# A Glimpse Into the Future of Data Acquisition Systems

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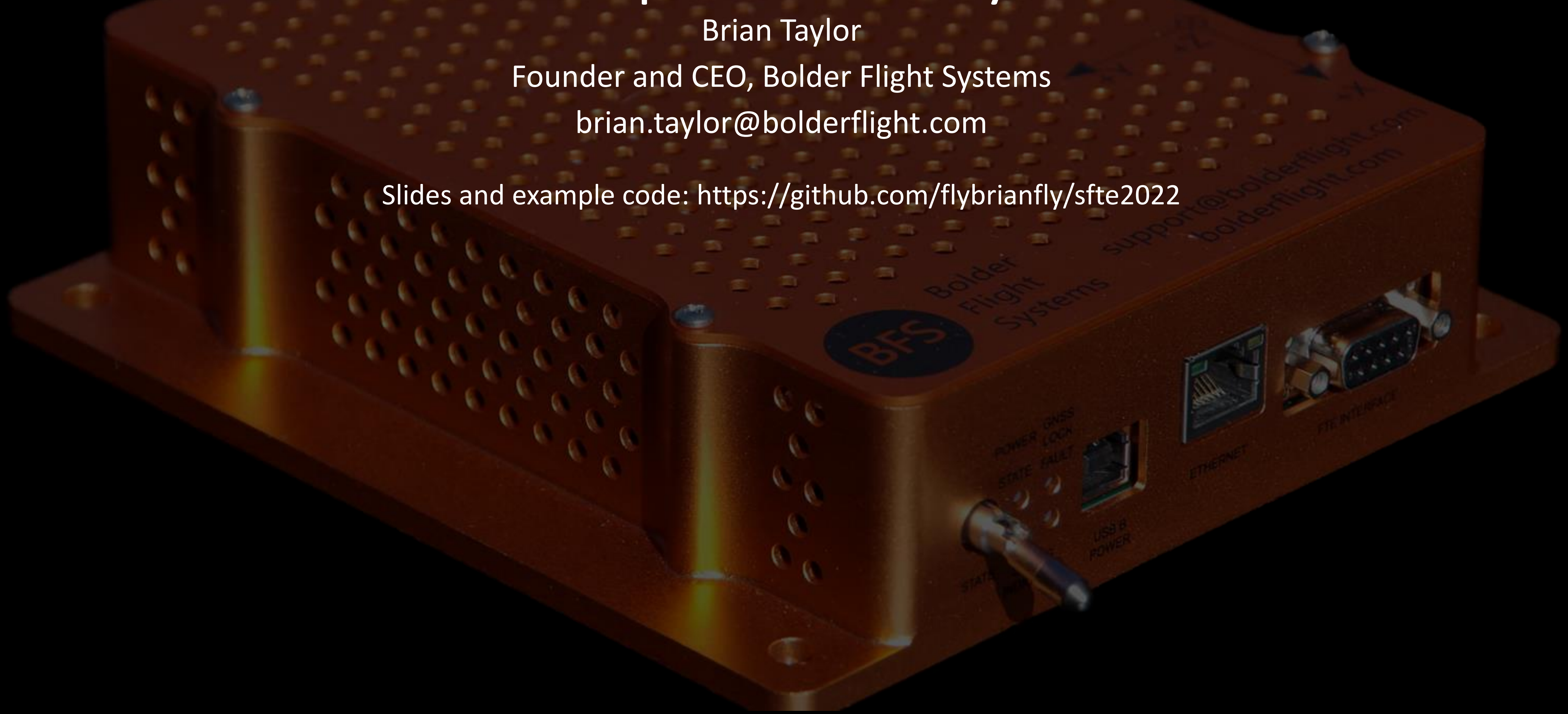
Slides and example code: https://github.com/flybrianfly/sfte2022

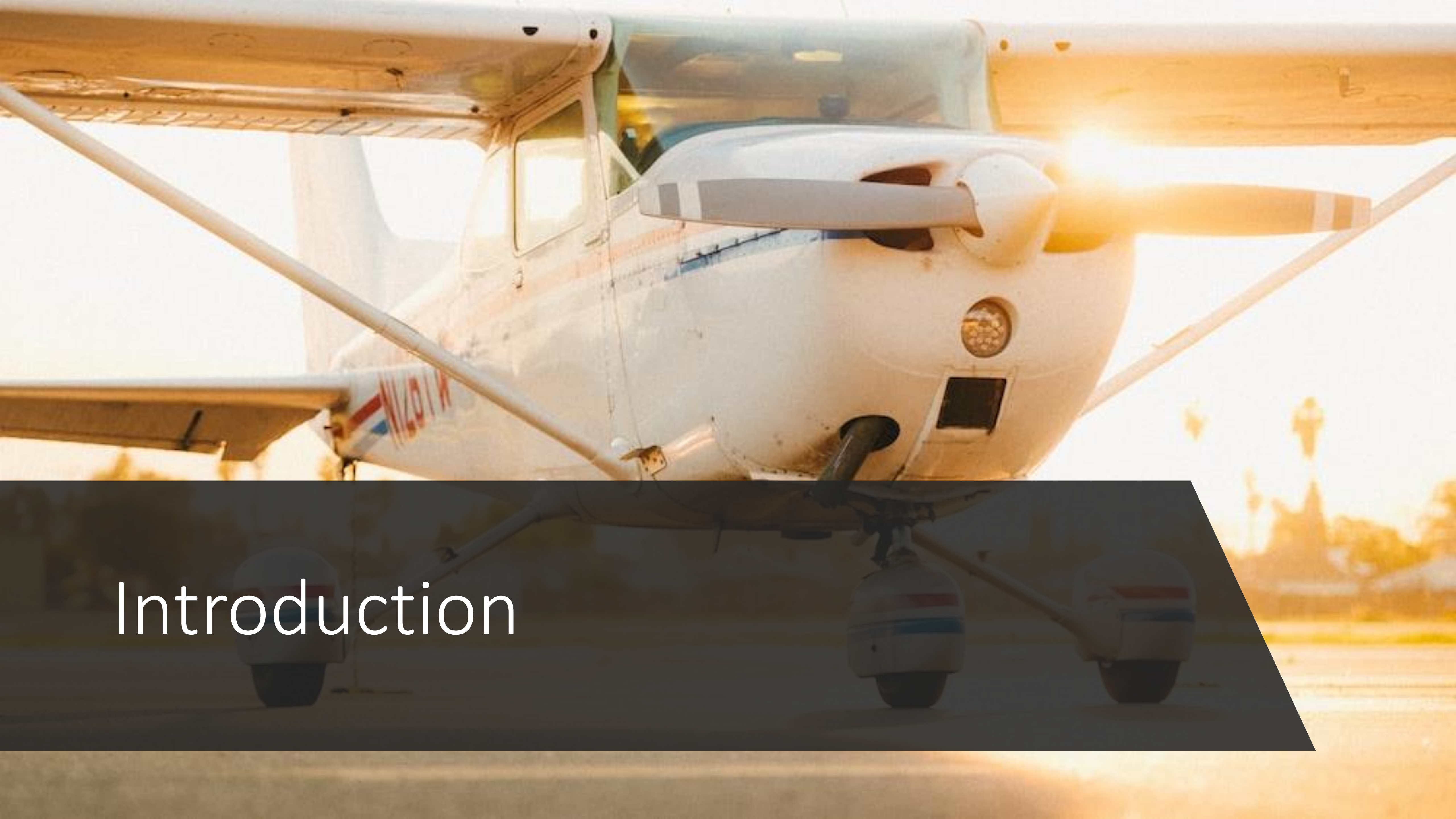


# Goals

- Understand current state of the art and where it is headed
- Gain hands-on knowledge of many common sensing and state estimation techniques
- Be able to select sensors and algorithms to meet requirements

# Agenda

- Intro
- GNSS
- INS
- Air Data
- Analog Input
- External Sensors
- Flight Data Analysis
- Flight Test Displays
- Future Developments



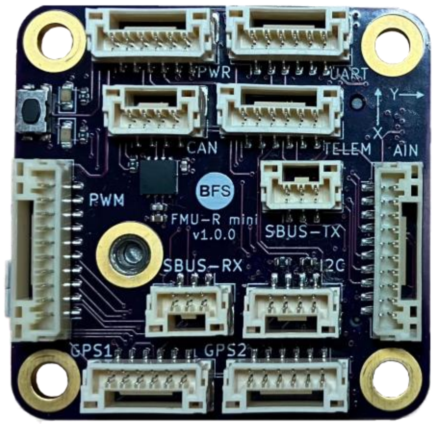
# Introduction

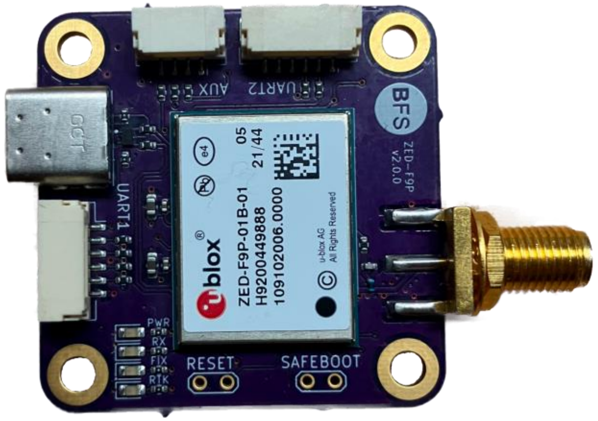
# Intro

- Work summary:
  - Bolder Flight Systems, Founder and CEO, 2016 – Present
  - University of Minnesota, Director, UAS Research Labs, 2012 – 2016
  - NASA Armstrong Flight Research Center
    - Deputy Chief Engineer, X-48C, 2012
    - Research Engineer, Flight Controls and Dynamics, 2008 – 2012
- Develop, build, validate, and commercialize flight control and data acquisition systems for manned and unmanned aircraft
- Parameter and performance estimation on a wide range of manned and unmanned aircraft
- Led parameter estimation campaign on X-48B consisting of inertial swings, control surface position measurement and modeling, 14 dedicated test flights, and 450 test points


# Bolder Flight Systems

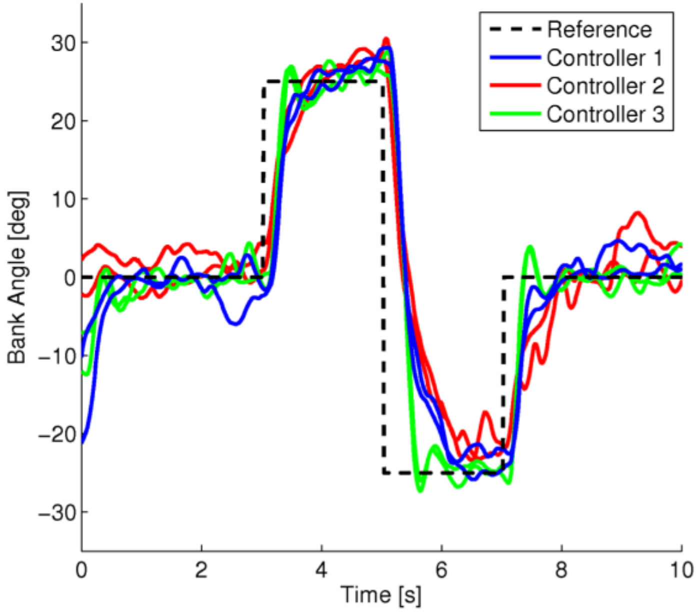
- Team of former NASA and DoD researchers and engineers
- Develop flight control and data acquisition systems with a focus on meeting the unique needs of the flight research community
  - Data quality, determinism, fixed-latency between sensing and actuation, and tight integration with MATLAB and Simulink
- Off the shelf products, engineering services, and research grants




# Motivation

- Flight data critical for aeronautics research, development, certification, and training
  - Performance characterization
  - Flight validated aircraft simulations
  - Control law development
  - Flying qualities and handling qualities
  - Certification
  - Test pilot and Flight Test Engineer (FTE) training
- Production aircraft often lack the necessary instrumentation or data rates

# How to acquire flight data

- Use a test aircraft
- Build custom instrumentation into the aircraft
- Use a Portable Data Acquisition System


# The Portable Data Acquisition System (PDAS)

- 200 Hz sample rate
- Size: 160 x 155 x 40 mm, 700 grams
- GNSS-aided INS
  - Pitch / roll accuracy: 0.1 deg
  - Heading accuracy: 0.3 deg
  - Position: 8 ft
  - Inertial velocity: 0.1 knots
- Pitot-Static
  - Range: 0 – 340 knots
  - Accuracy: 1 knot, typical
- RTD
  - 2, 3, and 4 wire
  - PT10, PT50, PT100, TP200, PT500, and PT1000
  - Range of excitation currents
  - 0.1C accuracy over full temperature range

# The Portable Data Acquisition System (PDAS)

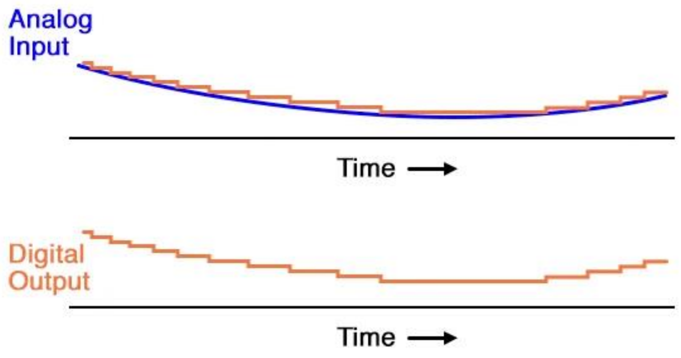
- 12 analog channels
  - 16 bit resolution
  - CH 0 – 5: configurable gain of 1, 10, 100, 1000
  - CH 6 – 11: configurable gain of 1, 2, 4, 8
  - Differential and single ended input on each channel
  - Ultra low noise 5V source available on each channel
  - Anti-alias cutoff frequency: 55 Hz
- Maximum ratings:
  - Acceleration: +/- 16G
  - Rotation: +/- 2,000 deg/s
  - Airspeed: 0 – 340 knots
  - Altitude: -10,000 to +70,000 ft
  - Temperature: -10 to +50C

# PDAS Familiarization

# Instrumentation Basics

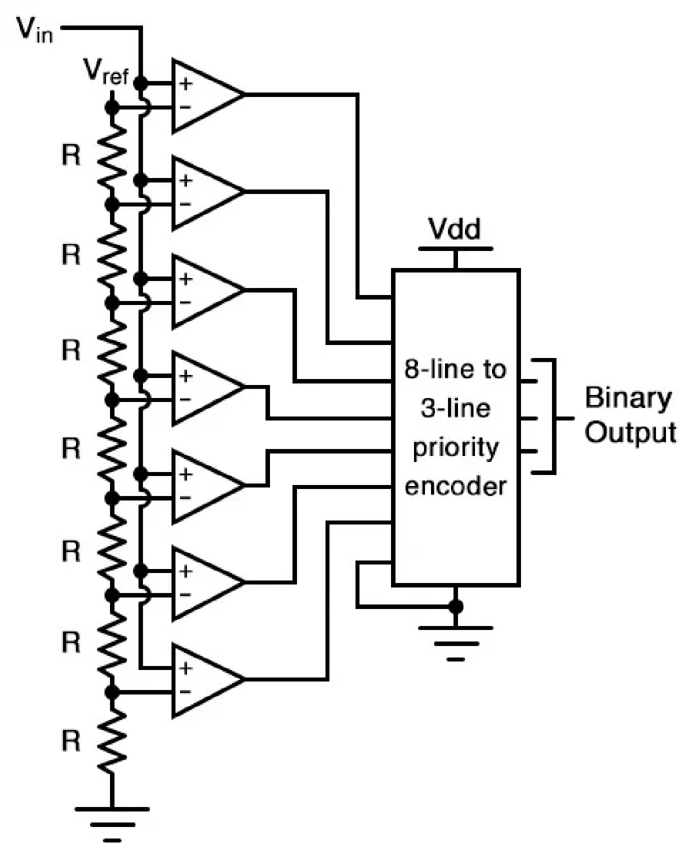
# Analog to Digital Conversion

- Nearly all our sensor measurements will start as analog
- Many are converted to digital within the sensor IC
- Analog to Digital Converts (ADCs) convert an analog signal to a digital signal
- Primarily concerned with the conversion speed and the effective number of bits of resolution
- Many different approaches to ADCs exist, three of the most common are:
  - Flash: Fastest conversion speed, worst resolution
  - Successive Approximation Register (SAR): Good balance between conversion speed and resolution
  - Delta Sigma (or Sigma Delta): Excellent resolution, slower conversion speed



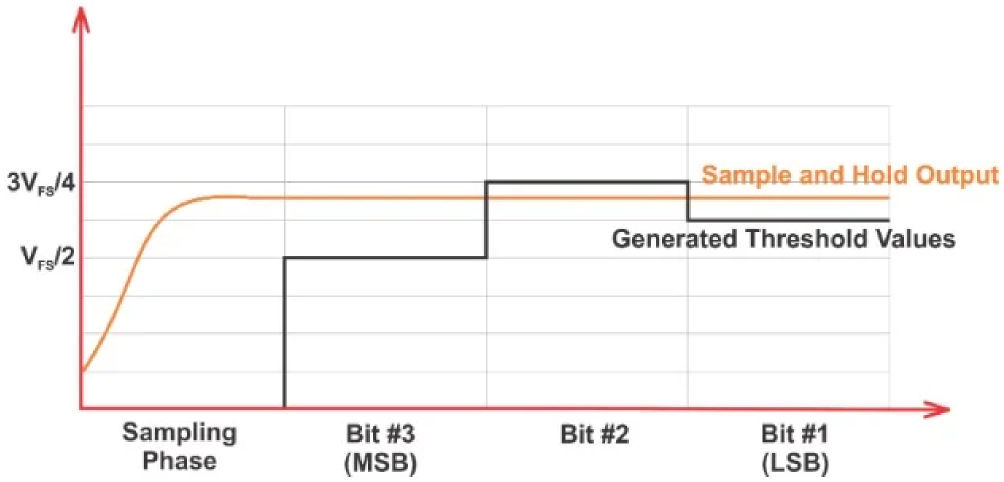
# Analog to Digital Conversion – Flash

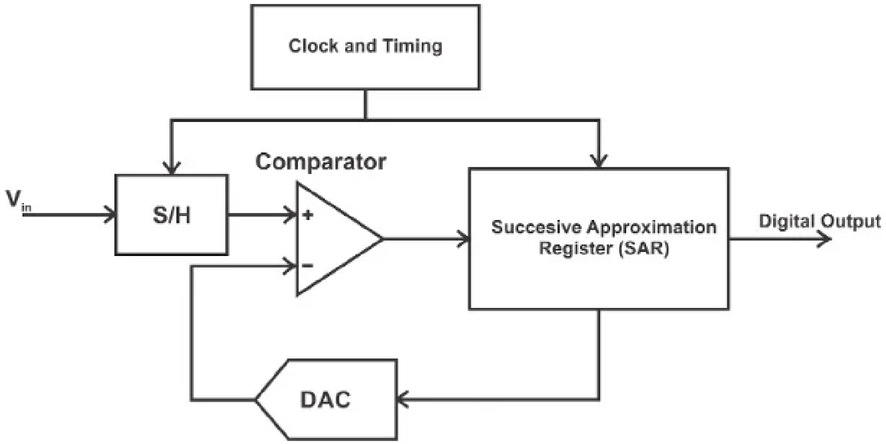
- 3-bit flash ADC shown
- 255 comparators needed for 8-bit ADC
  - 8-bit resolution is inadequate for most applications
- Exceptional conversion speed
- High component count and cost at high resolutions



# Analog to Digital Conversion – SAR

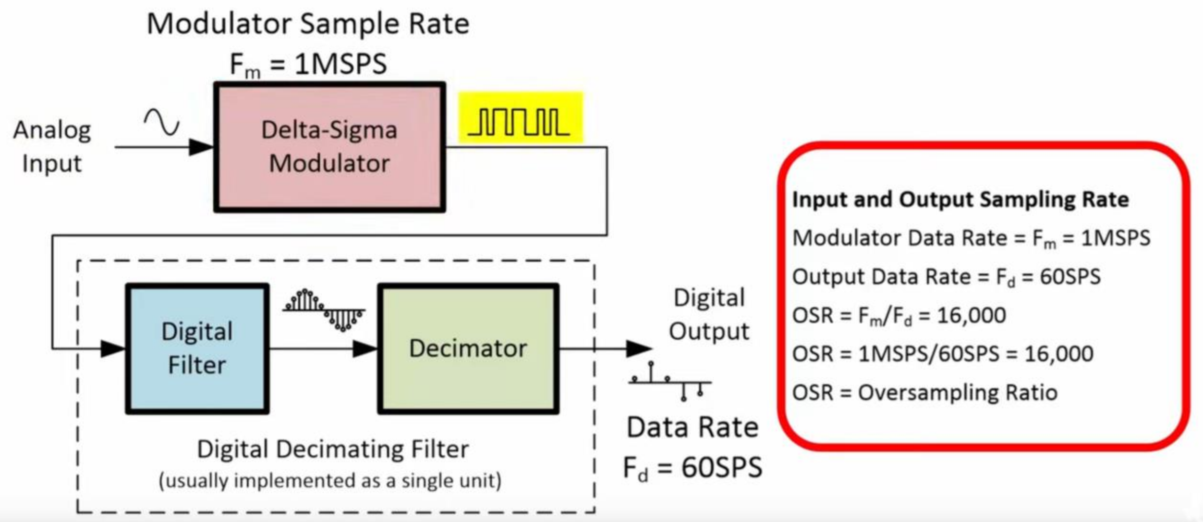
- Generates a reference value equal to half the full-scale value
- Generates a reference value half again in the direction of the signal
- Continues this process for however many bits the ADC resolution is

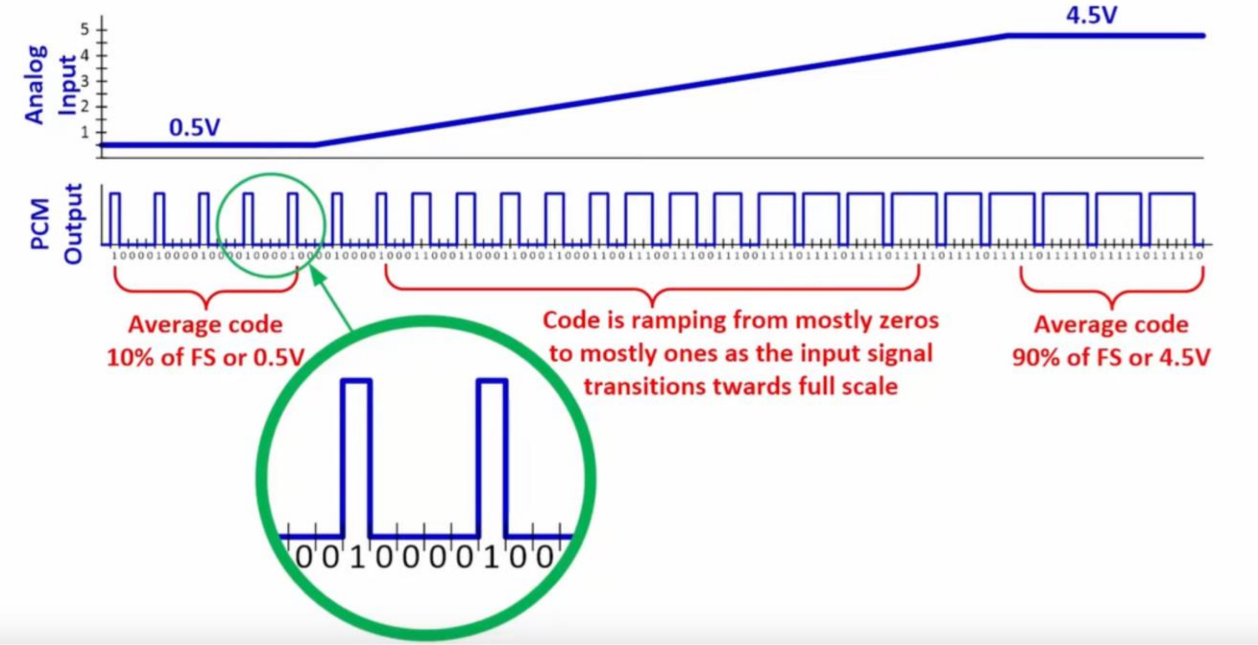


# Analog to Digital Conversion – Sigma Delta

- Relies on oversampling and digital filtering
- 1 bit converter to transform analog signal into Pulse Code Modulated bit stream
- Massively oversampled
- Noise shaping and filtering
- High latency and low sample rate



# GNSS

# GNSS Overview

Video from: https://www.youtube.com/watch?v=FU_pY2sTwTA&t=5s

# GNSS Overview

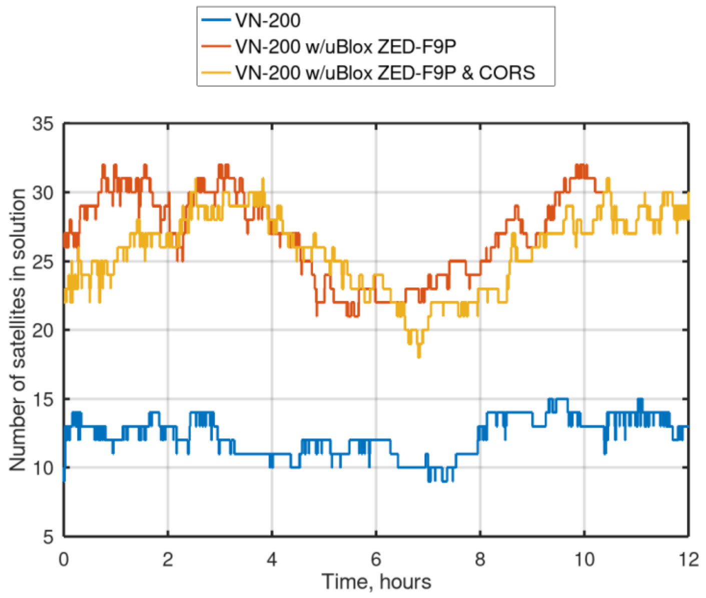
- Code phase messages and ephemeris messages to estimate pseudorange from each satellite
- Used to estimate position of the receiver
- Most of the time to first fix is to download the ephemeris data
  - Ephemeris: precise orbital data, valid for 4 hours
  - Almanac: low resolution orbital info for every satellite, valid for 2 weeks
  - The full almanac takes 12.5 minutes to receive
  - Cell phones typically use their cellular network to download the almanac much faster

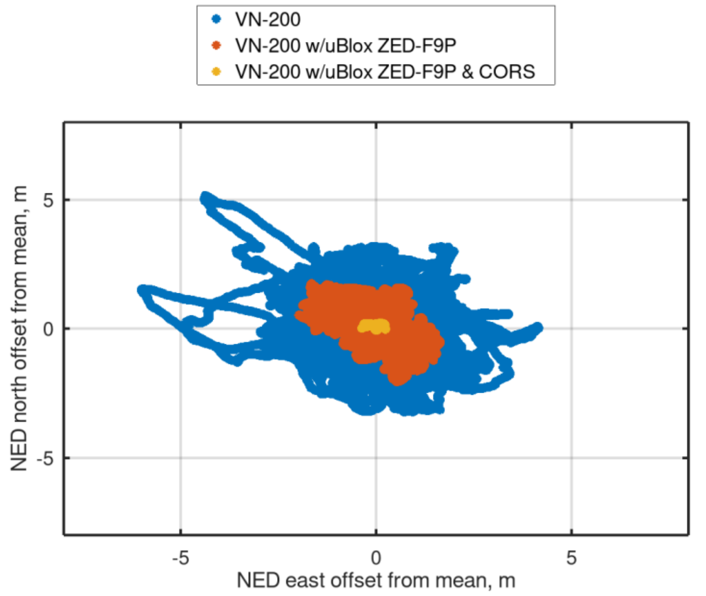
# Time to First Fix

- Cold start: the GNSS receiver has no information, it must search for all possible satellites and start downloading almanac and ephemeris data.
- Warm start: the receiver has estimates of its current time and position and accurate almanac data. It can search for specific satellites to download ephemeris data and compute a solution.
- Hot start: the receiver has accurate ephemeris data and just needs to start pseudoranging from satellites in view.

# GNSS Receivers

- Multi-constellation: new receivers are able to track other constellations in addition to GNSS
  - More satellites in view
  - Faster time to first fix and a more robust solution
- Multi-frequency: receivers tracking L1 and L2 have recently become much more affordable
  - The L2 frequency, in addition to L1, enables better accuracy by reducing the effect of the ionosphere in the pseudorange estimate
  - Improved robustness against jamming
  - Substantially improved RTK usage and robustness



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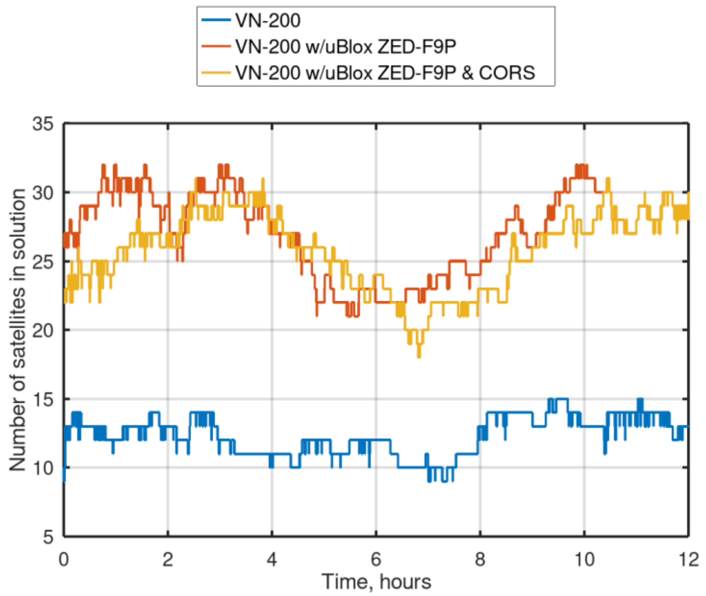
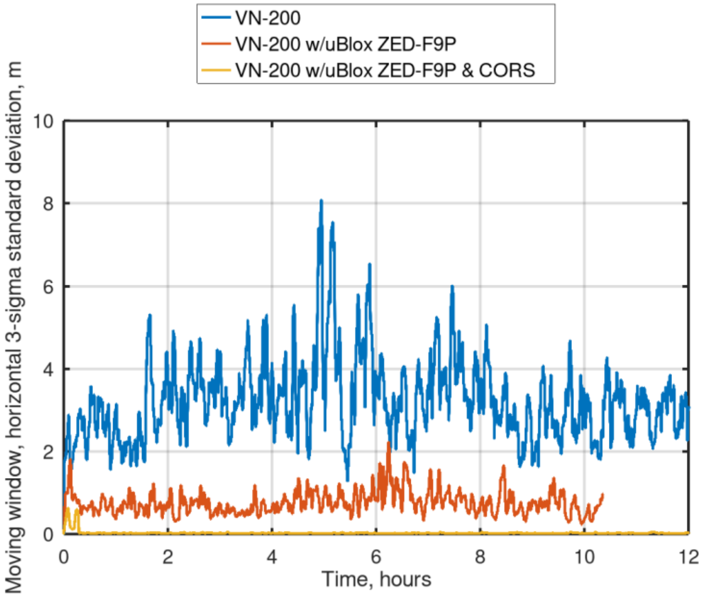
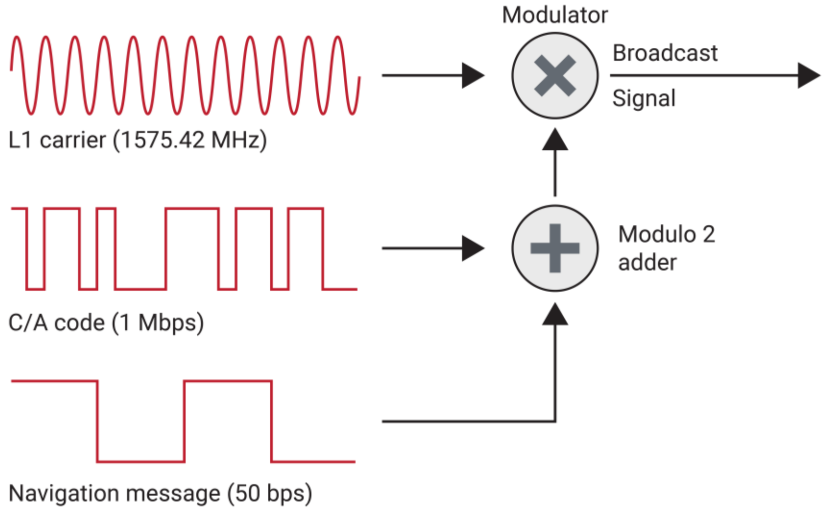
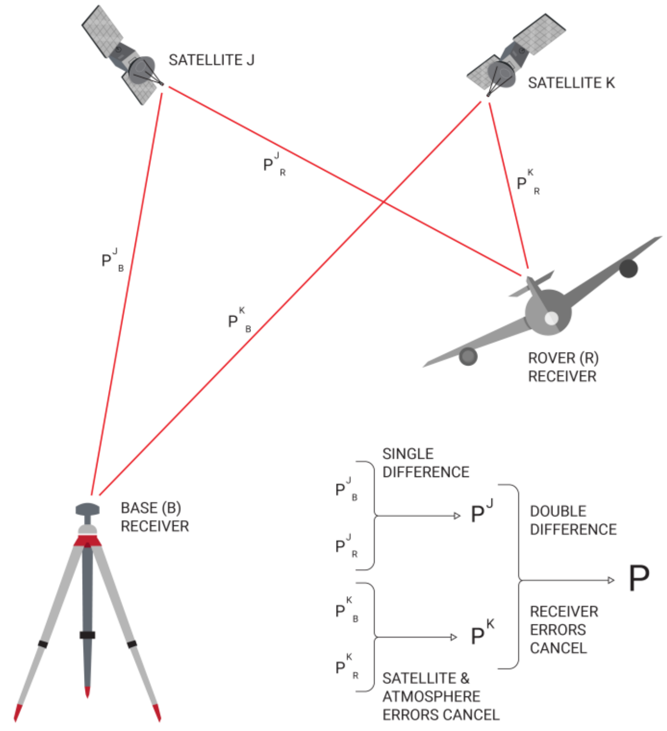


# Real Time Kinematic (RTK)

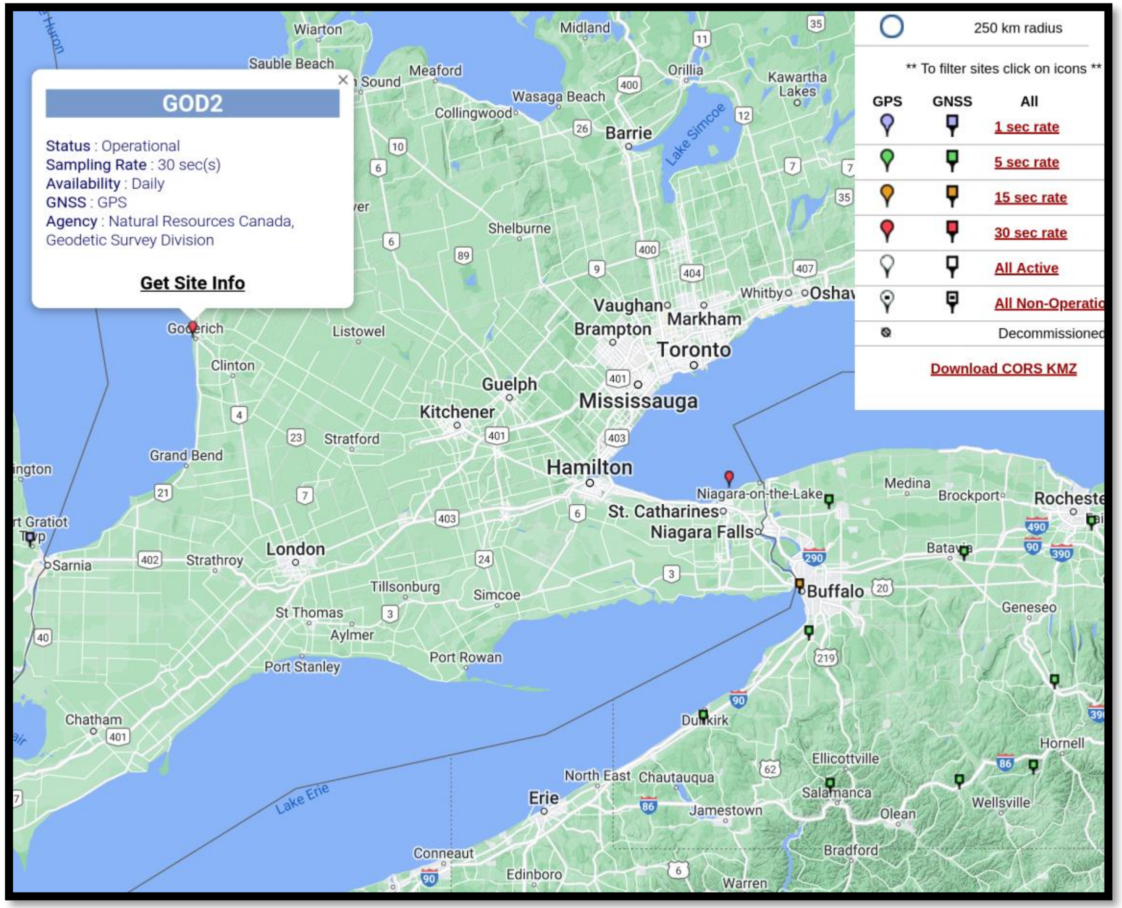
- GNSS receivers use a pseudo random code to determine the travel time to a satellite, referred to as code phase
- RTK uses the carrier phase of the GNSS signal comparing the number of carrier phase cycles observed between two receivers
  - Requires at least 2 satellites and 2 receivers
  - Multi-frequency receivers can reduce the number of feasible solutions to the integer ambiguity problem, substantially reducing the time to find an RTK solution



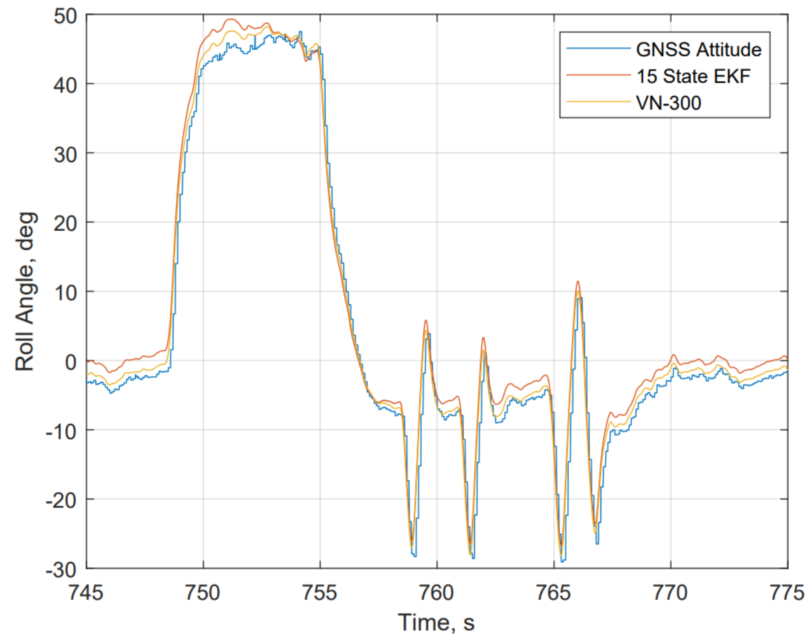
# Stationary and Moving Base Stations

- RTK can provide mm accuracy of the relative position between two receivers
- If one of the receivers is a stationary, surveyed-in base station, this can result in mm global accuracy
- Survey-in can be performed professionally, using Continuously Operating Reference Station (CORS) network corrections, or performed on device
- A moving base station can be used for GNSS heading and GNSS attitude estimation as well as tasks like autolanding



# GNSS Heading and Attitude

- Multiple receivers can be installed on a vehicle to estimate heading and attitude
  - Heading works with 2 receivers, a full attitude solution requires 3
  - 10 Hz update rate achievable
- Flight validated on a small UAS using multi-constellation, multi-frequency receivers




# GNSS Summary

- Great source of inertial position and velocity
- Multi-constellation receivers offer better time to first fix and better robustness
- Multi-frequency receivers have better accuracy at the expense of higher cost
- RTK can be used to measure relative position with mm accuracy and can be used to estimate heading or attitude
- Coupled with a surveyed in base station or corrections from a CORS network, RTK can provide excellent global accuracy

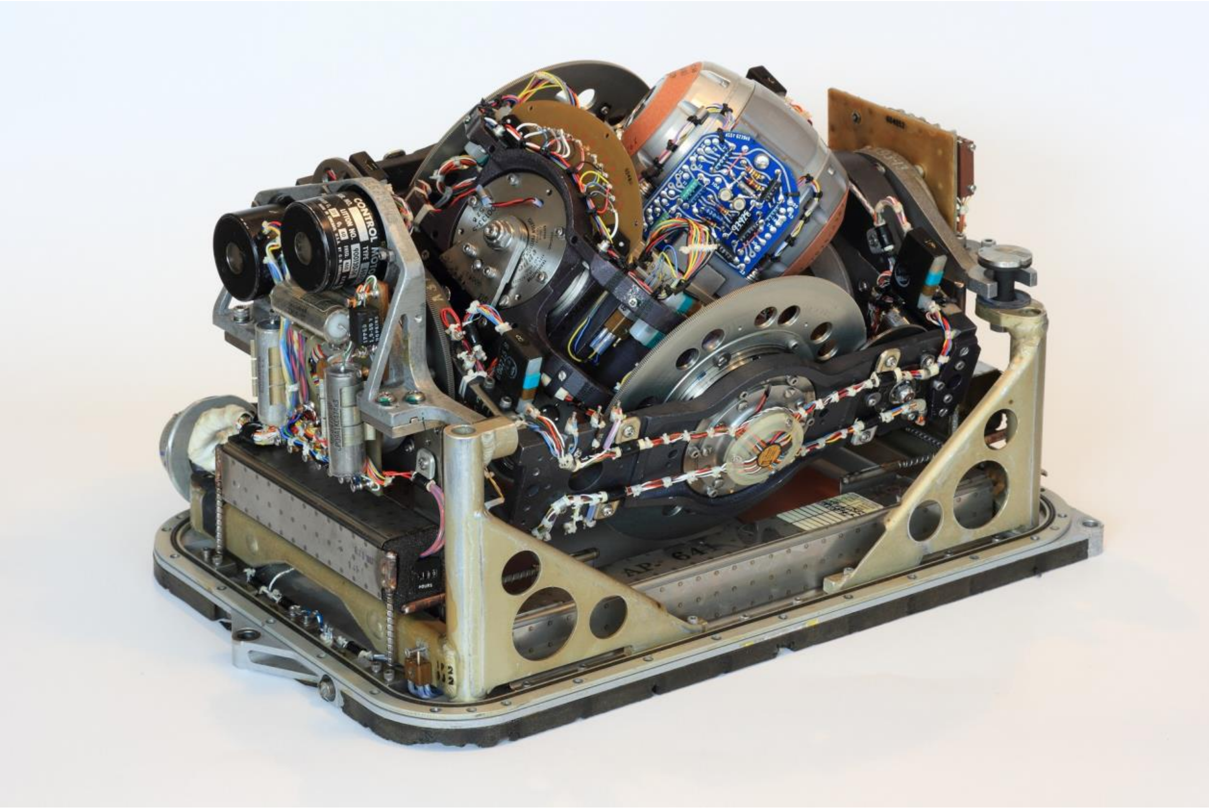
# Inertial Navigation Systems

# Purpose

- Measure and estimate inertial states at a high-rate
  - Attitude
  - Inertial position, velocity, and acceleration
  - Inertial rotational rate
- Sensors
  - Gyroscope
  - Accelerometer
  - Magnetometer*
  - GNSS*

# Spinning Gyro

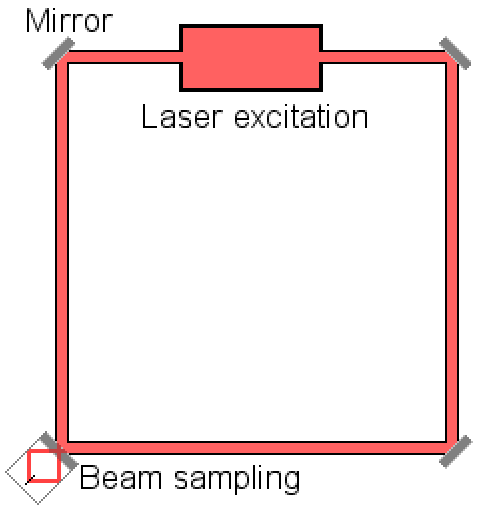
- Gyro stabilized platform
- Heated sensors to maintain consistent temperature
- Excellent performance
- Mechanically complex

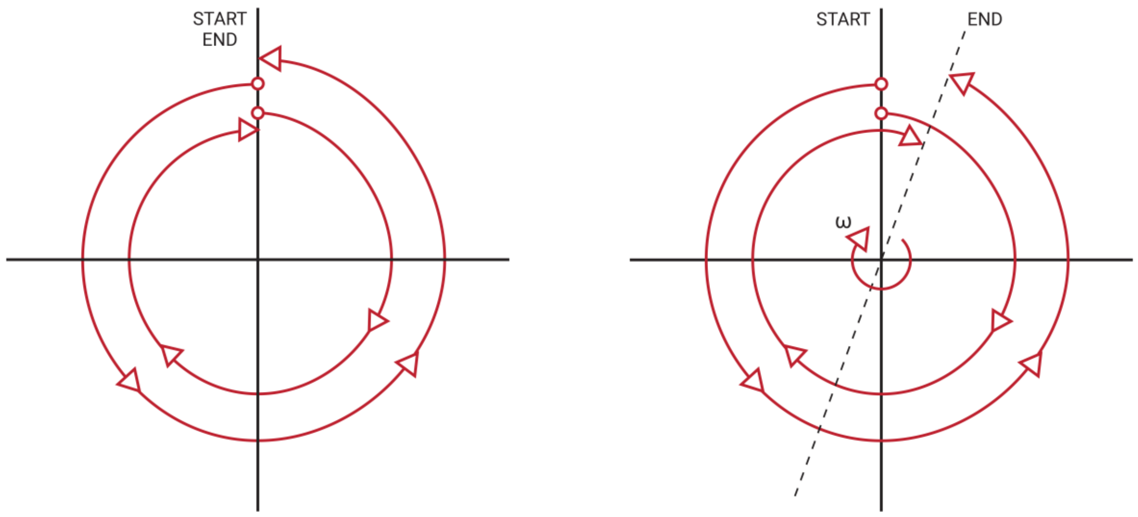


Litton LN-3

# Ring Laser Gyro (RLG)

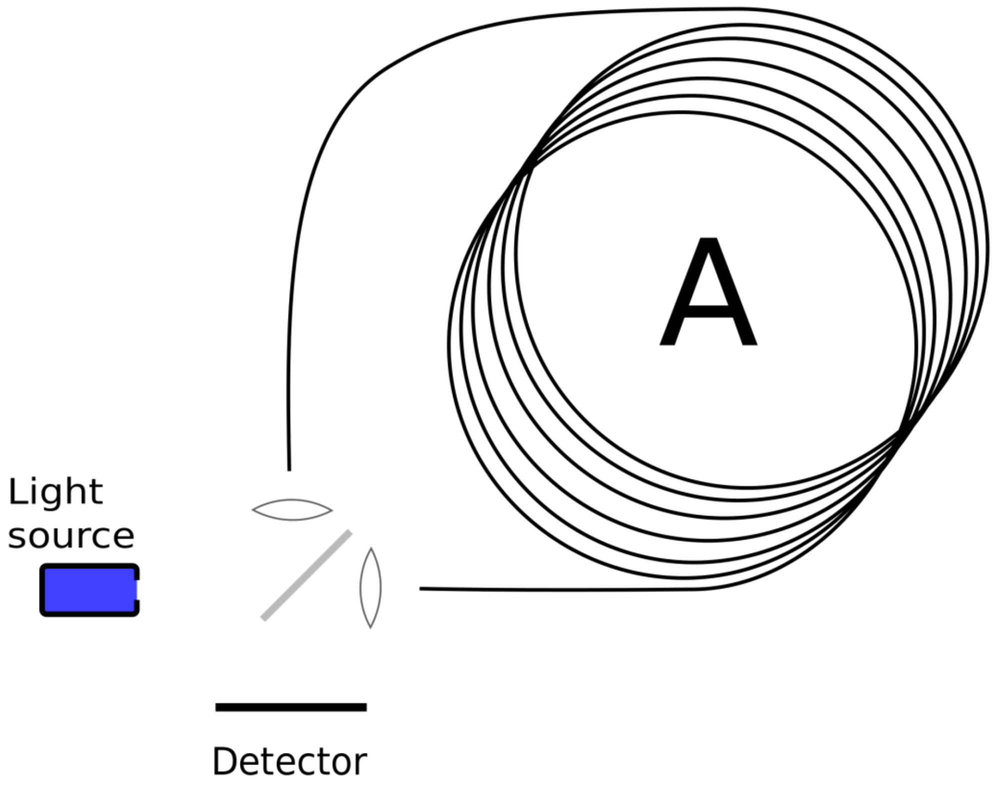
- Laser is split and traverses ring in both directions in an evacuated cavity
- At the sampling location the phase differential between the two beams can be used to accurately measure the rotation rate of the RLG
- Drift on the order of 0.01 deg/hour
- Used on many commercial and military aircraft
- Expensive and ITAR restricted



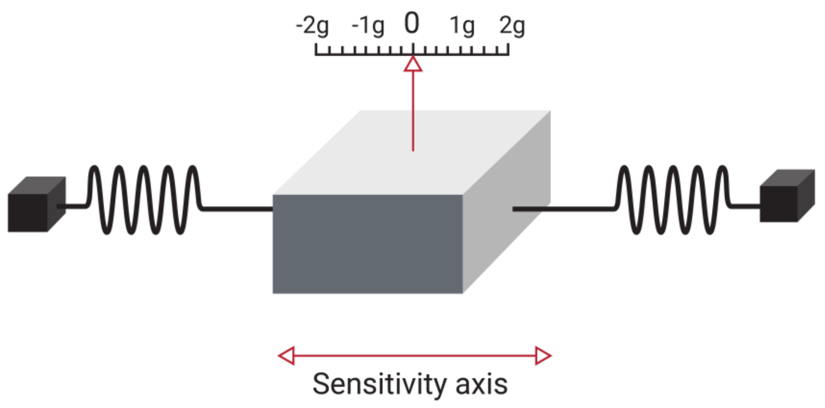
# Fiber Optic Gyro (FOG)

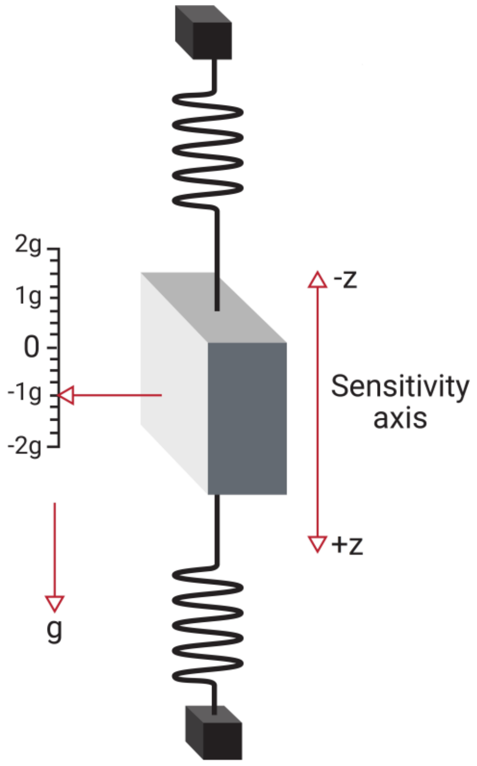
- Same principal as the RLG
- Uses light passed through a very long fiber optic cable instead of a laser
- Performance depends on the length of the fiber optic cable
- Can approach RLG performance and be much more cost competitive

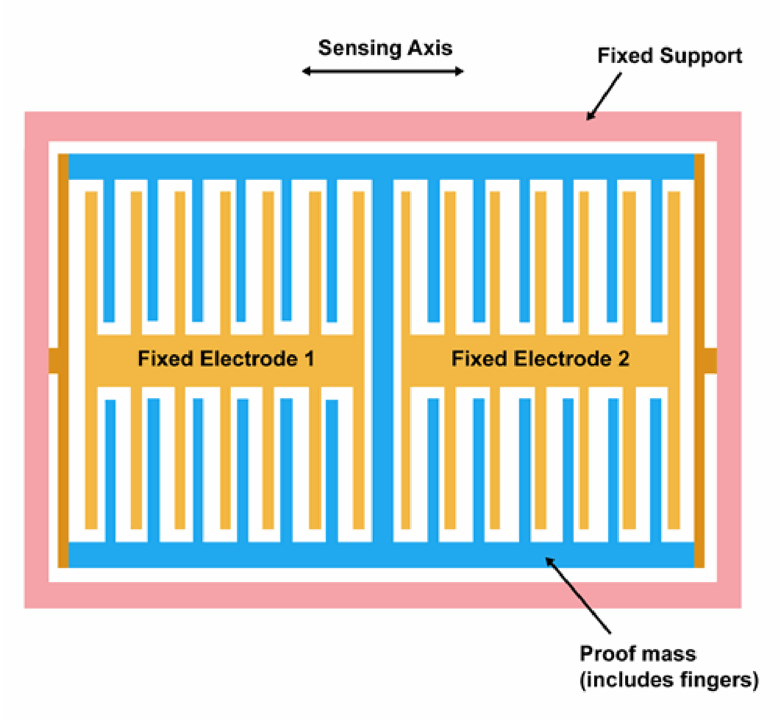


# MEMS Accelerometer

- Microelectromechanical systems (MEMS)
- Proof mass that shifts proportional to acceleration

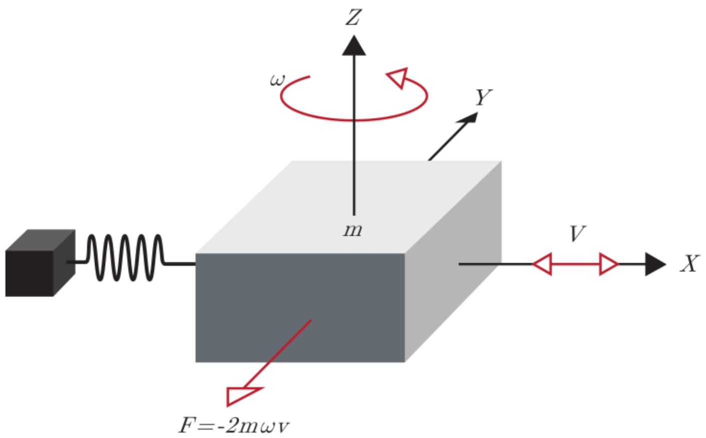


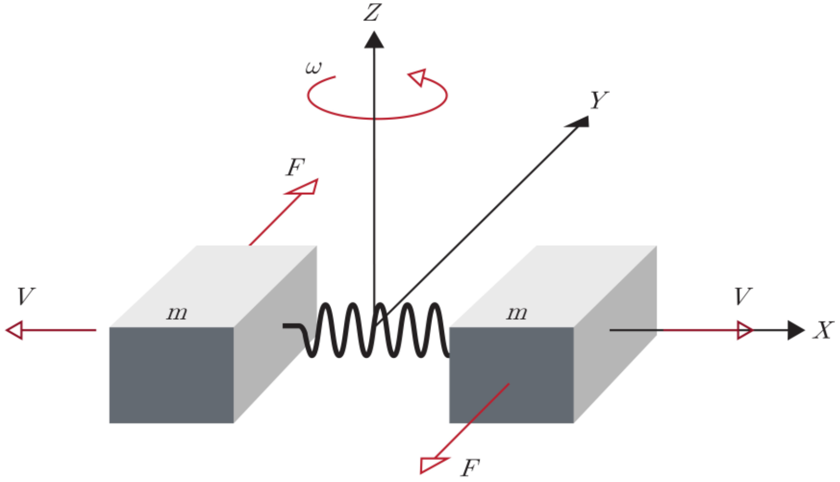



# MEMS Gyro

- Use Coriolis force to measure rotational rate
- An oscillation is induced on the x axis
- Rotation causes displacement on the y axis
- Tuning fork configurations typically used to reduce affect of acceleration on measurement output



# Sources of Errors

- Non-orthogonality
- Mis-alignment
- Turn-on bias stability
- In-run bias stability
- Temperature bias stability
- Scale factor non-linearities
- Cross axis sensitivity
- G-sensitivity

$$\begin{bmatrix} x \\ y \\ z \end{bmatrix} = \begin{bmatrix} S_x & 0 & 0 \\ 0 & S_y & 0 \\ 0 & 0 & S_z \end{bmatrix} \begin{bmatrix} 1 & \alpha_1 & \alpha_2 \\ \alpha_3 & 1 & \alpha_4 \\ \alpha_5 & \alpha_6 & 1 \end{bmatrix} \left( \begin{bmatrix} \tilde{x} \\ \tilde{y} \\ \tilde{z} \end{bmatrix} - \begin{bmatrix} b_x \\ b_y \\ b_z \end{bmatrix} \right)$$

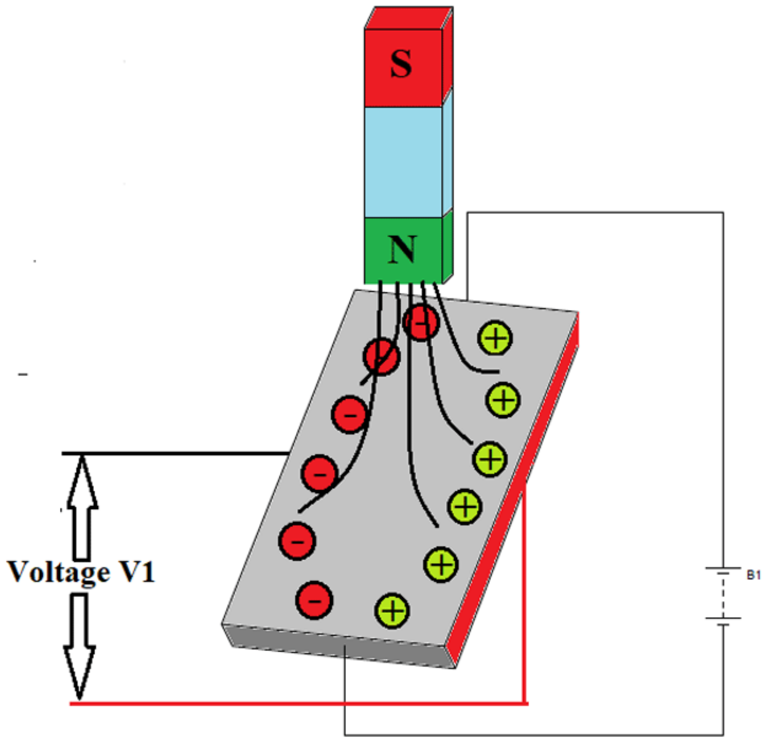
# IMU Calibration

- MEMS IMUs range in price from approx. $5 to $18k
    - Fundamentally little difference in the underlying technology
    - Mostly the price differential is a result of the level of calibration from the factory
- At a minimum, you should estimate the gyro biases on every startup
- Accelerometer turn-on biases are relatively stable, you can estimate a bias and scale factor using the gravity vector
- Extended Kalman Filters (EKFs) can estimate accelerometer and gyro biases in real-time, great for in-run and temperature bias instabilities

# IMU Calibration Demo

# MEMS Magnetometer

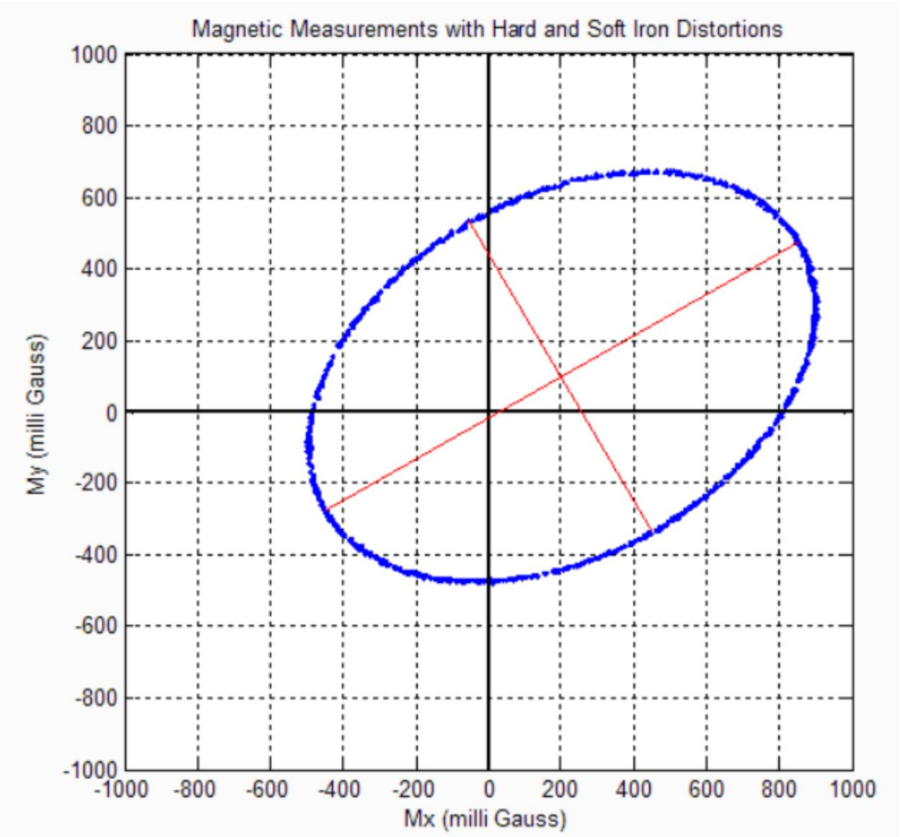
- Typically hall effect sensors
- Current driven over plate, can measure voltage to estimate magnetic field strength



# Magnetometer Error Sources

- Magnetometer senses Earth's magnetic field and local electromagnetic disturbances
  - Hard and soft iron
  - Earth's magnetic field is relatively weak and it's necessary to calibrate the magnetometer
  - Typically a 3D calibration is performed by rotating the magnetometer in a figure 8 and fitting the data to a sphere
  - This should be performed in the vehicle with all the electronics running

$$\begin{bmatrix} m_{c_x} \\ m_{c_y} \\ m_{c_z} \end{bmatrix} = \begin{bmatrix} C_{00} & C_{01} & C_{02} \\ C_{10} & C_{11} & C_{12} \\ C_{20} & C_{21} & C_{22} \end{bmatrix} \begin{bmatrix} \tilde{m}_x - b_{H_0} \\ \tilde{m}_y - b_{H_1} \\ \tilde{m}_z - b_{H_2} \end{bmatrix}$$



# Attitude Estimation Using the Accelerometer and Compass

- Can use accelerometer data to estimate pitch and roll angle
- Magnetometer can be tilt compensated and used to estimate heading
- Works well for low dynamic environments

# Tilt Compass Demo

# Attitude Estimation using the Gyro

- The gyro can be integrated to estimate the current attitude as a delta from a starting attitude
- Great for high dynamic environments
- Noise in the gyro data can cause the solution to drift over time

# Gyro Integration Demo

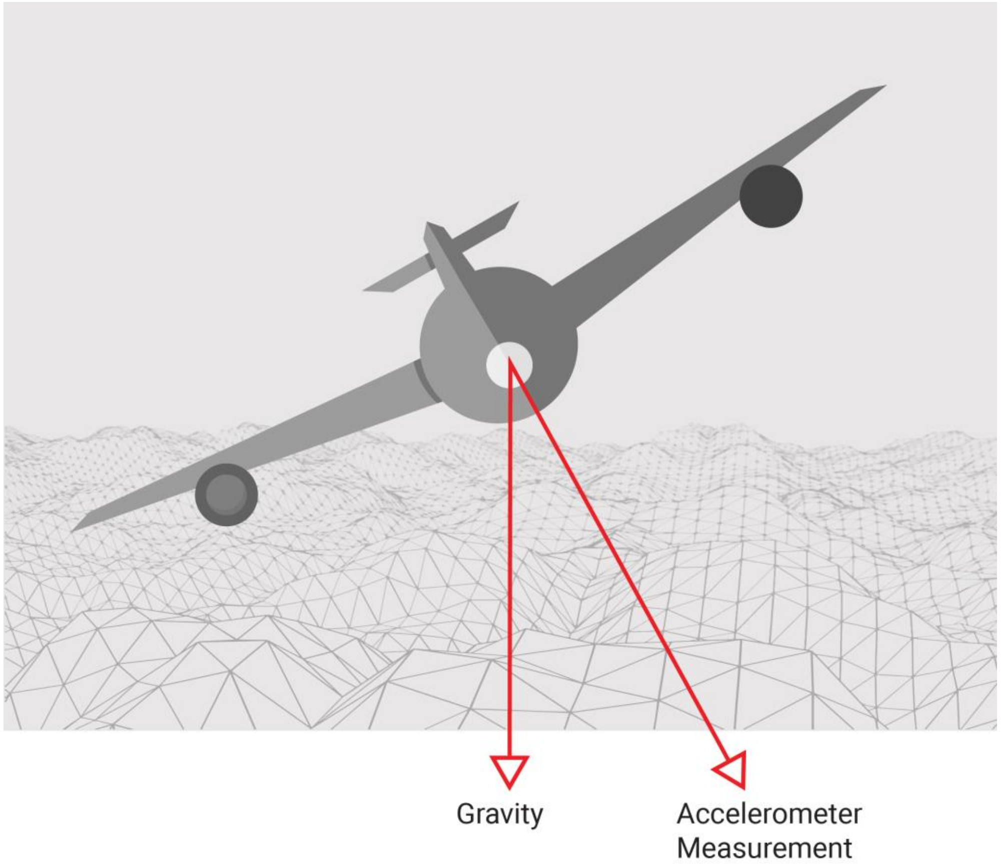
# Arresting Error Growth using an AHRS

- Can integrate the gyro data and use the accelerometer and magnetometer data to occasionally provide an independent source of attitude information to arrest the error growth from the gyro noise
- Attitude and Heading Reference System (AHRS)
  - Typically an Extended Kalman Filter (EKF) is used for this process
  - Gyro data is integrated in the *Time Update*
  - Accel and magnetometer data is applied as a correction in the *Measurement Update*
  - Several mathematical formulations ranging from using quaternions to using Euler angles, each with benefits and limitations
  - Can add extra layers to aide the estimation process
    - High pass filter gyros, low pass filter accels
    - Only apply measurement update when total acceleration is below a set threshold

# AHRS Demo

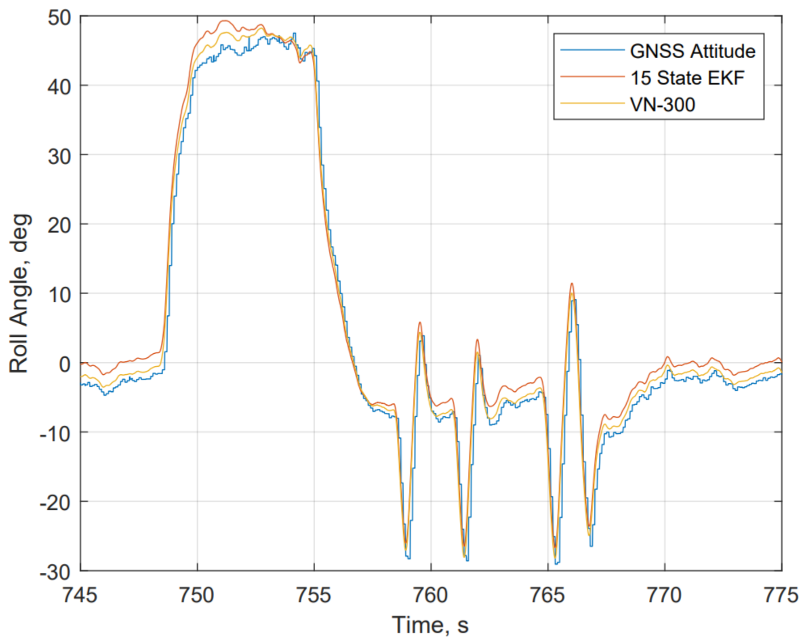
# AHRS Sources of Errors

- A common aeronautical source of AHRS errors are prolonged coordinated turns
  - The gyro will accurately pick up the initial bank angle for the turn
  - Measurement updates will pull the solution back to wings level
  - Over time the AHRS will indicate zero bank even though the aircraft is still in a turn
- If position is dead-reckoned with an AHRS, the double integration of the accelerometer data tends to drift rapidly
  - Can somewhat arrest this drift using airspeed and altitude data



# GNSS Aided INS

- Estimate the initial state
  - Tilt compass for attitude and heading
  - GNSS for position
- Integrate the gyro and accelerometer data in the time update
- Arrest the drift using GNSS position and velocity in the measurement update
- Able to estimate real-time accel and gyro biases!
- Good heading estimation at inertial speeds above approx. 5 m/s
- This is the process used in PDAS and many commercial MEMS INS systems
- Excellent for high-dynamic environments, need to switch to an AHRS for low-dynamic environments



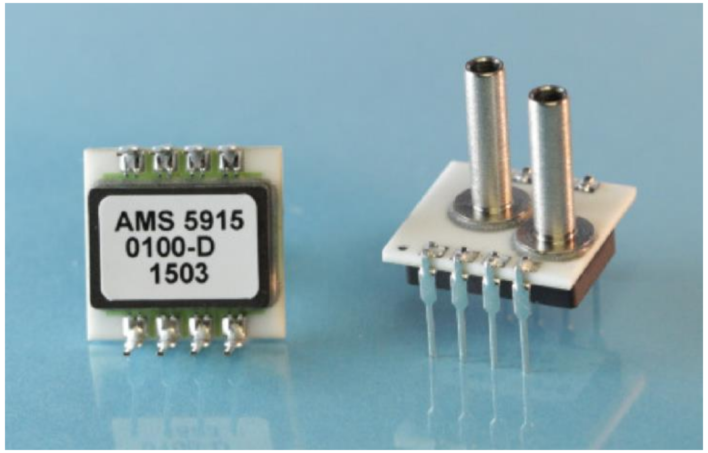
# INS Summary

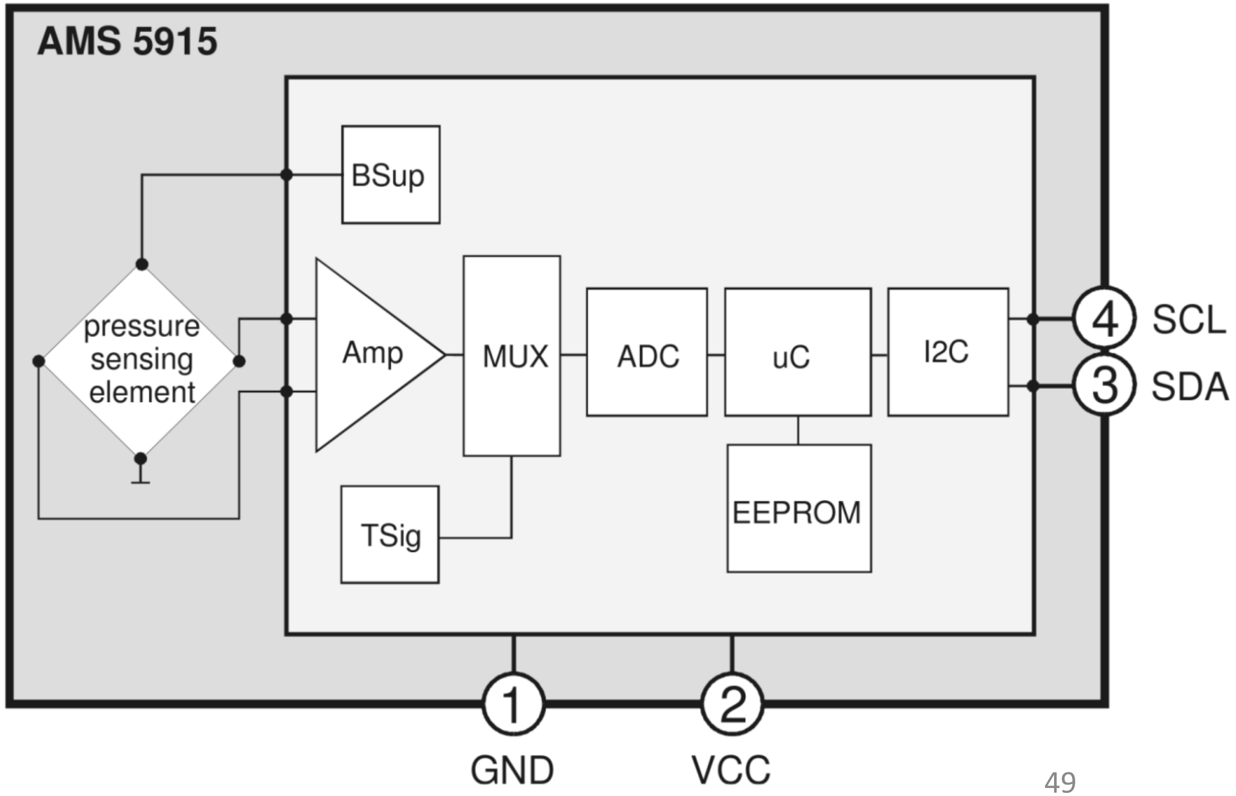
- GNSS-aided INS with a MEMS IMU is a very cost-effective and accurate approach
- Good heading estimation accuracy at inertial speeds above 5 m/s
  - GNSS RTK can provide good heading estimates below 5 m/s
  - Magnetometer based heading estimates are generally poor
- Not much difference between MEMS IMUs except for amount of calibration performed by the factory
- Always estimate turn-on bias for gyros
- Can estimate accel scale factor and bias using gravity vector
- Temperature calibration is not necessary if your EKF can estimate gyro and accel biases in real-time

# Air Data

# Pressure Transducers

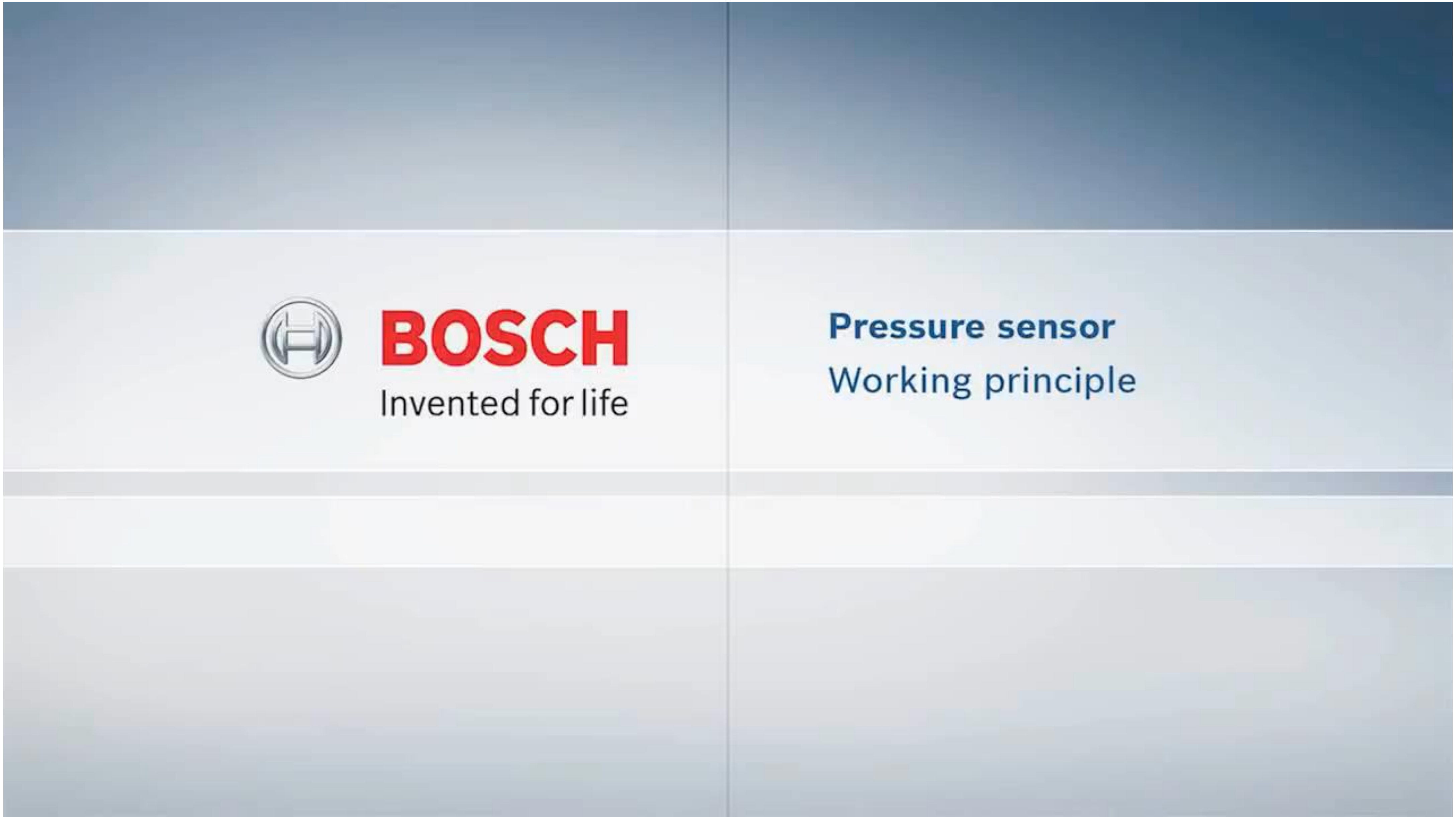
- Measure static and differential pressure
- Critical for estimating airspeed and altitude
- Theory of operation:
  - Flexible membrane that changes resistance based on pressure
  - Wheatstone bridge to measure resistance
  - Commonly, analog front end and digitization



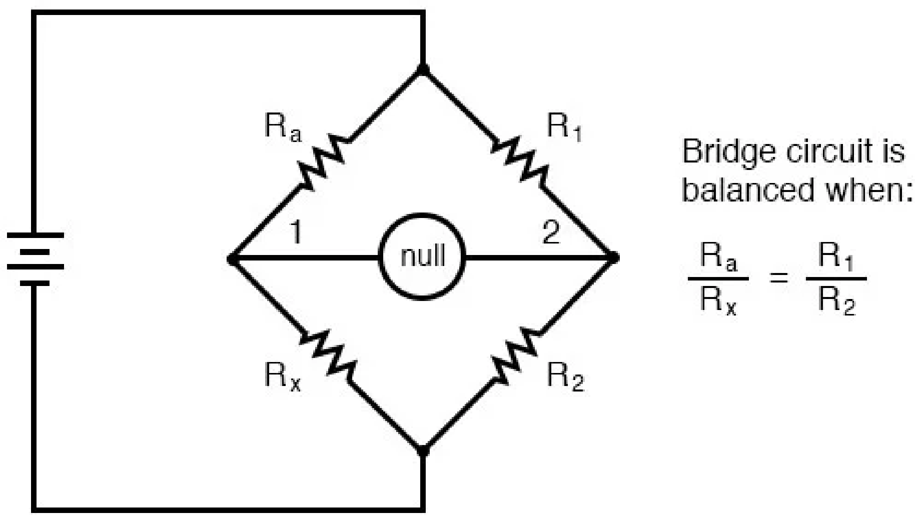
# Concept of Operation

Video from: https://www.youtube.com/watch?v=zXIeqeT_FC8



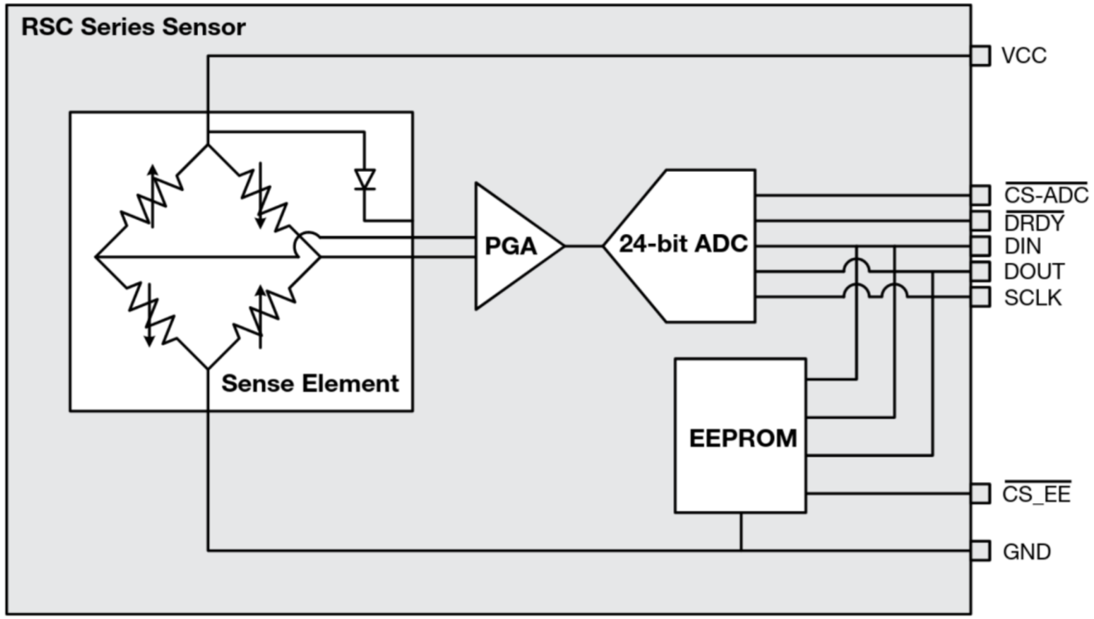
# Wheatstone Bridge

- With all resistors equal, output voltage is zero
- When resistors are not equal, output voltage is proportional to the change in resistance
- Good approach for analog circuits that measure the environment through changes in resistance



# Another Implementation Example

- Similar to the AMS-5915
- No integrated microcontroller, so our processor needs to read and apply corrections from EEPROM
  - Leads to a more complicated software interface
- Much higher resolution ADC



# Balancing Measurement Accuracy and Range

- Ideally, balance transducer type with application
  - Absolute / baro for static pressure measurement
  - Differential for differential pressure measurement
  - Bi-directional differential for bi-directional pressure measurement (i.e. 5-hole probe angle of attack and angle of sideslip)
- This is not always the case and often bi-directional transducers are used for differential pressure measurement
  - Pro: pressure taps can be installed either way
  - Con: wasting half the pressure measurement range (reduced resolution and greater total error)

# Enhancing Accuracy and Range

- Total error is based directly on the measurement range
- Burst pressure is often much greater than the measurement range
- Can stack multiple pressure transducers to achieve low error across a wide pressure range

| | | | | |
|---|---|---|---|---|
| **Overall error [6] (pressure meas.) @ *T = -25 .. 85 °C*** | | | | |
| Ultra low pressure sensors (5, 10 mbar) | | | ± 2.0 | %FSO |
| Low pressure sensors (20, 50, 100 mbar) | | | ± 1.5 | %FSO |
| Standard pressure sensors | | | ± 1.0 | %FSO |

# Enhancing Accuracy and Range

| Sensor type (code) | Pressure type | Pressure range in mbar | Burst pressure[1)] in bar | Pressure range in PSI | Burst pressure in PSI |
|---|---|---|---|---|---|
| **Ultra low pressure** | | | | | |
| AMS 5915-0005-D | differential / relative | 0 .. 5 | > 0.35 | 0 .. 0.0725 | > 5 |
| AMS 5915-0010-D | differential / relative | 0 .. 10 | > 0.35 | 0 .. 0.145 | > 5 |
| AMS 5915-0005-D-B | bidirectional differential | -5 .. +5 | > 0.35 | -0.0725 .. +0.0725 | > 5 |
| AMS 5915-0010-D-B | bidirectional differential | -10 .. +10 | > 0.35 | -0.145 .. +0.145 | > 5 |
| **Low pressure** | | | | | |
| AMS 5915-0020-D | differential / relative | 0 .. 20 | > 0.5 | 0 .. 0.290 | > 7.5 |
| AMS 5915-0050-D | differential / relative | 0 .. 50 | > 1 | 0 .. 0.725 | > 15 |
| AMS 5915-0100-D | differential / relative | 0 .. 100 | > 1 | 0 .. 1.450 | > 15 |
| AMS 5915-0020-D-B | bidirectional differential | -20 .. +20 | > 0.5 | -0.290 .. +0.290 | > 7.5 |
| AMS 5915-0050-D-B | bidirectional differential | -50 .. +50 | > 1 | -0.725 .. +0.725 | > 15 |
| AMS 5915-0100-D-B | bidirectional differential | -100 .. +100 | > 1 | -1.450 .. +1.450 | > 15 |
| **Standard pressure** | | | | | |
| AMS 5915-0200-D | differential / relative | 0 .. 200 | 5 | 0 .. 2.901 | 72 |
| AMS 5915-0350-D | differential / relative | 0 .. 350 | 5 | 0 .. 5.076 | 72 |

# Considerations for Flight Research

- Sensitive to temperature changes
  - Typically calibrated across a die temperature range
- Turn-on bias for differential pressure transducers is significant and should be estimated
- Pressure transducers should be placed near the pressure source to minimize pneumatic lag
- Digital low pass filtering should be employed, pressure data is typically slow to change

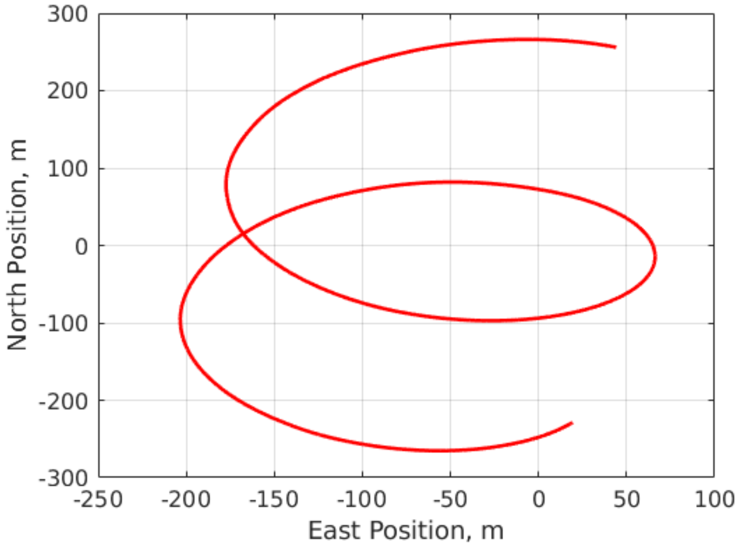
# PDAS Inspection

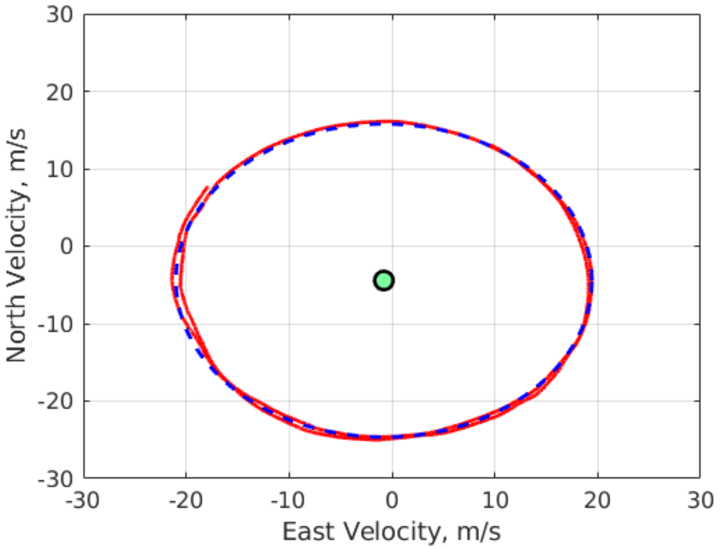
# Calibrating Airspeed Data in Flight

- Sources of error
  - Installation and alignment
- Flight test technique
  - Constant airspeed, constant bank angle circles
  - Perform at multiple airspeeds across flight envelope
    - Fit a polynomial to the data to apply correction
  - Use GNSS north and east velocity data to estimate wind speed, wind direction, and airspeed

# Analyzing Airspeed Calibration Data

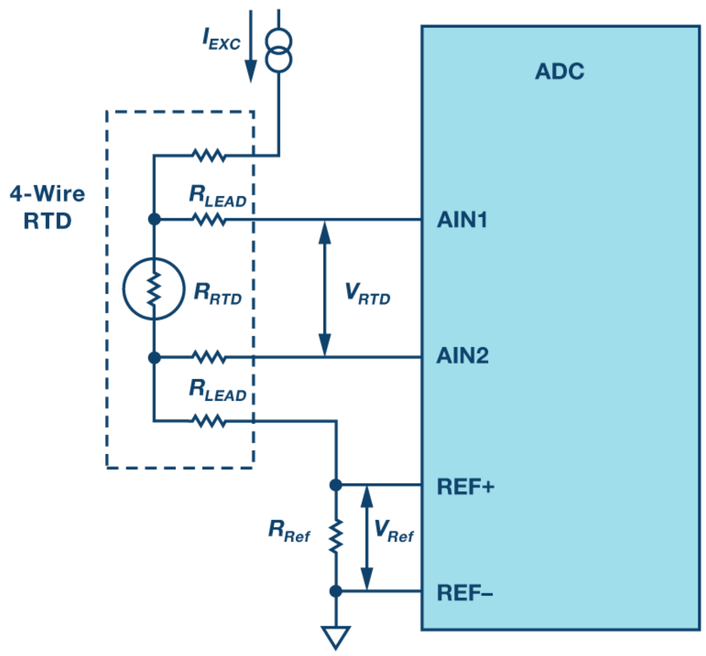
- Position shows a spiral as the wind moves the air mass the aircraft is flying in
- Fitting a circle to the velocity data gives the true airspeed (circle radius) and north / east components of the wind speed, which can be used to find the wind speed and direction
    - Assumption: wind speed is constant during the maneuver



# Temperature Measurement

- Resistive Temperature Detector (RTD)
  - Typically used for applications below 500C
  - Slower response time than thermocouples
- Probe created from platinum
  - Nearly linear relationship between resistance and temperature from 0 – 100 C
- Ratiometric with reference resistor
  - Eliminates sources of error, such as drift of the current source
  - It does require a precise, low temperature drift resistor
    - PDAS uses a 0.01% tolerance, 0.2 ppm / C resistor
- Resistance from the leads can be significant, at least a 3 wire RTD should be used to remove the effect
- Self heating can occur if the excitation current is too high, typically select a value under 1 mA




$$R_{RTD} = \frac{Code_{RTD} \times R_{Ref}}{Code_{ADC\_Fullscale}}$$

# Temperature Measurement Demo with PDAS

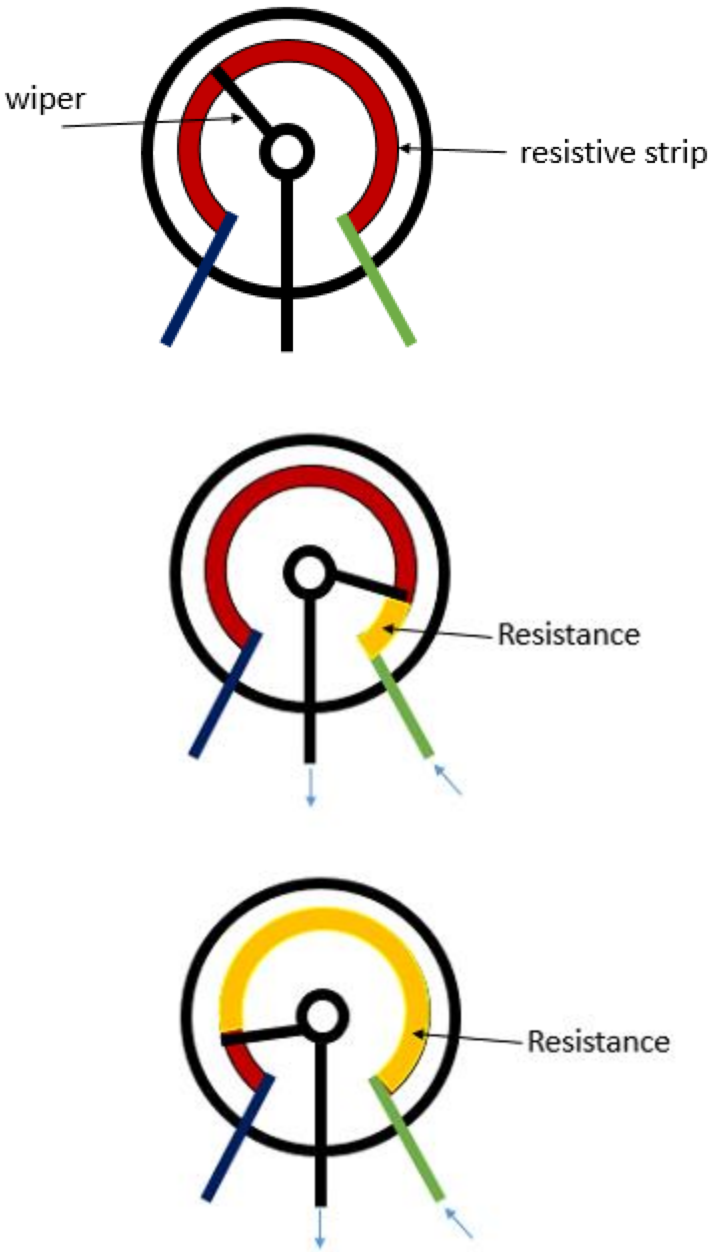
# Air Data Summary

- Use the highest resolution sensors available
- Stack differential sensors across the airspeed range, assuming the burst pressure allows it
- Always estimate turn-on bias for differential pressure transducers
- Use at least a 3 wire RTD for OAT measurement

# Analog Input Measurement

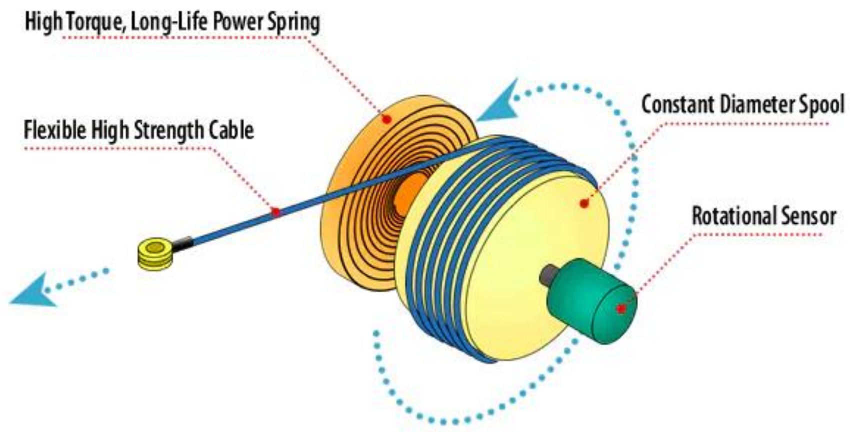
# Potentiometers

- Provide analog voltage in and measure shaft position based on output voltage
- Ratiometric output not sensitive to noisy power supplies



# Stick / Control Surface Position

- String or rotary potentiometers typically used
- Requires calibrating voltage to desired output (i.e. +/- 1)
    - PDAS enables polynomial fitting to save engineering data output
        - Better than needing to save and keep track of the calibration data and the raw output




# Stick Force

- Typically load cells used to measure force
- Requires significant amplification
- Datasheet used to transform voltage to engineering units
  - mV/V at full output
  - 2 mV/V, excited with +5V will provide a 10 mV output at full load

# Demonstration with PDAS

# Analog Input Summary

- Typically used for measuring stick or control surface position and stick force
- Should calibrate measured voltage to engineering units
- Programmable Gain Amplifiers (PGAs) enable zooming data for potentiometers that are mechanically limited or strain gages, which need high levels of amplification

# External Sensors

# Integrating External Sensors

- PDAS supports 40 single precision and 5 double precision floating point variables over a UART interface, enabling adding capability
  - Interfacing with aircraft avionics systems and buses (Garmin G3X, 1553, etc.)
  - Interfacing with additional sensors
  - Adding additional analog channels
- Developing a PDAS to CAN bridge to enable greater flexibility
  - CAN Aerospace, DroneCAN (formerly UAV CAN), and ARINC-825 are common protocols
  - Enables plug-and-play integration with devices made by other vendors or developed in-house
  - Publisher / subscriber approach

# Integrating External Sensors

- PDAS expects:
  - 2 header bytes to sync the start of the packet
  - Meta data describing the packet
  - Fletcher-16 checksum

| Byte | Description |
|---|---|
| 0 | Header 0x42 |
| 1 | Header 0x46 |
| 2 | Starting Single Precision Index |
| 3 | Starting Double Precision Index |
| 4 | Number of Single Precision Variables |
| 5 | Number of Double Precision Variables |
| X | Single Precision Variable Data |
| Y | Double Precision Variable Data |
| 5 + X + Y + 1 | Fletcher 16 Checksum LSB |
| 5 + X + Y + 2 | Fletcher 16 Checksum MSB |

# Integrating External Sensors Demo with PDAS

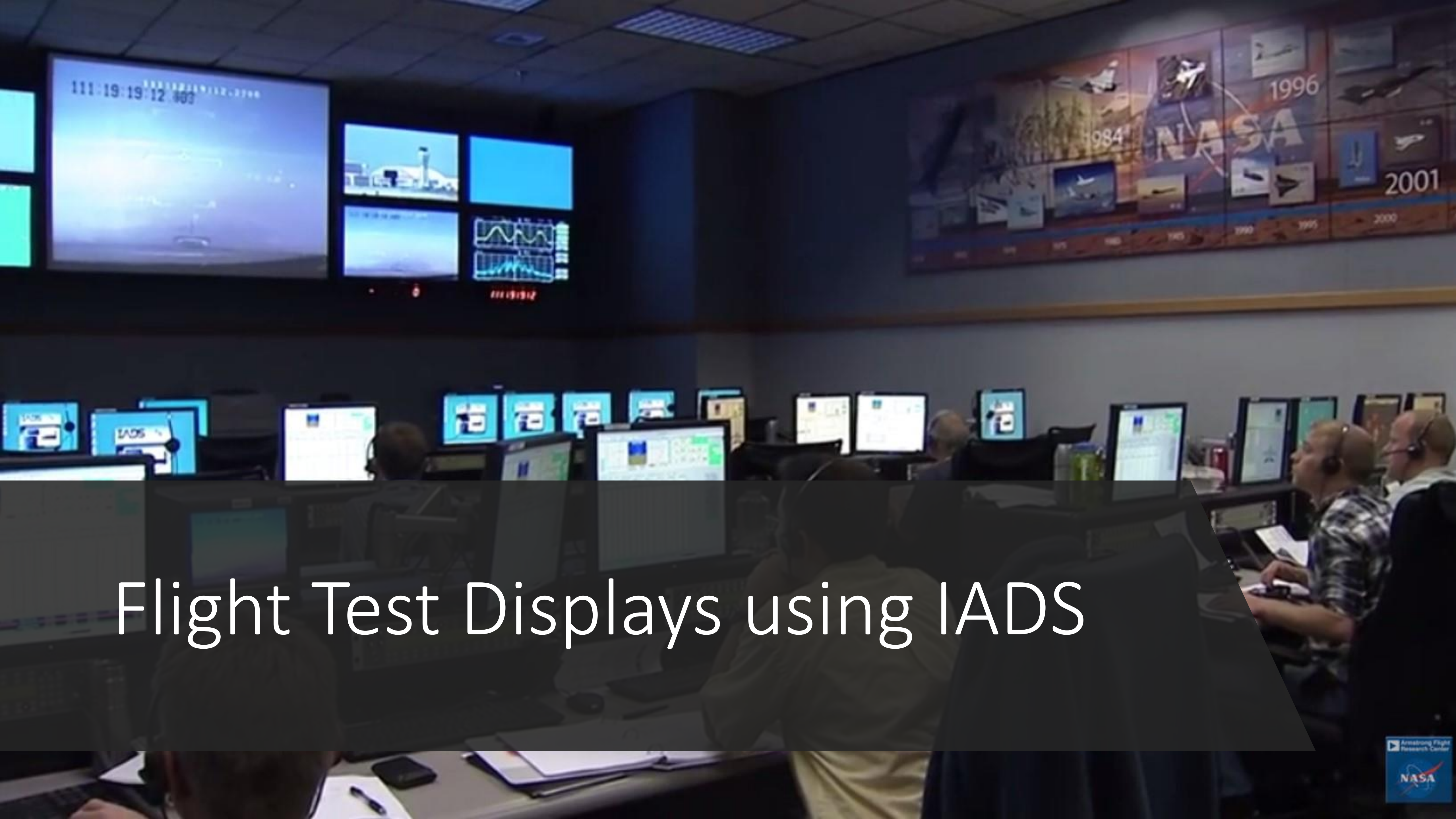
# Flight Data Analysis

# Tagging and Analyzing Flight Data

- PDAS is designed to be turned on as part of the pre-flight checklist and left on until after landing
  - This approach reduces pilot and FTE workload and ensures that all test points are recorded
- Datasets can be very large for long test flights
- FTE interface enables marking flight data as inactive or active
- A number auto-increments every time data is marked as active
- Approach to quickly finding flight test data:
  - Select *active* a few seconds before the test point to gather trim shot data
  - Record the number in the flight test cards
  - Select *inactive* a few seconds after the maneuver is complete
  - Search the data for the test point number and the active flag

# Tagging and Analyzing Flight Data Example with PDAS

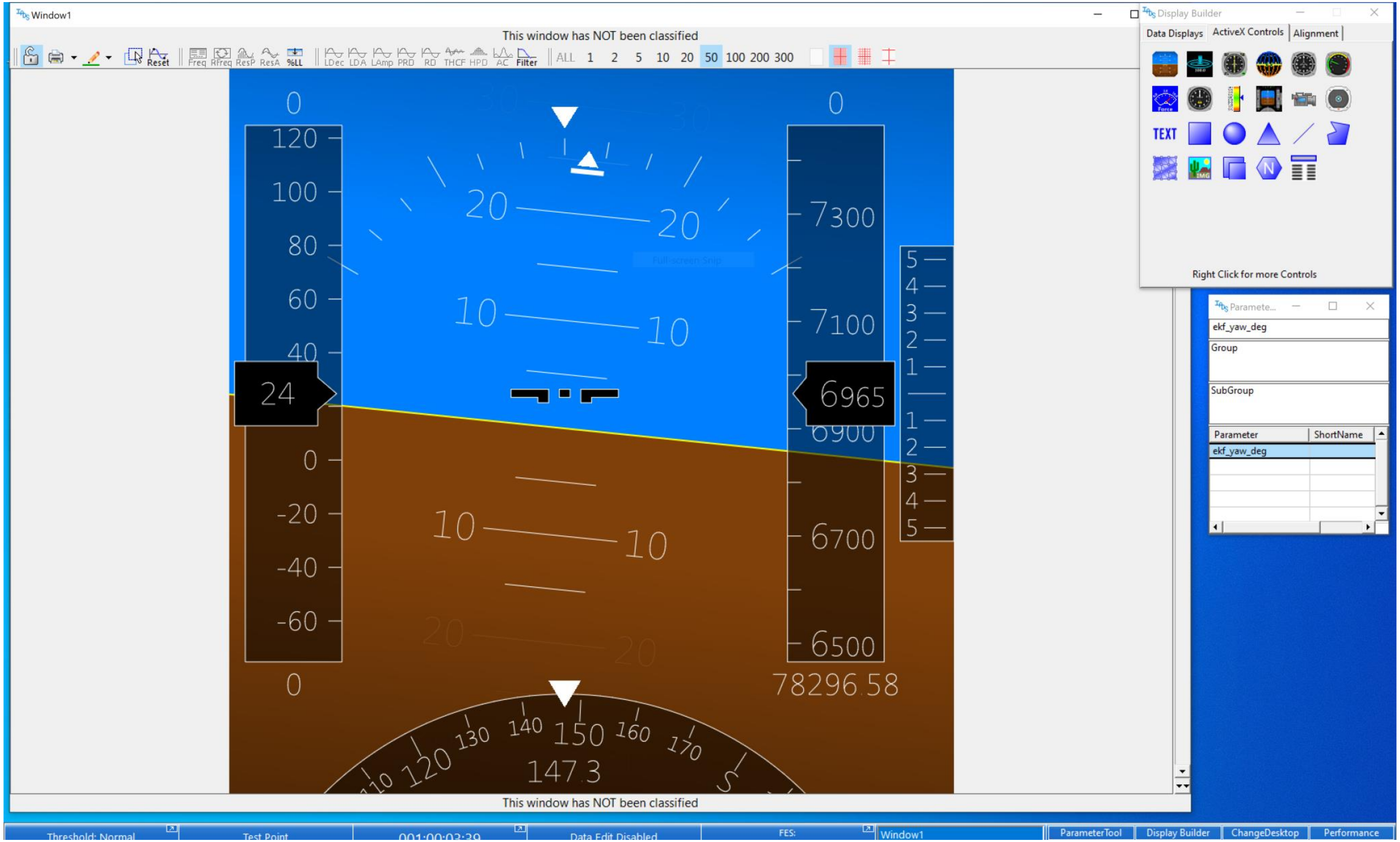
# Flight Test Displays using IADS



# IADS

- Available from Curtiss-Wright Corporation
- Receives PDAS data at 50 Hz over ethernet
- Works in standby and run modes
- Includes all PDAS data and status indicators
  - State, GNSS lock, fault, test point number, test point active
- Can be used to quickly develop flight test displays and strip charts
- Perfect for an FTE position or paired with a radio modem to feed data into a ground control station

# IADS Example



# IADS Demo with PDAS

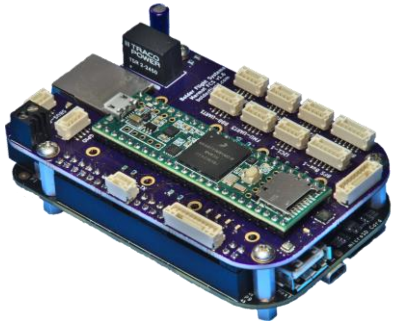
# Future Developments in Data Acquisition Systems

# BlueBird

- Stand-alone data acquisition system that can mount to a wing tie-down bolt or GoPro mount
  - Inspired by Prof. Mujahid Abdulrahim at UMKC who is using this system for conducting 20-minute flight tests
- Targeting low-cost for academia, flight-schools, and individual pilots
  - MATLAB and CSV output
  - Integration with online platforms and electronic logbooks, i.e. Flight Data
- Availability expected by EAA AirVenture 2023

# Common Flight Control System (C-FCS)

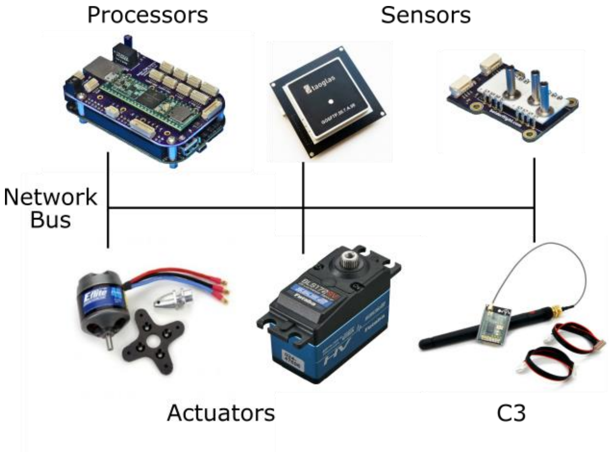
- Plug-and-play modular flight control and data acquisition system with scalable redundancy from single-string to triple-redundant
- Developed under a Phase I and Phase II STTR with AFWERX and the AFRL
- Flight testing a prototype with Beta Technologies in November 2022
- General commercial availability expected by summer 2023

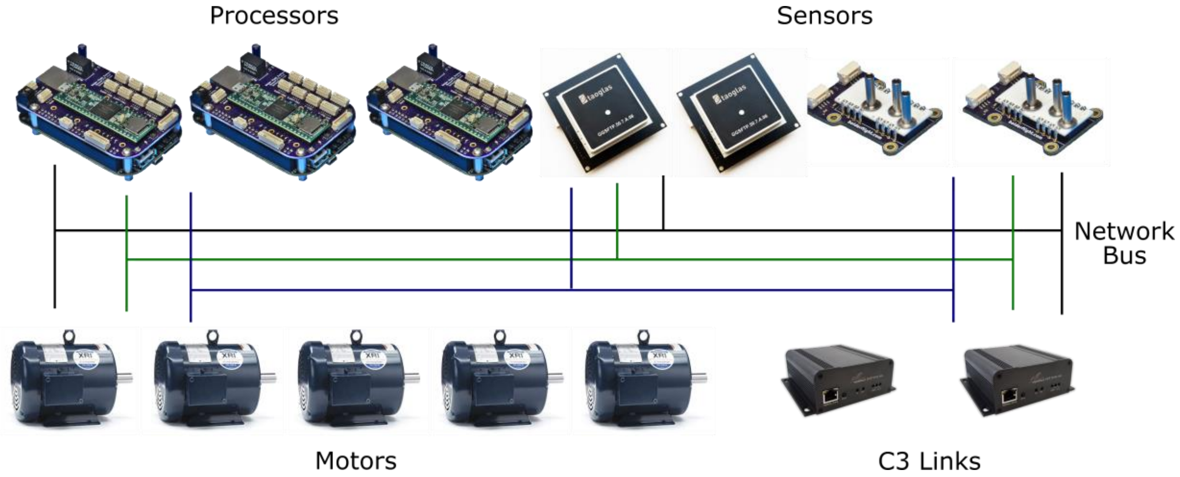


***Single-String, Redundant, Fully-Autonomous, Remotely-Piloted, and Piloted Vehicles, All Safely Controlled by a Fault-Tolerant, Common Flight Control System (C-FCS)***

# C-FCS Architecture

- CAN bus modules
- INS, air data computer, battery monitoring, LIDAR, analog input, C3, flight control computer, data logger, effector output, configuration interface
- Publisher / subscriber network
- Compatible with DroneCAN (near-term) and ARINC-825 (long-term)
- MATLAB Simulink autocode and C++ software development




Single-String, hand-launched UAS

Redundant UAM, supporting autonomous, remotely-piloted, and piloted operations

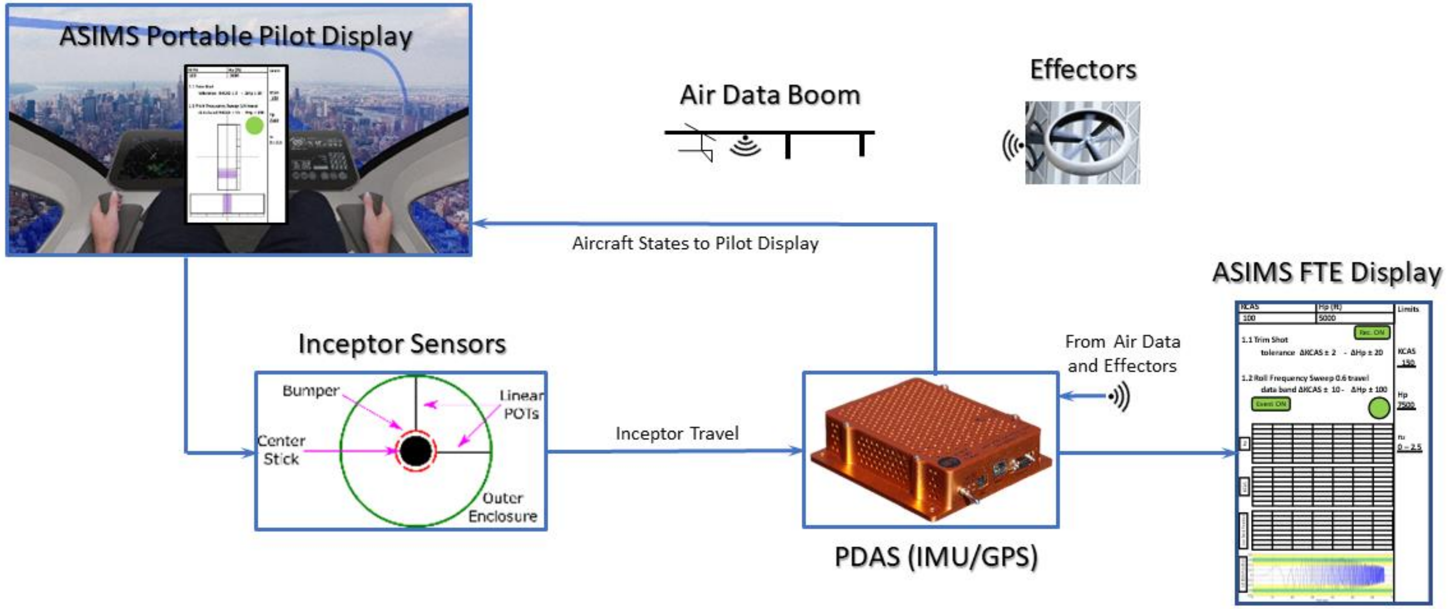
# Interoperability

- Standards define how messages are published to the CAN bus
  - Enables interoperability between manufacturers and with in-house modules
  - Promotes modularity, i.e. easy to swap INS modules based on mission or research requirements
  - Data bus – pair of wires supports any number of modules
    - Caveats: need to pay attention to bandwidth limitations, however, CAN-FD alleviates many of the constraints with CAN 2.0

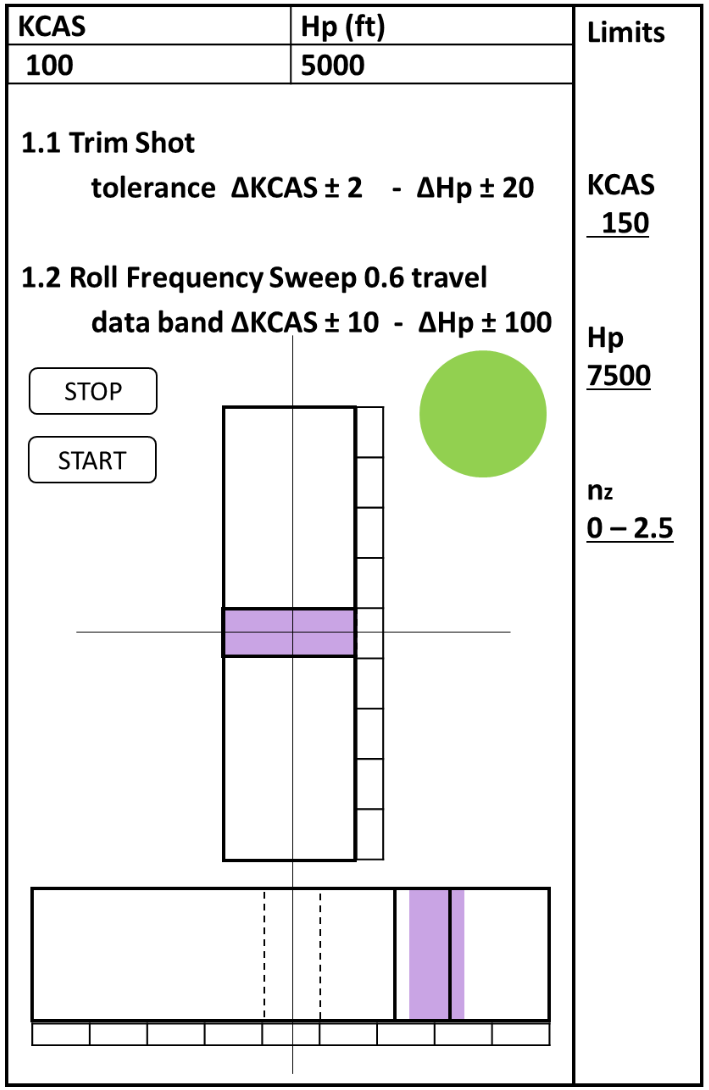
| CAN identifier | Flight state parameter name | Suggested data types | Units | Notes |
|---|---|---|---|---|
| 300 ($12C) | Body longitudinal acceleration | FLOAT SHORT2 | g | forward: + aft: - |
| 301 ($12D) | Body lateral acceleration | FLOAT SHORT2 | g | right: + left: - |
| 302 ($12E) | Body normal acceleration | FLOAT SHORT2 | g | up: + down: - |
| 303 ($12F) | Body pitch rate | FLOAT SHORT2 | deg/s | nose up: + nose down: - |
| 304 ($130) | Body roll rate | FLOAT SHORT2 | deg/s | roll right: + roll left: - |
| 305 ($131) | Body yaw rate | FLOAT SHORT2 | deg/s | yaw right: + yaw left: - |

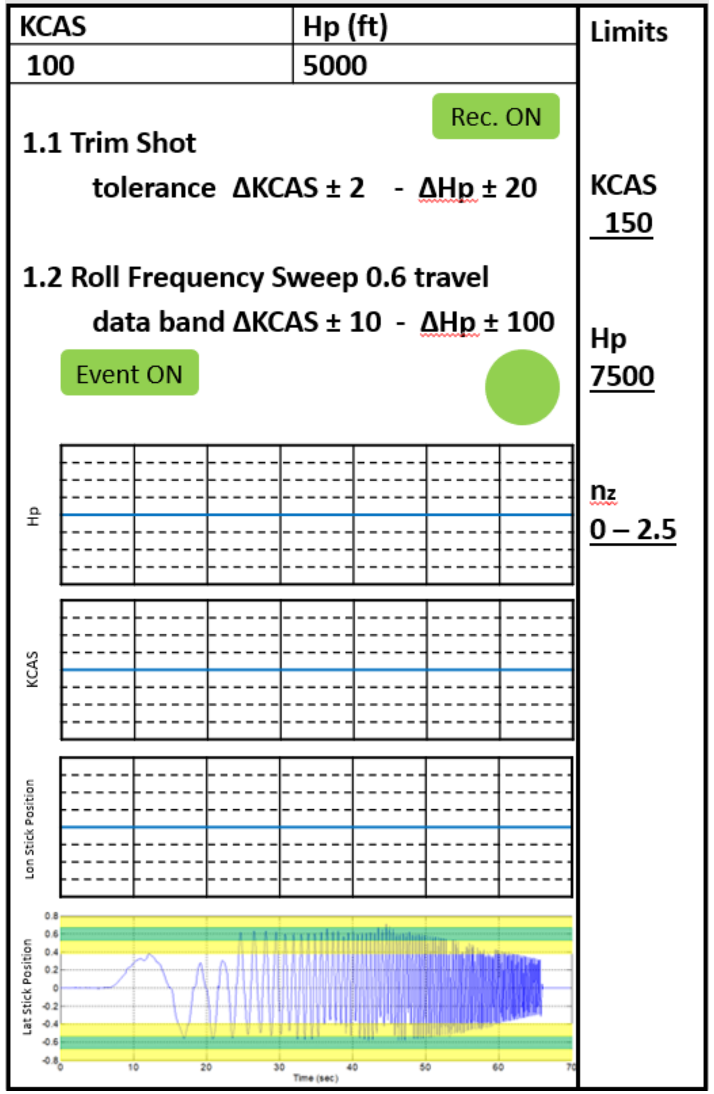
# Aircraft System Identification Measurement System (ASIMS)

- Real-time guidance of pilots and flight test engineers through a system identification campaign
- Real-time data analysis to provide feedback on excitation amplitude and to clear the flight envelope
- NASA Phase I SBIR lead by Systems Technology Inc. (STI)



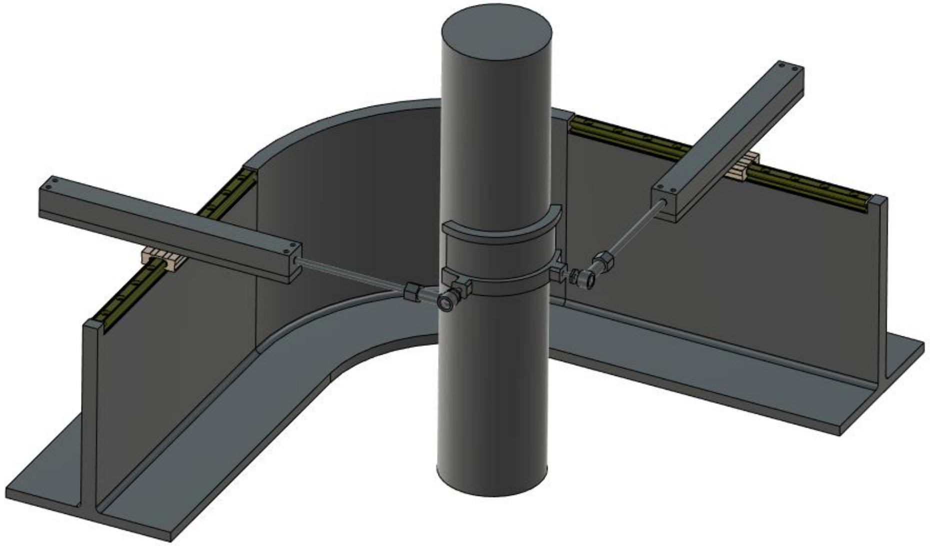
# ASIMS Displays



# Inceptor and Air Data Measurement

- Developing a wireless air data boom and Inceptor Position Adapter (IPA) as part of ASIMS
  - Small device to measure stick position and force
  - Researching mechanical and accelerometer-based approaches
  - Demonstrating feasibility in December 2022 on a piloted simulation



# Means of Compliance Requirements for UAM Evaluation and Ratings (MCRUER)

- Virtual MTE courses to evaluate handling and flying qualities against
- NASA Phase I and II SBIR lead by Systems Technology Inc. (STI)
- Flight demonstration in 2023 with the NRC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# Summary

# Summary

- Gained familiarity with PDAS and used it to learn about the current state of the art in data acquisition systems
- Gained hands-on knowledge of common sensing and state estimation techniques and how to select sensors to meet requirements
- Learned about current research topics


# Additional Resources

brian.taylor@bolderflight.com

- ADC explanation video:
  - https://www.youtube.com/watch?v=_gZjBx9cdro&t=857s
- Delta sigma ADC videos:
  - Part 1: https://www.youtube.com/watch?v=SFAS8nE4_ZM
  - Part 2: https://www.youtube.com/watch?v=mCWC0X2naY0
- VectorNav INS primer (full “book” available after registering):
  - https://www.vectornav.com/resources/inertial-navigation-primer
- Optimal State Estimation by Dan Simon:
  - https://www.amazon.com/Optimal-State-Estimation-Nonlinear-Approaches/dp/0471708585
- Bolder Flight Systems GitHub:
  - https://github.com/bolderflight/