National Aeronautics and Space Administration

Open Architecture for Data Mining and PHM

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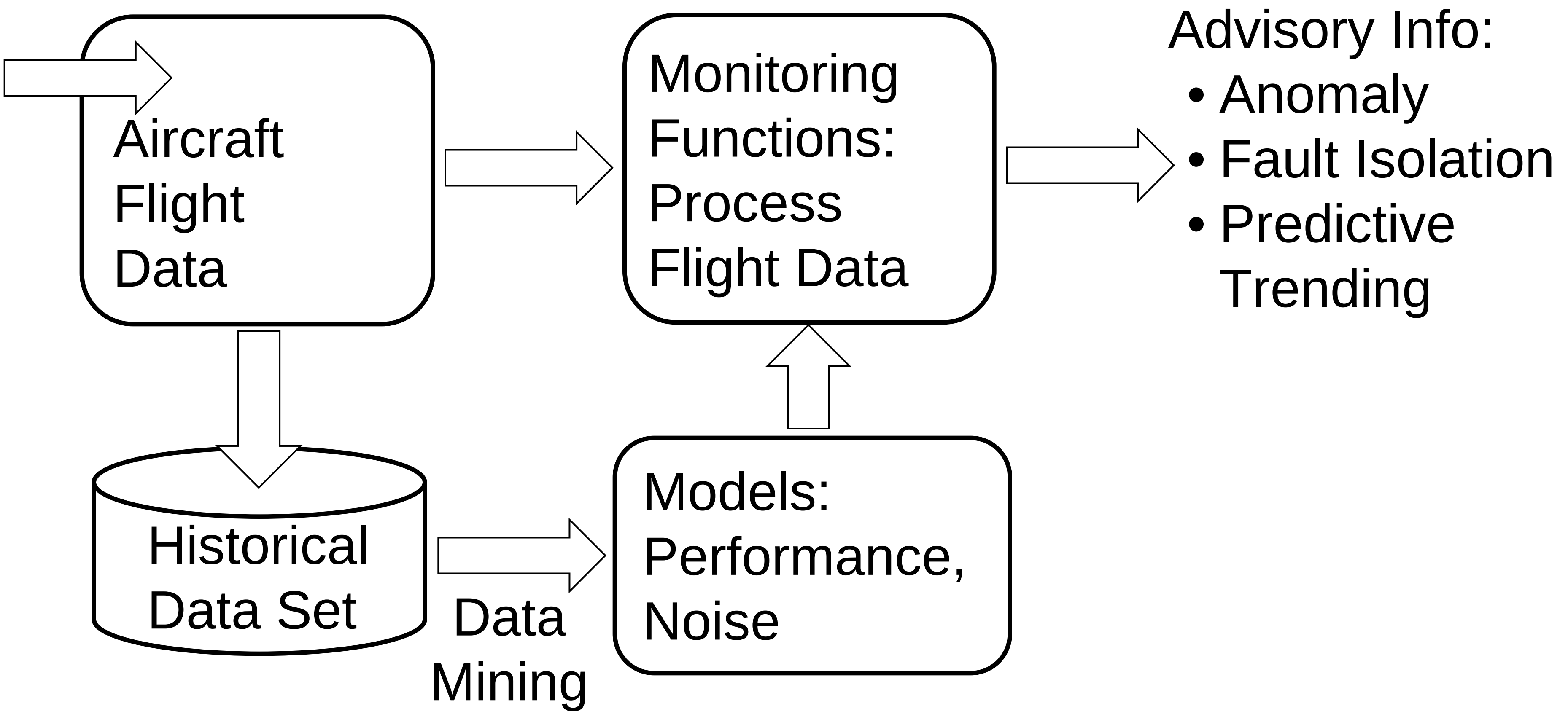
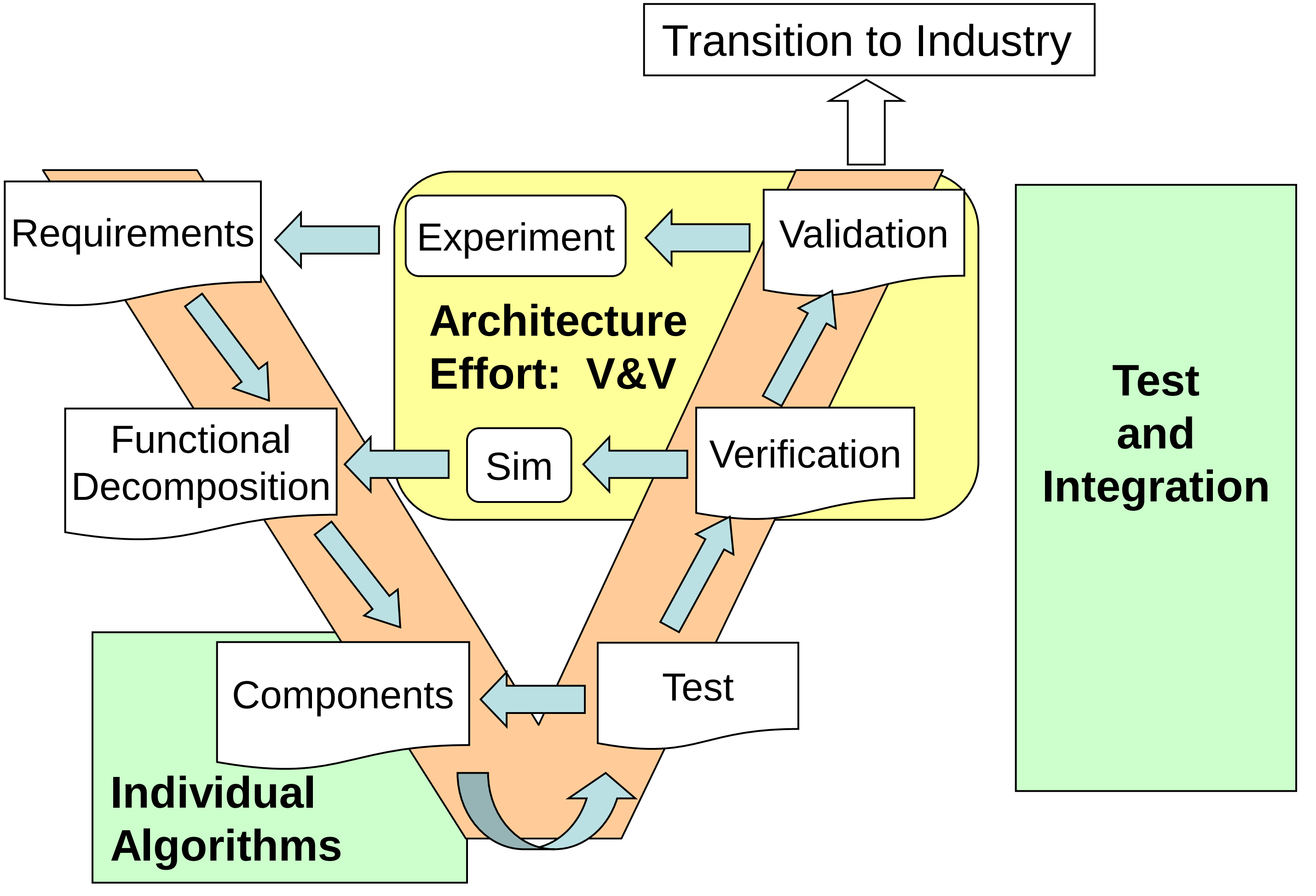
Aircraft Data Monitoring



Data Mining Functions

- Data exploration
  – Model structure selection
  – Off line, is not a part of deployed monitoring function
- **Model training**
  – Multivariate regression
- **Data exploitation**
  – Anomaly detection
  – Fault isolation (diagnostics)
  – Predictive trending

V&V for Data Mining and PHM



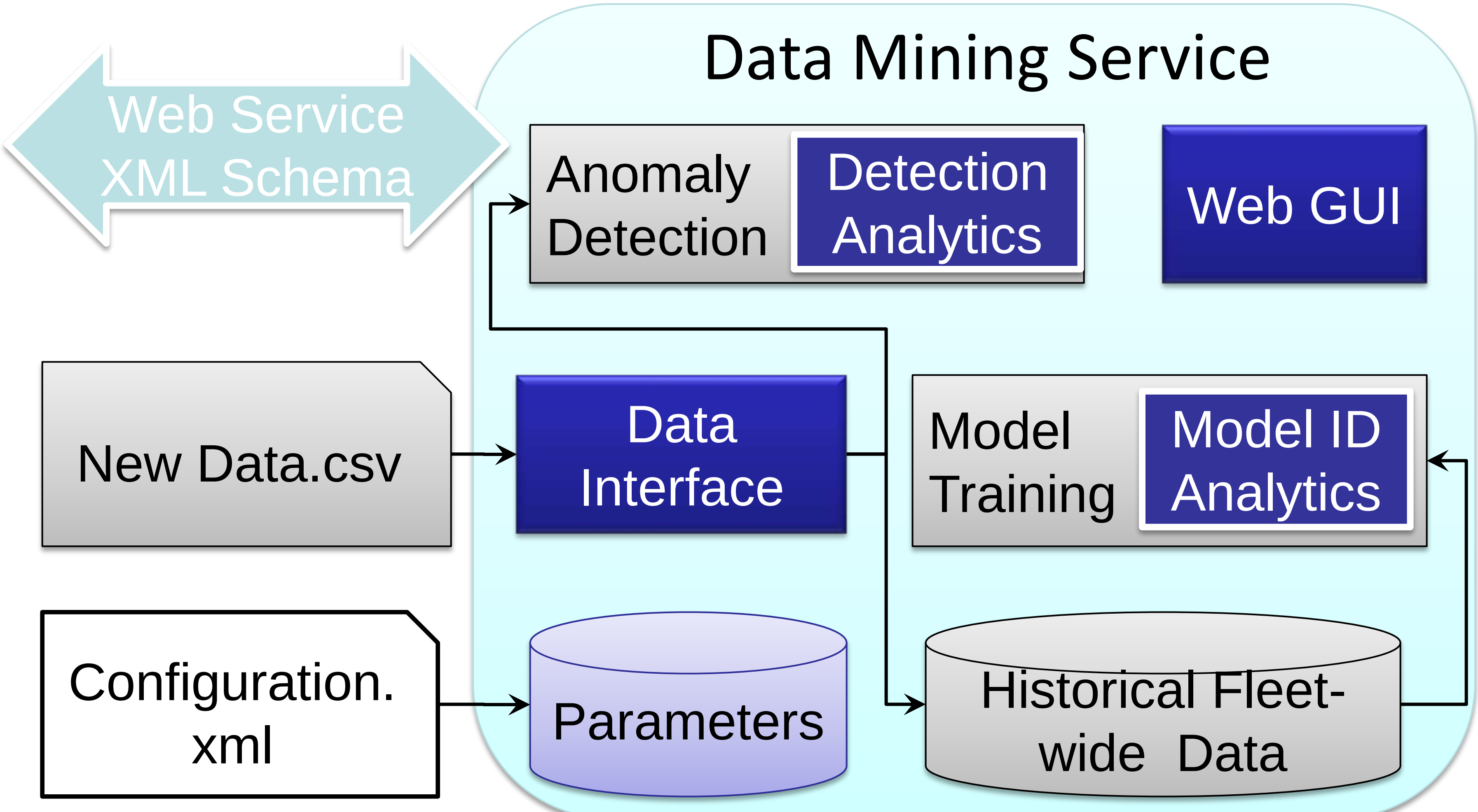
Outline

- Background and past effort
  – Where did we come from?
- **Completed effort**
  – **Where are we now?**
- On-going effort
  – What are we going currently?
- Extensions
  – What are the follow-on steps?

Data Mining Demo

- Java EE SOA software: Openalytics
- Functions from Stanford NRA
  - Regression modeling of aircraft dynamics
  - Anomaly detection from residuals - MSPC
  - Detail in E. Chu, D. Gorinevsky, and S. Boyd, AIAA Infotech@Aerospace, 2010
- FOQA data from NASA FLTz simulator
  - Cruise flight segment
  - Many flights with varying conditions

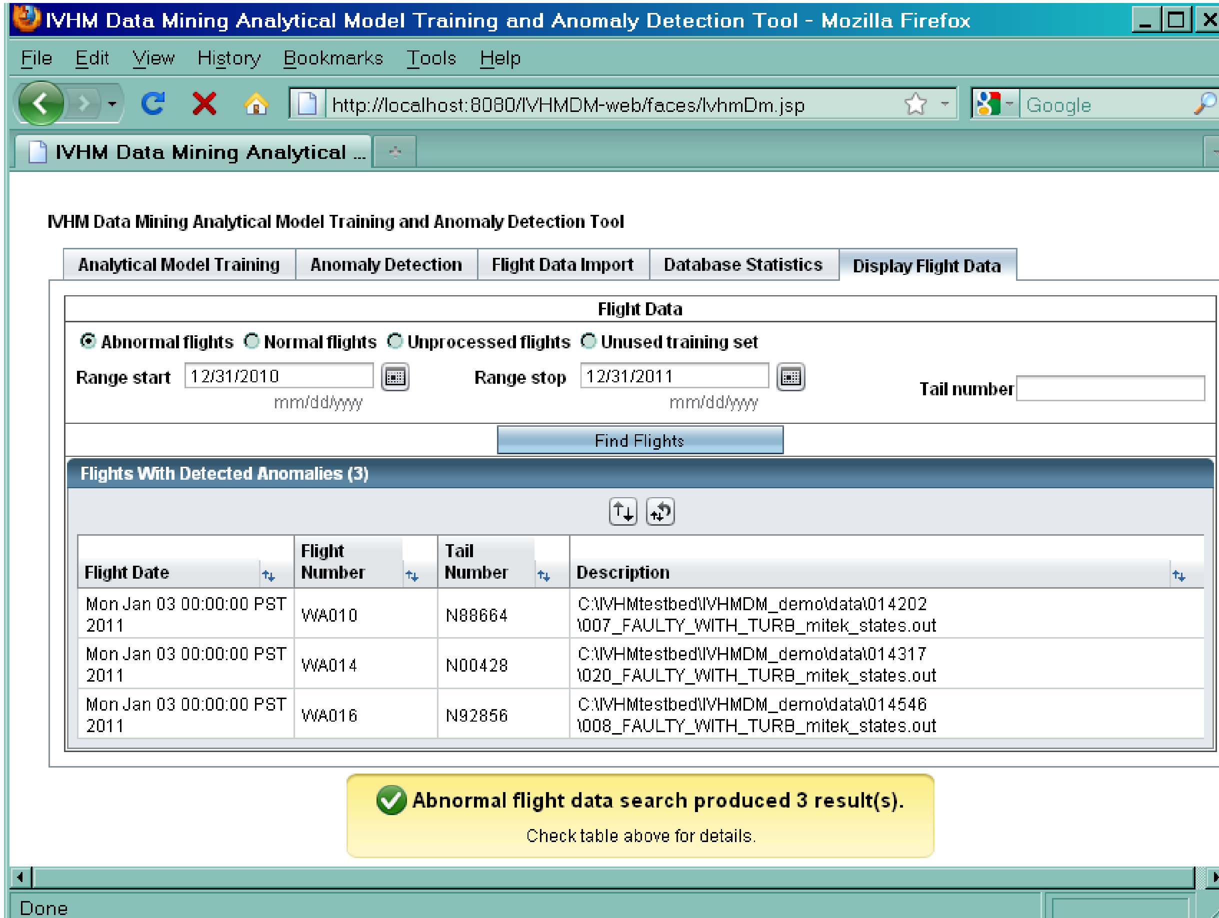
Openalytics SOA



Integrated Demonstration

- Historical database with 25,000 flights

- Openalytics:
  - GlassFish server
  - JSF Web GUI
- 100Gb db4o database
- Model trained in a few minutes
- Seeded faults detected well



Outline

- Background and past effort
- Completed effort
- **On-going effort**
- Extensions

Verification for FOQA Data

- NASA has FOQA data sets
  - Could implement regression-based algorithms
  - But the data access is restricted…
- Software integration and verificiation
  - Have to be done off site
  - Require testing with realistic data
- Solution: simulator for FOQA data

Simulator scope

- Generate realistic FOQA data sets
- Base aerodynamic configuration
  – Cruise, end of climb, beginning of descent
- Quasi-steady flight
  – Smooth accelerations, decelerations, turns
- Linearized performance models
  – Of the aircraft and of the engines
- Models are calibrated on real data

Airframe Dynamics

- Airframe dynamics: near-steady flight

$$m(a\text{-}g) = F_{aero}+F_{thrust}$$

- Propulsion thrust

$$F_{thrust}=c_{\mathrm{e,L}}\rho_{air}N_{\mathrm{1,L}} + c_{\mathrm{e,R}}\rho_{air}N_{\mathrm{1,R}} - c_{\mathrm{e,M}}M$$

  – $N_{\mathrm{1,L}}$, $N_{\mathrm{1,R}}$ are engine fan RPMs, M is Mach number

- Aerodynamic forces

$$F_{aero}= qC_{\mathrm{a,0}}+qC_{\mathrm{a,1}}\alpha +qC_{\mathrm{a,2}}u_{1}+ \ldots+qC_{\mathrm{a,n+1}}\, u_{\mathrm{n}}$$

  – $q= ½\rho_{air}V^2$ is dynamic pressure
  – α is AOA
  – $u_1, \ldots , u_{\mathrm{n}}$ are control surface positions

Airframe Attitude

- Pitch dynamics

$$Ia_{pitch}=C_{\mathrm{p,m}}(m-m_0)+qC_{\mathrm{p,1}}\alpha+qC_{\mathrm{p,0}}+qC_{\mathrm{p,2}}u_{\mathrm{stab}}+qC_{\mathrm{p,2}}u_{\mathrm{elev}}$$

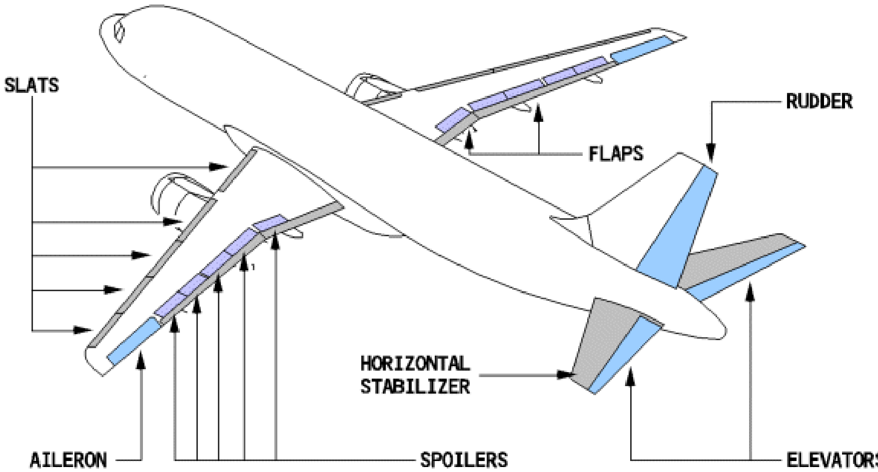
- Roll dynamics

$$Ia_{roll} = qC_{\mathrm{r,1}}r_{roll} + qC_{\mathrm{r,2}}u_{\mathrm{aileron}} + qC_{\mathrm{r,2}}u_{\mathrm{rudder}}$$

- Yaw: coordinated turn

Actuator Allocation

- Symmetric allocation
  - Left elevator = Right elevator
  - Left aileron = -Right aileron
- Stabilizer = $c \cdot$ Elevator
- Slats, flaps, spoilers
  - are not deployed



Regression Model

- Linear regression models

$$y_j = B_j x_j + v_j$$

  - y_j performance variables
  - x_j regressors
  - B_j regression parameters
  - v_j noise
- LS model fit (training)
  - For one channel at a time

A319 Data Set

- The model is trained on A319 FOQA data set at NASA ARC
  - The data provided by an airline partner to NASA under a confidentiality agreement
  - The model completely depersonalizes flight data
  - Modeling of aircraft performance has no relation to airline operation.

Airframe Regression Model

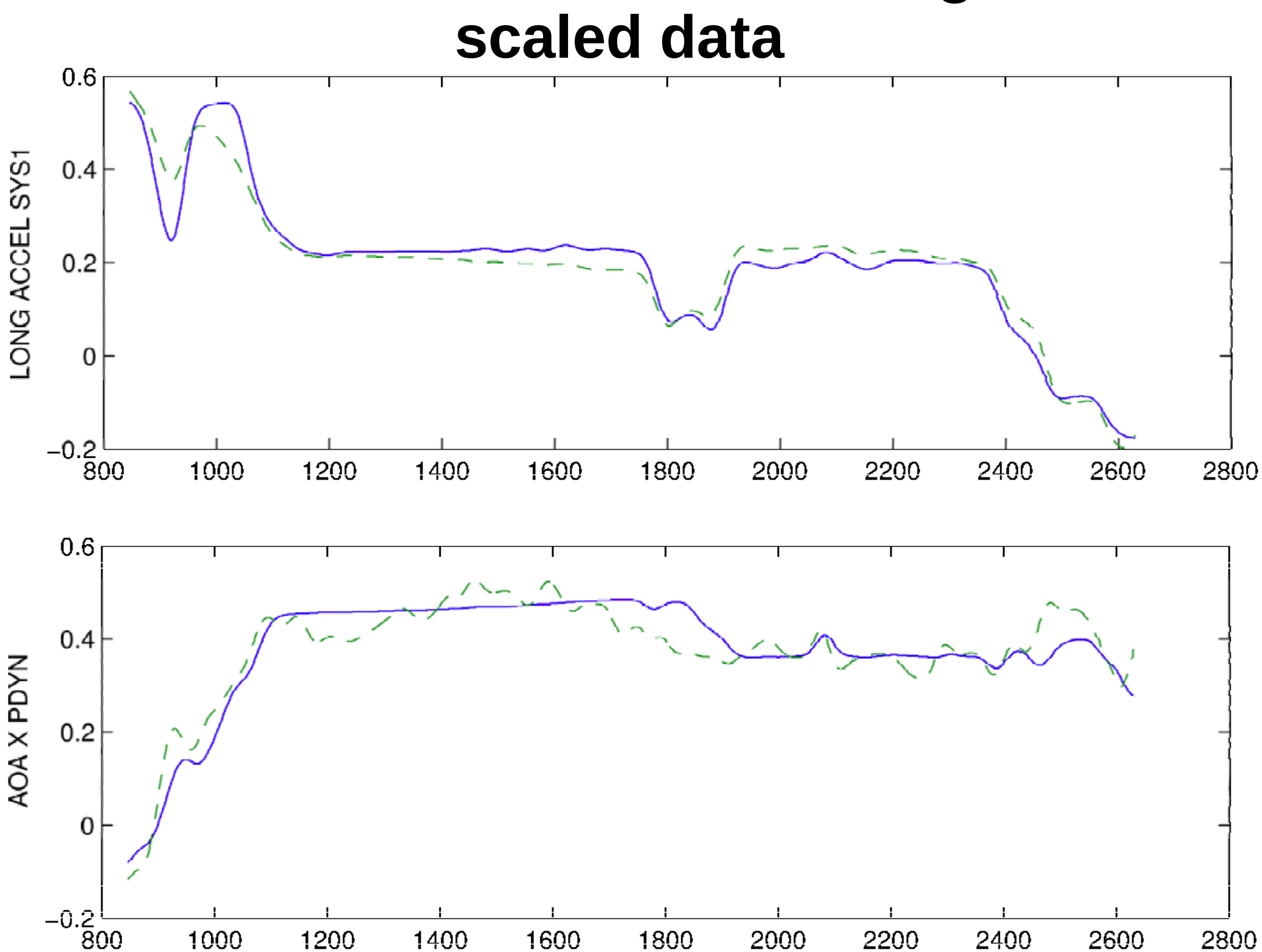
scaled data

	RHO X N1 SUM	DELTA M	DELTA M X A-LAT	DELTA M X LONG	DELTA M X NORM	DELTA M X ROLL	AOA X PDYN	ROLL RATE X PDYN	DIFF AIL X PDYN	SUM ELEV X PDYN	STABILIZER X PDYN	RUDDER X PDYN	DYN PRESS
LAT ACCEL			-1.0000 ± .0000						-0.0483 ± .0133			-0.1023 ± .0282	-0.0386 ± .0348
LONG ACCEL	0.3927 ± .0258			-1.0000 ± .0000									-0.1854 ± .0328
NORM ACCEL					-1.0000 ± .0000		3.0586 ± .3441						2.1192 ± .5006
ROLL ACCEL						-0.2000 ± .0000		-0.0032 ± .0007	-0.0061 ± .0013			0.0018 ± .0008	0.0003 ± .0007
AOA X PDYN		0.8926 ± .1133								-1.0604 ± .1954	-0.7143 ± .0980		0.7017 ± .1021

Flight Surface Allocation

	STABILIZER X PDYN	RUDDER X PDYN	DYN PRESS	ONES
AILR SUM				-0.5152 ± 0.1467
N1 DIFF				0.0000 ± 0.0001
ELEV DIFF				-0.0090 ± 0.0741
SUM ELEV x PDYN	0.1403 ± 0.0476		-0.1209 ± 0.0835	

Regression Fit: a_{longit}, AOA



Engine Regression Model

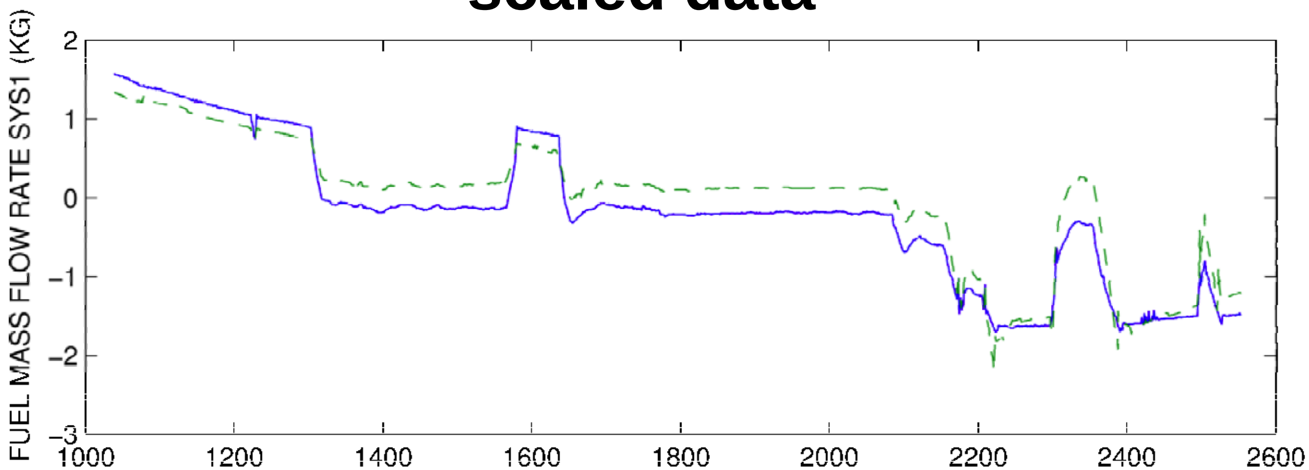
- Linearized performance model of the engine

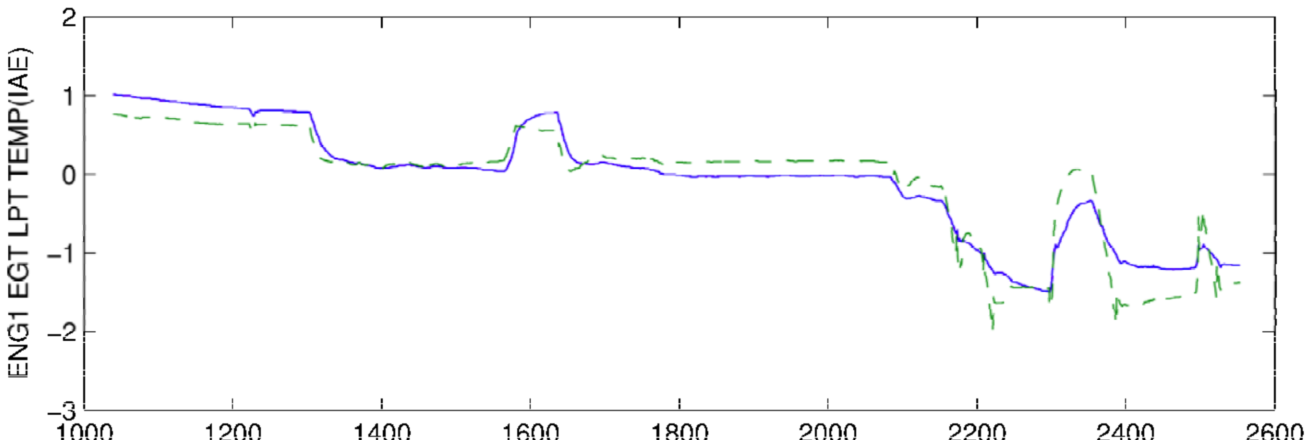
scaled data

	AOA	N1	TOTAL AIR TEMP	VARB BLD VALVE	VARB STATR VANE	MACH	TOTAL AIR PRESS	ONES
N2	0.0332 ± 0.0023	0.2841 ± 0.0029	0.0163 ± 0.0011			0.0258 ± 0.0023	0.0109 ± 0.0011	0.3053 ± 0.0032
EGT LPT TEMP(IAE)	-0.0083 ± 0.0359	1.4024 ± 0.1641	0.3544 ± 0.0161	-0.0505 ± 0.0074	-0.3537 ± 0.0220	0.0687 ± 0.0503	-0.0184 ± 0.0189	-1.2769 ± 0.1388
T3 (HPC EXIT TEMP)	-0.1221 ± 0.0289	1.2868 ± 0.1330	0.4152 ± 0.0114	-0.0261 ± 0.0056	-0.4742 ± 0.0201	0.0852 ± 0.0334	-0.0166 ± 0.0135	-1.1573 ± 0.0987
FUEL MASS FLOW RATE	-0.6324 ± 0.0507	1.8989 ± 0.1916	0.1574 ± 0.0259	-0.0586 ± 0.0084	-0.3534 ± 0.0241	-0.5733 ± 0.0829	0.1633 ± 0.0271	-0.8648 ± 0.1450

Regression Fit: Fuel Rate, EGT

scaled data

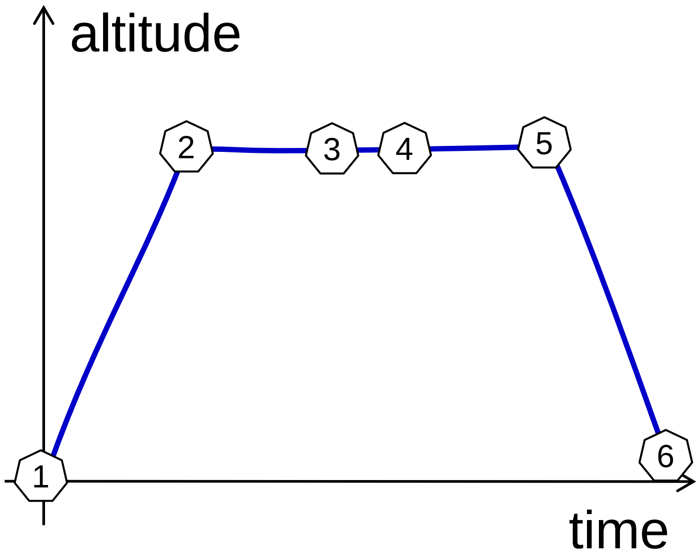


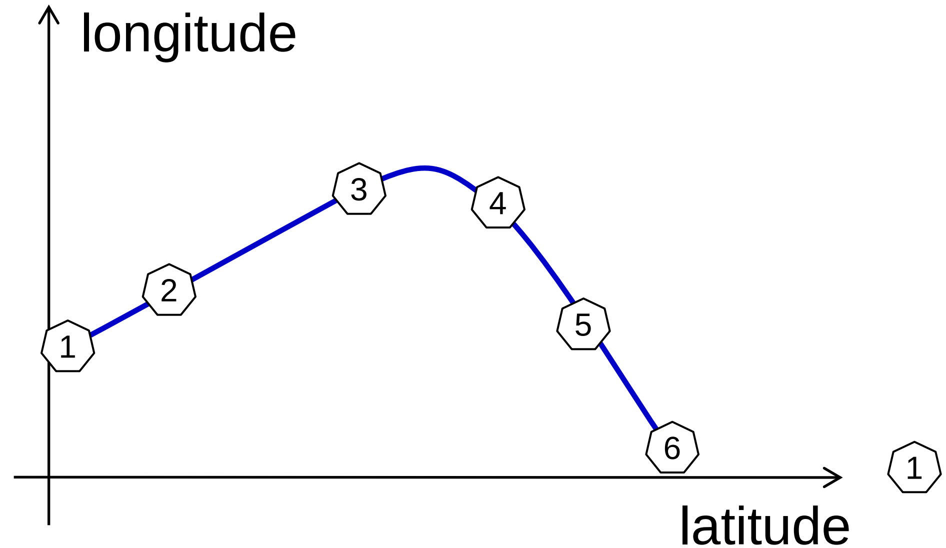


Simulator Development

- Coded in Matlab
  - Almost completed
  - Stand-alone executable
- Uses the regression models
- Will generate most/all FOQA data channels

Flight Plan





Flight segments

- Climb: 1-2
- Descent: 5-6
- Level: 2-3 and 4-5
- Turn: 3-4

Kinematics

- Climb rate, speed change → accelerations
- Coordinated turn: $a_{lateral}=0$
- Turn rate → roll

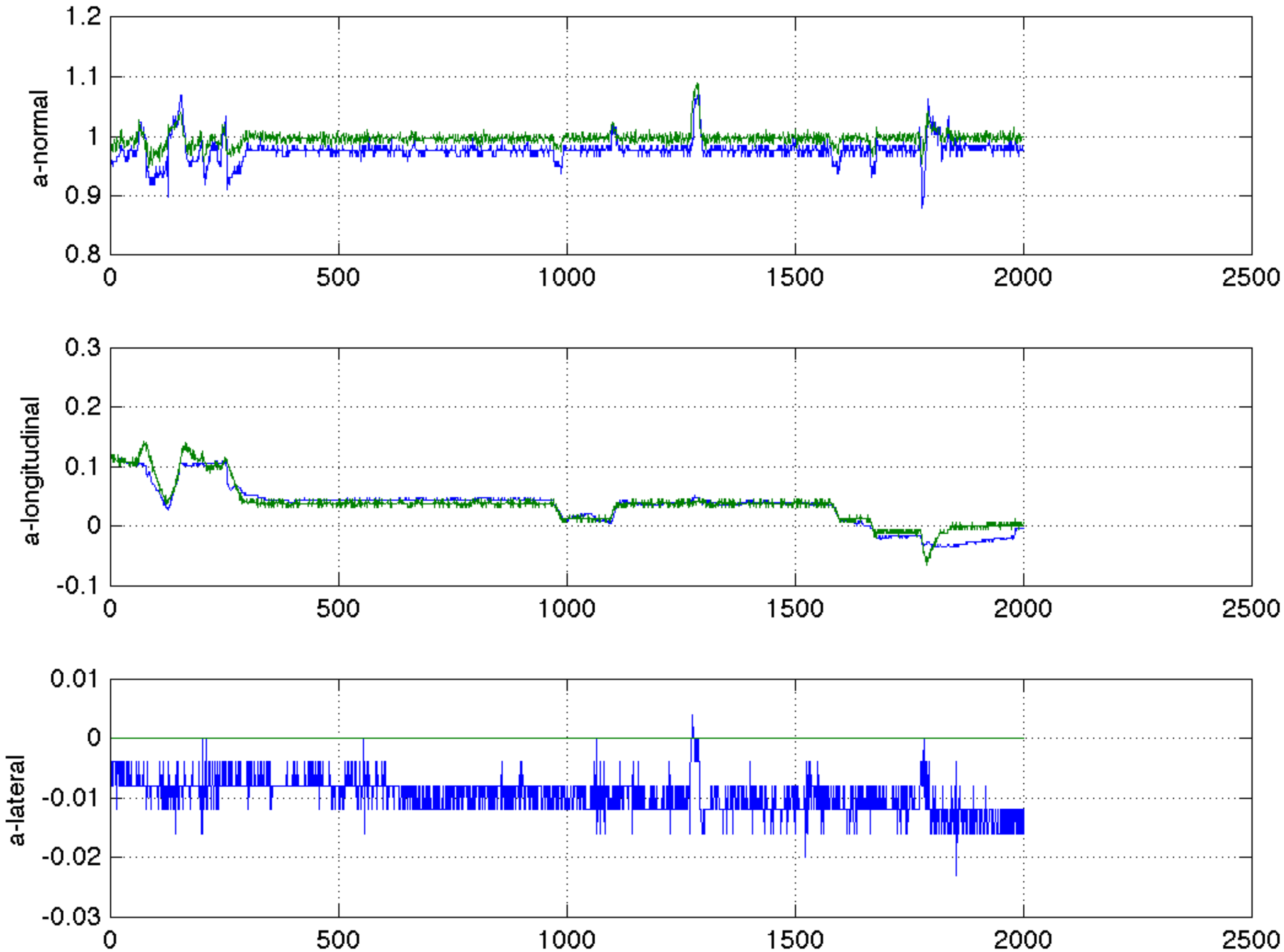
Overall Simulator Logic

- Flight Plan
  - → Accelerations (Kinematics)
  - → Airframe Attitude (Coordinated Flight)
  - → Flight Actuators (Regression)
  - → Engine Dynamics (Regression)
  - → Mass Change (Integration)
- Triangular model structure

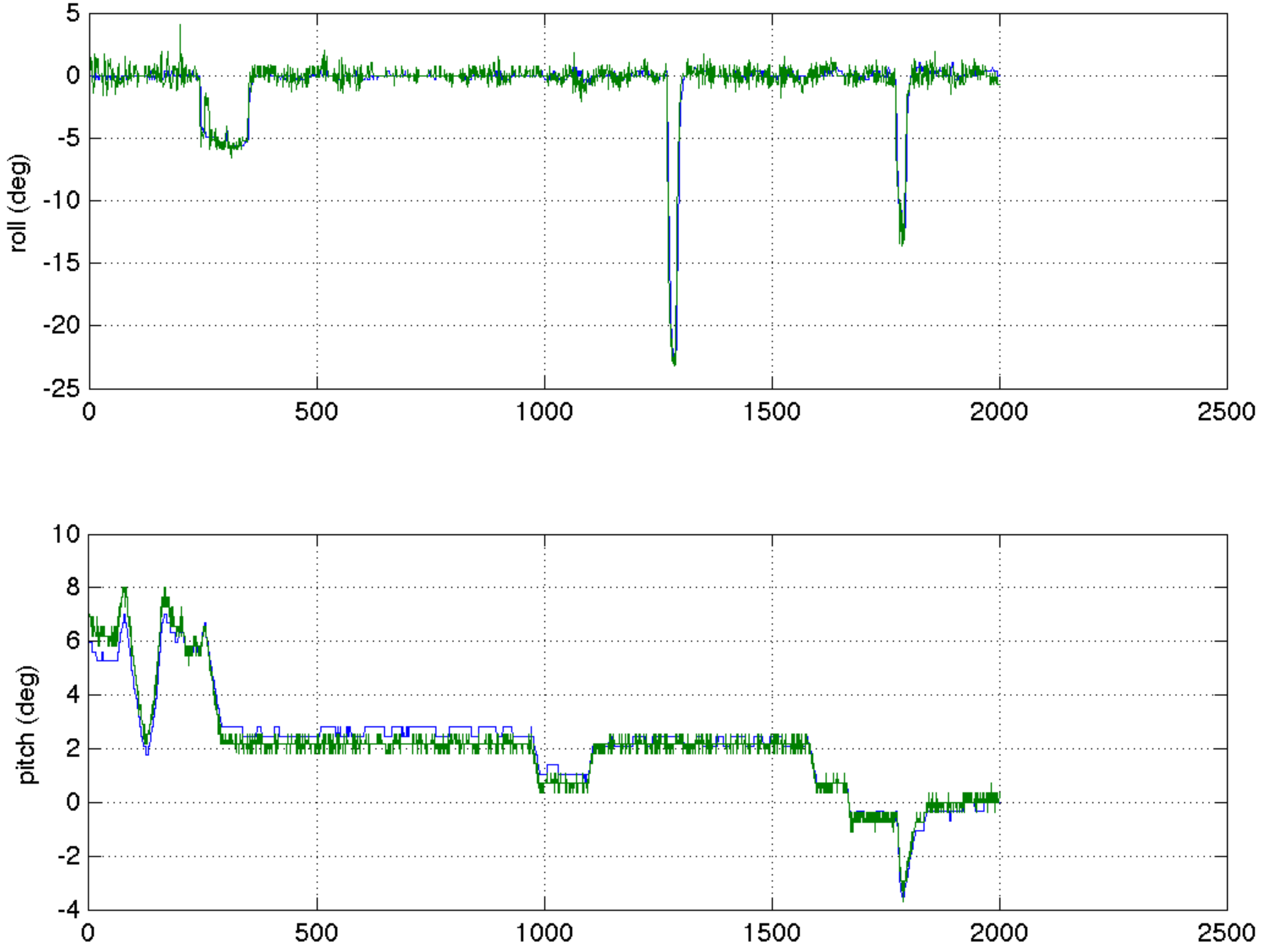
Simulator Verification

- Accelerations
  - From flight plan (kinematics)
- Airframe attitude
  - Coordinated flight
- Flight actuators, engine dynamics
  - Regression models
  - Were shown earlier

Accelerations



Airframe Attitude



Simulator Performance

- Most/all FOQA data channels
- 10-20% accurate in its range
- Generates 5000 s of data in 1 s on a PC
  – 40Mb csv file
  – Writing to disk adds time

Outline

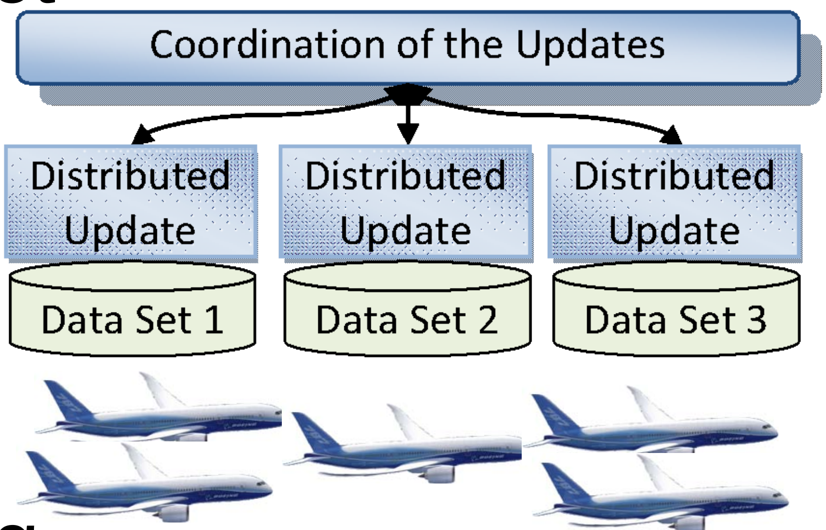
- Background and past effort
- Completed effort
- On-going effort
- **Extensions**

Fleet Data Monitoring

- Many flights of many aircraft
- Fixed effects
  - Tail-to-tail model variation
  - Flight-to-flight variation, e.g., loading
- Eric Chu’s talk on Wednesday

Distributed Data Mining

- New NASA SBIR project
- Aircraft fleet data
  - Distributed data sets
  - Fixed effect models
  - Distributed computing
- Model-based monitoring
  - Train model
  - Use it for monitoring



Conclusions

- Formulated technology transition path for ground monitoring of FOQA data
  - Model training (data mining)
  - Monitoring (data exploitation)
- Demonstrated SOA software framework
- Working on distributed computing software for scalable aircraft fleet monitoring

Backup Slides