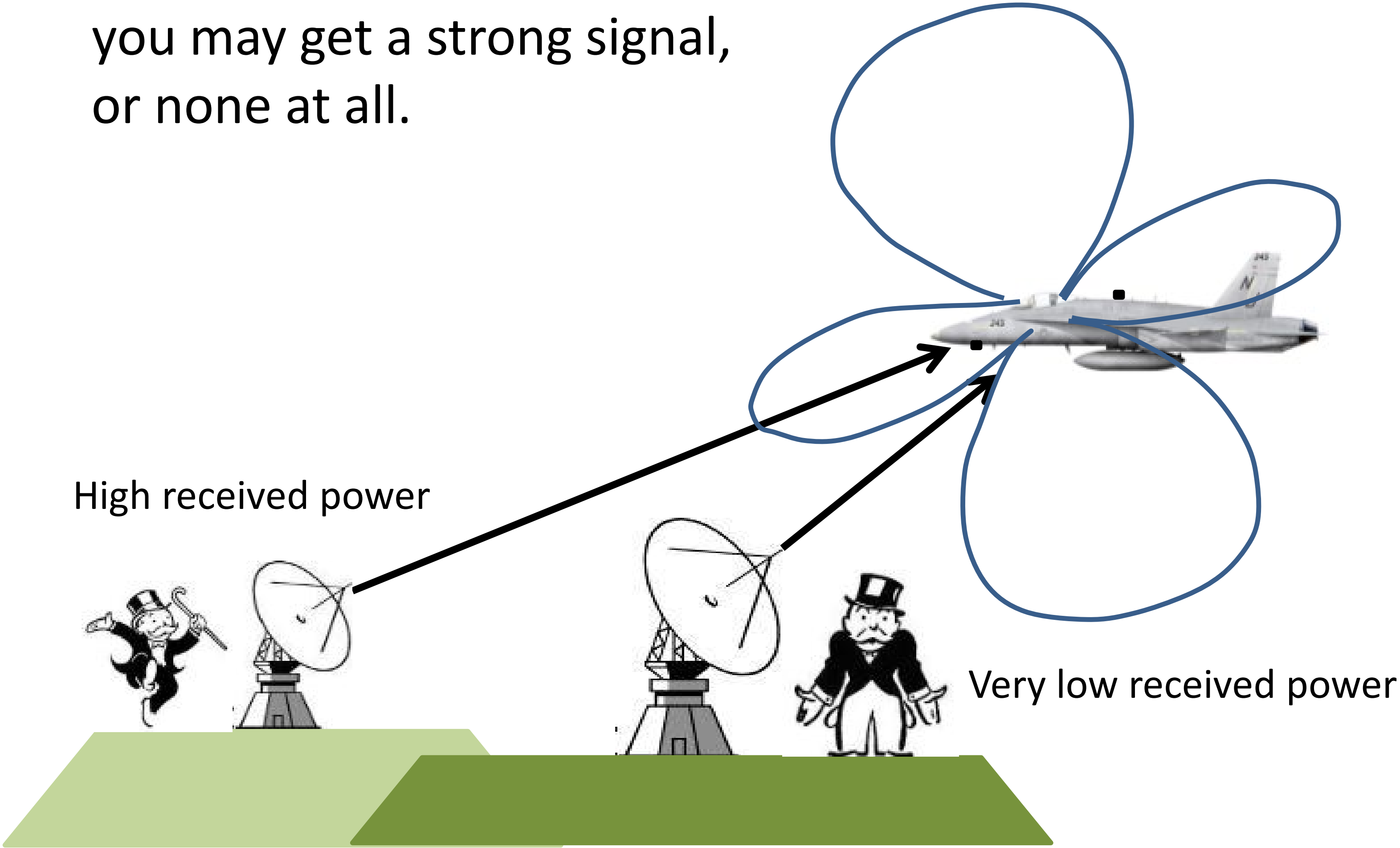



$$d = \frac{n\lambda}{2}\text{, n is odd}$$

The TM signals from each antenna will destructively interfere, causing a null in the antenna pattern if the difference in the received path of the two signals is an odd multiple of half the wavelength, λ. The length of separation depends on the orientation of the aircraft to the receiving antenna.

Antenna Pattern Interference

- Two transmitting antennas each transmitting the same power would produce an antenna pattern similar to what is shown below. Depending upon the position of the receiving antenna, you may get a strong signal, or none at all.



Antenna Power – The Link Budget

When designing the telemetry system, you must know how much power is expected at each antenna and verify that power level.

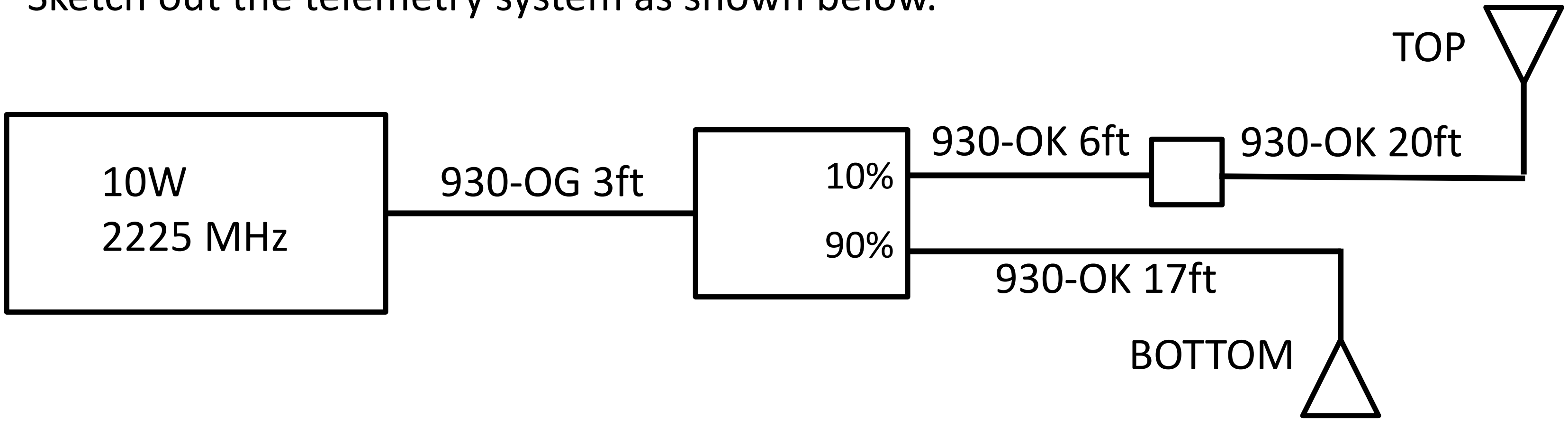
There are many components within the system that will attenuate the power:

- Cable – attenuation determined by cable type and center frequency
- Connectors – contribute -0.1dB for each connector (a barrel connector will count as two connectors)
- Splitter – divides the power to each output.

Draw out your telemetry system and determine the drops along each element of the system.

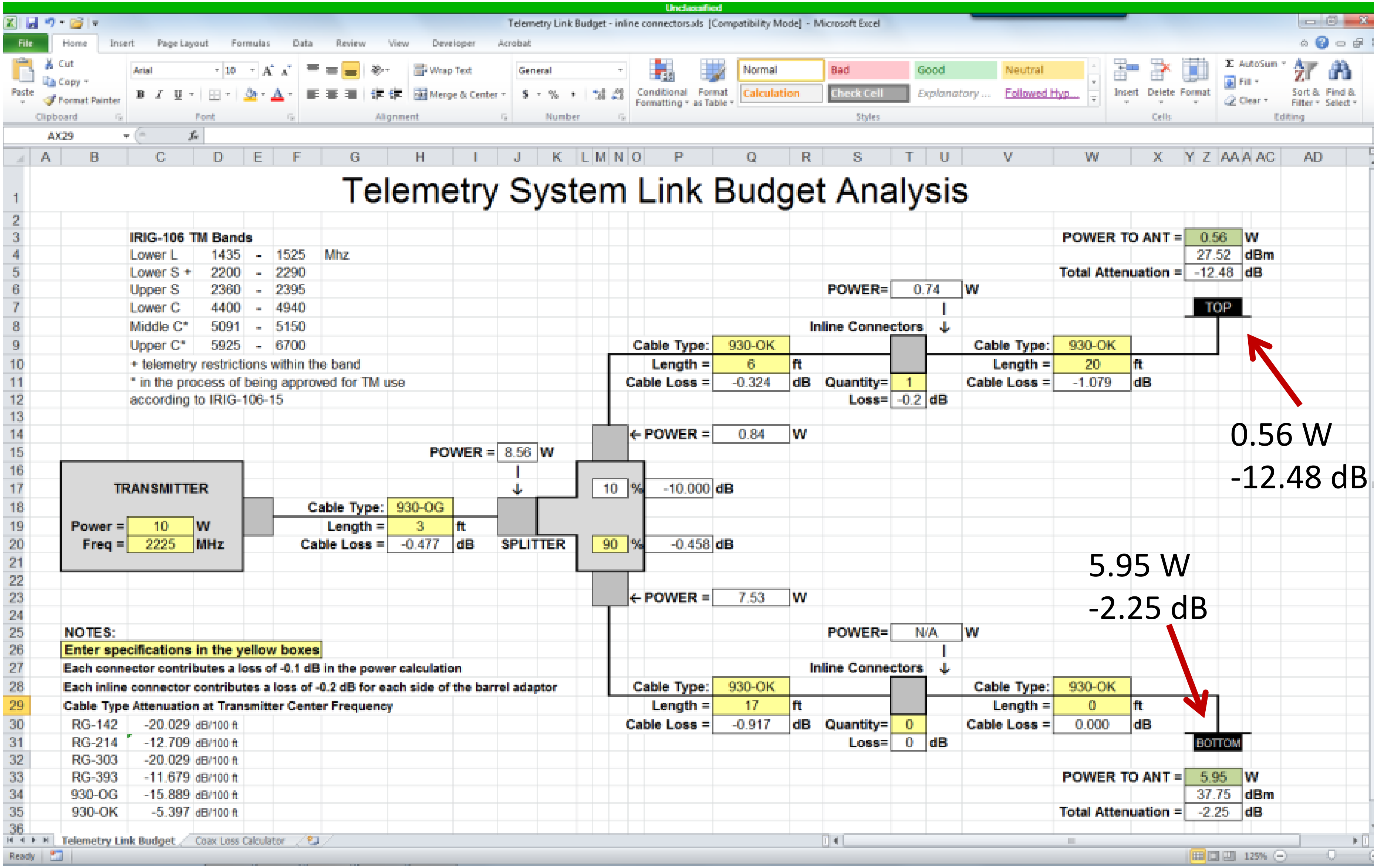
Antenna Power – The Link Budget

Say we have a 10W transmitter that will have a center frequency of 2225 MHz. The power will be split 90/10, with 90% going to the bottom antenna. 930-OG will be run from the transmitter to the splitter, and 930-OK will be used from the splitter to the antennas. The run to the top antenna will have a barrel connector.
Sketch out the telemetry system as shown below.



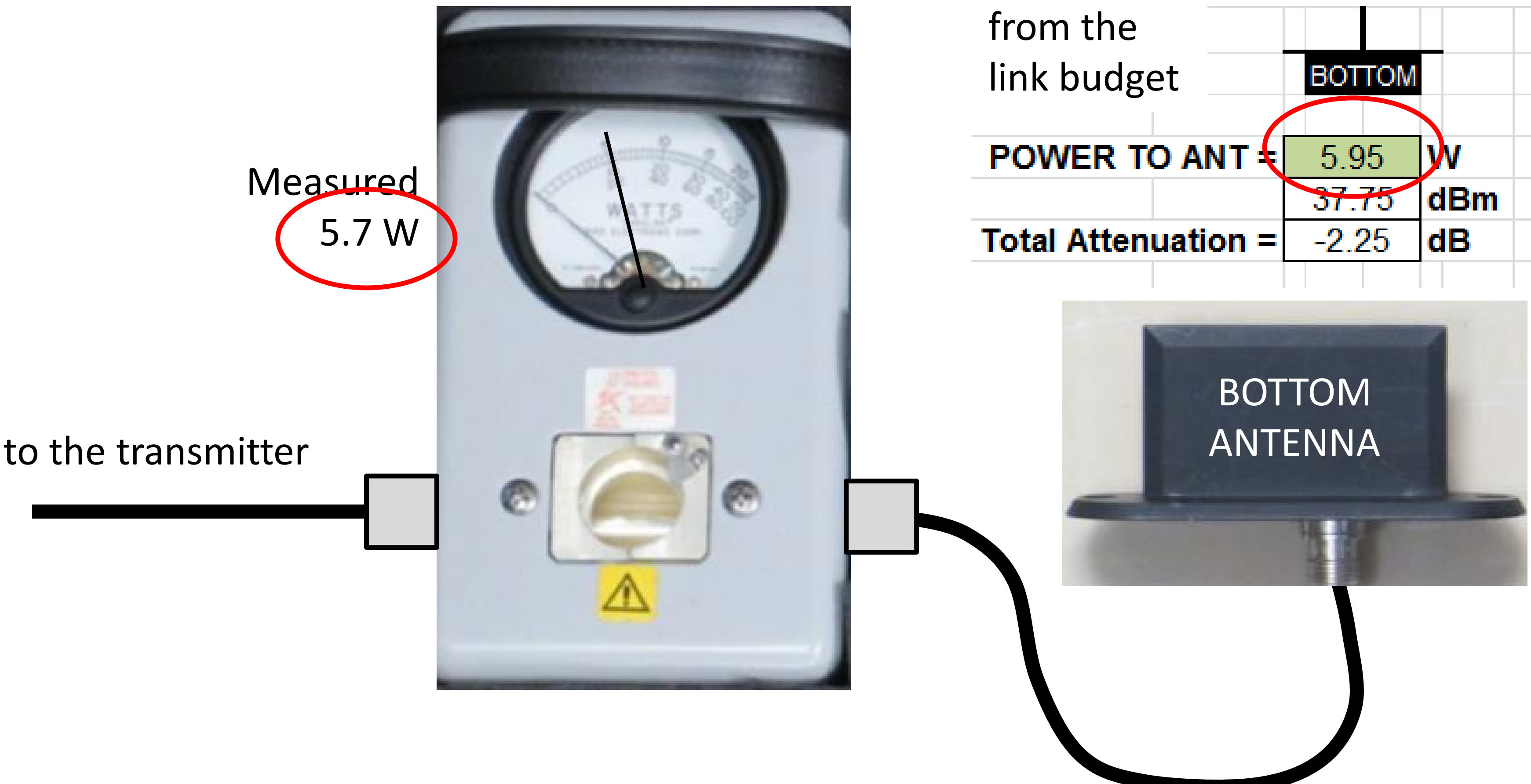
Take each segment of cable and connector to calculate the power loss. Each path's loss is added to determine the amount of power at the antenna. The results are on the next slide.

Antenna Power – The Link Budget



Antenna Power – The Link Budget

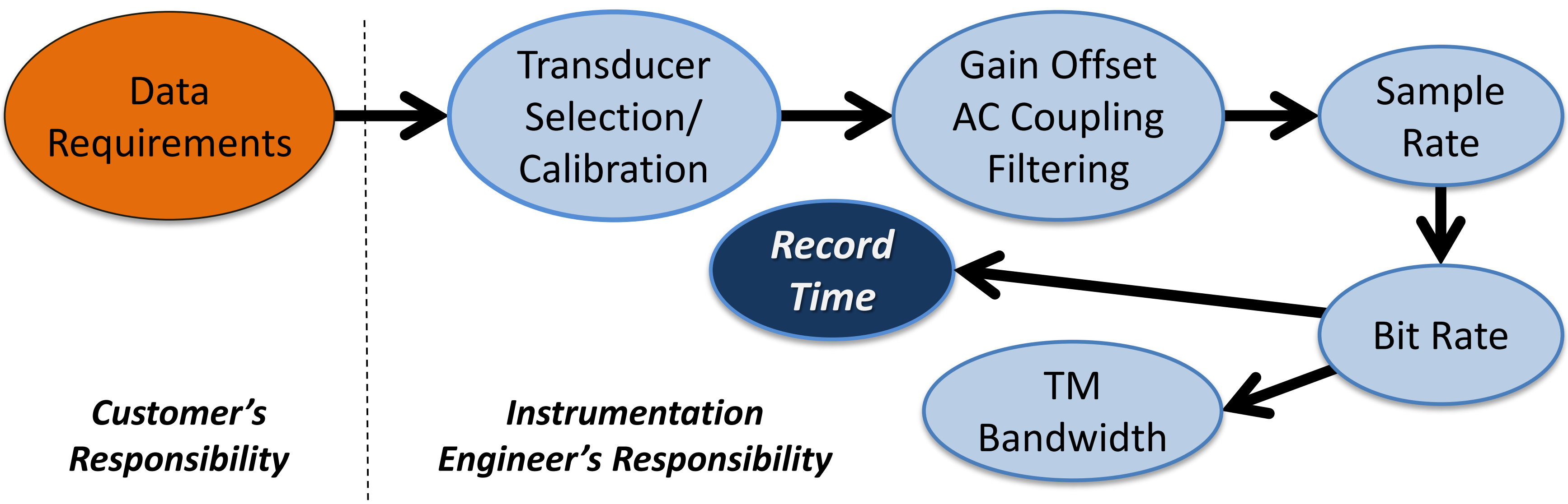
The measured power levels should be close (within ½W) to the theoretical value calculated in the link budget. If not, check the power at the other connections and try to narrow down where the issue may lie.



Record Time

Record Time

- The memory capacity of the recorder is determined by the bit rate and the amount of record time is needed for a test.
- Some tests require recorded data from when the aircraft leaves the line, to when it returns. Others require turning the recorder on and off before and after events.
- Make sure you understand what you need because a change could result in a different recorder having to be used.



Chapter 4 Recorders

- Chapter 4 recorders only record one PCM data stream.
- Here is a portion of a data file in a .bin file format (expressed in hexadecimal). The data file structure is in 16-bit "Little Endian" form. The PCM format being recorded follows overhead words created by the recorder for each minor frame.

ADDEEFBE7B7ECCDF0A0C1F826BFE40281C007B7ECCDFE80B692F04F9…

DEAD	Block Header	Recorder Overhead
BEEF		
7E7B	Header Time (245:14:34:34.363082)	
DFCC		
0C0A		
821F	PCM Info Word (recorder status word)	
FE6B	PCM Frame Sync	
2840		
001C	Sub Frame ID (29TH minor frame)	
7E7B	PCM Embedded Frame Time (245:14:34:34.363048)	
DFCC		
0BE8		
2F69	PCM Data Words	
⋮		

Example: Pressure Altitude $2F69_H$ = 12,137 counts equivalent to 6,608.5 feet

Record Time / Memory Capacity

- Required record time is the amount of time you need to be recording data.
- The size of the memory cartridge is determined from the bit rate of the Pulse Code Modulation (PCM) stream multiplied by the amount of record time.
- For the example with the accelerometer measurement, the recording of a PCM stream with a bit rate of 1.6 Mbps for four hours
  - The amount of bits to be recorded in four hours is

$$\left(1.6x10^6\,\frac{bits}{sec}\right)(4\ hours)\left(\frac{60\ min}{hour}\right)\left(\frac{60\ sec}{min}\right) = 2.3x10^{10}bits$$

  - There are 8 bits in a Byte, so the capacity needed is $2.88x10^9$ Bytes or 2.88 GB
- If the recorder adds overhead bits to the PCM stream (which in the previous slide it does), you would even need more memory capacity.

Record Time / Memory Capacity

- This particular recorder adds the overhead to each minor frame.

PCM Minor Frame = 288 bits

```
DEAD BEEF 7E7B DFCC 0C0A 821F FAF3 2000 52A7 F682 44A7 … 3D76
```

Recorder Overhead = 96 bits FS SFID 21 DATA WORDS

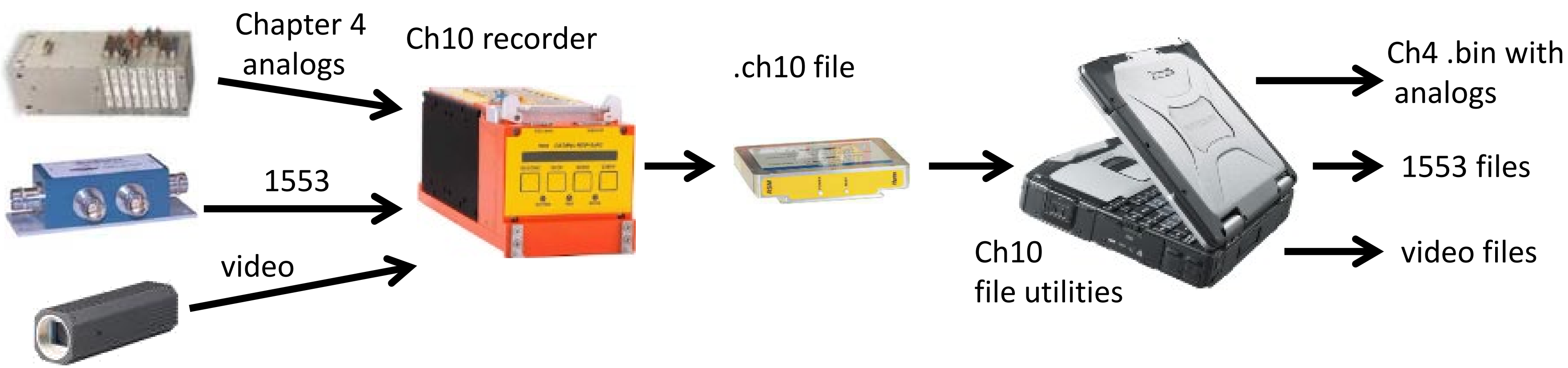
$$\frac{Overhead\ and\ Minor\ Frame\ Bits}{Minor\ Frame\ Bits} = \frac{96 + 288}{288} = \frac{384}{288} = 1.3333$$

- With 33.3% more bits to record per minor frame, the memory capacity required is:

1.3333 x 2.88 GB = 3.84 GB, so a 4 GB cartridge would be adequate.

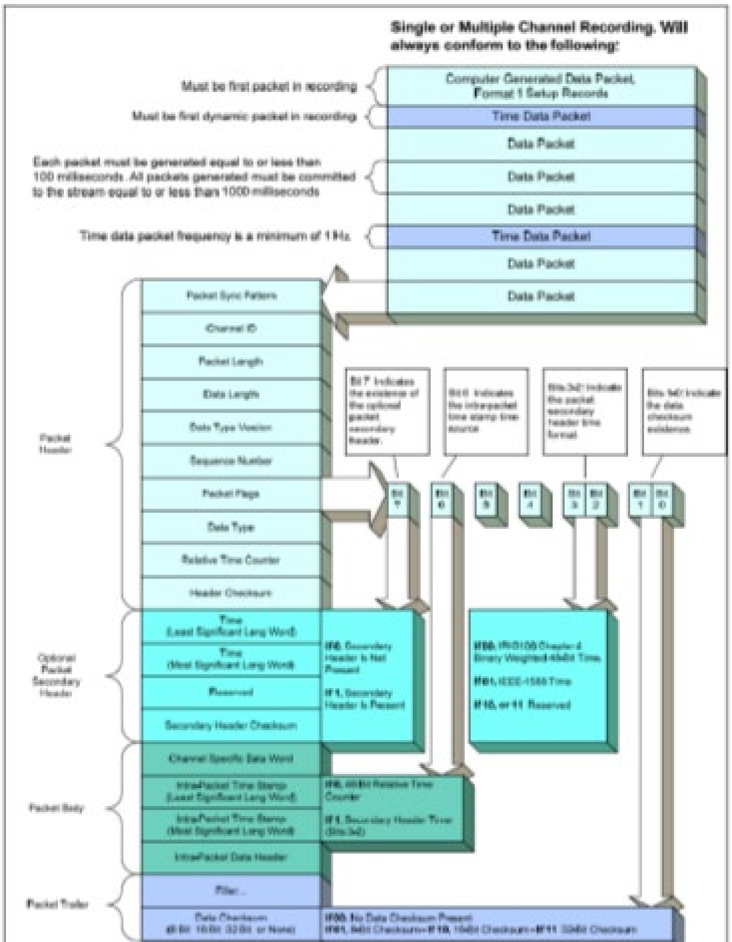
Chapter 10 Recorders

- The advantage of using a Chapter 10 recorder is that it allows one or more data streams to be multiplexed into one file. The data streams can be a raw 1553, Ethernet, or an ARINC-429 signal, and not necessarily a Chapter 4 PCM stream.
- For example, one can record these data streams into a .ch10 file:
  - Ch4 PCM with analog parameters
  - 1553 Busses
  - Multiple video sources
- Chapter 10 file utilities can strip out the individual streams into separate files.



Chapter 10 Recorders

- If the data is going to be recorded to a Chapter 10 recorder along with other data sources, the record time will be more difficult to calculate due to the overhead the recorder adds to the data.



- Chapter 10 is much more complex as shown in the diagram. Data is stored in packets onto the solid state media.
- General Packet Format:

PACKET SYNC PATTERN	Packet Header
CHANNEL ID	
PACKET LENGTH	
DATA LENGTH	
DATA TYPE VERSION	
SEQUENCE NUMBER	
PACKET FLAGS	
DATA TYPE	
RELATIVE TIME COUNTER	
HEADER CHECKSUM	
TIME	Packet Secondary Header (Optional)
RESERVED	
SECONDARY HEADER CHECKSUM	
CHANNEL SPECIFIC DATA	Packet Body
INTRA-PACKET TIME STAMP 1	
INTRA-PACKET DATA HEADER 1	
DATA 1	
:	
INTRA-PACKET TIME STAMP n	
INTRA-PACKET DATA HEADER n	
DATA n	
DATA CHECKSUM	Packet Trailer

Time and GPS

Time

- Time is critical when it comes to data. It is the means of correlating data when events occur.

1	Parameter Time	Altitude	Airspeed	NZ
2	Parameter Units	feet	Knots	Gs
3	245:14:19:20.000080	23734	125.6	1.01
4	245:14:19:20.000089	23744	125.7	1.04
5	245:14:19:20.000098	23745	125.4	1.02
6	245:14:19:20.000107	23742	125.4	0.98
7	245:14:19:20.000115	23751	125.6	0.99
8	245:14:19:20.000124	23755	125.5	1.01
9	245:14:19:20.000133	23759	125.2	1.03
10	245:14:19:20.000142	23760	125.0	1.00
11	245:14:19:20.000150	23762	124.9	0.99

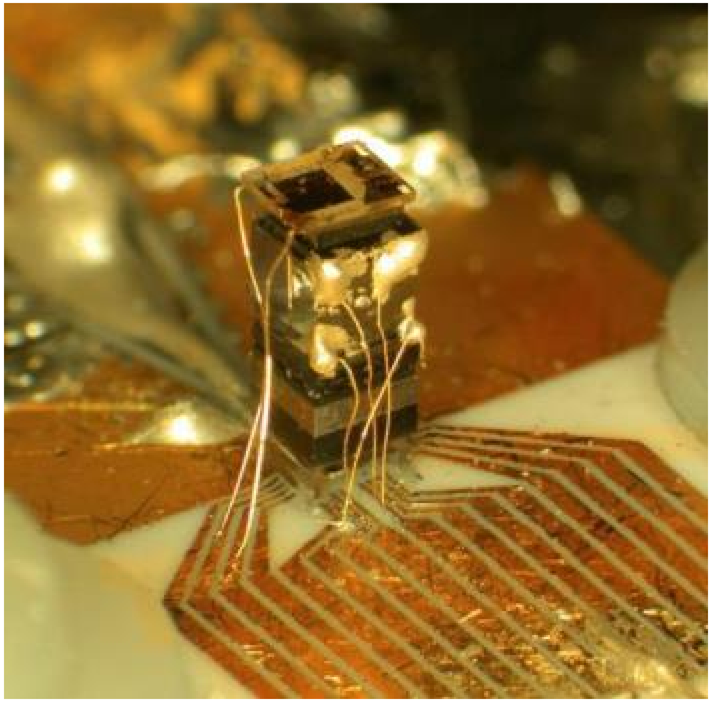
This data point corresponds in time to this frame of video.

The time stamps won't be exact because the sampling time of the data acquisition system and the shutter of the camera are not synchronized.

Time Source

- In many data acquisition systems, the source of time is GPS time. It is an inexpensive, accurate source of time and is very accessible.

- Atomic clocks can cost in the range of $50-100K. To have one in each receiver would not make the GPS system cost effective. However, each receiver can synchronize to the atomic clock in the satellites to essentially provide an inexpensive atomically accurate clock source.



Atomic clocks are not atomically powered. They get their name from the atom (Cesium-133) used in the timing oscillator.

GPS and UTC Time

- GPS time and UTC (Universal Time Coordinated) time are not the same.
- The time utilized by most data acquisition hardware is UTC which was known as Greenwich Mean Time (Greenwich, England).
- Note that these two time standards are different with GPS time leading UTC time by a fixed amount of seconds, and that offset changes periodically.
- Example:

local	2017-03-13 06:34:00	Monday	day 072	timezone UTC-4
UTC	2017-03-13 10:34:00	Monday	day 072	MJD 57825.44027
GPS	2017-03-13 10:34:18	week 1940	124458 s	cycle 1 week 0916 day 1

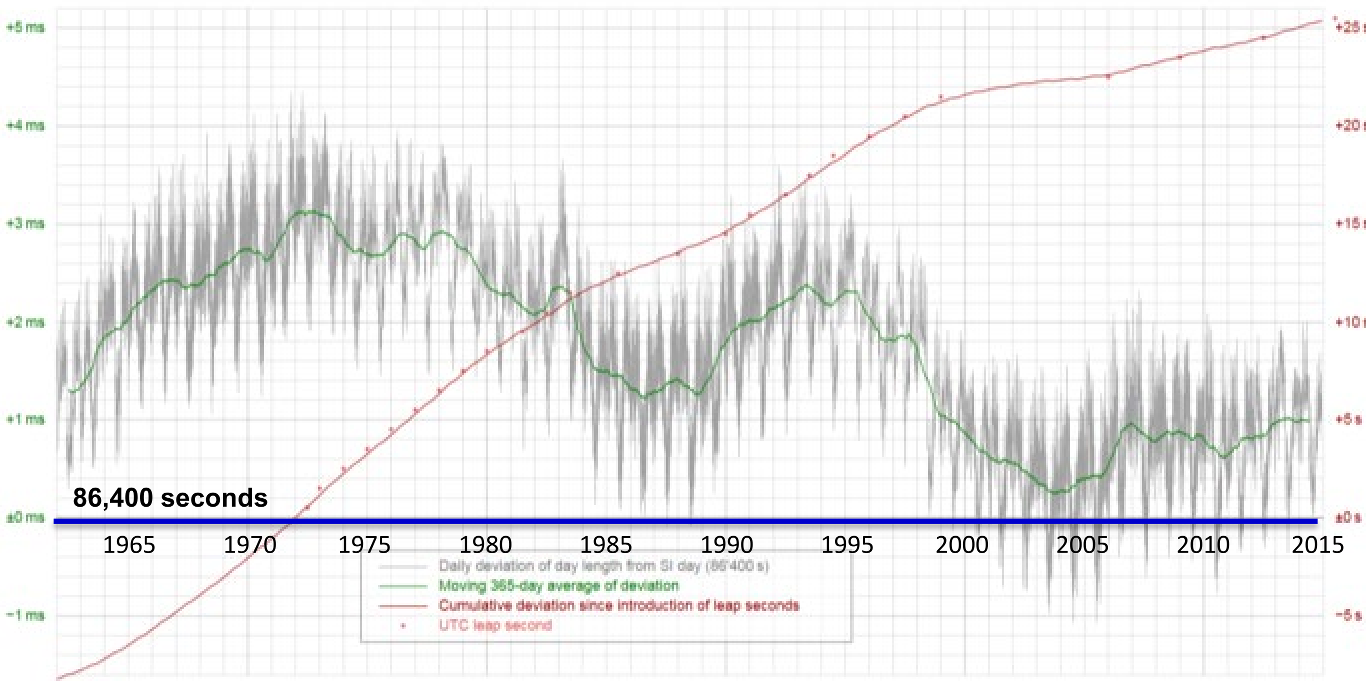
As of 1/1/17, GPS time leads UTC time by 18 sec.

Why the offset between the two times?

GPS and UTC Time Offset Explanation

- Variations in the Earth's rotational speed have caused days to be longer than 86,400 seconds. To make up for this, UTC time is offset from GPS by an ever increasing amount. This offset is transmitted from the GPS satellites and no upgrades to receiving hardware needs to be done.

Variation of a standard 86,400-second day in msec

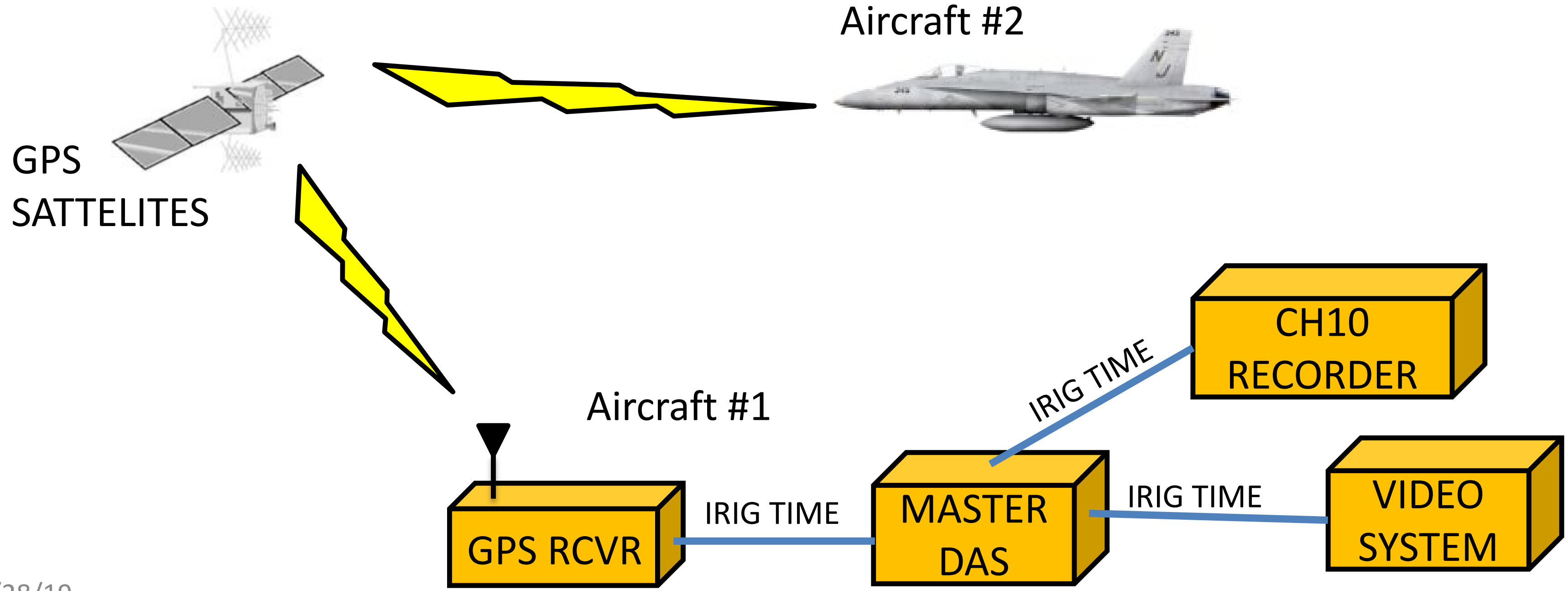


An additional 1ms per day adds 0.365 seconds in a year.

Date	GPS - UTC
Jan 6 1980	0 sec
Jul 1 1981	1
Jul 1 1982	2
Jul 1 1983	3
Jul 1 1985	4
Jan 1 1988	5
Jan 1 1990	6
Jan 1 1991	7
Jul 1 1992	8
Jul 1 1993	9
Jul 1 1994	10
Jan 1 1996	11
Jul 1 1997	12
Jan 1 1999	13
Jan 1 2006	14
Jan 1 2009	15
Jul 1 2012	16
Jul 1 2015	17
Jan 1 2017	18

IRIG Time Formats

- Once time is synchronized to a time source, it must be distributed throughout the instrumentation system (and multiple aircraft depending on the flight test).
- In order for the time to be synchronized between various vendor's hardware, a standard had to be created.
- IRIG-200 IRIG SERIAL TIME CODE FORMATS describes the time signal format that can be received and decoded by various data acquisition systems in order to synchronize in time.

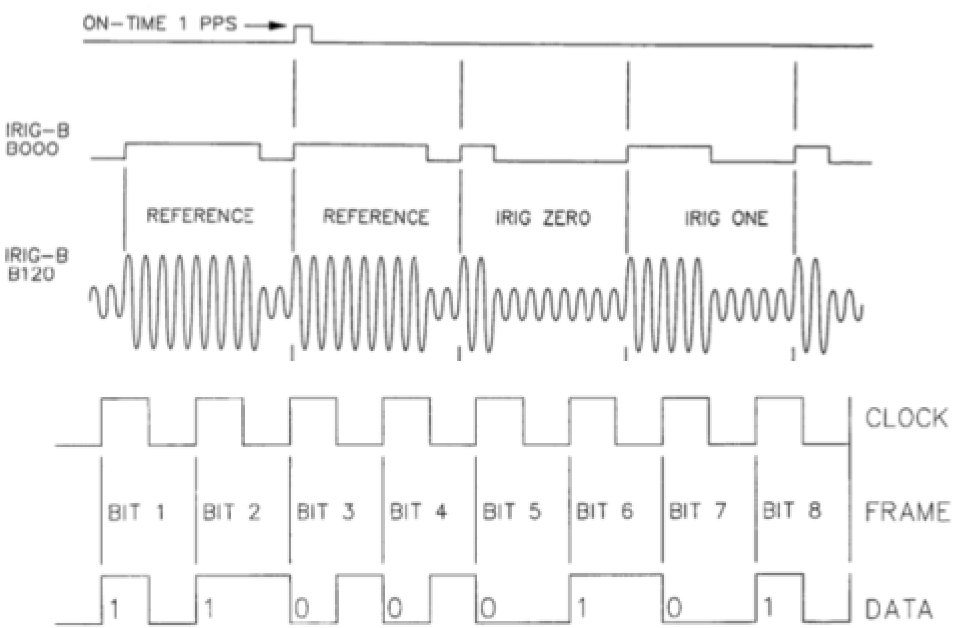


IRIG-B Time Format

- IRIG-B time is the version used in the instrumentation community. So when time is discussed it usually is referring to this format in the IRIG-200 standard.

- IRIG-B represents time in binary-coded decimal (BCD) of time of the year in days, hours, minutes and seconds (down to the microsecond).

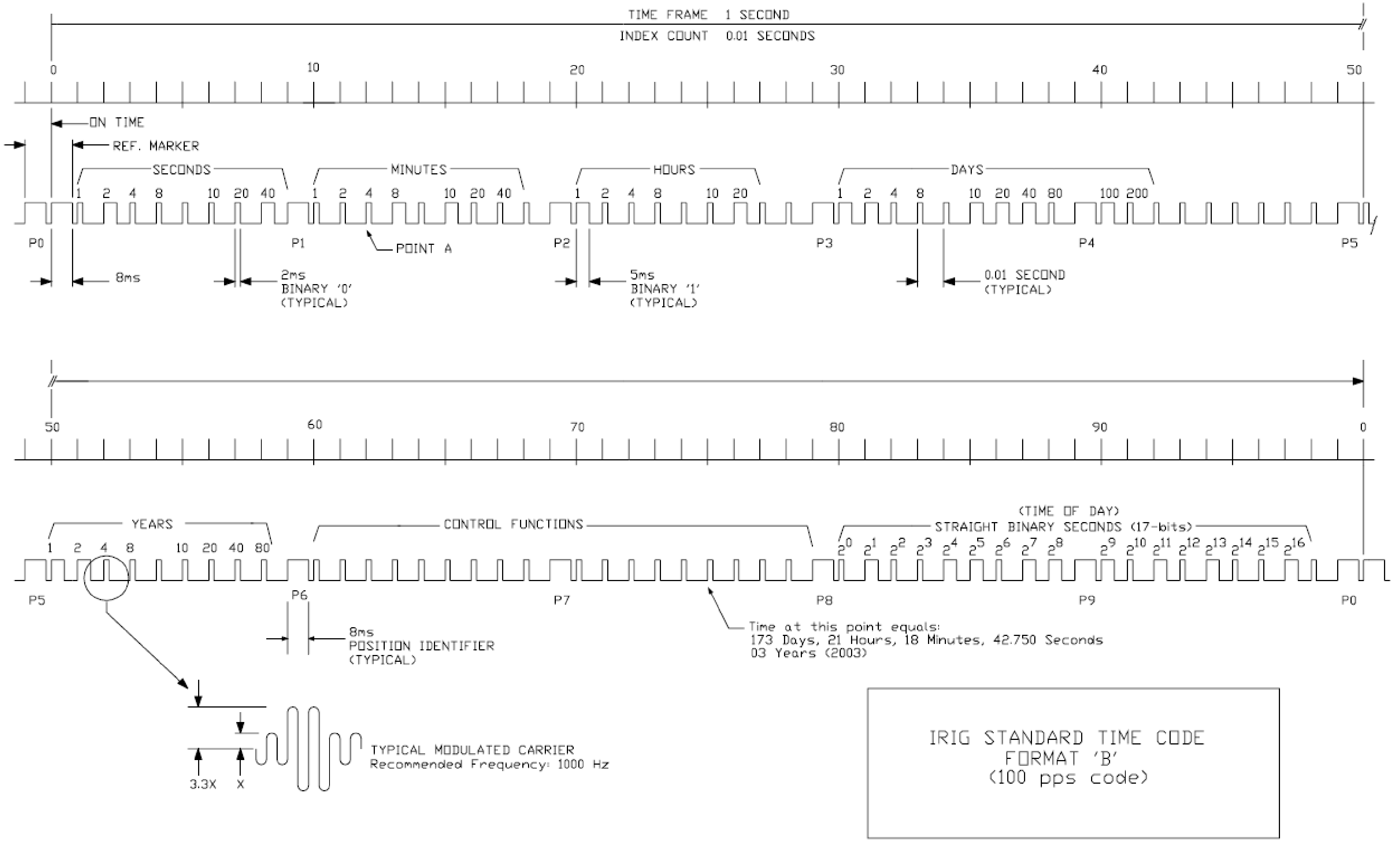
- There are two electrical representations of IRIG-B.
  - IRIG-B (AC) for analog code
  - IRIG-B (DC) for digital code



IRIG-B (AC)
Single ended signal
AM modulated Code

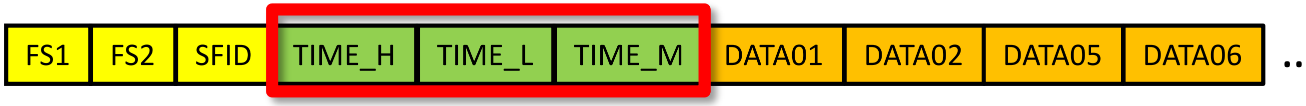
IRIG-B (DC)
Differential signal
Modified Manchester coding

IRIG-B Time Format

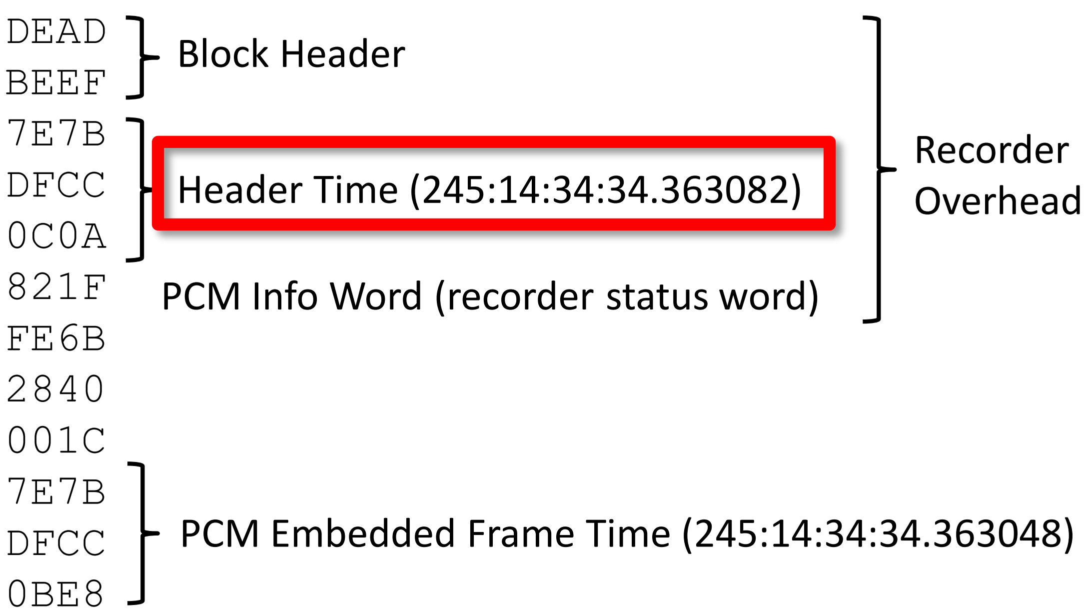


Locations of Time in the Data

- **Embedded Time:** The time that is embedded within each minor frame of the PCM. This is the best source of time for when the data is sampled.



- **Header Time:** The time that the PCM minor frame is written to the solid state memory of a Chapter 4 recorder. The time is located in the recorder overhead.



Locations of Time in the Data

- **Chapter 10 Time Packets:** This time packet is recorded once a second. It contains the year, month, day, and time to a resolution of 0.01 seconds.

Table 10-18. General Time Data Packet, Format 1
Packet Header
Channel-Specific Data
Time Data
Packet Trailer

MSB 15	14 … 12	11 … 8	7 … 4	LSB 3 … 0
0	TSn	Sn	Hmn	Tmn
0	0 1 0	0 1 0 0	0 0 0 0	0 0 0 0

0	0	THn	Hn	0	TMn	Mn
0	0	0 1	0 0 0 1	0	0 1 1	1 0 0 1

0	0	0	0	0	0	HDn	TDn	Dn
0	0	0	0	0	0	1 0	0 1 1 0	0 1 0 1

HDn	TDn	Dn		THn	Hn		TMn	Mn		TSn	Sn		Hmn	Tmn	
2	6	5	days	1	1	hours	3	9	minutes	2	4	.	0	0	seconds

Locations of Time in the Data

- **Chapter 10 Data Packet Time:** There can be two packet times within a Chapter 10 data packet.

Table 10-8. 32-Bit Packet Format Layout

MSB 31	16	15	LSB 0	
CHANNEL ID		PACKET SYNC PATTERN		
PACKET LENGTH				
DATA LENGTH				
DATA TYPE	PACKET FLAGS	SEQUENCE NUMBER	DATA TYPE VERSION	Packet Header
RELATIVE TIME COUNTER				
HEADER CHECKSUM		RELATIVE TIME COUNTER		
TIME (LEAST SIGNIFICANT LONG WORD [LSLW])				(Optional) Packet Secondary Header
TIME (MOST SIGNIFICANT LONG WORD [MSLW])				
SECONDARY HEADER CHECKSUM		RESERVED		
CHANNEL-SPECIFIC DATA				
INTRA-PACKET TIME STAMP 1				
INTRA-PACKET TIME STAMP 1				
INTRA-PACKET DATA HEADER 1				
DATA 1 WORD 2		DATA 1 WORD 1		
DATA 1 WORD N		:		
INTRA-PACKET TIME STAMP 2				
INTRA-PACKET TIME STAMP 2				
INTRA-PACKET DATA HEADER 2				
DATA 2 WORD 2		DATA 2 WORD 1		Packet

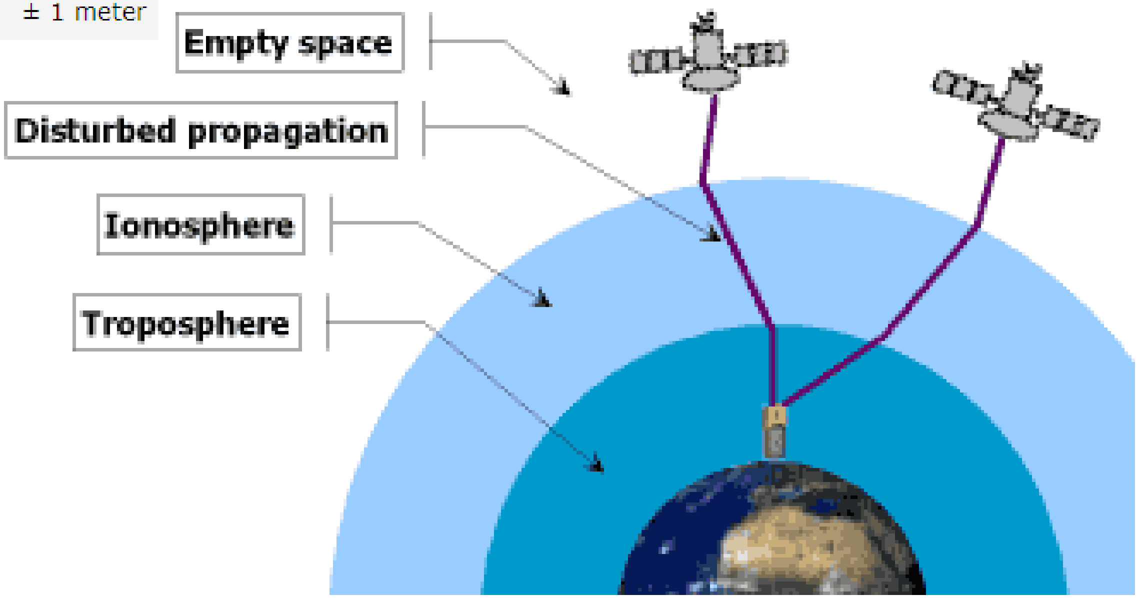
Packet Time –
when the packet was
created in the recorder

Intra-Packet Time Stamp –
when the data was written into
memory

Errors in GPS Data

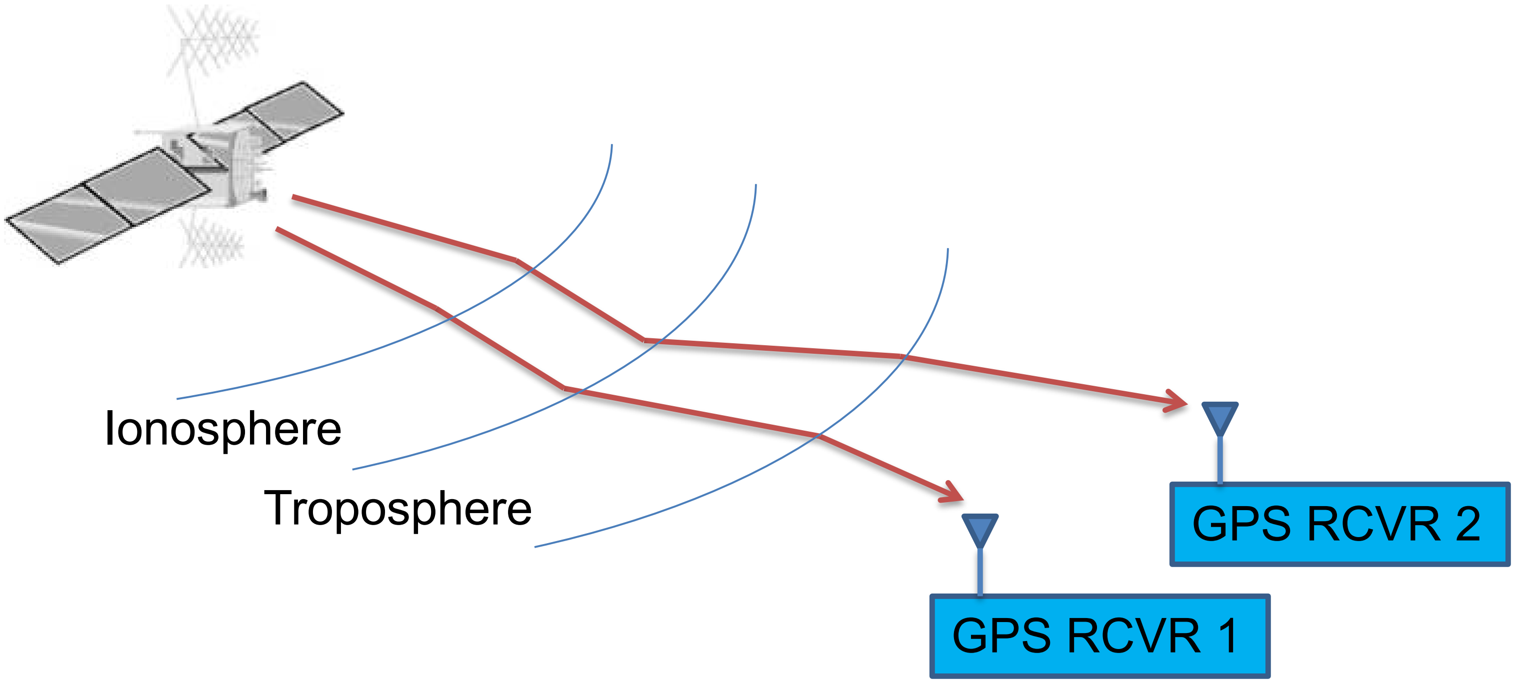
- A GPS receiver from any manufacturer can achieve accuracies of approximately 10 meters. Positional errors are induced when the telemetry signal from the satellites travel through the various layers of the Earth's atmosphere delaying the signal by various amounts.

Ionospheric effects	± 5 meters
Shifts in the satellite orbits	± 2.5 meter
Clock errors of the satellites' clocks	± 2 meter
Multipath effect	± 1 meter
Tropospheric effects	± 0.5 meter
Calculation- und rounding errors	± 1 meter



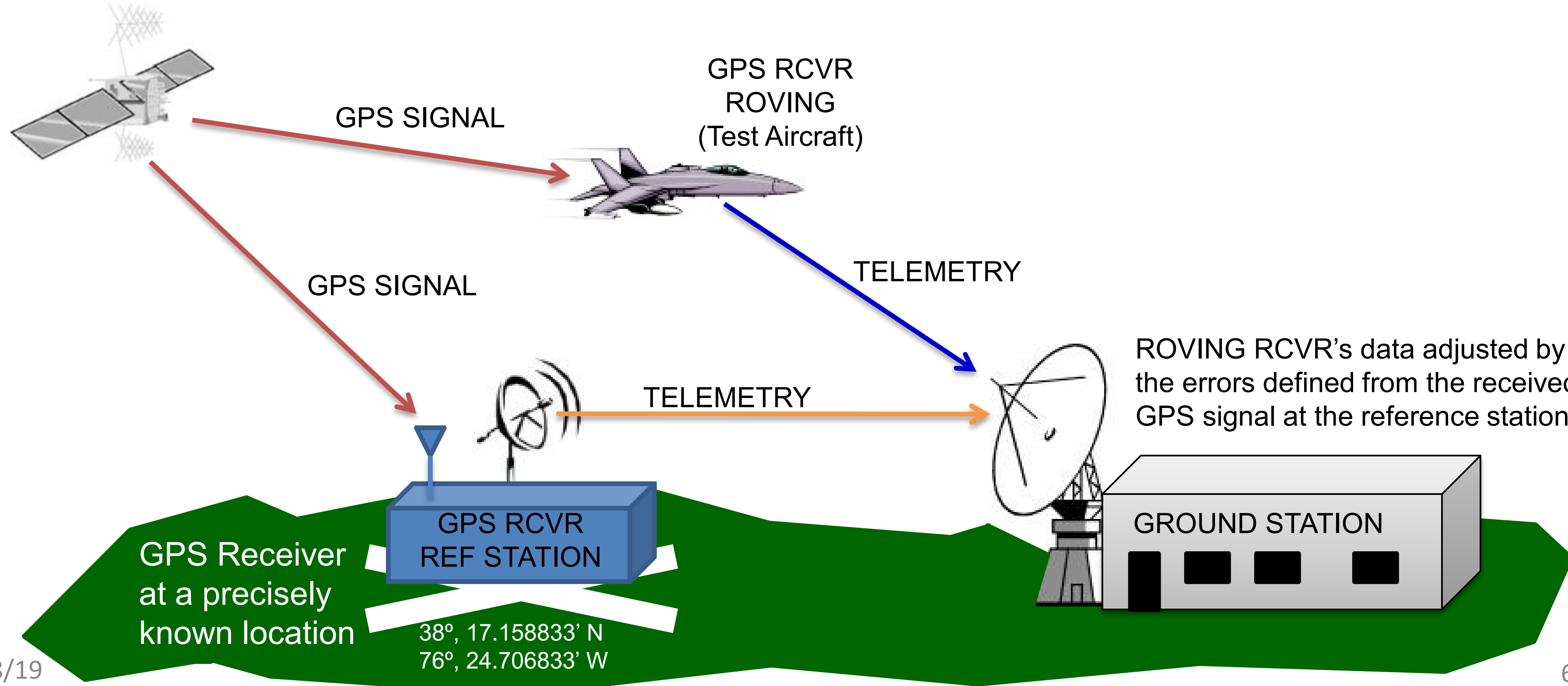
Minimizing Errors Using Differential GPS

- To achieve greater accuracies from one to two meters up to a few centimeters—requires differential correction of the data.
- The underlying premise of differential GPS (DGPS) is that any two receivers that are relatively close together will experience similar atmospheric errors.



Differential GPS

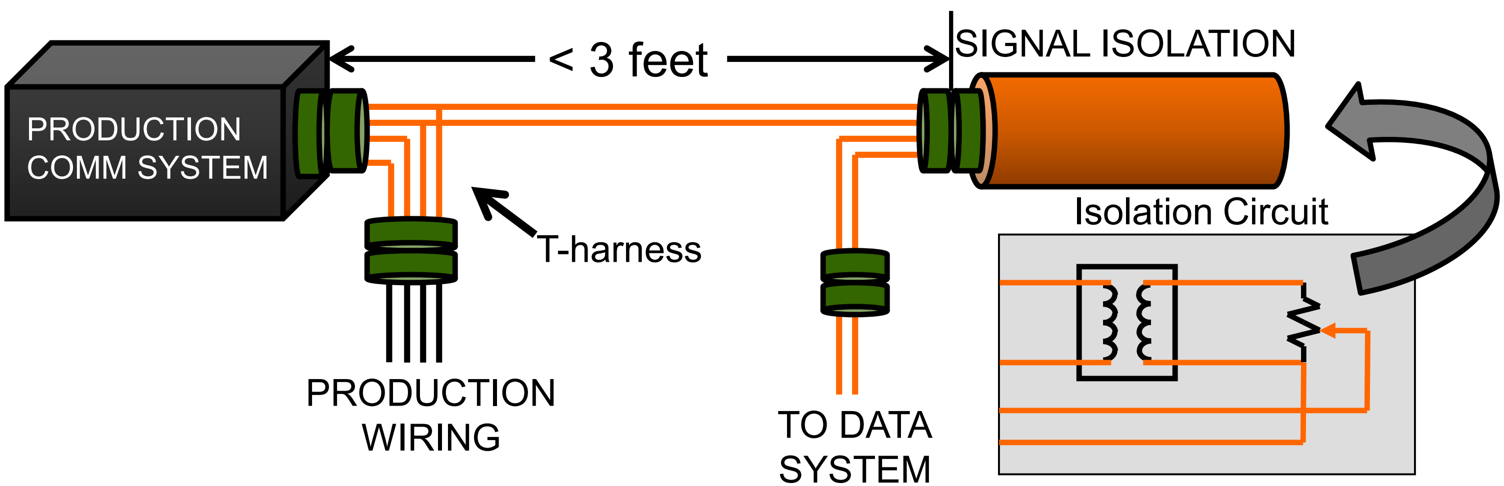
- Differential GPS (DGPS) requires that one GPS receiver be set up on a precisely known location. This GPS receiver is the base or reference station. The base station receiver calculates its position based on satellite signals and compares this location to the known location. The difference is applied to the GPS data recorded by the second GPS receiver, which is known as the roving receiver. The corrected information can be applied to data from the roving receiver in real time in the field using radio signals or through post-processing after data capture using special processing software.



AUDIO

Audio

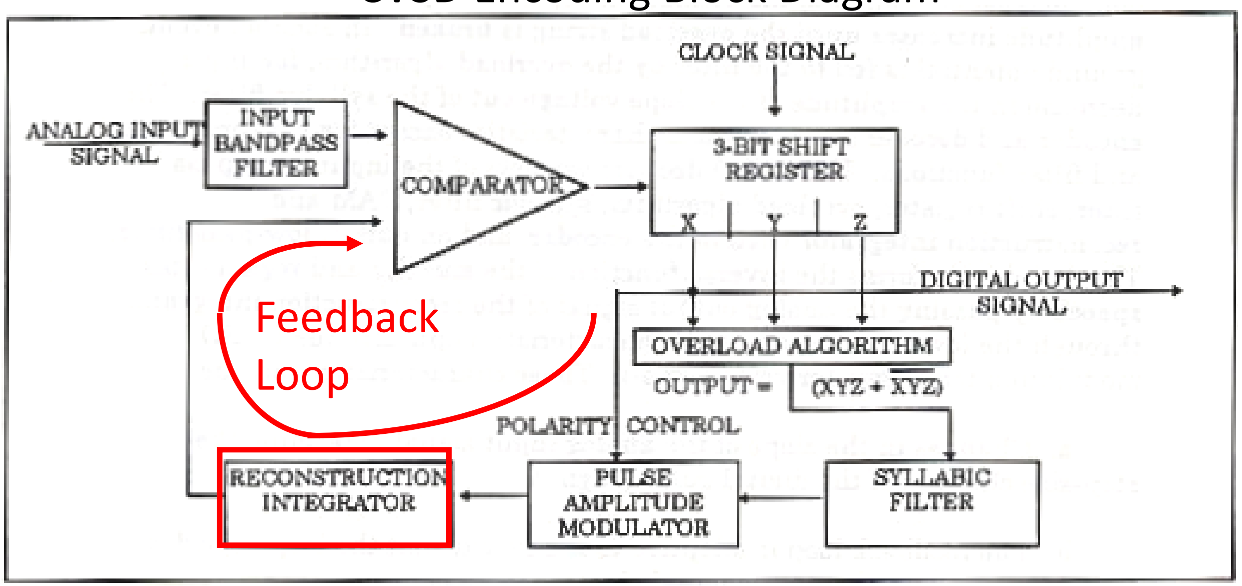
- Audio is an important element of a flight test.
- It provides much information as to what is occurring during a test.
- Because audio is obtained by tapping into a production system on the aircraft, it must be isolated from the instrumentation system.
- Usually an audio transformer and a potentiometer for level adjustment is used for isolation.



Audio – CVSD Modulation

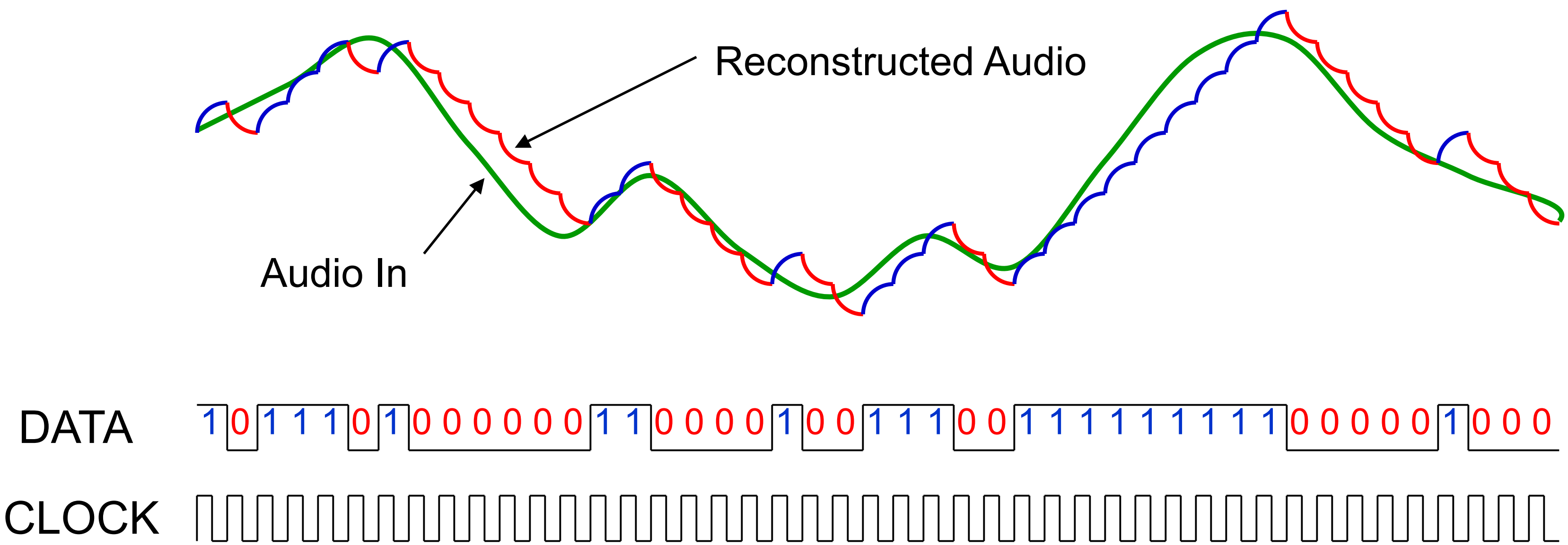
- Audio is much more forgiving as compared to an actual measurement. Our hearing can decipher any anomalies in the audio signal.
- Because of this, audio is not digitized the same way as a signal from an accelerometer.
- Audio is digitized using a method called Continuously Variable Slope Delta Modulation (CVSD) and this is described in **Chapter 5** of the IRIG-106 standard.

CVSD Encoding Block Diagram



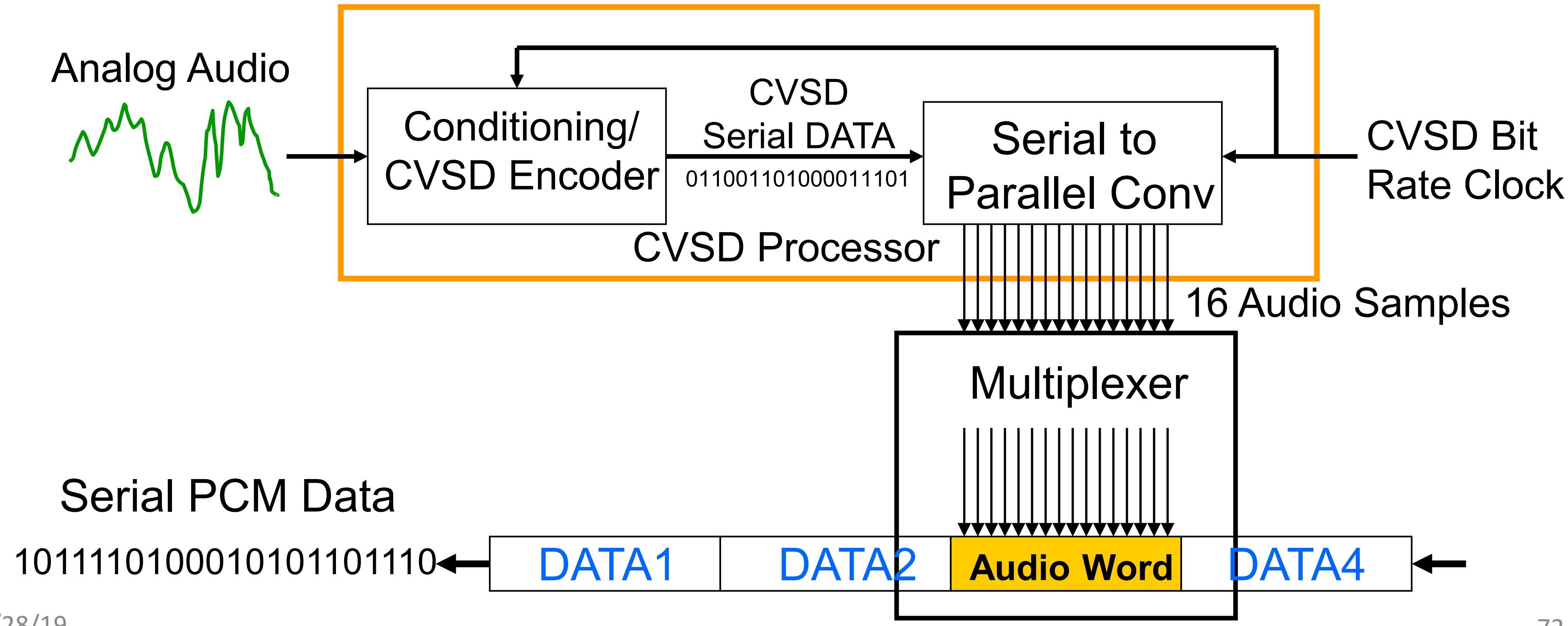
Audio – CVSD Modulation

- The CVSD encoding technique is a method of digitizing a band limited audio signal.
- The modulator is in a sense a 1-bit analog to digital converter.
- Each bit represents an incremental increase or decrease in signal amplitude.
- The bits are then put into a serial stream at the rate of the CVSD sampling clock.
- For decent sounding audio, usually the clock rate is 20K – 30Kbps.



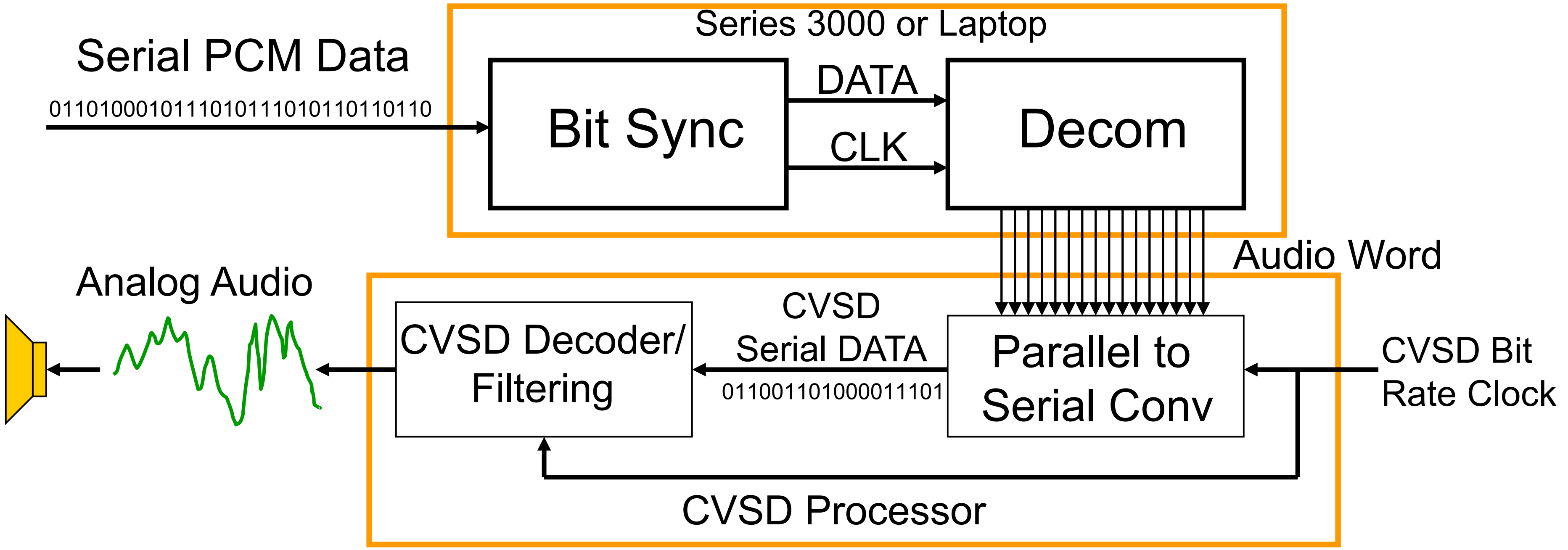
Inserting CVSD Bits into the PCM Bit Stream

- The analog audio is conditioned (gained and filtered) and CVSD encoded at the desired CVSD bit rate. The output of the encoder is a serial stream of bits where each bit is one sample. The bits are put into a 16-bit word and fed to the multiplexer which places it into the serial PCM stream.
- A bandwidth savings occurs because the PCM word contains 16 samples, vice only one in a traditionally sampled PCM word.



Playing Back Audio from the PCM Bit Stream

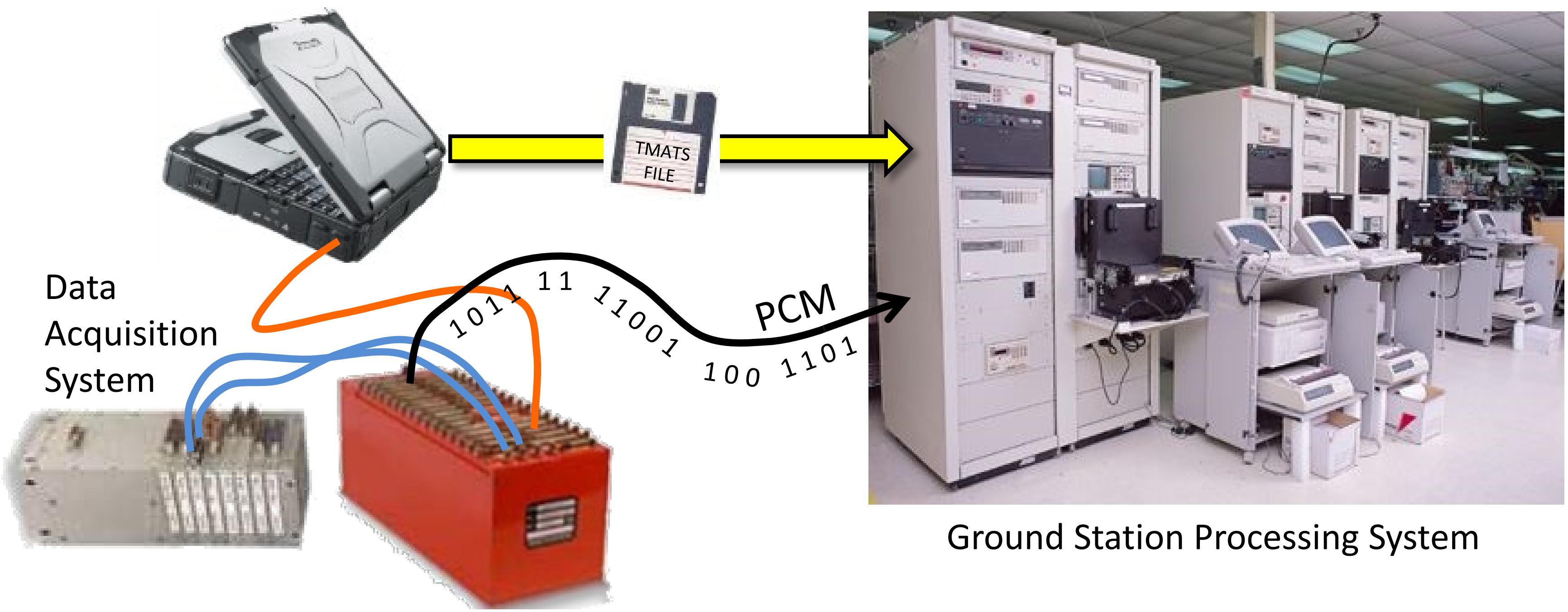
- To play back embedded CVSD audio within a PCM stream, you will need a bit synchronizer, a decommutator, a CVSD decoder, and a computer with an integrated speaker or speaker output.



Telemetry Attributes Transfer Standard (TMATS)

TMATS

- The Telemetry Attributes Transfer (TMATS) file contains all the information needed to decode and convert all the ones and zeros in a PCM data stream into EUs at the ground station. The same computer that programs the data acquisition system usually generates the TMATS file.



TMATS

- Not all ground stations use the same processing hardware and software, so a standard was written to describe the attributes of the telemetry.

- Telemetry attributes are those parameters required by the receiving/processing system to acquire, process, and display the telemetry data received from the test article. TMATS is described in **Chapter 9** of the IRIG-106 Telemetry Standards.

TMATS

- TMATS files have file extensions of .tma or .tmt.

- The attributes are subdivided into the following categories:
  - G Group: General Information
  - T Group: Transmission Attributes
  - R Group: Recorder-Reproducer Attributes
  - M Group: Multiplex/Modulation Attributes
  - P Group: PCM Format Attributes
  - P, D, B, S Groups: Digital Data Attributes
  - C Group: Data Conversion Attributes
  - H Group: Airborne Hardware Attributes
  - V Group: Vendor-Specific Attributes

TMATS – Examples of Labels

Group C and D attributes shown below

- A TMATS file is basically a text file describing the PCM format and the measurements in identified fields.
  - Word location(s) in the PCM map
  - Bits within the word used in the measurement
  - Date of the on-aircraft calibration
  - Calibration equipment
  - Name of the measurement
  - Engineering units
  - Conversion type
  - Coefficients for the EU conversion

```
D-1\LT-1-24:WDFR;
D-1\MML\N-1-24:1;
D-1\MNF\N-1-24-1:1;
D-1\WP-1-24-1-1:8;
D-1\WI-1-24-1-1:22;
D-1\FP-1-24-1-1:1;
D-1\FI-1-24-1-1:1;
D-1\WFM-1-24-1-1:1111111111110000;
D-1\WFT-1-24-1-1:M;
D-1\WFP-1-24-1-1:1;
D-1\MN-1-25:VDC_ESSBUS;
D-1\MN1-1-25:NO;
D-1\MN2-1-25:D;
D-1\MN3-1-25:M;
C-25\DCN:VDC_ESSBUS;
C-25\TRD1:Attenuator;
C-25\TRD2:Attenuator;
C-25\TRD3:10L AC ATTEN;
C-25\TRD5:04-27-2009;
C-25\POC1:Trowell/Miller;
C-25\POC2:AID 5.2.9.4;
C-25\POC3:HGR 101;
C-25\POC4:301-757-4271;
COMMENT:6267B HP DC Power Supply s/n 1643A02982;
C-25\MN1:VDC_ESSBUS;
C-25\MN3:Volts;
C-25\MN4:PCM;
C-25\BFM:UNS;
C-25\SR:0;
C-25\CRT:04-27-2009-15-22-22;
C-25\DCT:COE;
C-25\CO\N:1;
C-25\CO1:N;
C-25\CO:-51.699592;
C-25\CO-1:0.025243941;
```

TMATS – Decoding a TMATS Label

- Here is an example of the accelerometer measurement and some labels in the TMATS file used for data conversion.

C-21\CO\N:1;

↑ Description for the 21st parameter

↑ C Group: Data Conversion Attributes

Reading the Group C table in Chapter 9 of the IRIG-106:

Coefficients			
ORDER OF CURVE FIT	C-d\CO\N	Allowed when: When C\DCT is "COE" Required when: Allowed Range: 1-100	Specify the order of the polynominal curve fit, n.

This TMATS label is describing the order of the curve fit to convert the count value of the data into the engineering units. In this example it is a first ordered equation, which we would expect to have two coefficients.

EU = C1 (counts) + C0

TMATS – Decoding a TMATS Label

C-21\MN3:Gs;

Reading the Group C table in Chapter 9 of the IRIG-106:

ENGINEERING UNITS	C-d\MN3	Allowed when: When C-d\DCN is specified Range: 16 characters	Define the engineering units applicable to the output data.

This TMATS label defines the engineering units of this measurement. For the accelerometer example, it is in Gs.

Gs = C1 (counts) + C0

TMATS – Decoding a TMATS Label

C-21\CO:-31.648246;
C-21\CO-1:0.01538419;

Reading the Group C table in Chapter 9 of the IRIG-106:

COEFFICIENT (0)	C-d\CO	Allowed when: When C\DCT is "COE"	Value of the zero-order term (offset).
		Required when: Allowed	
		Range: Floating Point	
N-TH COEFFICIENT	C-d\CO-n	Allowed when: When C\DCT is "COE"	Value of the coefficient of the n-th power of x (first order coefficient is the equivalent of bit weight).
		Required when: Allowed	
		Range: Floating Point	
NOTE: Repeat until all n+1 coefficients are defined.			

These TMATS labels are defining the two coefficients of first ordered equation,
C0 = -31.648246 and C1 = 0.01538419

Gs = 0.01538419 (counts) -31.648246

TMATS – Converting the Counts to EUs

- The ground station will receive the transmitted PCM stream, and using the TMATS file, find the 12-bit binary word in the PCM map that corresponds to the accelerometer measurement.

HEADING	AIRSPEED	ACCEL3	ALTITUDE	PITCHATT
0111 0110 0010	1101 0110 1110	101100100101	0000 0010 1001	0000 0010 0111

- The binary value of ACCEL3 is 101100100101

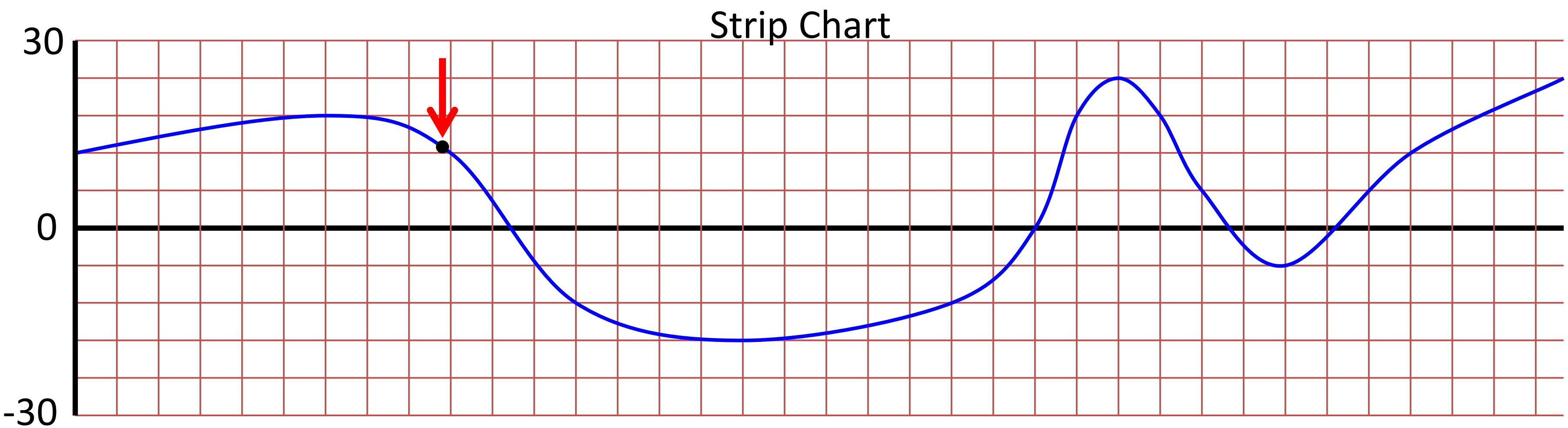
- The TMATS file defines the 12-bit word as binary encoded, so converting into decimal, we get 2853 counts.

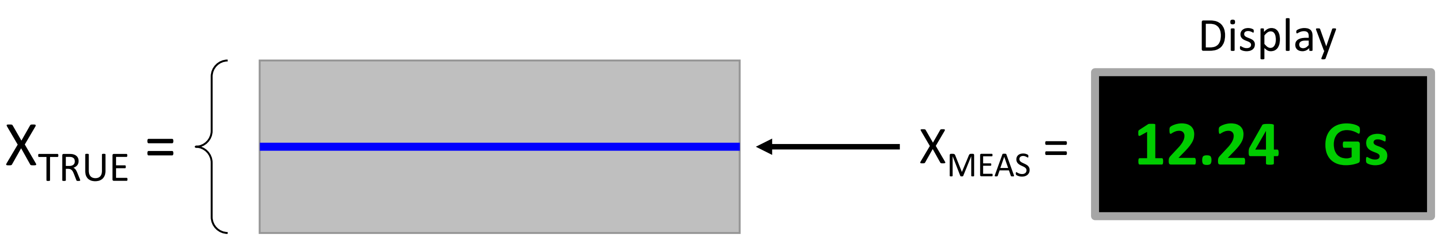
- Using the EU conversion equation,

$$Gs = 0.01538419 (2853) -31.648246 = 12.24 \text{ Gs}$$

From the Accelerometer on the Aircraft to a Strip Chart Display on the Ground

- The ground station will then display the 12.24 Gs in a display or on a strip chart.



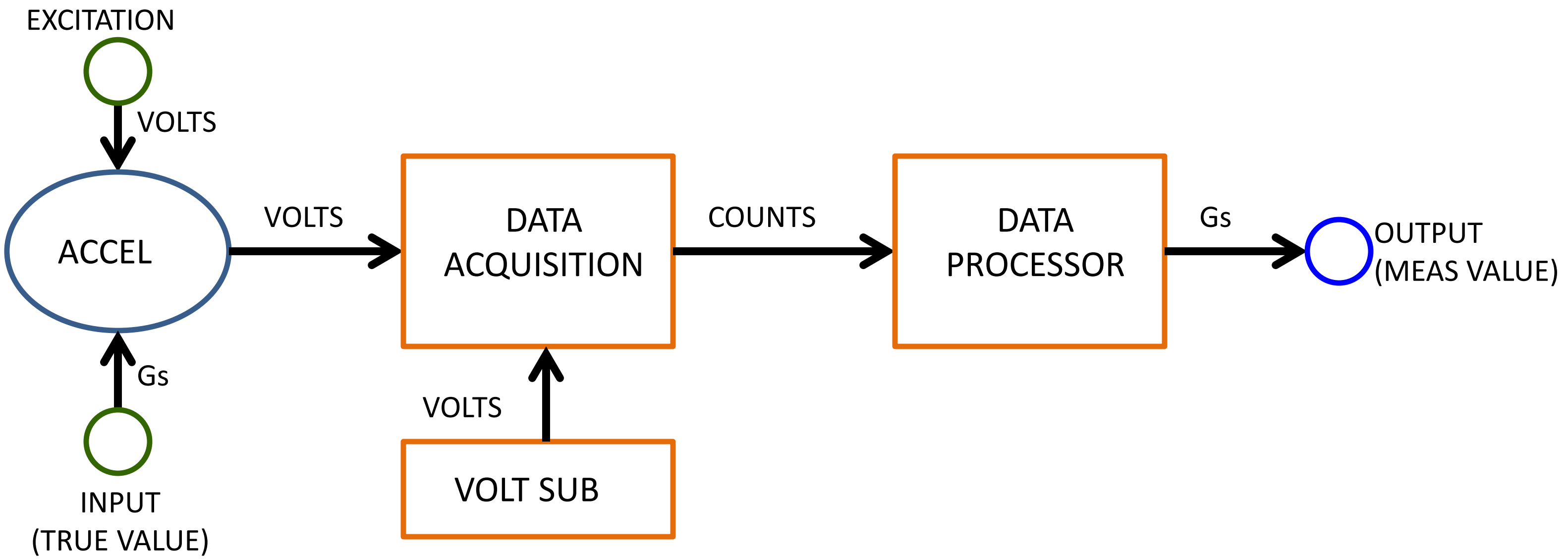


Next we will define error bound, so we can estimate where the true value of this measurement lies. It was requested to fall within ±3% of full scale of the measured value (±1.8 Gs).

Measurement Uncertainty
Interpreting the Results

Measurement Uncertainty

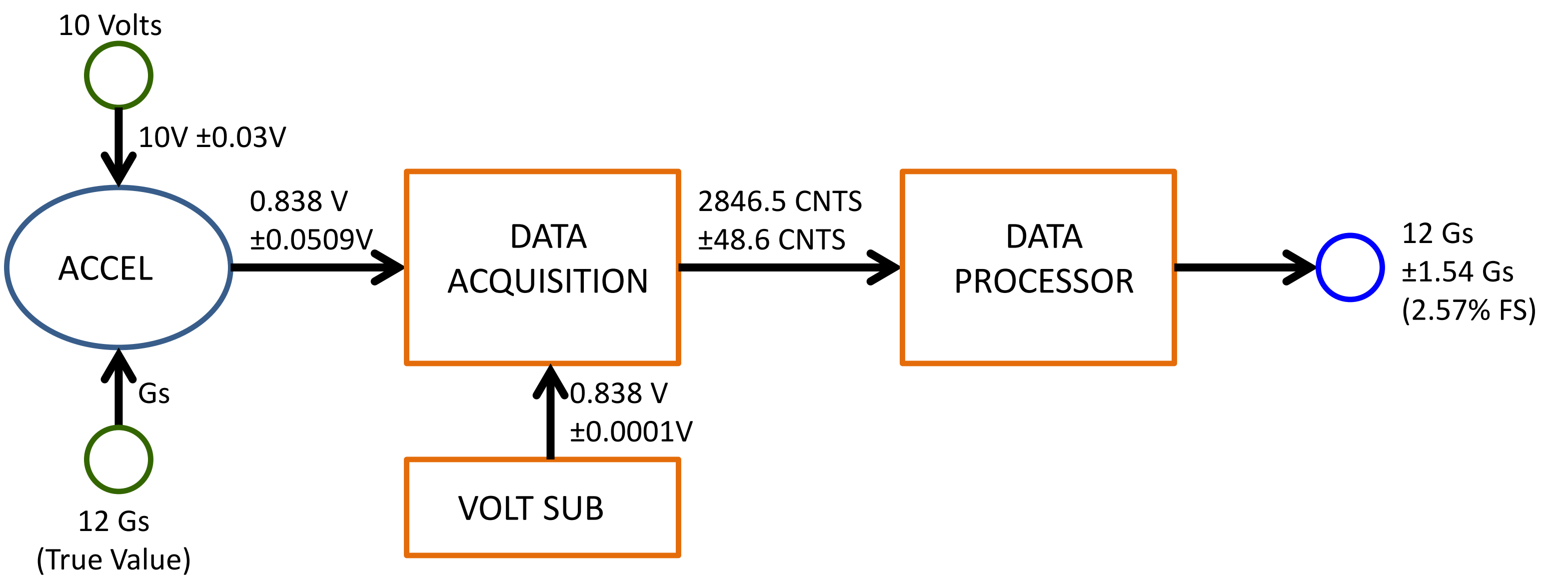
- Now we will look at he uncertainty of the acceleration measurement. The uncertainty describes the bound where the true value of the measurement can be found. In cases where this bound is critical, an uncertainty analysis is performed.



- The methodology for doing an uncertainty analysis can be found in IRIG-122 Uncertainty Analysis Principles and Methods. These methods are automated in ISG's software Uncertainty Analyzer.

Measurement Uncertainty

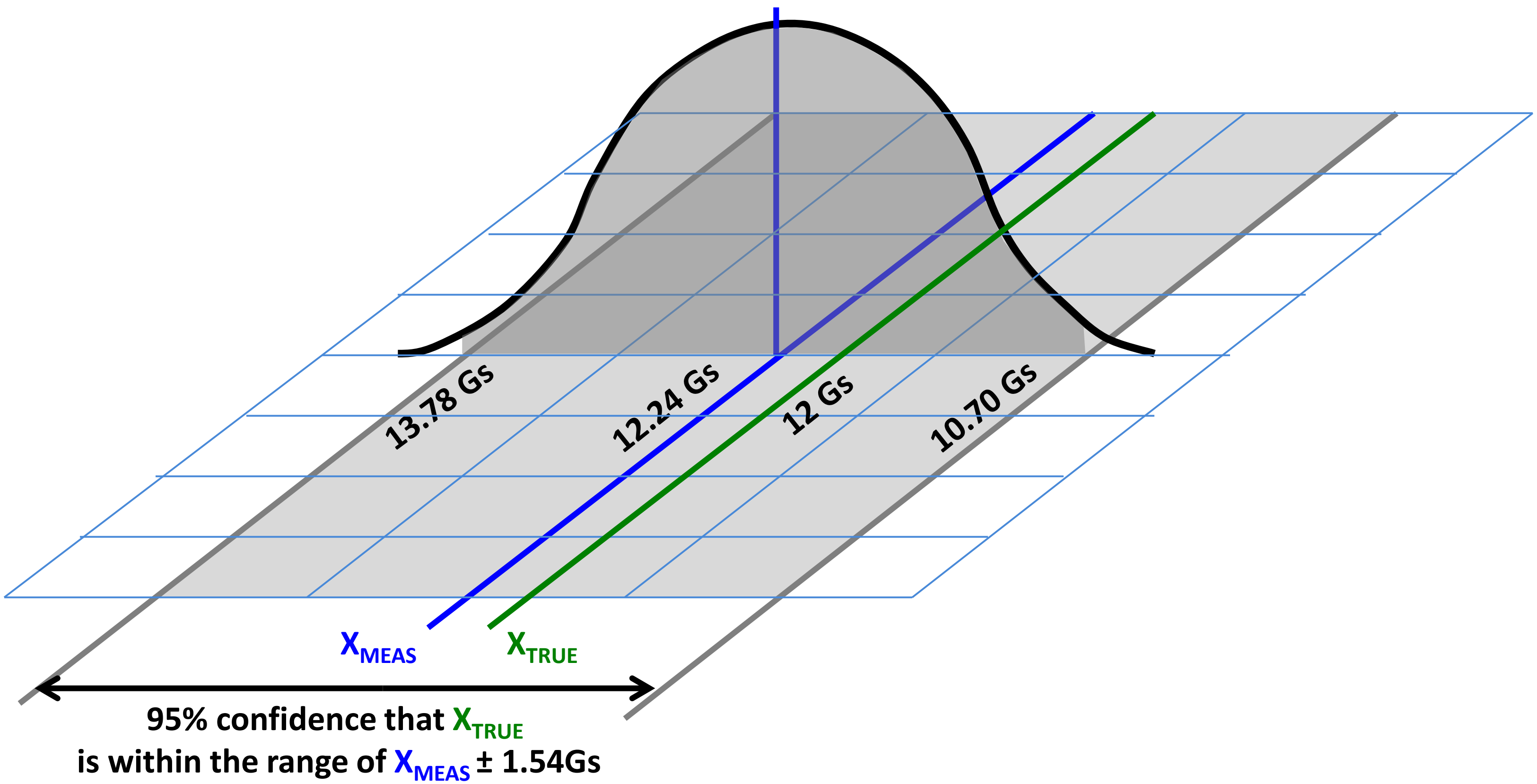
- After the error sources are identified and quantified, the numbers are run through the software which takes care of all the math to properly combine the uncertainties. A simple root-sum-squared method is not used.



- The document describing how the numbers were arrived and the assumptions made for this particular analysis was 14 pages long. The result is a 95% confidence that the true value is within ±1.54 Gs of the measured value (±2.57% FS). The original requirement for the example accelerometer measurement was ±3%.

Measurement Uncertainty

- This graphic depicts the measurement and the unknown true value.

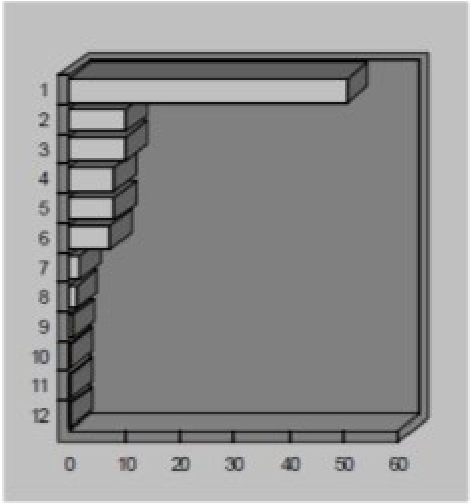


Measurement Uncertainty

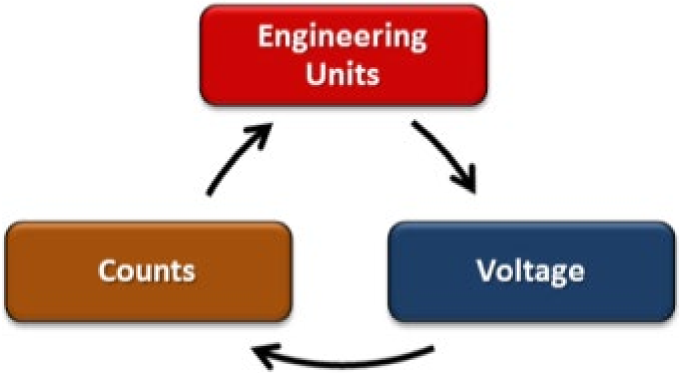
- If the 3% uncertainty requirement was exceeded, then the sources of the error would have to be identified and see if it could be reduced. For this example, over 50% of the error in the accelerometer was due to temperature. From there, the large error sources can be identified and improved upon. If 2% was requested, probably another accelerometer would have to be procured with better temperature specs.

Pareto Diagram: (for accelerometer only)

Rank	Error Component	Type	Weight (%)
1	Vostherm	B	50.697 ←
2	Non-linearity and Hysteresis	B	10.139
3	Thermal Sensitivity	B	10.009
4	Magnetic Susceptiblility	B	8.341
5	Transverse Sensitivity	B	8.341
6	Voltage Excitation Sensitivity	B	7.507
7	Voltage offset from excitation	B	1.927
8	Thermal transient error	B	1.251
9	Base Strain	B	0.834
10	Nominal Sensitivity	B	0.400
11	Resolution	B	0.373
12	Residual Noise	B	0.182



Summary



This completes the measurement cycle that was introduced earlier in this training. Think of the many technical decisions having to be made to display the 12.24 Gs sample on the strip chart.

We covered a lot of information in one day. Remember to refer to the IRIG-106 Telemetry Standards and Document 121 Instrumentation Engineers Handbook if you need more detail into the topics we covered.