# UAS Flight Testing

Eli Cohen and John Sullivan

# Goals of Flight Testing

As flying any aircraft poses a danger to the airframe, especially in the early stages of development, flight testing should always be undertaken with a clear set of objectives. Some possible general goals are listed below. As flight testing is truly a systems test, each subsystem should evaluate how their work can be evaluated and what tests should be done to maximize data gathering at a minimum of risk.

**Aircraft**

handling qualities
performance

endurance
climb
glide
turn
stall
spin
structure
deflection
flutter
thermal

**Operators**

proficiency
standard procedures
emergency procedures

**System**

system performance
datalinks
failsafes
mission performance
payload
maintenance
data analysis

# Safety

- as always, safety is #1 priority
- many small errors and oversights may add up a catastrophic event
- role of everyone on team to contribute to safe operations
- develop and adhere to safety and operating procedures

Do NOT try to catch your aircraft. In a hot air balloon. Surrounded by other people. And fire.

# Operating Limits

- Do not operate in unsafe conditions that exacerbate risks of operating an autonomous aircraft!
- Pressure to meet flight testing goals can cause poor choices to sound logical
- Develop and adhere to “no-go” criteria

some no-go criteria:

cloud cover

min/max temperature

max wind speed at ground

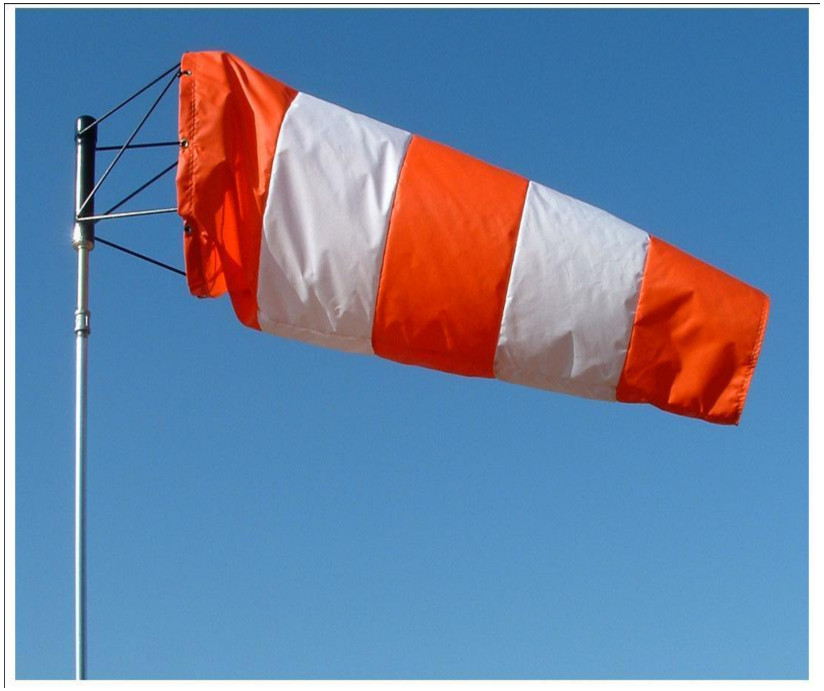
max crosswind component

structural failures

RF interference

battery voltage

operator skill/fatigue/frostbite due to polar vortex

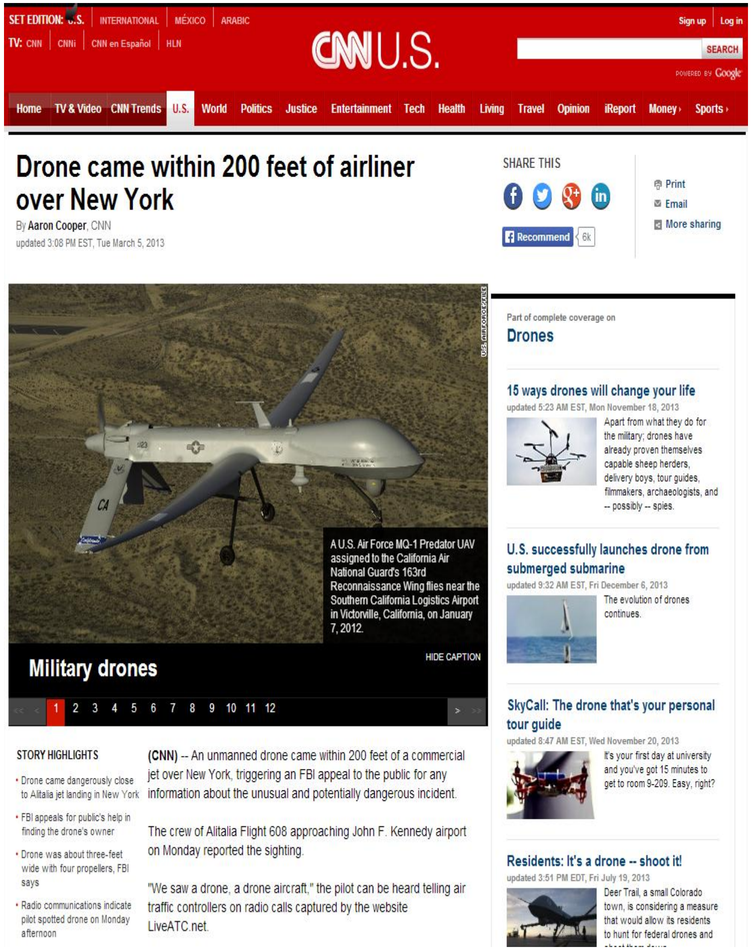


# Paperwork and Briefings!

- Although tedious, proper paperwork and preflight briefings add tremendous value to flight testings while also reducing risk.
- Letting people know their responsibilities, where to stand, and what the test will consist of allows pilot and operators to concentrate on what is occurring in the air instead of what is happening on the ground.
- See http://flighttestsafety.org/best-practices for best practices, sample documents.

# Special Considerations

- UAV's are under a lot of scrutiny
- bodily harm, property damage, airspace violations can all harm image with public, FAA
- take every possible measure to fly responsibly and in accordance with best practices
- You do NOT want to see the headline "___ University students kill private pilot, cause Cessna to crash into school bus, killing students en route to charity event"



SET EDITION: U.S. | INTERNATIONAL | MÉXICO | ARABIC

TV: CNN | CNNi | CNN en Español | HLN

CNN U.S.

Sign up | Log in

SEARCH

POWERED BY Google

Home | TV & Video | CNN Trends | U.S. | World | Politics | Justice | Entertainment | Tech | Health | Living | Travel | Opinion | iReport | Money › | Sports ›

## Drone came within 200 feet of airliner over New York

By Aaron Cooper, CNN

updated 3:08 PM EST, Tue March 5, 2013

SHARE THIS

Recommend 6k

Print

Email

More sharing

U.S. AIRFORCE/FILE

A U.S. Air Force MQ-1 Predator UAV assigned to the California Air National Guard's 163rd Reconnaissance Wing flies near the Southern California Logistics Airport in Victorville, California, on January 7, 2012.

HIDE CAPTION

Military drones

1 2 3 4 5 6 7 8 9 10 11 12

STORY HIGHLIGHTS

- Drone came dangerously close to Alitalia jet landing in New York
- FBI appeals for public's help in finding the drone's owner
- Drone was about three-feet wide with four propellers, FBI says
- Radio communications indicate pilot spotted drone on Monday afternoon

**(CNN)** -- An unmanned drone came within 200 feet of a commercial jet over New York, triggering an FBI appeal to the public for any information about the unusual and potentially dangerous incident.

The crew of Alitalia Flight 608 approaching John F. Kennedy airport on Monday reported the sighting.

"We saw a drone, a drone aircraft," the pilot can be heard telling air traffic controllers on radio calls captured by the website LiveATC.net.

Part of complete coverage on

Drones

15 ways drones will change your life

updated 5:23 AM EST, Mon November 18, 2013

Apart from what they do for the military; drones have already proven themselves capable sheep herders, delivery boys, tour guides, filmmakers, archaeologists, and -- possibly -- spies.

U.S. successfully launches drone from submerged submarine

updated 9:32 AM EST, Fri December 6, 2013

The evolution of drones continues.

SkyCall: The drone that's your personal tour guide

updated 8:47 AM EST, Wed November 20, 2013

It's your first day at university and you've got 15 minutes to get to room 9-209. Easy, right?

Residents: It's a drone -- shoot it!

updated 3:51 PM EDT, Fri July 19, 2013

Deer Trail, a small Colorado town, is considering a measure that would allow its residents to hunt for federal drones and

# Some anecdotes...

Aircraft brought from FL to CA for flight testing at military range. Aircraft “home location” left in FL at previous testing ground. Aircraft lost link, attempted to fly back to FL. Landed on side of highway.

**Correct aircraft behavior, operator oversight that could have been checked very easily.**

Aircraft took off for quick autopilot test. Had previously completed multiple flights. Appeared to turn to first waypoint, operator noticed it didn’t enter orbit once it reached waypoint. Aircraft was in “stabilize” mode and was weathervaning, by chance, towards waypoint. Aircraft too far to bring back, geofence not activated, crashed 1 mi away, still on range.

**Aircraft appeared to be behaving correctly. Operator did not confirm aircraft was in autonomous mode. Operator did not activate geofence. Loss of link failsafe not enabled.**

Highly unstable aircraft had been flight tested many times with max flight time rarely exceeding 20 seconds. After adding stability augmentation, aircraft immediately flew for over 6 minutes whereupon it made a horrible noise, lost power, and spun into ground. It was discovered that 3D printed motor housing melted after 6+ minutes of running but never got hot enough to notice after 20 seconds.

**Unforeseen thermal issue. Prior history of short flights never led to static test of motor thermal properties during long operation.**

# More Anecdotes

Aircraft operated in restricted airspace that could be called “hot” via NOTAM up to either 2k’ or 4k’. Restricted airspace used as approach to local GA airport when not hot. MULTIPLE incidents of GA aircraft blasting through airspace due to not reading NOTAM. UAV and GA aircraft at same altitude, immediate action had to be taken to deconflict. Required spotters to keep eyes out for airspace incursions.

**Correct UAS operational procedure hampered by failure of GA operators to comply with NOTAMs. Required emergency procedure to be developed for “impossible” situation.**

Aircraft had encrypted radios installed, bypassing normal radios. Had been tested for over 20 hrs without fault including 6 hr “burn in” test. In flight, onboard radio crashed, aircraft noticed fault and returned to loiter point and after not regaining link, landed itself.

**Correct aircraft behavior. Thorough testing did not reveal failure mode in radios. Further testing never discovered reason for failure. Radios never used again as fault was not traceable.**

There are many, many possible ways a flight test can go very wrong, very quickly. Even systems that have been tested extensively may fail in new and exciting ways. Understanding all failure modes requires every team member to contribute knowledge to “red team” the system.

# Developing Procedures

- Solicit input from all team members
  - Identify major areas of risk
  - Determine what actions can reduce risk
  - Identify goals of flight testing
  - Integrate flight test goals into project schedule with a clear understanding of how results can change path ahead
- Iterate on flight test goals and procedures
- Stay organized!
- Keep records of everything!

# Recording Procedures

- Especially when changing multiple elements of an aircraft configuration, proper recordkeeping provides engineers with clearest picture of impact of changes.
- Record as much data as possible!
  - Pilot voice recorder
  - autopilot data
  - telemetry data
  - video
  - photos
  - log sheets

UAV APM MISSION CHECK LIST http://diydrones.com/forum/topics/preflight-checklist

FLIGHT #

DATE:______ AIRCRAFT: ______________ LOCATION:___________________

TEMP:______ WIND SPEED/DIRECTION: _____/_____ CLOUD COVER:_________

PRE - PRE FLIGHT (HANGER)

APM Version ___________

Planner Version ___________

HK GCS Version ___________

PID .param File Name ___________

WP File Name ___________

NOTE: PROP REMOVED!

[ ] TX and RX Power ON in RC Mode BIND AS REQUIRED

[ ] APM in CLI Mode (Planner -> COM 4 - 115200 -> terminal USB)

[ ] setup > erase > reset > radio

[ ] Remove all LOG files (logs -> erase)

[ ] Verify Mode assignments (setup -> modes)

Switch down ______

Switch mid ______

Switch up ______

[ ] Verify XBees test > xbee Range Test with C-CTU

UN PLUG USB

[ ] APM to Fly Mode - reset - Observe LED sequences - Wait for GCS Lock

Start Mega Planner COM5 - 57600 -> Connect

Planner to Configuration Mode

[ ] Load .para file Write Pads

Planner to Flight Planner Mode

[ ] Planner > Read WPs Verify Correct If not, Load WP file,

Write WPs

Planner to Flight Data Mode

[  ]   Verify Connection, Verify Map, Verify Home
[  ]   Change Flight Mode from RC to STABILIZE (or FBW A) to AUTO  Verify with Flight Data
[  ]   Change Mode to STABILIZE or FBW A
[  ]   Bank and pitch Aircraft - Verify aircraft control surfaces move in the correct direction
[  ]   Change Mode to RC. - Verify proper control surface and throttle RC response

HK GCS PREFLIGHT  (If used)

[  ]   Cell Phone ON - LapTop WiFi Connected
[  ]   Connect COM (COM5) Verify Serial Data
[  ]   On Google Earth disp. 'Overhead'  'Set Home'
[  ]   Read Waypoints - verify intended flight path
[  ]   ON GCS disp. set Home Alt., Zero Yaw
[  ]   Go to 'Data File'; Enter File Name __________

MEGA PLANNER  If Used)

[  ]   Connect COM (COM5) Verify Serial Data
[  ]   Flight Mode  Verify Map.
[  ]   Verify Home position - Set Altitude

## AIRCRAFT PRE FLIGHT

[ ] Install Wing - Hook up Pitot tube
[ ] Install Prop
[ ] Check and record flight battery voltage, size: ______/_______
[ ] Verify proper CG
[ ] RC Transmitter set to proper aircraft/model BIND AS REQUIRED
[ ] Verify pitot and static tubes are clear
[ ] Change Mode from RC to STABILIZE to AUTO
- **NOTE: THIS WILL CAUSE THE MOTOR TO COME ON WHEN IN AUTO!!**
[ ] Change Mode to STABILIZE or FBW A
[ ] Bank and pitch Aircraft - Verify aircraft control surfaces move in the correct direction
[ ] Change Mode to RC. - Verify proper control surface and throttle RC response
[ ] Range Check

[ ] Start GCS Record
[ ] Take off and start timer - Reset GCS timer

## POST FLIGHT

[ ] STOP RECORDER
[ ] Record flight battery voltage. _____________
[ ] Record flight time _____________
[ ] Verify and save log files _____________
[ ] Save .param file _____________

MISSION LOG

**Aircraft Configuration:** ________________________

**Aircraft changes since last flight:** ____________________________________________

____________________________________________________________________________

**Payload:** ___________________________________________________________________

**WP File:** ___________________________________

**WP Description:** ____________________________________________________________

_______________________________________________________________________________

**Mission Objectives:** _________________________________________________________

____________________________________________________________________________

____________________________________________________________________________

____________________________________________________________________________

____________________________________________________________________________

**Flight Data:**__________________________________________________________________

____________________________________________________________________________

____________________________________________________________________________

____________________________________________________________________________

____________________________________________________________________________

**Post Flight Analysis:**____________________________________________________________

____________________________________________________________________________

____________________________________________________________________________

____________________________________________________________________________

____________________________________________________________________________

**Additional Notes:** _____________________________________________________________

____________________________________________________________________________

____________________________________________________________________________

____________________________________________________________________________

____________________________________________________________________________

____________________________________________________________________________

# AMA *Recommended RC Flying Site Specifications*

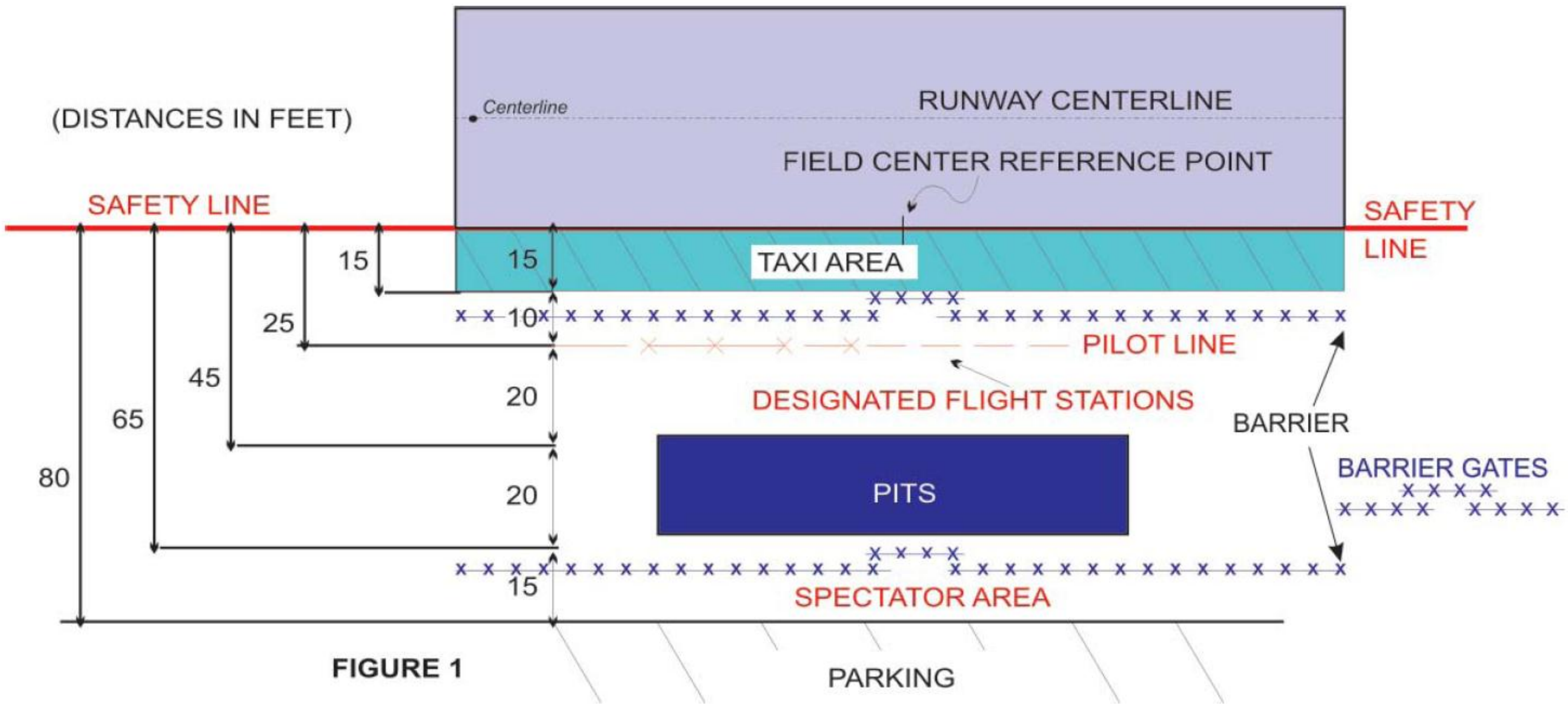



FIGURE 1

# ***Academy of Model Aeronautics National Model Aircraft Safety Code***

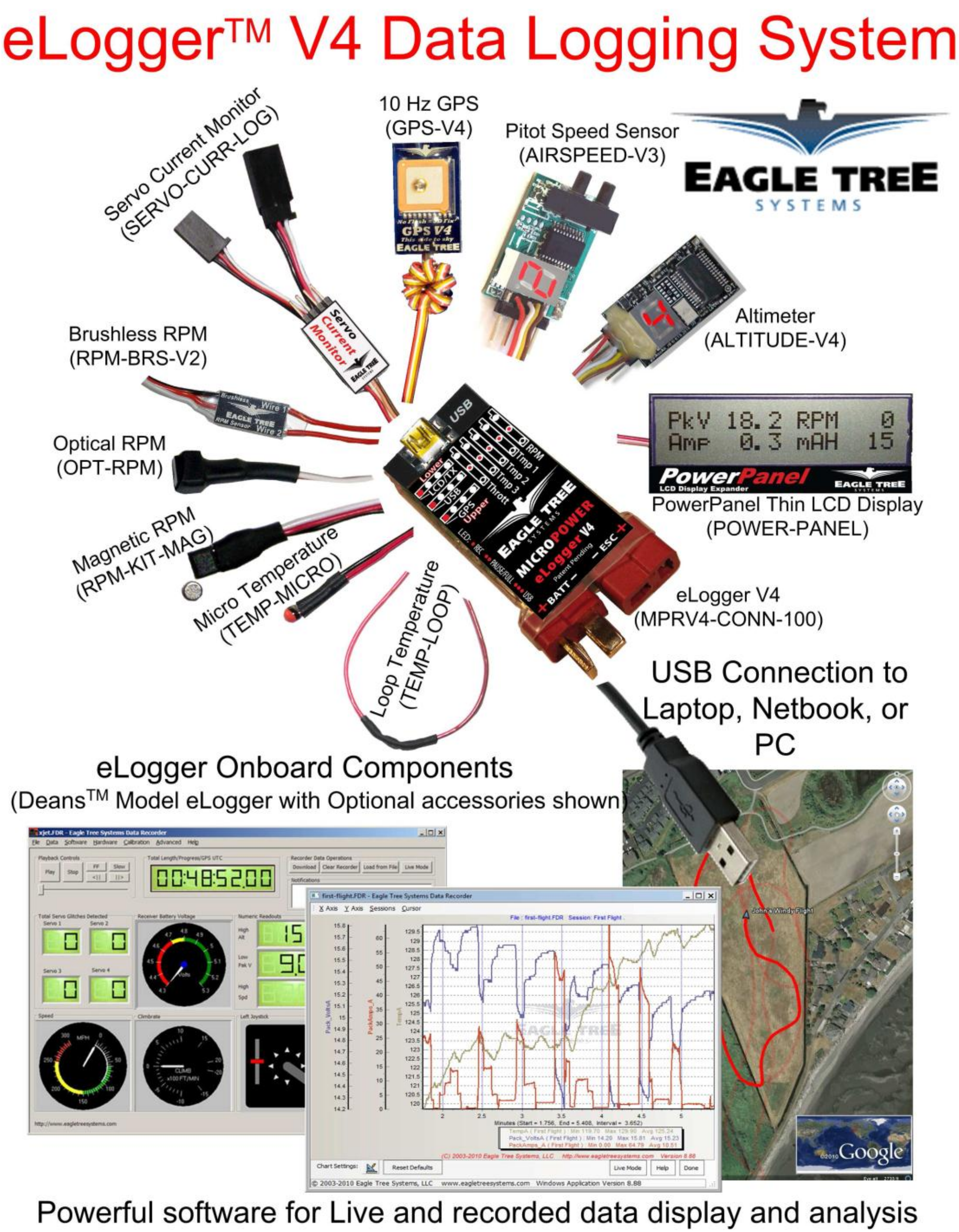
On CorpU

# Simple Tests

- Glide
- Straight Level Flight
- Stall

Using outputs from the Ardupilot , Eagletree or other data logger

# Eagle Tree


eLogger™ V4 Data Logging System
EAGLE TREE SYSTEMS
Servo Current Monitor (SERVO-CURR-LOG)
10 Hz GPS (GPS-V4)
Pitot Speed Sensor (AIRSPEED-V3)
Altimeter (ALTITUDE-V4)
Brushless RPM (RPM-BRS-V2)
Optical RPM (OPT-RPM)
Magnetic RPM (RPM-KIT-MAG)
Micro Temperature (TEMP-MICRO)
Loop Temperature (TEMP-LOOP)
PkV 18.2 RPM 0
Amp 0.3 mAH 15
PowerPanel
PowerPanel Thin LCD Display (POWER-PANEL)
eLogger V4 (MPRV4-CONN-100)
USB Connection to Laptop, Netbook, or PC
eLogger Onboard Components
(Deans™ Model eLogger with Optional accessories shown)
Powerful software for Live and recorded data display and analysis

# Ardupilot/Pixhawk

**Sensors:**

ST Micro L3GD20 3-axis 16-bit gyroscope

ST Micro LSM303D 3-axis 14-bit accelerometer / magnetometer

Invensense MPU 6000 3-axis accelerometer/gyroscope

MEAS MS5611 barometer

voltage and current
analog measurements

GPS

Airspeed

# Glide

Series of glides at different speeds

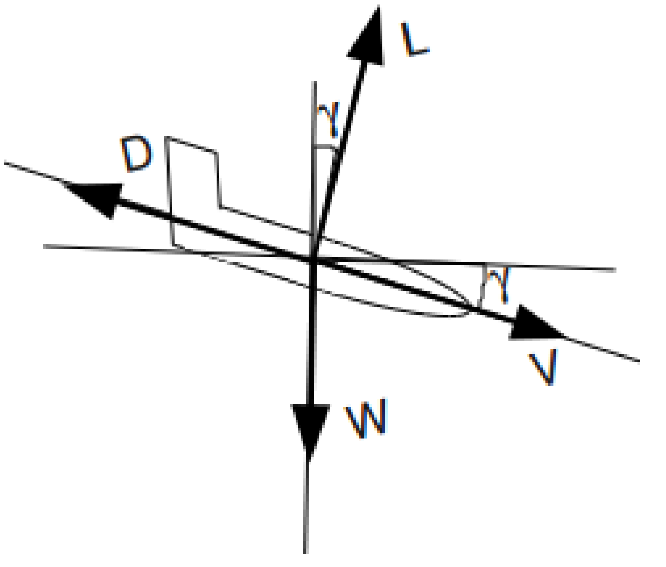
$$D = C_D \frac{1}{2} \rho V^2 S = -W \sin\gamma$$

$$L = C_L \frac{1}{2} \rho V^2 S = W \cos\gamma$$

$$\dot{h} = V \sin\gamma$$

$$\dot{r} = V \cos\gamma$$

L/D = tan($\gamma$)



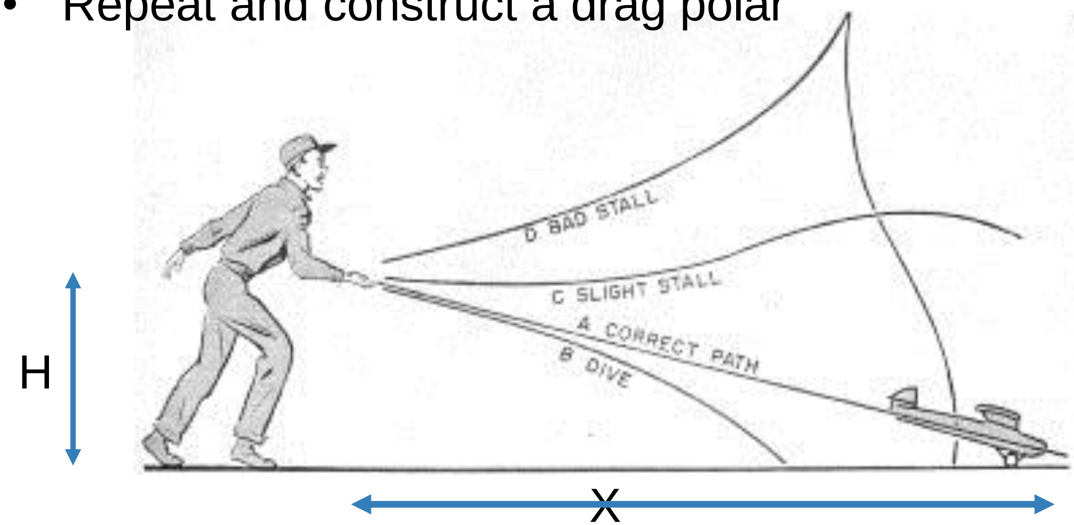

Measure $\gamma$ , W and calculate the drag polar

Measure V and calculate $C_L$ and $C_D$

Issue: Propeller drag, solution use a folding prop

# Simple glide test **Instrumentation needed – tape measure**

- With power off, hand launch from about shoulder height
  - Grip airplane at the CG and throw straight and level
- Measure launch height and distance traveled
  - i.e. H= 5ft, X =45 ft. , L/D =9
- Re-trim by shifting CG or adjusting stabilizer
  - Repeat and construct a drag polar




Observe very carefully how the plane behaves during its first hand-launched glide. The proper glide path is straight. smooth, and without dips until the plane strikes on wheels. If the plane dives slightly (B), increase the angle that the wing makes with the airstream, or decrease the angle of the stabilizer. In severe cases, move the weights in the plane backwards. If the plane stalls (C) or (D), increase the positive angle of the tail, or move weights forward. Be certain when you launch the plane that you do not throw it nose up, or too fast, especially in high winds, as this will produce a false stall, giving you an incorrect idea of the model's performance.

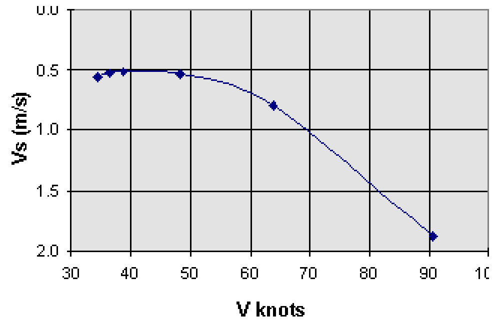
http://www.airplanesandrockets.com/resources/adjusting-the-power-rc-plane-jan-1955-pe.htm

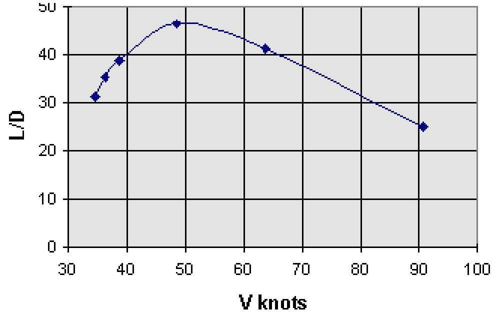
# Gliding Test

Instrumentation needed

Altitude ( barometric altimeter, GPS)

Velocity (pitot probe, GPS)




- Launch aircraft and climb to test plan altitude
  - ~100-300 feet
- Establish straight and level flight and cut power
- Establish trimmed glide
- Climb and repeat

# Straight and Level speed

- Lift = Weight and Thrust = Drag
- Calibrated motor/propeller in wind tunnel test
- Obtain thrust by using RPM and velocity to calculate the advance ratio

- Can also use the motor voltage and current to calculate the battery power used at various velocities. Then

# Senior Telemaster

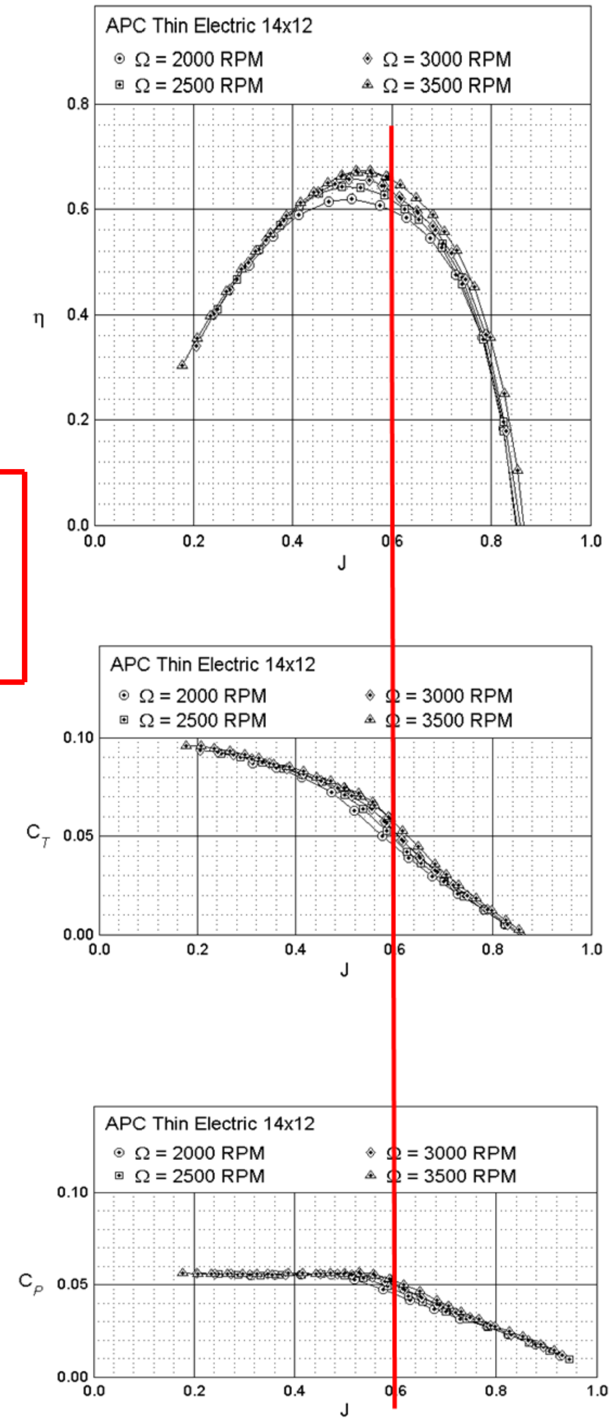
http://www.hobbyexpress.com/ready_built_senior_telemaster_red_white_airplane_2270_prd1.htm


| | | | | |
|---|---|---|---|---|
| Weight | 10.5 | lbs | 46.71 | N |
| Area | 1330 | in^2 | 0.86 | m^2 |
| span | 94 | in | 2.39 | m |
| AR | 6.64 | | | |
| W/S | 54.43 | N/m^2 | 18.19 | oz/ft^2 |

| | | | | |
|---|---|---|---|---|
| Cruise | | | | |
| V | 20 | m/sec | 44.74 | mph |
| q | 245 | N/m^2 | | |
| CL | 0.2222 | | | |
| e | 0.9 | | | |
| Cdi | 0.0026 | Induced drag | | |
| Cdo | 0.0375 | Historical estimate | | |
| Cd | 0.0401 | total drag coefficient( parasitic plus induced) | | |
| Drag | 8.44 | N | | |
| L/D | 5.54 | | | |
| P mech | 168.72 | | | |

# Propeller APC 14 x 12 E

| | | | | | | |
|---|---|---|---|---|---|---|
| Dia | 14 | in | 0.356m | | | |
| J | 0.60 | Guess near Maximum efficiency | | | | |
| n | 93.74 | rev/sec | 5624.3RPM | | 589.0 | rad/sec |
| Ct | 0.06 | From data graph | | | | |
| Thrust | 8.43 | iterate until thrust = drag | | | | |
| Cp | 0.06 | From data graph | | | | |
| Efficency | 0.65 | | | | | |
| P prop | 257.59 | watts | | | | |
| Torque | 0.44 | N-m | | | | |

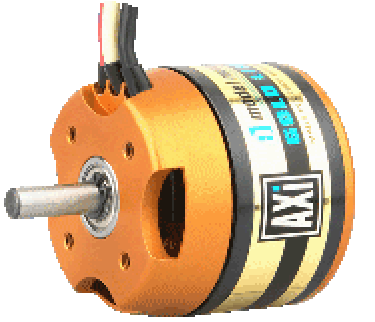



From UIUC Web site
http://m-selig.ae.illinois.edu/props/propDB.html

# Motor AXI 4120-18

1 - PM412018 AXI Gold 4120/18 Outrunner Motor

| | | | | | |
|---|---|---|---|---|---|
| Kv | 515 | RPM/V | 53.9 | (rad/sec)/volt | |
| Kt | | | 0.01854 | N-m/Amp | |
| Io | 1.5 | Amps | | | |
| Rm | 0.07 | ohms | | | |




$$RPM = 60n = K_V\left(V_{in} - I_{in}R_M\right)$$

Voltage 11.03volts

$$Torque = Q_{MS} = K_T\left(I_{in} - I_0\right)$$

Current 25.09amps

$$\eta_M = \frac{P_{out}}{P_{in}} = \frac{K_T K_V\left(I_{in} - I_0\right)\left(V_{in} - I_{in}R_M\right)}{V_{in}I_{in}}$$

eff 0.93

P elec 276.60watts

# Battery
# 4500mAh 4S 14.8V 20C LiPo Battery w/ Deans

| | | | | | |
|---|---|---|---|---|---|
| Technical Specifications: | | | | | |
| Length: | 6" | | | | |
| Width: | 1-3/4" | | | | |
| Height: | 1-1/4" | | | | |
| C Rating: | 20C | | | | |
| Weight: | 16.5 oz. | 1.035lbs | | 4.587N | |

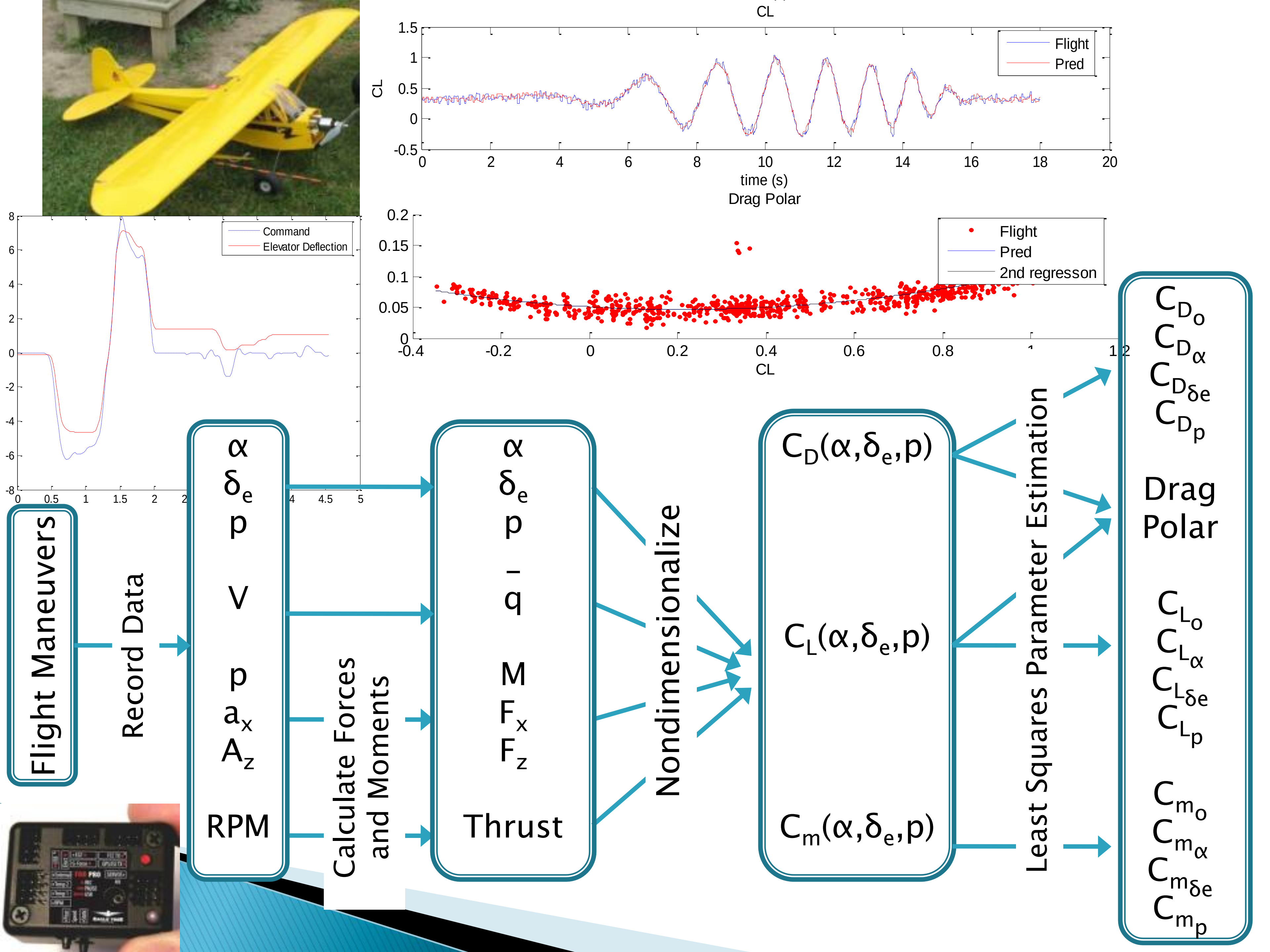

| | | | | |
|---|---|---|---|---|
| | 4.5 | amp-hours | | |
| Current | 25.09 | amps | | |
| Flight Time | 0.179 | hours | 10.8 | Min. |

| | | | | |
|---|---|---|---|---|
| Range | 12.92 | km | 8.03 | miles |
| | | | | |
| P/W | 5.52 | W/N | 24.53 | W/Lb |
| | | | | |
| Clmax | 1.2 | | | |
| Stall Speed | 8.61 | m/sec | | |
| | | | | |
| CL max L/D | 0.8393 | | | |
| V at L/D max | 10.29 | m/sec | | |

# Stall

- Trim aircraft at 1.5 times the estimated stall speed. Slowly decrease power and speed until stall.
- Repeat
- Calculate $C_{lmax}$

# Flight Testing of Remotely Piloted Aircraft for System Identification


CL
Flight
Pred
time (s)
Drag Polar
Flight
Pred
2nd regresson
CL
Command
Elevator Deflection
Flight Maneuvers
Record Data
α
δe
p
V
p
ax
Az
RPM
Calculate Forces and Moments
α
δe
p
q̄
M
Fx
Fz
Thrust
Nondimensionalize
CD(α,δe,p)
CL(α,δe,p)
Cm(α,δe,p)
Least Squares Parameter Estimation
CDo
CDα
CDδe
CDp
Drag Polar
CLo
CLα
CLδe
CLp
Cmo
Cmα
Cmδe
Cmp

- Extra

# Outline

- Background
- Methods
- Experimental Setup and Procedure
- Results
- Conclusions and Recommendations

# Flight Test Design

- Instrumentation Needed
  1. Sampling Frequency
  2. What to measure
  3. Sensor Range and Resolution
- Inputs/Maneuvers
  1. Sampling Frequency
  2. What to measure
  3. Sensor Range and Resolution
- Constraints that determine Design
  1. Limits on input and/or output amplitude
  2. Limited resolution or range for the sensors or data acquisition system
  3. Limited time available for each maneuver and/or for the overall experimental investigation
  4. Sensor limitations, characteristics, or availability
  5. Limitations on how the aircraft can be excited

# Sampling Frequency

- Min recommended frequency is 25x frequency to measure
  - Most aircraft frequencies ~2Hz max, thus 50Hz required Klien Aircraft system Identification
- Frequency scales with geometric scale factor

$$f_{model} = \frac{1}{\sqrt{s}} f_{aircraft}$$

  - Aircraft size range reflect ¼– 1/8 scale of full size GA aircraft, thus would need 100–140Hz
  - Use 5x factor reduces to reasonable range , 20–30Hz

# Sensor Range and Resolution

- Sensor must cover full expected range plus safety factor for unexpected results
- Resolution due to A/D conversion or mechanical limits must be small enough to not cause large step increments
  - Determines lower end of sensor accuracy

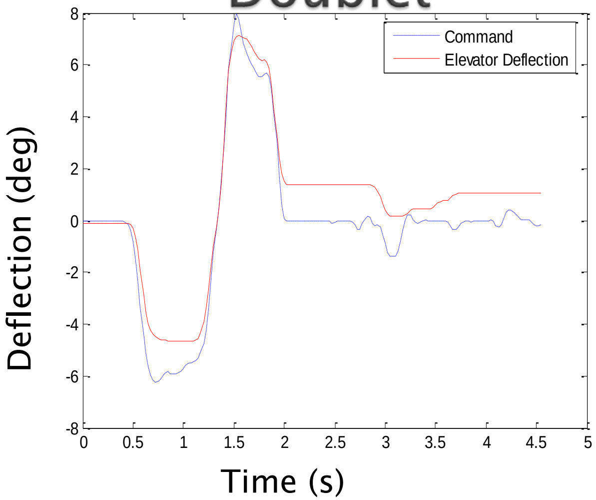
# What to Measure

- Airspeed
  - Pitot static
- Angle of Attack / Angle of Sideslip
  - Aerodynamic vane
  - Need to be corrected for
    - Proximity to aircraft body
    - Induced velocity due to rotational rate and offset from CG
- Angular Velocity
  - Rate gyros
  - Should keep near CG to eliminate any position effects
- Translational Accelerometers
  - Must be kept as close to CG as possible to eliminate need to use Angular Accelerations to correct for offset
- Control Surface Deflections
  - potentiometers

# Flight Test Maneuvers / Input Design

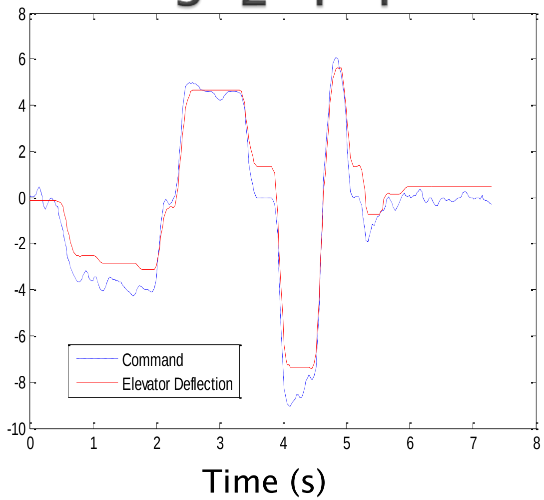
- Determine Amplitude of inputs based so that signal to noise ratio is large enough, but maneuver amplitude is not so large as to break assumptions

## Doublet



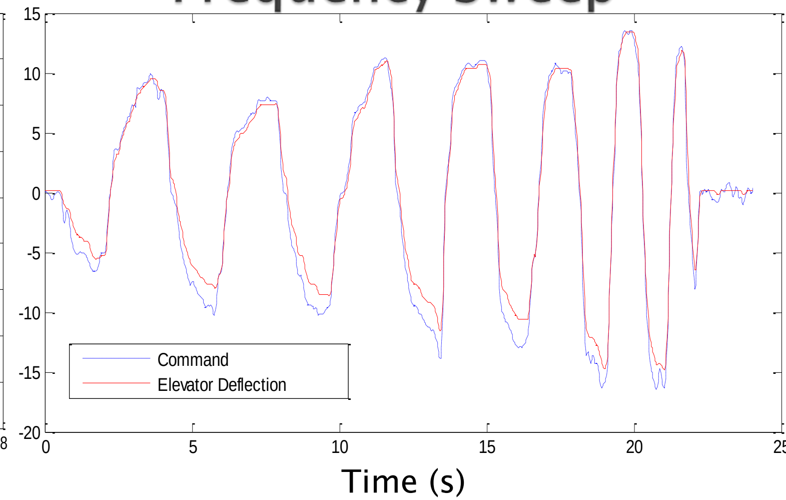

- Square wave approximation of a single period of a sine wave
- Small frequency excitation range
  - Need to determine frequency to use prior to test or try several input lengths
- Easiest and shortest maneuver to execute

## 3-2-1-1




- Similar to doublet but uses several inputs
- Larger frequency coverage than doublet
- Poor mans frequency sweep

## Frequency Sweep




- Uses increasing frequency input
- Most common when no *a priori* info available
- Rich frequency coverage
- Long flight period needed (~60sec)

# 6-DoF Model

- Based on "flatearth" simulation model written by Professor Andrisani

- Nonlinear Model

$$\dot{x} = g(x,u),\ x(0)$$

$$\bar{y} = \bar{h}(\bar{x},\bar{u})$$

$$u(t) = specified$$

- Linear approximations used to predict stability, control, and aerodynamic properties for model (highlighted in yellow)
  - Based on inputs of ~100 geometric and basic aerodynamic values
- Predictions based on empirical and theoretical calculations from Roskam
- Flight Simulation executed via Matlab's Simulink
- Models:
  - Inputs
  - Aircraft
  - Data Acquisition System (with noise and instrument limitations modeled)

$$C_D = K\left(C_{L_0} - C_{L_{drag\ min}}\right)^2 + C_{D\ Min}$$

$$C_L = C_{L_0} + C_{L_\alpha}\Delta\alpha + C_{L_{\delta_e}}\delta_e + C_{L_{\dot{\alpha}}}\frac{\dot{\alpha}\bar{c}}{2V_0}\dot{\alpha} + C_{L_q}\frac{\bar{c}}{2V_0}q$$

$$C_Y = C_{Y_0} + C_{Y_\beta}\Delta\beta + C_{Y_{\delta_r}}\delta_r + C_{Y_{\delta_a}}\delta_a + C_{Y_r}\frac{b}{2V_0}r + C_{Y_p}\frac{b}{2V_0}p$$

$$C_l = C_{l_0} + C_{l_\beta}\Delta\beta + C_{l_{\delta_r}}\delta_r + C_{l_{\delta_a}}\delta_a + C_{l_p}\frac{b}{2V_0}p + C_{l_r}\frac{b}{2V_0}r$$

$$C_m = C_{m_0} + C_{m_\alpha}\Delta\alpha + +C_{m_{\delta_e}}\delta_e + C_{m_{\dot{\alpha}}}\Delta\dot{\alpha} + C_{m_q}\frac{\bar{c}}{2V_0}q$$

$$C_n = C_{n_0} + C_{n_\beta}\Delta\beta + C_{n_{\delta_r}}\delta_r + C_{n_{\delta_a}}\delta_a + C_{n_p}\frac{b}{2V_0}p + C_{n_r}\frac{b}{2V_0}r$$

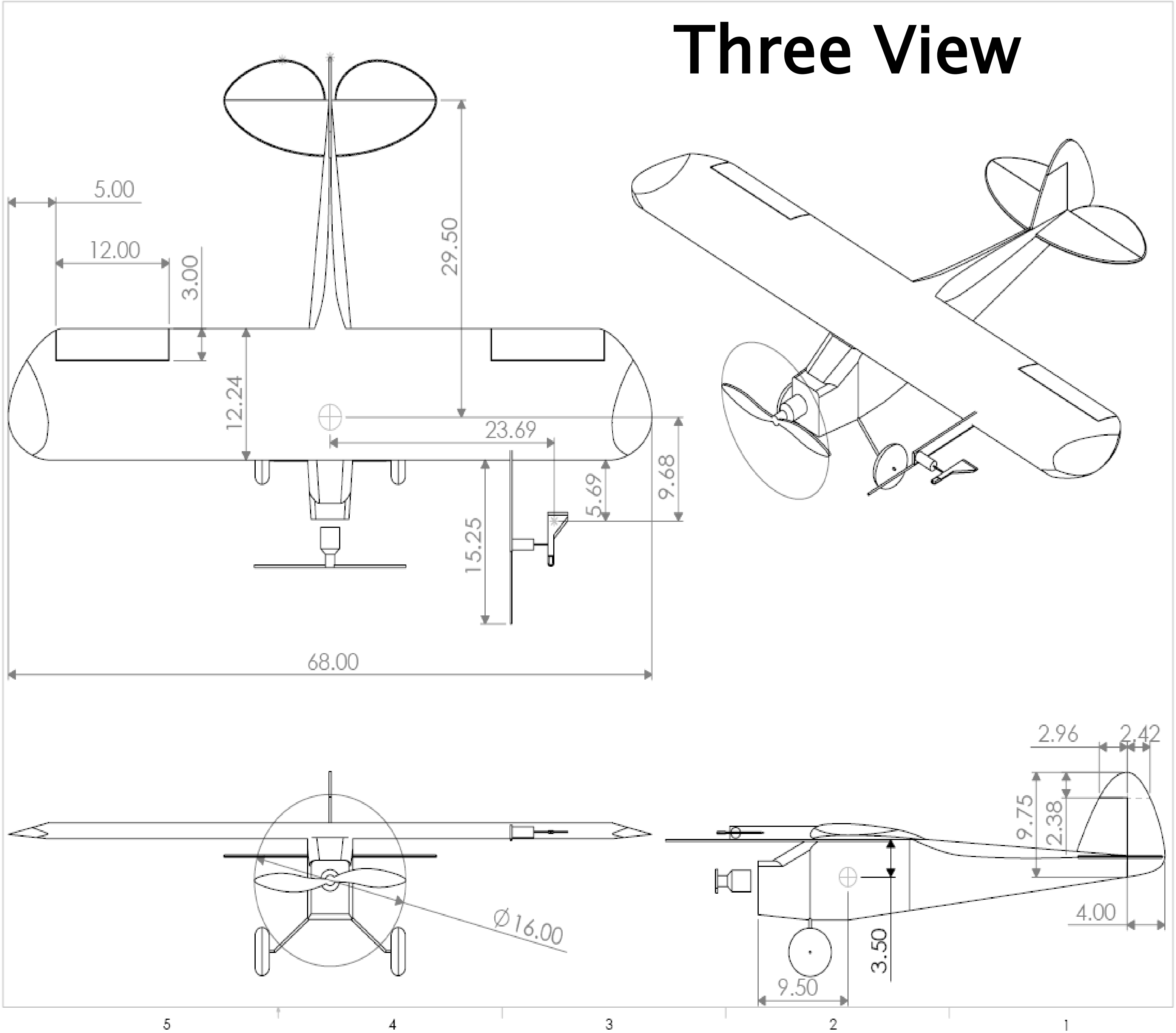
# Experimental Setup

# Aircraft Selection

- Essential characteristics
  - Aircraft similar to small UAV and prototype aircraft
    - Weight 5-15lbs
    - Span 4-8ft
    - Flight speed 30-100 ft/s
  - Ample room and easy installation for instrumentation
  - Conventional, Stable, design
  - Easily Transportable, Durable

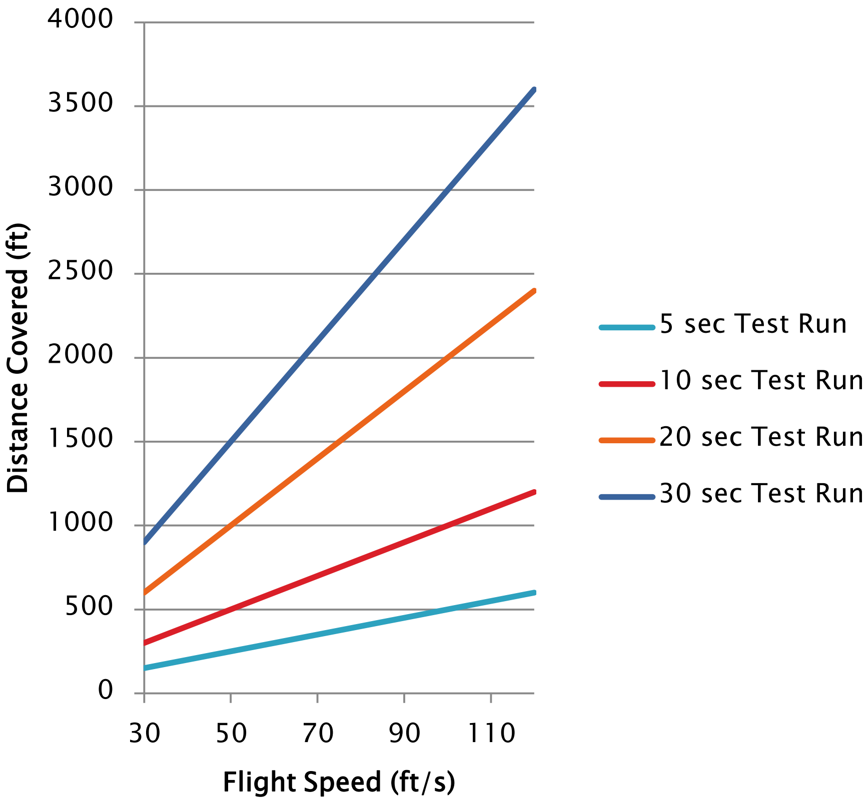
| Clipped Wing Goldberg Anniversary Piper Cub Specs | |
|---|---|
| GW | 9 lbs |
| Length | 3.95 ft |
| Span | 5.67 ft |
| Height | 1.58 ft |
| Chord | 1 ft |
| Airfoil | Clark Y |
| Wing Incidence | 2.7 deg |
| Tail Incidence | 2.5 deg |

# Three View


5.00
12.00
3.00
29.50
12.24
23.69
5.69
9.68
15.25
68.00
Ø16.00
2.96
2.42
9.75
2.38
4.00
3.50
9.50
5
4
3
2
1

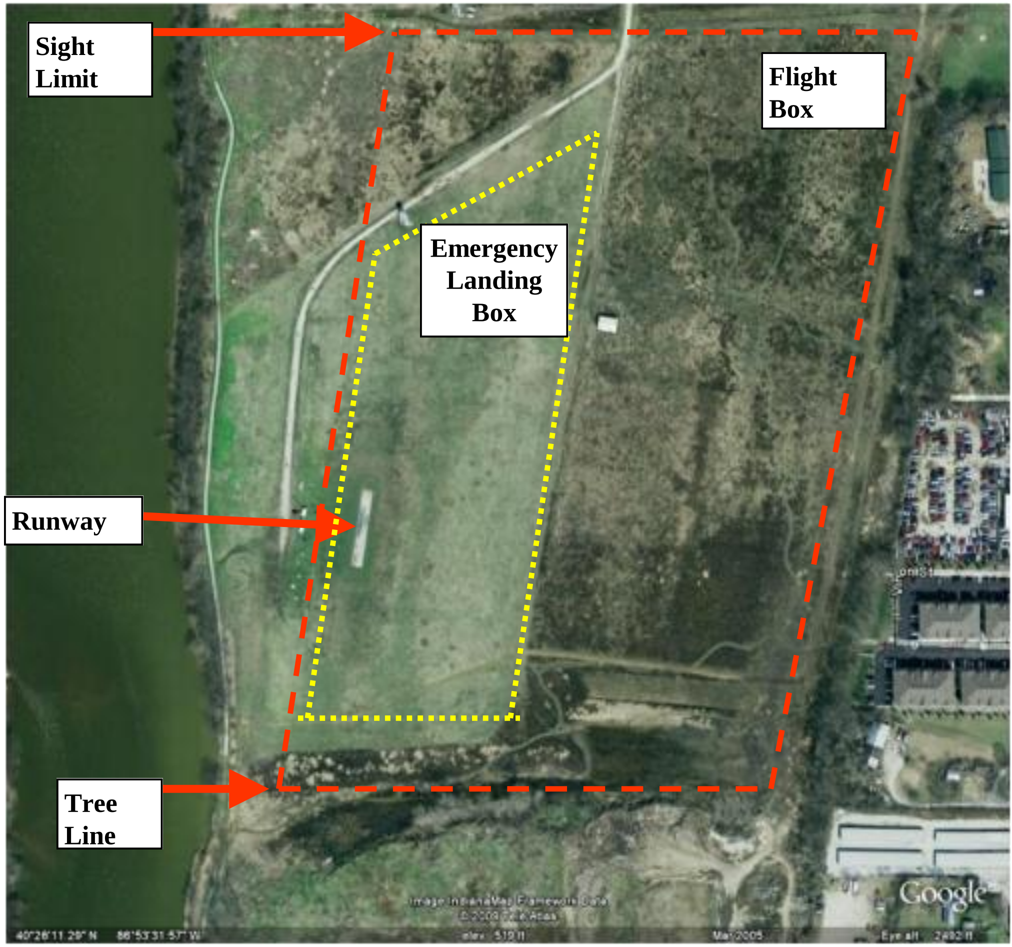
# Test Facility Selection

- Considerations when selecting
  1. Public Safety
  2. Accessibility
  3. Flight box size
  4. Prevailing Winds
  5. Runway
  6. Emergency Landing location
- Necessary flight box determined by aircraft size and time required to complete a maneuver



# Selected Test Locations

| | Primary Location | Secondary Location |
|---|---|---|
| Max leg distance | 1800 ft | 3000ft |
| Runway | Paved 200ft x 20 ft | Packed Gravel 1000ft x 10 ft |
| Emergency Landing | 1100ft x 400ft tall unsmoothed grass | 3000ft x 100ft grass runway |
| Runway Orientation | North-South | East-West |
| Wind Protection | High, sits in valley | Moderate, Surrounded by trees |
| Travel time to reach | 10 min, 3.1 miles | 30 min, 14.6 miles |
| Concerns | Floods several times a year | none |
| AMA field? | Yes | Yes |



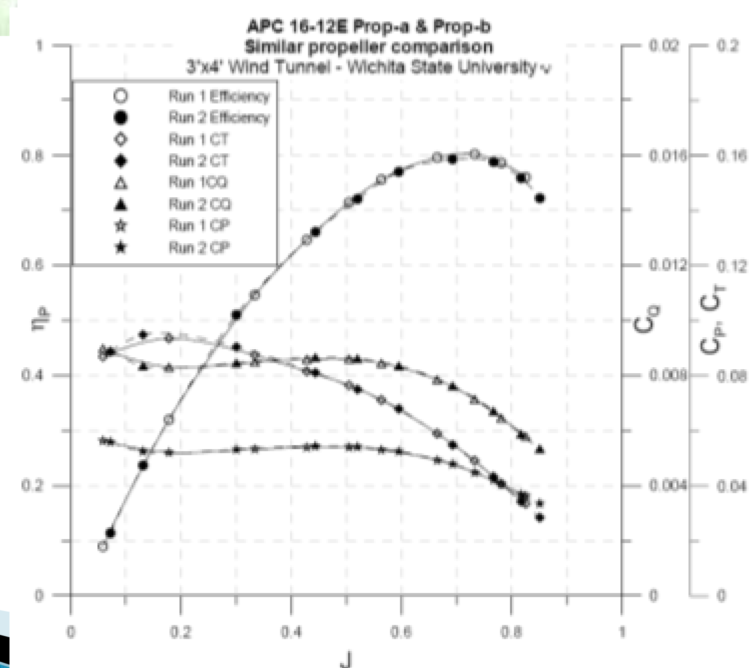
# Data Acquisition System

- Cost Limited number of available options to three
  - Eagle Tree Systems Flight Data Recorder Pro (FDR)
    - $300 Base cost
    - Low cost expanders (GPS = $150)
    - Able to read in Servo positions
    - A-D inputs available
    - 40Hz data logging onboard standard
  - RCATS UAV system
    - $250 Base cost
    - Only able to have 2 expanders
    - High Cost Expanders (GPS = $270)
    - Unable to read in servo positions
    - GPS Expander required for onboard recording
    - 10Hz data logging
  - Scratch Built
    - Would be too time consuming and prone to design and manufacturing error. Want to use off the shelf components whenever possible
- Choose Eagle Tree Systems FDR Pro
  - Familiarity with the system (5+ years experience)
  - Easily and widely expandable
  - Able to read servo positions
  - 40Hz data logging
  - Lower Total Cost


# Data Acquisition Subsystems

- **Motor Parameters**
  - RPM: Brushless motor switching (chosen due to ease of installation)


- **Thrust Measurement**
  - Load cell not practical or cost effective
  - Use prop with known propeller polar
  - Use RPM and Airspeed to determine Advance Ratio



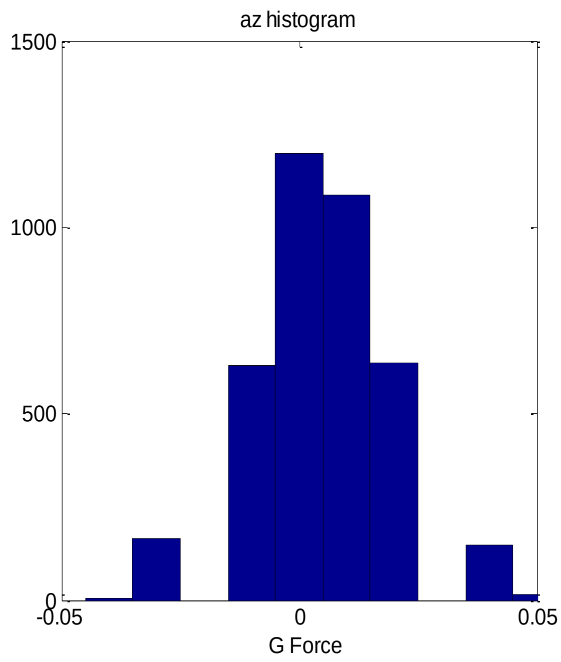

Merchant, Prop Thesis

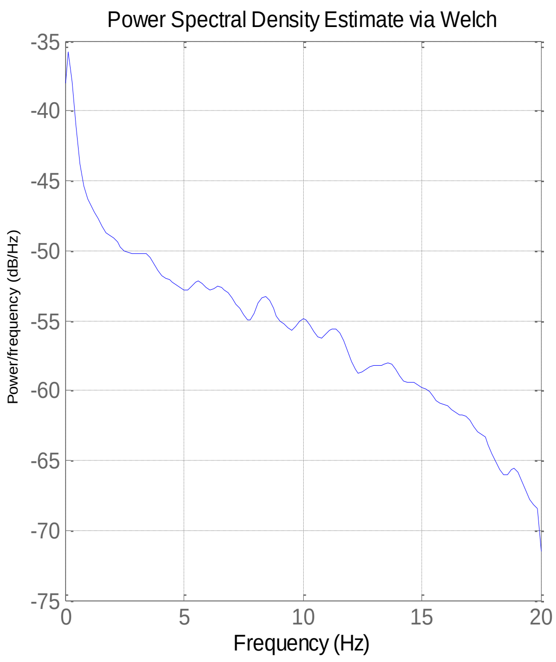
**Pitot Static System**

- Pitot Probe on boom
  - Ahead of prop
  - Far enough from wing to neglect effects
  - ~1ft/s accuracy when at flight speeds
- Remote Static port
  - Located on side of aircraft far from any possible disturbances
  - ~1ft accuracy when in flight

# Acceleromters

- 2 axis plug and play (can have up to 2 expanders for 4 axis)
- 0.01G Accuracy
- +- 32G range
- Noise Analysis seen in graph

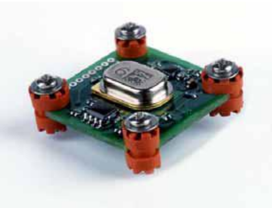


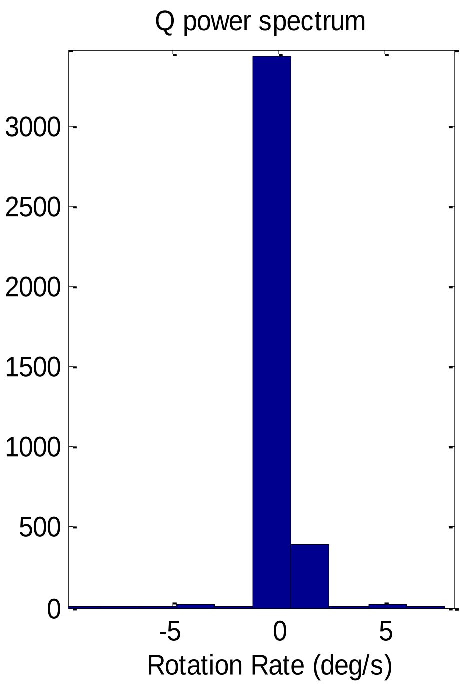

Standard Deviation: 0.014
Variance: 0.0002

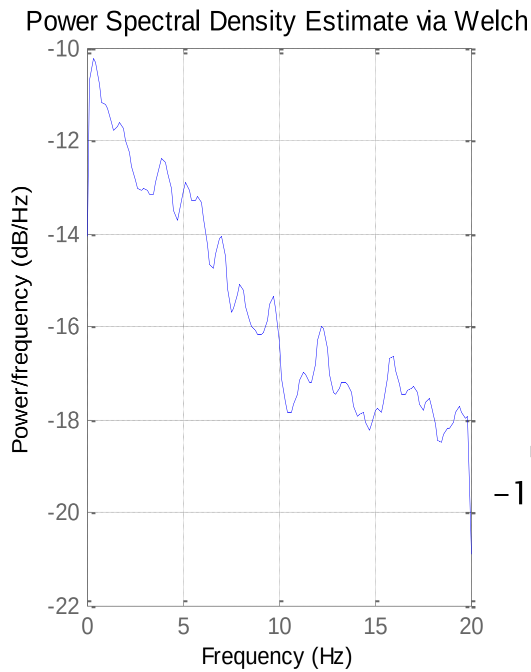
# Rotation Rate Gyros

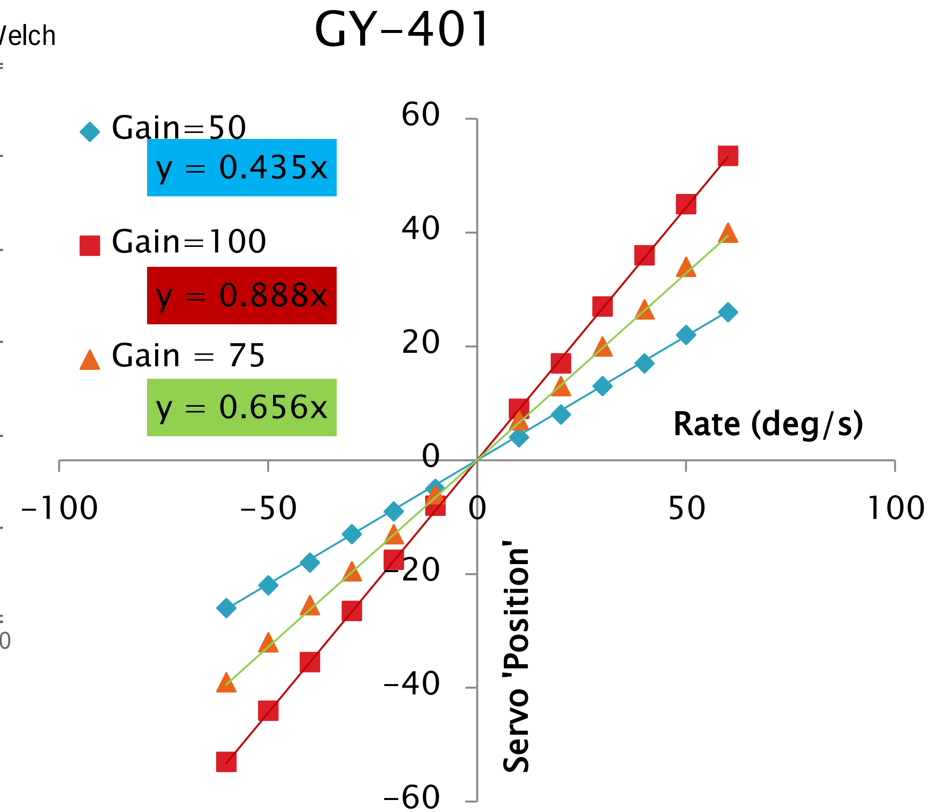
- FDR does not provide for Rotation Rate sensors.
- 2 methods of input
  - Servo Pulse Width
  - A-D board (+$100)
- Need to minimize cost
- 3 options found that met needs and requirements of FDR
- Further Investigation on PG-03 and GY401
- GY401 chosen for calibration linearity and sensitivity

| Model | Systron LGC 50  | GWS PG -03  | Futaba GY401  |
|---|---|---|---|
| Input Method | A-D | Servo Pulse Width | Servo Pulse Width |
| Cost | $260 | $39 | $140 |
| Specifications Available | Yes | No | No |
| Adjustable gain | No | Yes | Yes, Remotely |

# Rate Gyro Calibration



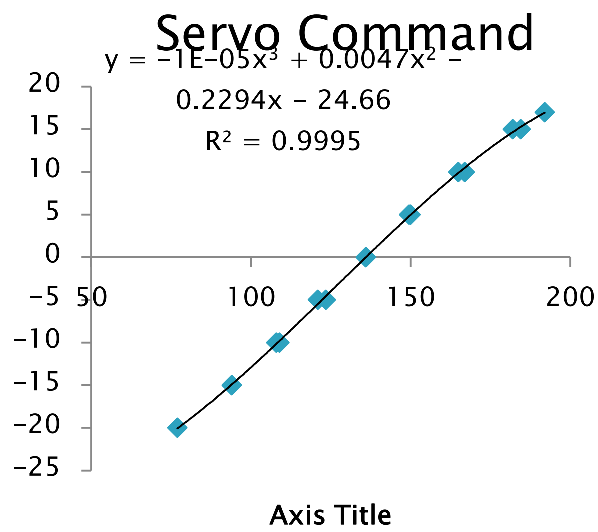

Standard Deviation: 0.80
Variance: 0.64

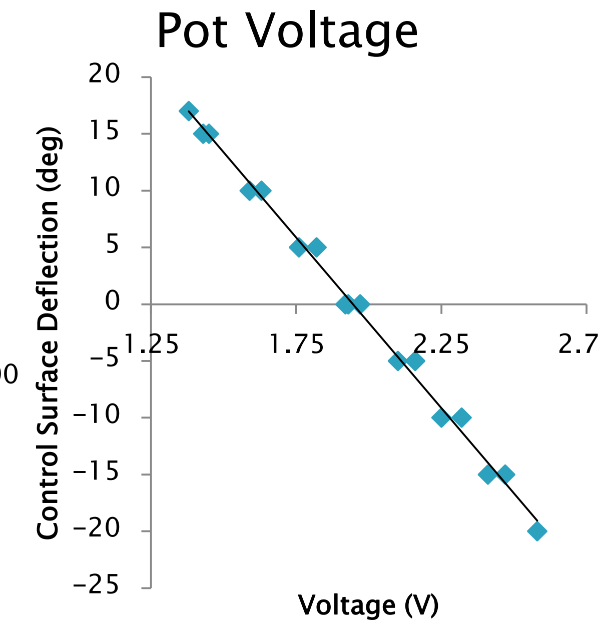
- Calibrations performed using 4th and 5th axis of 5axis CNC machine with known rotation rates

| Gain (%) | Max Rate (deg/s) | Sensitivity (deg/s) |
|---|---|---|
| 100 | 114 | 1.1 |
| 75 | 152 | 1.5 |
| 50 | 229 | 2.3 |

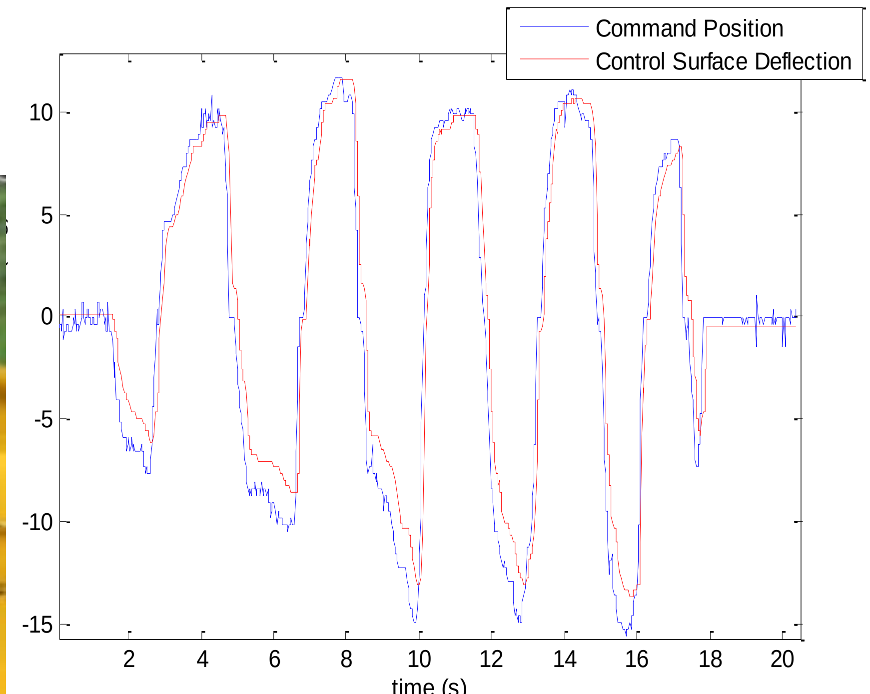
# Control Surface Position

- Servo Command Position
  - High Resolution
  - Does not account for flex in linkages and control surface
  - Does not account for speed of servo
- Position determined by Potentiometer
  - Determines position of surface not actuation servo
  - Has small dead band (~1 deg)



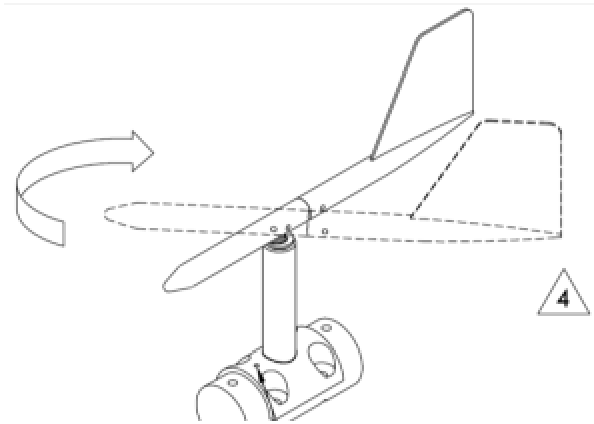




# Wind Tunnel Test

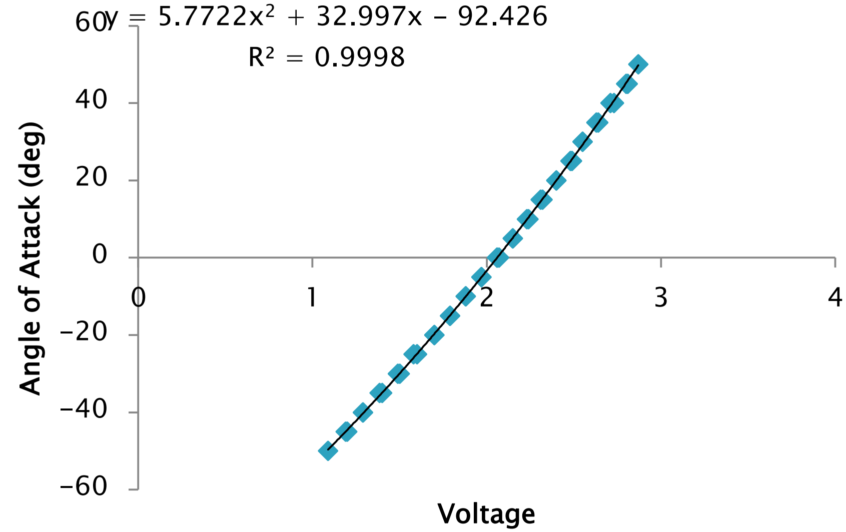
# AoA/AoS

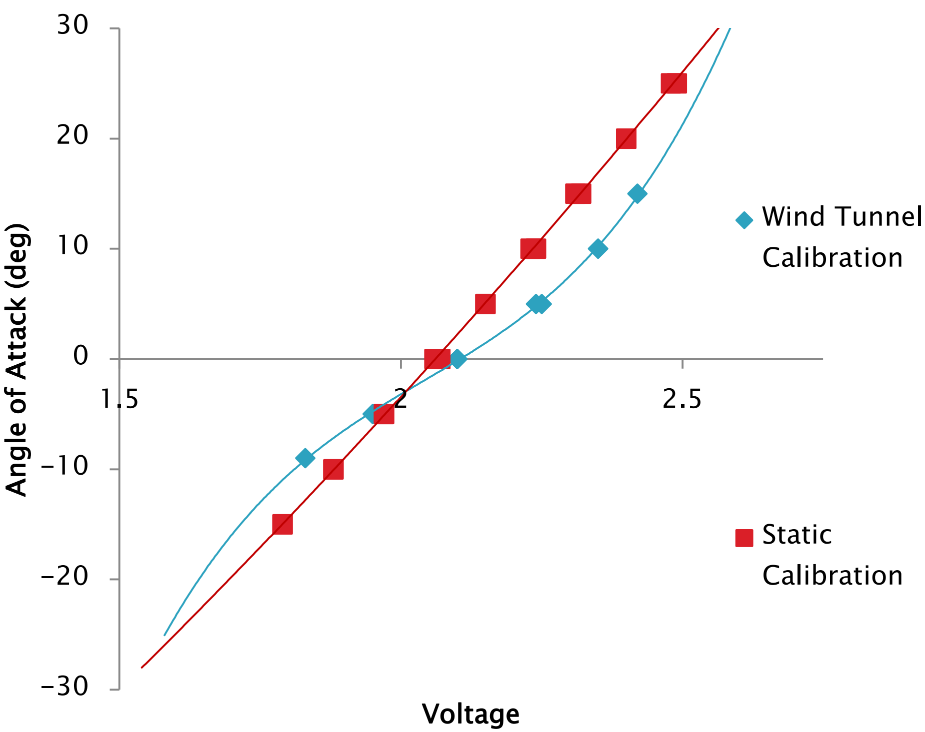
- Only one option commercially available
  - Space Age Controls Mini Vane
  - $800 cost prohibits use
- Must build sensor
  - Low friction angle indication
    - (hall effect angular position sensor)
  - Low friction pivots
    - Small Motor Gearbox
  - Light weight
  - Low rotational inertia for response time
    - Foam with carbon reinforcement

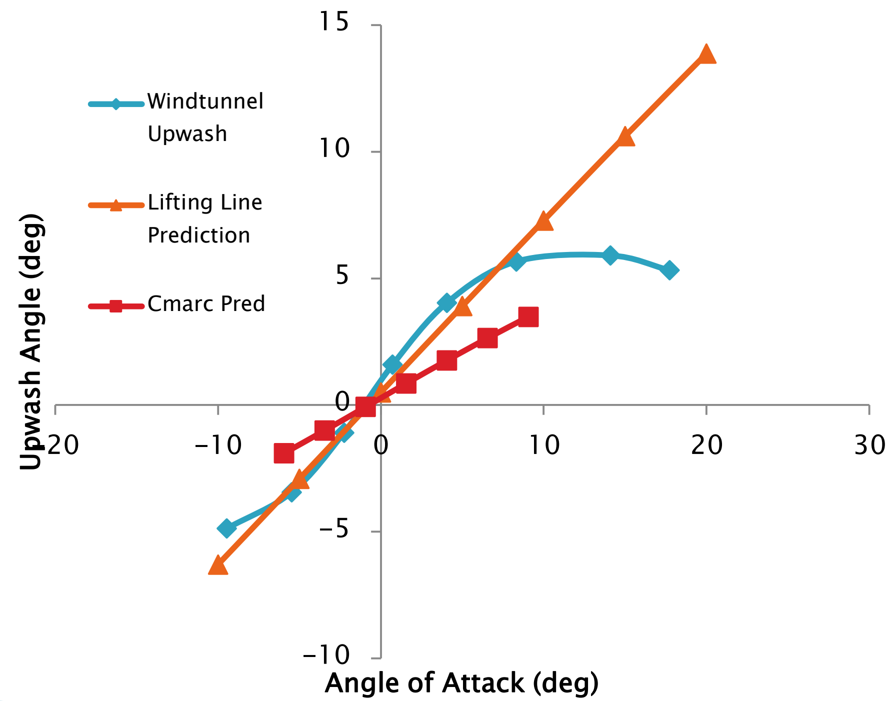



# AoA Calibration

- 2 Calibrations
  - Voltage →Position
  - Up wash effects due to wing
    - Initial CMARC model found to have errors
    - Used Wind Tunnel to calibrate
    - Compared with lifting Line theory
- Final Calibration



# Data Acquisition System Cost

- Flight Data Recorder: $300
- G-Force Expander: $80
- RPM Sensor: $15
- A/D board: $100
- Rate Gyros: $140 x 2
- AoA sensor: ~$50
- Pitot Probe: ~$25
- Control Surface Position: ~$10
- Total: $860

# Flight Test Procedure

- Three Phases
  - Initial Checks
    - Pilot Familiarization (takeoffs, landings, Stalls)
    - Practice rapidly trimming for different flight conditions due to small flight box
  - Longitudinal Tests
    - Instrumentation checkouts (perform maneuvers with known results to check instrumentation)
    - Maneuver Evaluation
      - Start by performing several of each maneuver on the same flight for direct comparison and determine improvements
      - Focus on single maneuvers per flight for detailed evaluation

# Data Reduction

- Upload from Recorder and saved in Text format
- Data loaded into matlab
  - Calibrations and Corrections applied
  - Three Options
    - A single analysis on one data set
    - Analysis on multiple data sets individually with parameter estimates for each data set output to a text file for analysis
    - Analysis of multiple data sets simultaneously with single set of parameter estimates that fits all of the data.

# Results

# Longitudinal Parameter ID

- Sample Results
  - Flight 5 data set 6
  - Frequency sweep
  - Cruise speed = 67 ft/s
  - δe max = 10 deg
- Initial Model
  - Note that $C_{D_{\delta e}}$ and $C_{Dq}$ have been dropped from drag term, values are smaller than noise levels
- Improved Model
- Flight Maneuver to use
- Effect of Flight speed and Control Amplitude

## Model

$$C_X = \frac{1}{\bar{q}S}(m a_x - T)$$

$$C_Z = \frac{m a_z}{\bar{q}S}$$

$$C_m = \frac{1}{\bar{q}S\bar{c}}[I_y \dot{q}] \quad \dot{q} = \frac{\delta}{\delta t} q$$

$$C_L = C_X \sin\alpha - C_Z \cos\alpha$$

$$C_D = -C_X \cos\alpha - C_Z \sin\alpha$$

$$C_D = C_{D_0} + C_{D_\alpha}\Delta\alpha + C_{D_{\alpha^2}}\Delta\alpha^2$$

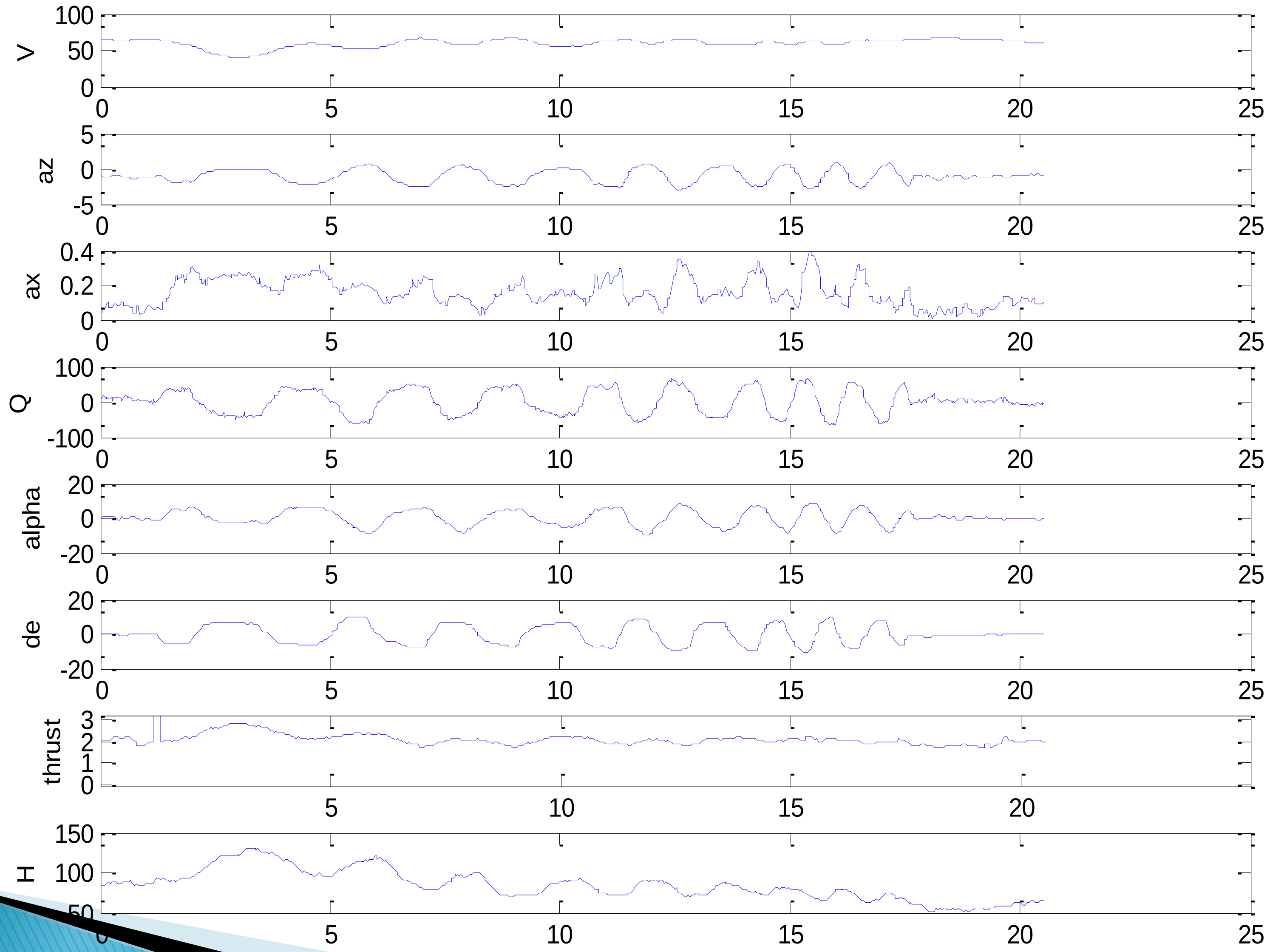
$$C_L = C_{L_0} + C_{L_\alpha}\Delta\alpha + C_{L_q}\frac{\bar{c}}{2V}q + C_{L_{\delta_e}}\delta_e$$

$$C_m = C_{m_0} + C_{m_\alpha}\Delta\alpha + +C_{m_q}\frac{\bar{c}}{2V}q + C_{m_{\delta_e}}\delta_e$$

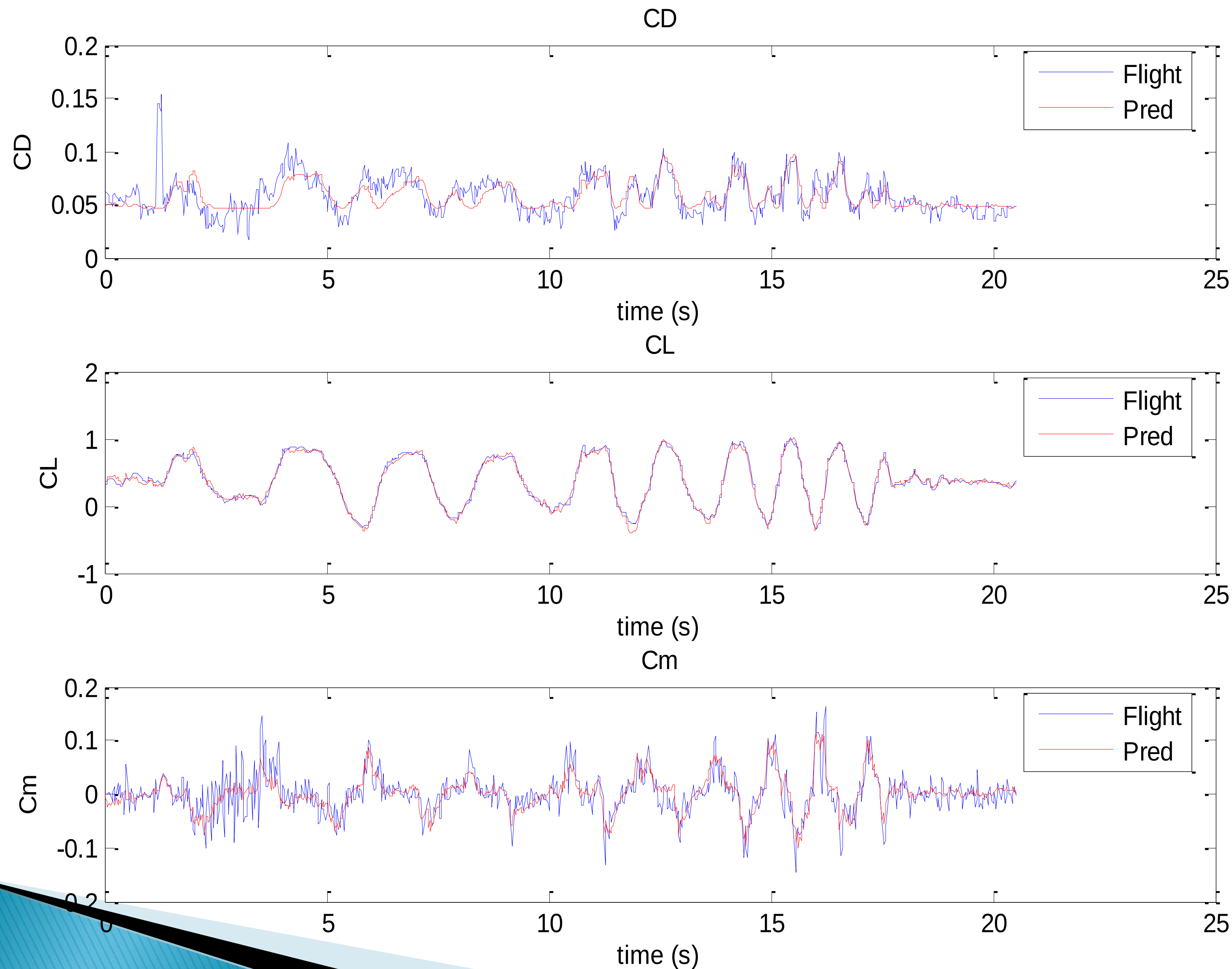
Flight Measured

Determined by Regression

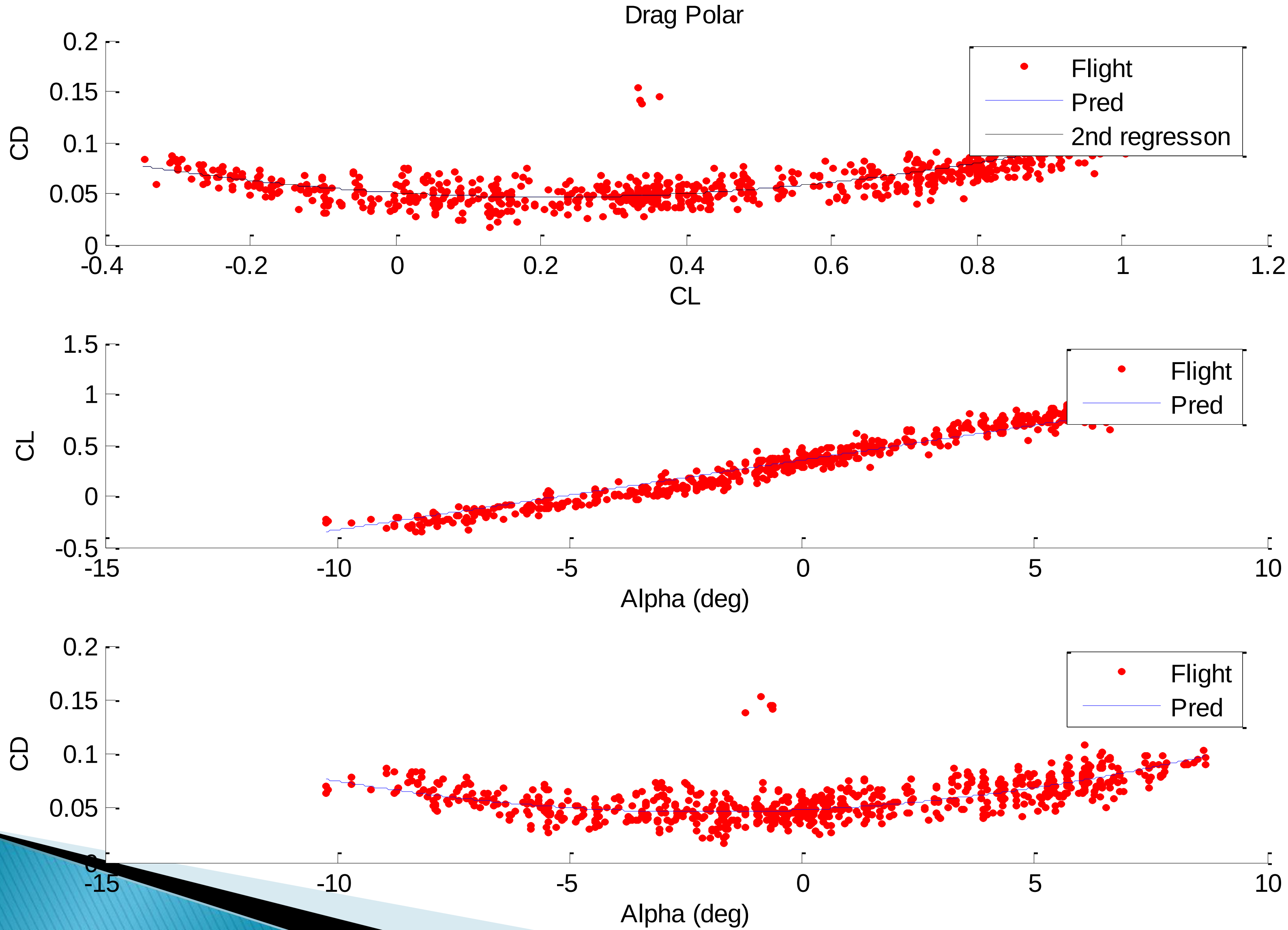
# Recorded Values



# Non dimensional forces and Moments

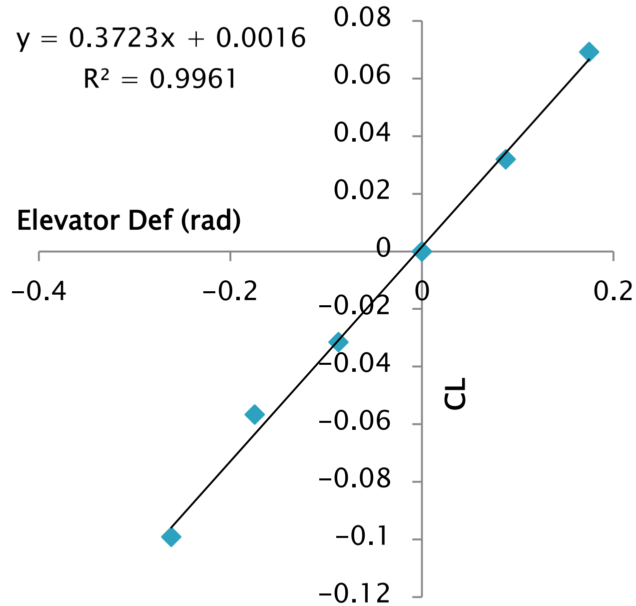


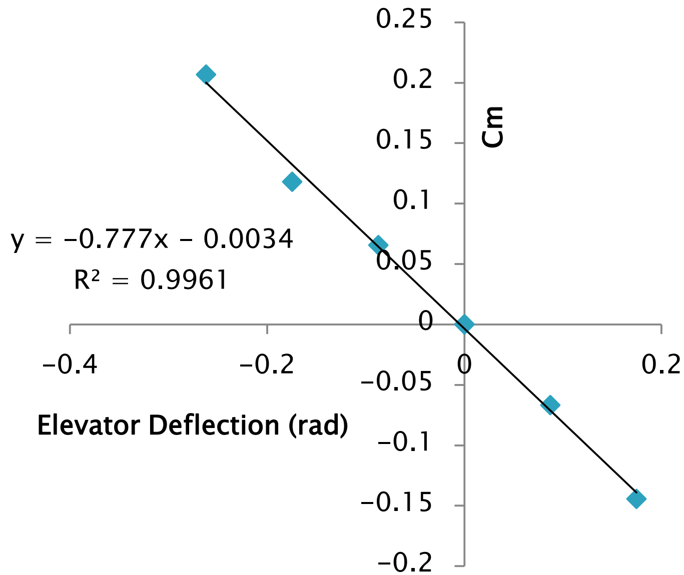
# Drag Polar


Drag Polar
CD
CL
Flight
Pred
2nd regresson
0.2
0.15
0.1
0.05
0
-0.4
-0.2
0
0.2
0.4
0.6
0.8
1
1.2
CL
1.5
1
0.5
0
-0.5
-15
-10
-5
0
5
10
Alpha (deg)
CD
0.2
0.15
0.1
0.05
0
-15
-10
-5
0
5
10
Alpha (deg)

# Initial Model

- Cmde, Cm_Q, CL_Q, and Cm_de predictions poor
- High colinearity between elevator deflection and pitch rate made least squares estimator ill conditioned.
  - Result is High variance and inability to accurately predict values for Cm




# Improved Model

- Used wind tunnel test to determine $Cm_{\delta e}=-0.777$ and $CL_{\delta e}=-0.372$
  - Standard deviation level amongst individual runs changed from 50% to 10%

# Comparison of Control Inputs

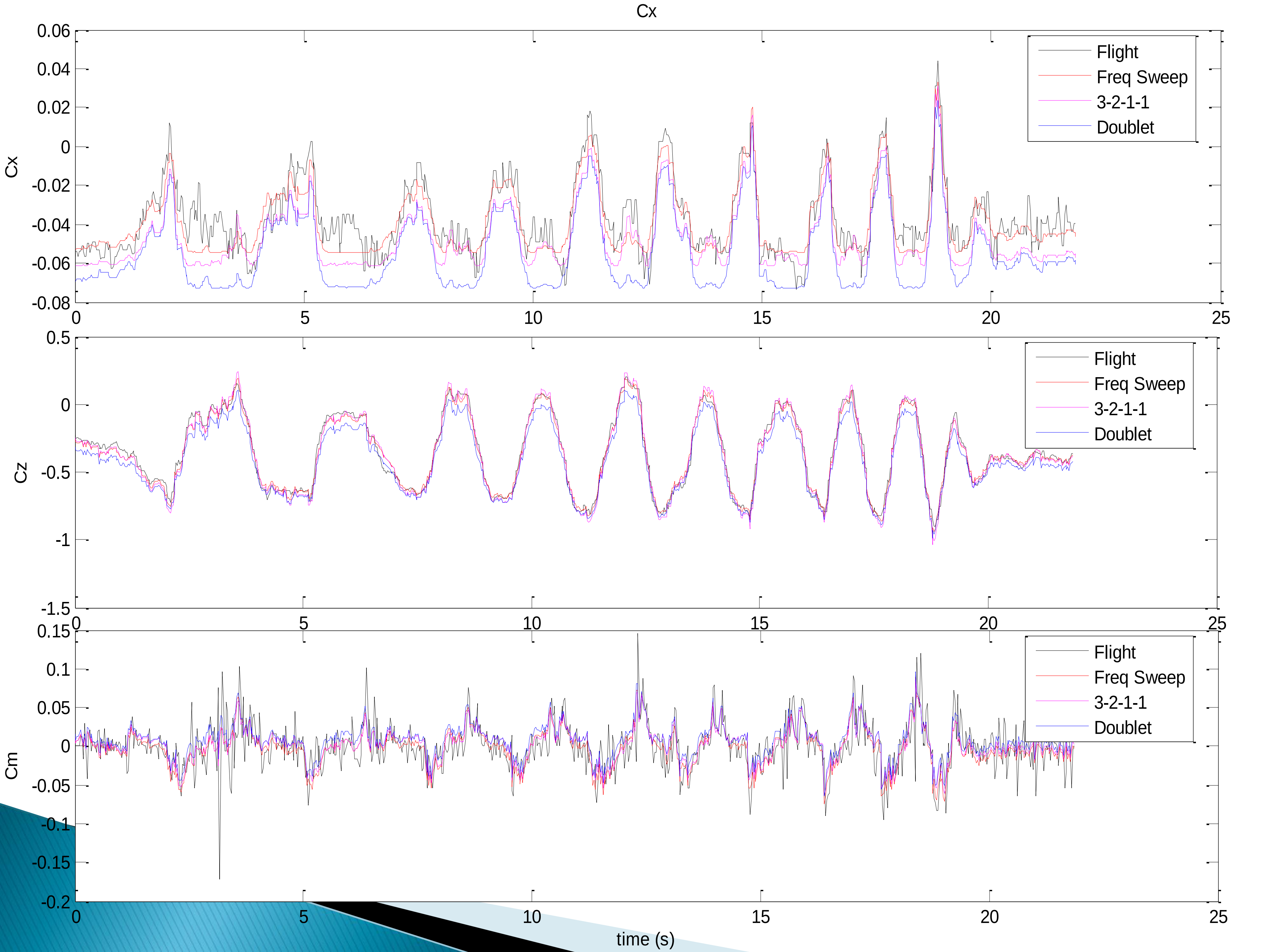
| | average value | | | STD/mean *100 | | |
|---|---|---|---|---|---|---|
| manuever | Doublet | 3-2-1-1 | Frequency | Doublet | 3-2-1-1 | Frequency |
| Cxo | -0.0644 | -0.0587 | -0.0517 | 22.37582 | 7.515106 | 12.461122 |
| Cx_alpha | 0.3232 | 0.2424 | 0.2485 | 28.79379 | 24.19383 | 12.673781 |
| Cx_alpha^2 | 3.0987 | 3.1576 | 2.7843 | 55.23879 | 34.48262 | 11.964337 |
| Czo | -0.4130 | -0.3454 | -0.3596 | 10.85549 | 4.952154 | 4.8979612 |
| Cz_alpha | -3.7406 | -4.2611 | -3.7930 | 12.09868 | 5.917806 | 6.9236917 |
| Cz_q | -20.4041 | -21.2120 | -23.9743 | 21.93477 | 13.81265 | 10.817768 |
| Cz_de | -0.3720 | -0.3720 | -0.3720 | 0 | 0 | 0 |
| Cmo | 0.0051 | 0.0045 | -0.0005 | 254.3339 | 85.07762 | 167.66794 |
| Cm_alpha | -0.2837 | -0.3249 | -0.3923 | 34.37153 | 29.22029 | 29.100513 |
| Cm_Q | -12.1839 | -9.6481 | -9.5818 | 32.24613 | 9.128631 | 7.8598966 |
| Cm_de | -0.7700 | -0.7700 | -0.7700 | 0 | 0 | 0 |
| Cdo | 0.0648 | 0.0573 | 0.0501 | | | |
| k2 | -0.0284 | -0.0163 | -0.0215 | | | |
| k1 | 0.0647 | 0.0590 | 0.0713 | | | |

- Regression performed on individual data sets that have then been averaged
- Note Frequency sweep yields lowest deviations

| | Coincident Regression | | | SE/mean * 100 | | |
|---|---|---|---|---|---|---|
| manuever | Doublet | 3-2-1-1 | Frequency | Doublet | 3-2-1-1 | Frequency |
| Cxo | -0.064419 | -0.059341 | -0.048794 | 0.593171 | 0.363712 | 0.2614486 |
| Cx_alpha | 0.2996 | 0.18637 | 0.24953 | 1.927056 | 1.890387 | 0.675826 |
| Cx_alpha^2 | 2.5389 | 3.5 | 2.5811 | 0.807494 | 1.990302 | 0.5232599 |
| Czo | -0.40264 | -0.34786 | -0.34659 | 0.414825 | 0.194664 | 0.1397688 |
| Cz_alpha | -3.4972 | -4.4393 | -3.8141 | 0.667396 | 0.472725 | 0.2584208 |
| Cz_q | -23.477 | -20.282 | -23.462 | 1.935154 | 1.155978 | 0.6342214 |
| Cz_de | -0.372 | -0.372 | -0.372 | 0 | 0 | 0 |
| Cmo | 0.0056863 | 0.0043602 | -0.002586 | 16.94351 | 13.33959 | 10.475188 |
| Cm_alpha | -0.28473 | -0.30641 | -0.40353 | 2.189792 | 2.6023 | 1.5558426 |
| Cm_Q | -11.629 | -10.207 | -9.9408 | 1.136962 | 1.139511 | 0.6837252 |
| Cm_de | -0.77 | -0.77 | -0.77 | 0 | 0 | 0 |
| Cdo | 0.065056 | 0.052301 | 0.050113 | | | |
| k2 | -0.034899 | 0.0035408 | -0.033866 | | | |
| k1 | 0.080622 | 0.047842 | 0.086005 | | | |

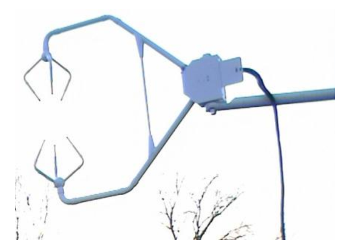
- Regression performed on all data sets simultaneously
- Again Frequency sweep yields lowest deviations

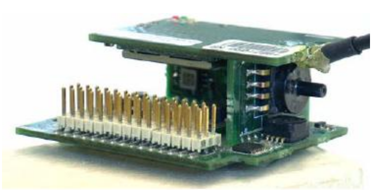
- Data is plotted vs actual data in next slide


Cx
Flight
Freq Sweep
3-2-1-1
Doublet
Cx
0.06
0.04
0.02
0
-0.02
-0.04
-0.06
-0.08
0
5
10
15
20
25
Cz
0.5
0
-0.5
-1
-1.5
Cm
0.15
0.1
0.05
0
-0.05
-0.1
-0.15
-0.2
time (s)

# INSTRUMENTATION


**SONIC ANEMOMETER**
3-D wind measurement
10 cm spatial resolution
10 Hz 20 Hz

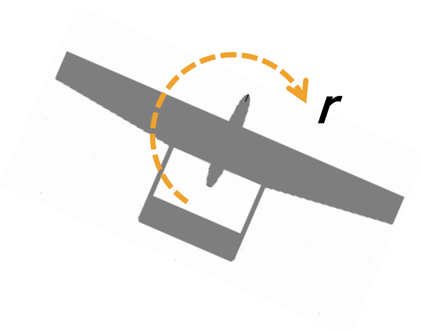


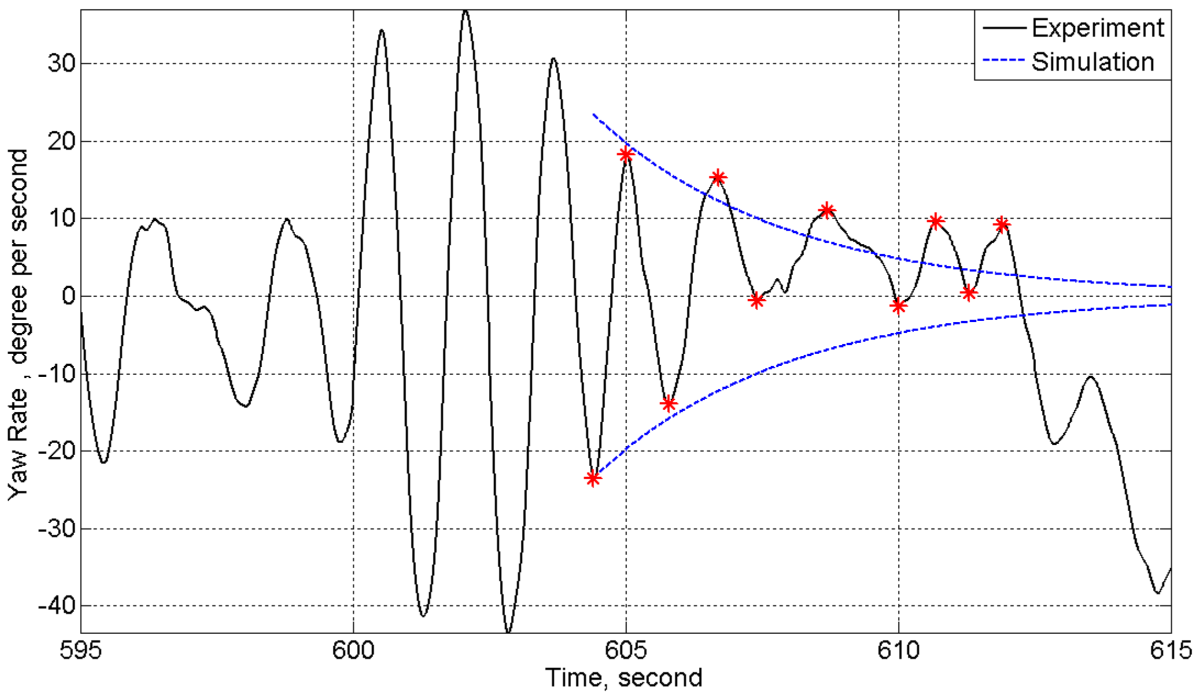


**INERTIAL MEASUREMENT UNIT**
3 Orthogonal Rate gyros
Altimeter-Barometer
50 Hz
Integrated GPS
3-D Position, Velocity
4 Hz

# RESULTS AND DISCUSSION

## DYNAMIC MODES




**Dutch Roll Mode Remarks:**

- ✓ Good trend
- ✓ Initial decay

- ❖ Turbulence
- ❖ Model Simplifications

battery voltage
**motor disconnected** – power ON
switch APM to test mode
run planner – enter terminal mode
    radio setup / test
    verify senors – gyros, IMU
    load way points verify HOME location
    verify PID
switch APM to flight mode
run ground station
    verify telemetry data
    load flight plan way points
radio / receiver range check
check balance
Your should always balance your RC airplane *before* coming to the flying field. However, it is always a good idea to check the forward/backward balance one more time before the first flight of each day. Remember that the fuel tank must be empty when checking the balance.
verify all connections – connect motor
verify GPS lock and **BUTTON UP**
    R/C equipment correctly located and fixed (not loose).
    R/C equipment connections OK (this can be visual if you have plugs cable tied or otherwise secured).
    All linkages correctly attached (check clevises etc).
    All flying surfaces correctly and securely attached (for models with removable wings etc).
    All control surfaces correctly attached and unobstructed (elevator / rudder / aileron / undercarriage etc).
    Propeller correctly attached and undamaged.
    Undercarriage correctly attached with free movement of wheels and retracts (where installed).
    Pitot tube clear (where installed).
    Static ports clear (where installed).
    Canopy / hatches secure.
Manual control – elevator, rudder, aileron's, throttle
Make sure the control surfaces are moving correctly with each stick movement of the transmitter.

switch to each UAV mode. In each, move plane to confirm that the control surfaces are moving correctly when you pitch and roll the plane.
**Clear for takeoff**