National Aeronautics and Space Administration

ATM Technology Demonstration 1 (ATD-1)

EcoDemonstrator ASTAR Guided Arrival Research (EAGAR)

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Project Outbrief
January 29, 2015

Sequence of Events Leading to EAGAR

In Spring 2013, high level NASA and Boeing management were seeking opportunities to collaborate on a flight test activity involving the ecoDemonstrator.

The Airspace Systems Program Office identified FIM as a viable candidate.

ATD-1 accepted the challenge.

Work began in July for a December 2013 flight test.

Objectives

Conduct a rapid collaborative development effort with Boeing to equip the 2013 ecoDemonstrator test aircraft (B787-800) with an ASTAR-based airborne spacing tool.

Conduct a flight test to demonstrate precision spacing between two aircraft with the aid of NASA's ASTAR algorithm.

Minimum Success Criteria

ATD-1: Successful rapid collaboration between NASA and Boeing

FIM operation: Both Target and FIM aircraft fly from initial waypoint to FAF without interruption (vectors, etc).

Was it feasible in the real world? **YES**

FIM software: Continuous progression to achieve assigned spacing goal behind Target aircraft.

Was the software robust and perform as expected? **YES**

“Stretch” Success Criteria

Demonstrate consistent final spacing within +/-5 seconds at the FIM termination point.

Run #	Delivery Accuracy
1	-7.5
2	1.5
3	1.4
4	2
5	-3.5
Std. Dev.	4.16
Range	9.5

Flight Test Approach

Equip the ecoDemostrator with the ASTAR-based application hosted on a laptop PC

Conduct an arrival sequence and connect to a published approach procedure into a dedicated test airport

Target and Ownship aircraft fly on the same route from TOD to runway:

- Start 100-120 miles from runway; line up with ATC help
- Arrival procedure is typed into the FMS, approach is loaded, then full route connected together
- Locate target, enter clearance, and initiate test

The Plan / The Reality

Lab Testing for software integration / Occurred at four locations

Ground Testing aboard the airplane to ensure laptop is receiving required data / ~7 hours over two days

4 meetings with Air Traffic Control supported by Boeing Flight Test Analysis and Flight Test Operations / Many more, but mostly without Analysis or Ops

2 hours of concurrent testing to monitor the system in flight / 8 hours in the air, no NASA personnel taking part

6 hours of dedicated flight time over 2 days, ~6 runs / ~6 hours, 1 day, 5 runs

Schedule Milestones

Intro ASRB briefing:	November 7, 2013
Simulation Requirements Review:	April 30, 2014
Initial Software build delivered to Boeing:	June 11, 2014
Laptop with ASTAR available for ground testing:	June 25, 2014
1st Dry Run in NASA sim:	June 26, 2014
Boeing Bench Testing	July-September 2014
ASRB briefing:	August 14, 2014
Boeing Aircraft Ground Testing	November 10-11, 2014
Function-Complete Code Freeze:	December 5, 2014
Bug-Fix Code Freeze:	December 5, 2014
Final Software build delivered to Boeing:	December 6, 2014
Concurrent Flight Testing:	December 6, 2014
Flight Demonstration:	December 12, 2014

Participants

NASA

- Laptop Operator
- Developers supporting flight
- Ground observers within FAA ATC facilities

Boeing

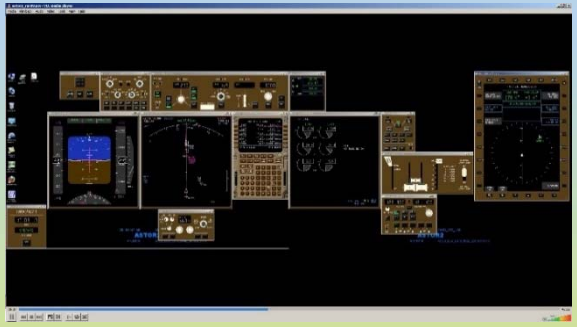
- Developer and Flight Test Engineers supporting the flight
- Test Pilots (2 B787 & 1 T-38)

FAA

- Seattle Center and Grant County Approach Air Traffic Controllers

Target Aircraft Search

Alaska Airlines B737NG



ASTOR Simulated Model

FAA Global Express 5000

T-33

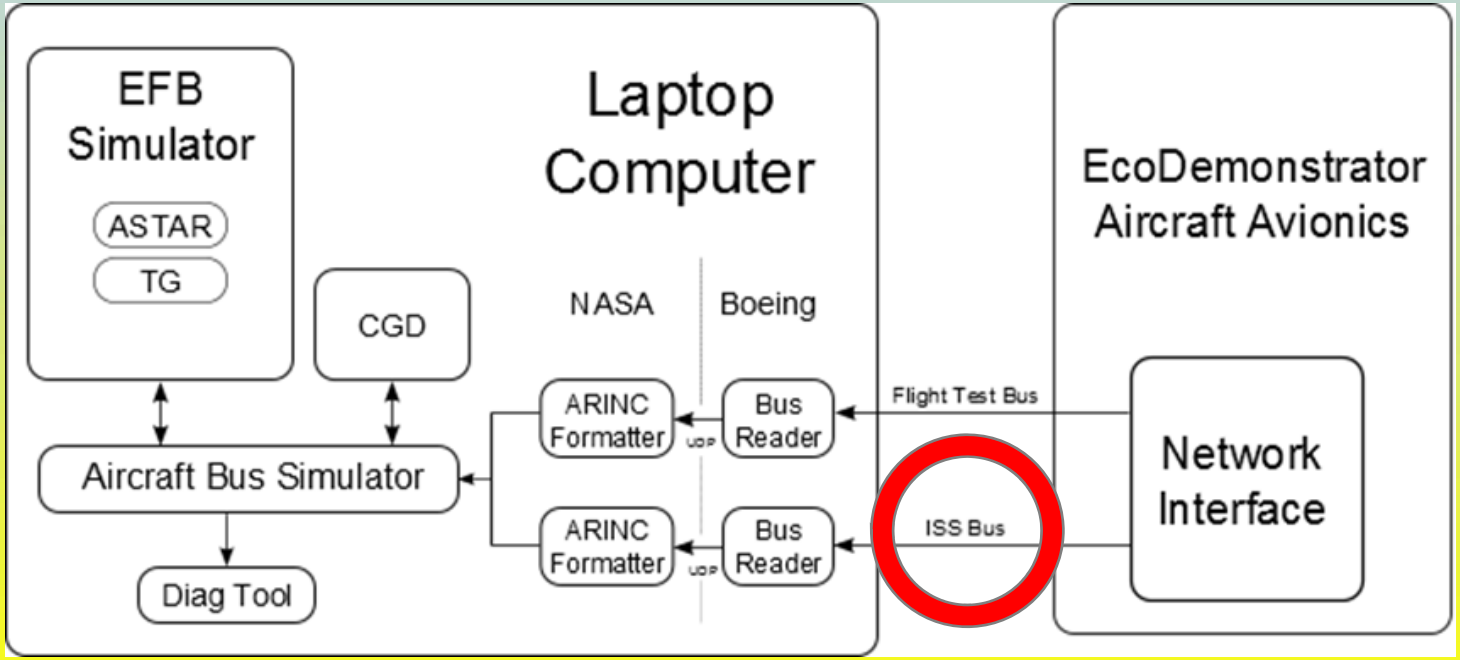
T-38

Airport Search

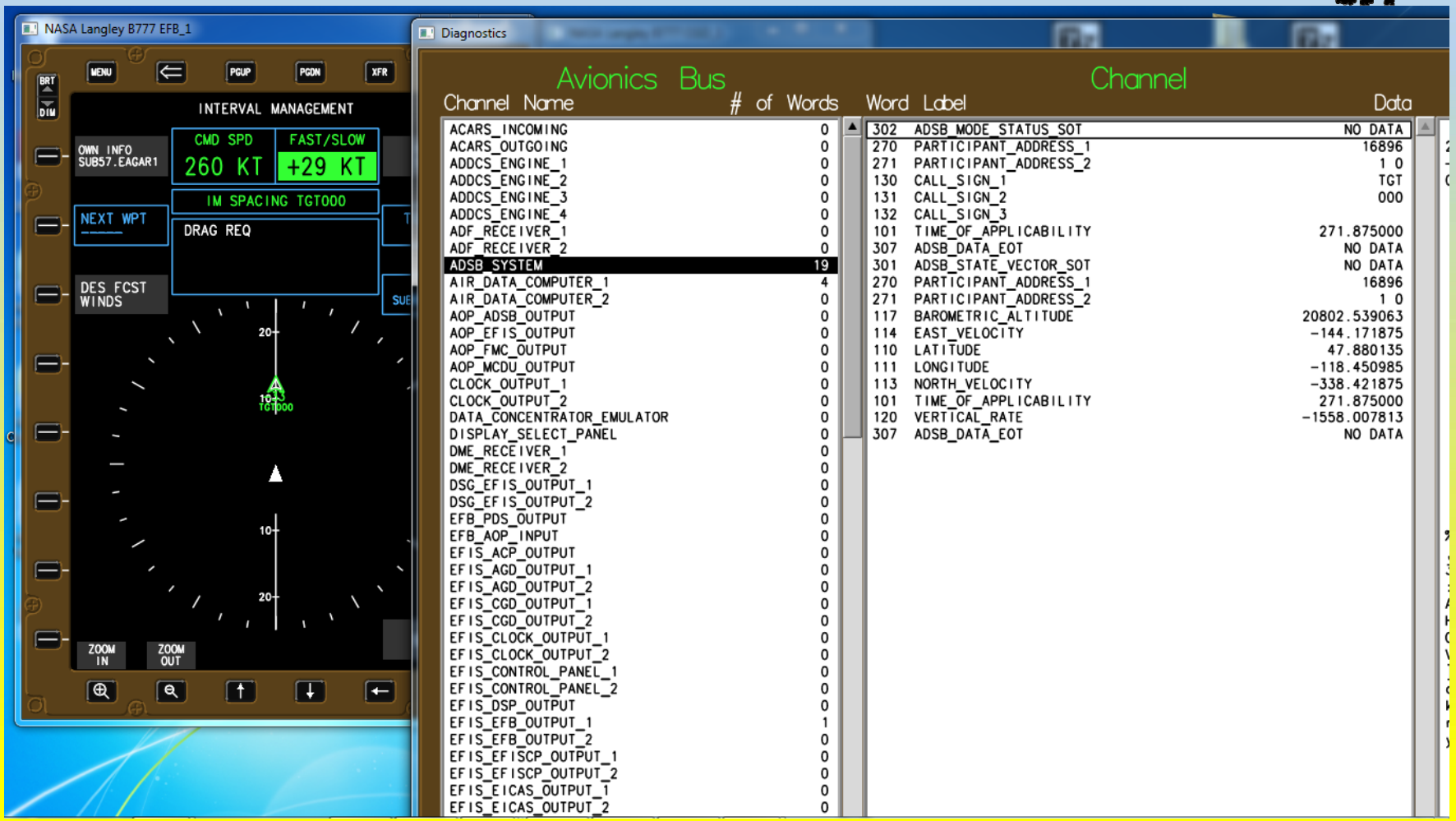
It took several months to settle on an airport

- Seattle, WA – KSEA
- Phoenix, AZ – KPHX
- Moses Lakes, WA – KMWH ✓
- Denver, CO – KDEN
- Glasgow, MT – KGGW

Avionics Architecture Overview



Diagnostic Tool Screenshot



Scheduling and Spacing Technologies

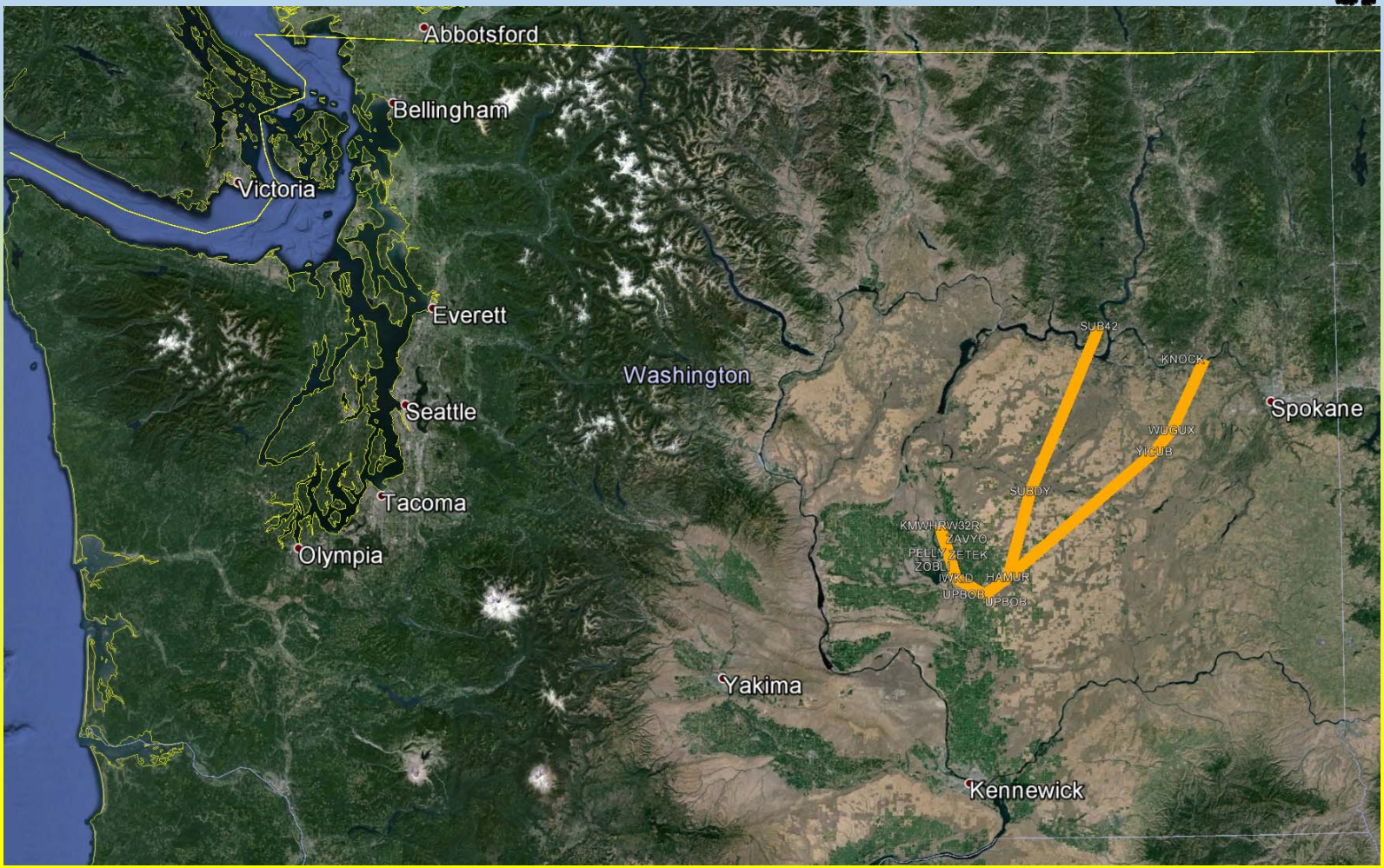
Flight Deck-based Interval Management

ASTAR Ver. 12

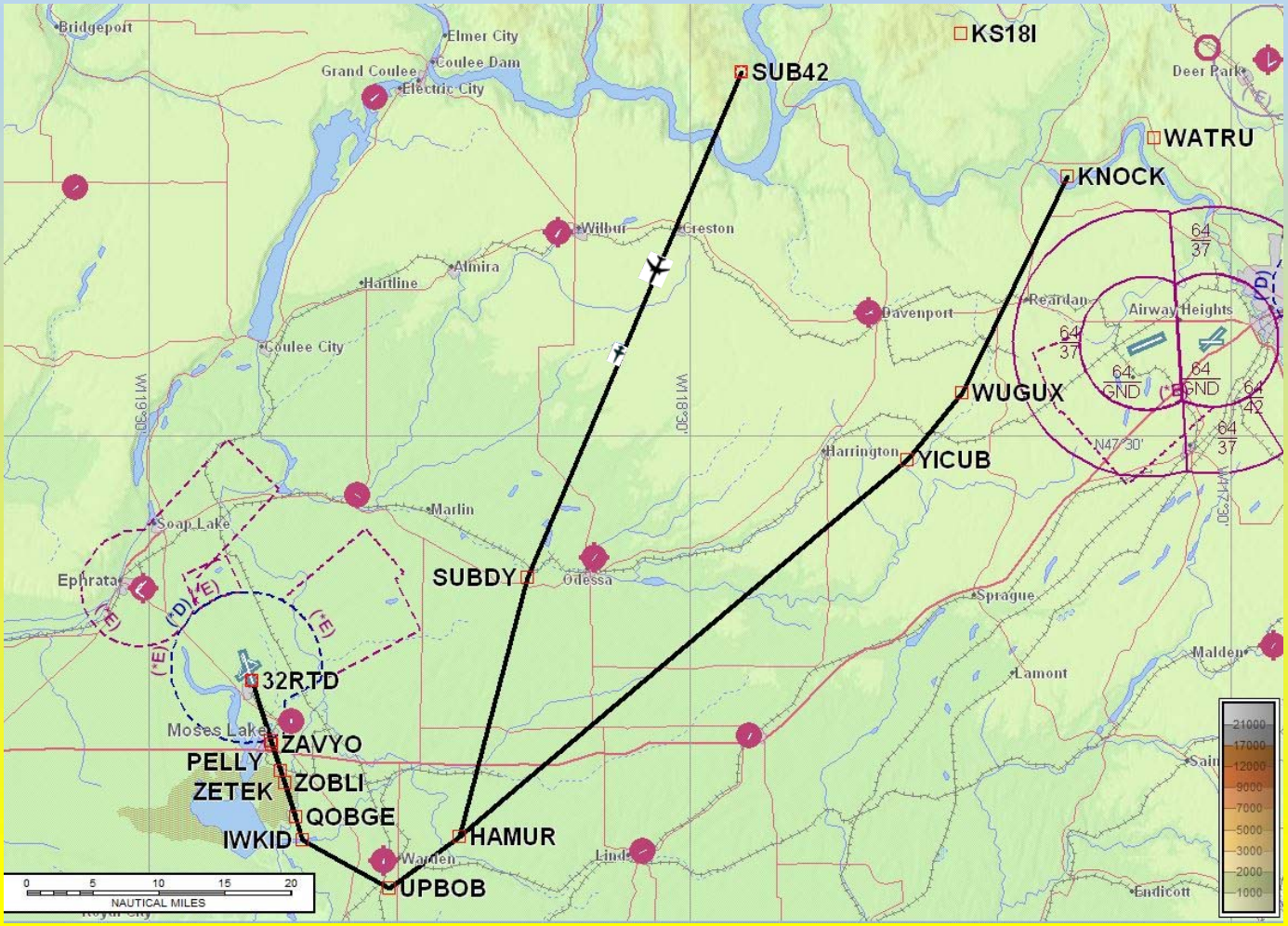
Build: EAGAR_14_5_2014DEC05R-PARTS.exe

Navigation Database Cycle 201412

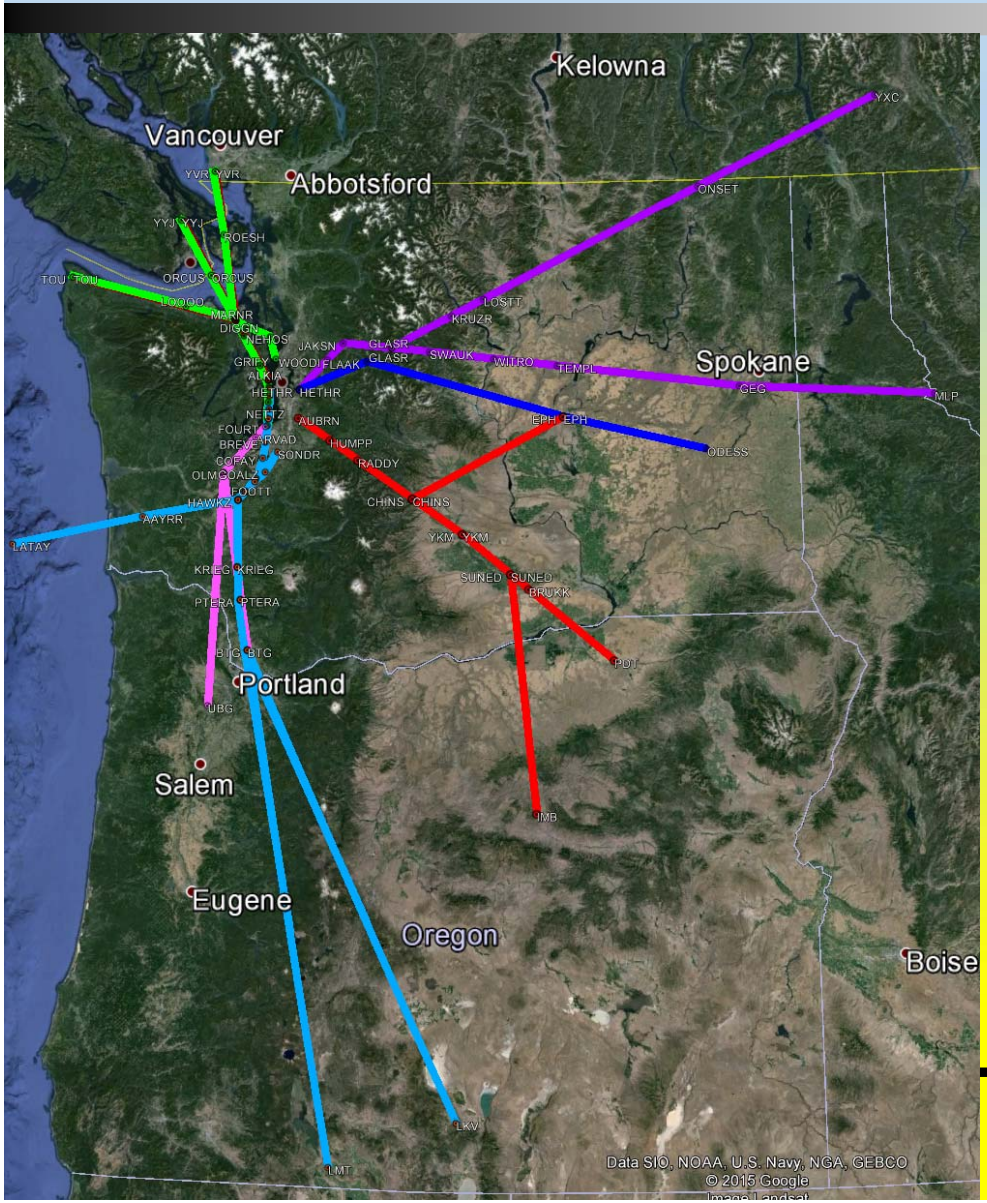
Demo Arrival Location



Full Route Structure



Concurrent Testing Route Structure



Test location dependent on weather

Development team built routes to cover all areas

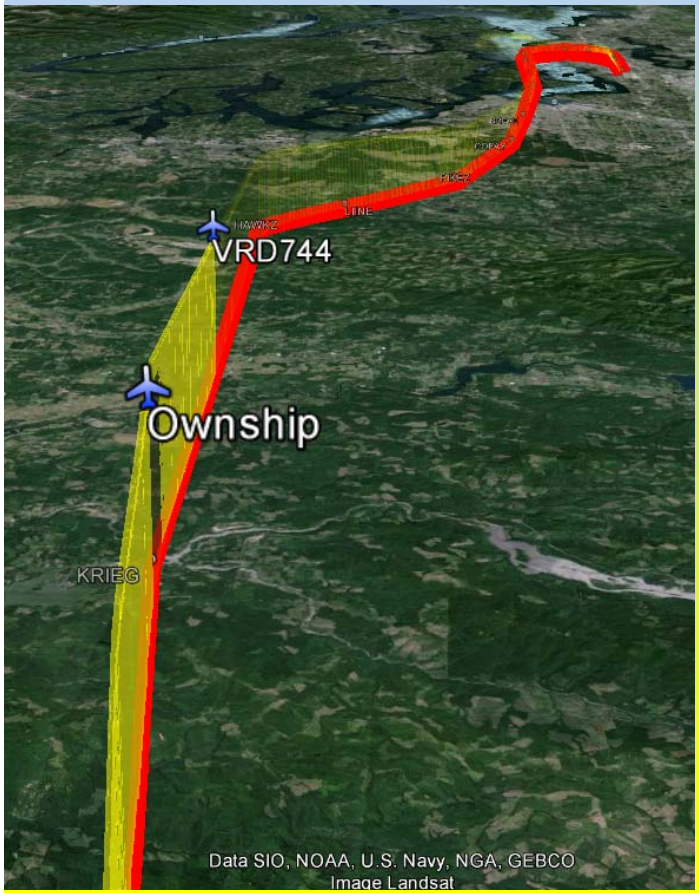
Location was decided the morning of test (over ocean)

Olympia Arrival built, tested, and e-mailed up while still flying

First FIM

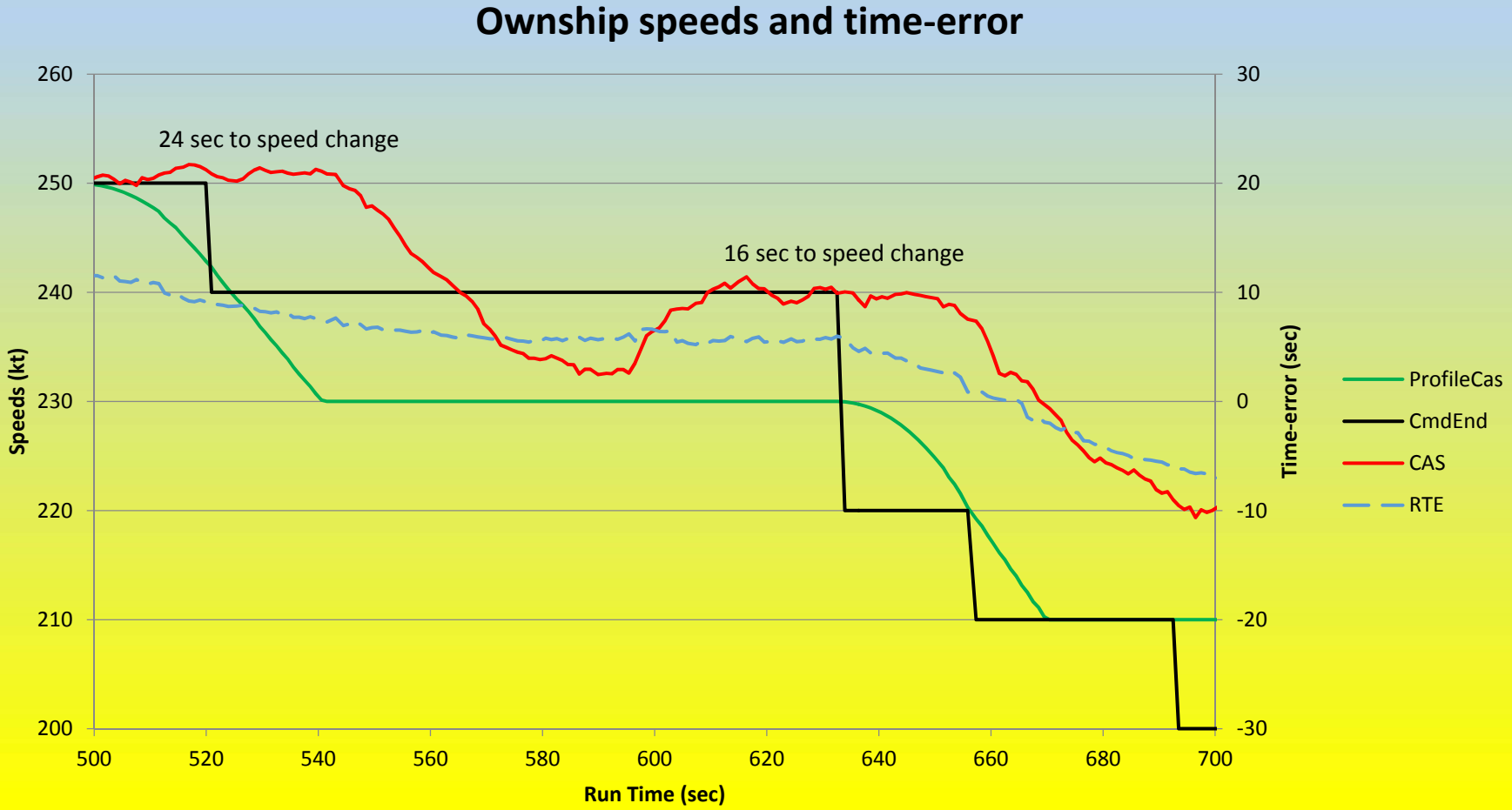

MENU
PGUP
PGDN
XFR
ENTER
BRT
DIM
PWR
INTERVAL MANAGEMENT
OWN INFO
BTG.HAWKZ4
CMD SPD
210 KT
FAST/SLOW
+13 KT
IM GOAL
120 SEC
PAIRED VRD744
NEXT WPT
TGT ACFT
VRD744
DES FCST
WINDS
TGT RTE
BTG.HAWKZ4
SUSPEND
ZOOM
IN
ZOOM
OUT
FAST
SLOW
CMD SPD
210 KT
PAIRED
VRD744
EARLY
LATE
00:41:38
Organize
Include in library
Share with
Burn
New folder
Favorites
Desktop
Downloads
Recent Places
Libraries
Name

Dec. 6 Concurrent Testing



IM Ops conducted over 64 nmi (77→13 nmi from Rwy)
~20 minutes

Dec. 6 Concurrent Testing



Dec. 6 Concurrent Testing

EAGAR Demonstration Flight

Flight Demonstration Materials

Flight Test Plan and Communication Protocol packet

Boeing Flight test plan

Controller Briefing Packet

Pilot Flight Test Cards

Briefing packet for ground observers at FAA ATC facilities

Test Setup

VHF radio frequency required to enable communication between the airplane and chase

Flight Interphone jacks and headsets at participant locations on B787

Ethernet connections from the cockpit to the ASTAR laptop

115 volt/60 Hz power available at all workstations

All laptops adhered to workstations with Velcro

All participants properly briefed

Test Requirements

Contiguous US – flight testing

Daylight only, VMC

See and Avoid – 14CFR 91.113(b)

Sparsely populated area or over water only

Coordinate with applicable ARTCC in advance. Stay under ATC control, or pre-coordinated agreements.

Below FL180, local altimeter setting used by both aircraft

Test Sequence

- Depart KBFI and fly test profile into KMWH to the FAF

Run #	Initial Speed	Initial Altitude	Arrival T-38	Arrival B787	In-Trail Distance
1	280	FL220	SUBDY	SUBDY	13 nm
2	280	FL220	KNOCK	KNOCK	16 nm
3	280	FL220	SUBDY	SUBDY	10 nm
4	280	FL220	SUBDY	KNOCK	Initial fixes at same time (7.5 nm)
5	280	FL220	SUBDY	KNOCK	

<u>Schedule:</u> Run 1 / T-38 refuel / Run 2-4 / T-38 refuel / Run 5

- Upon conclusion of demonstration, return to KBFI.

Dec. 12 Winds Aloft

Input winds: A selection of altitudes was requested by cockpit, the best altitudes available for input follow.

FL230	190 degrees / 64 knots
FL210	193 degrees / 54 knots
FL180	190 degrees / 40 knots
16,000	260 degrees / 19 knots

Input Speeds to ASTAR

Run	Cruise Speeds	Descent Speeds
1	0.65 Mach / *280 knots*	0.62 Mach / 270 knots
2	0.76 Mach / *340 knots*	0.62 Mach / 270 knots
3	0.64 Mach	0.62 Mach / 280 knots
4	0.65 Mach / *300 knots*	0.62 Mach / 280 knots
5	0.65 Mach	0.62 Mach / 280 knots

Weather at Grant County Airport

Initial METAR at KMWH 7000’ OVC

ATIS for KMWH (During Run 2): Calm, 10 miles visibility, 8500 OVC, Temp 6, Dewpoint 4, Altimeter 29.73.

Icing at 10,000 ft.

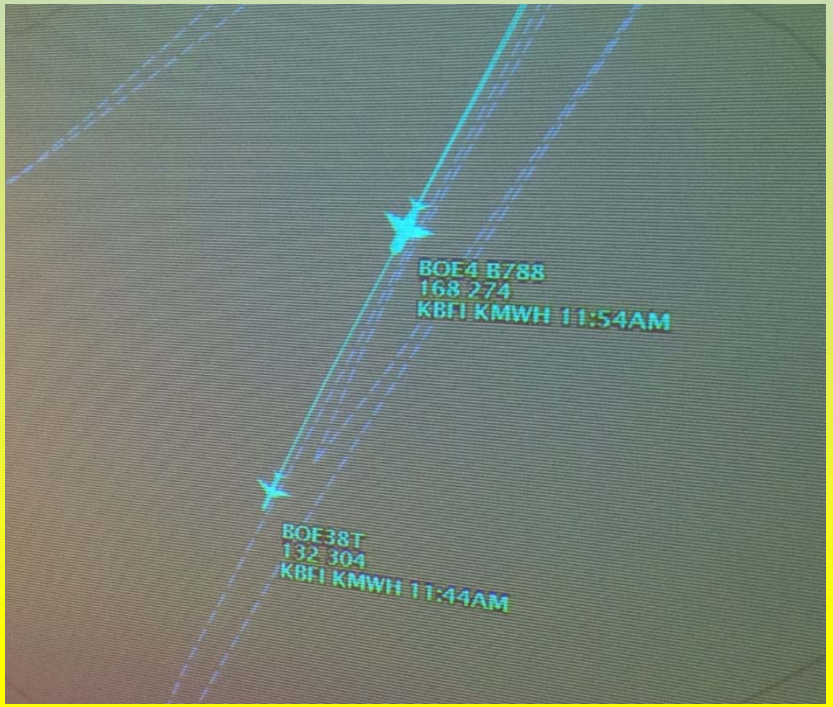
AIRMET in the vicinity with wind shear

RUN 1: Delivery Accuracy -7.5 sec. early

- Both aircraft on SUBDY Arrival
- 13 nm separation planned (12.5 nm actual)
- 120 seconds planned (112.5 @ FAF)

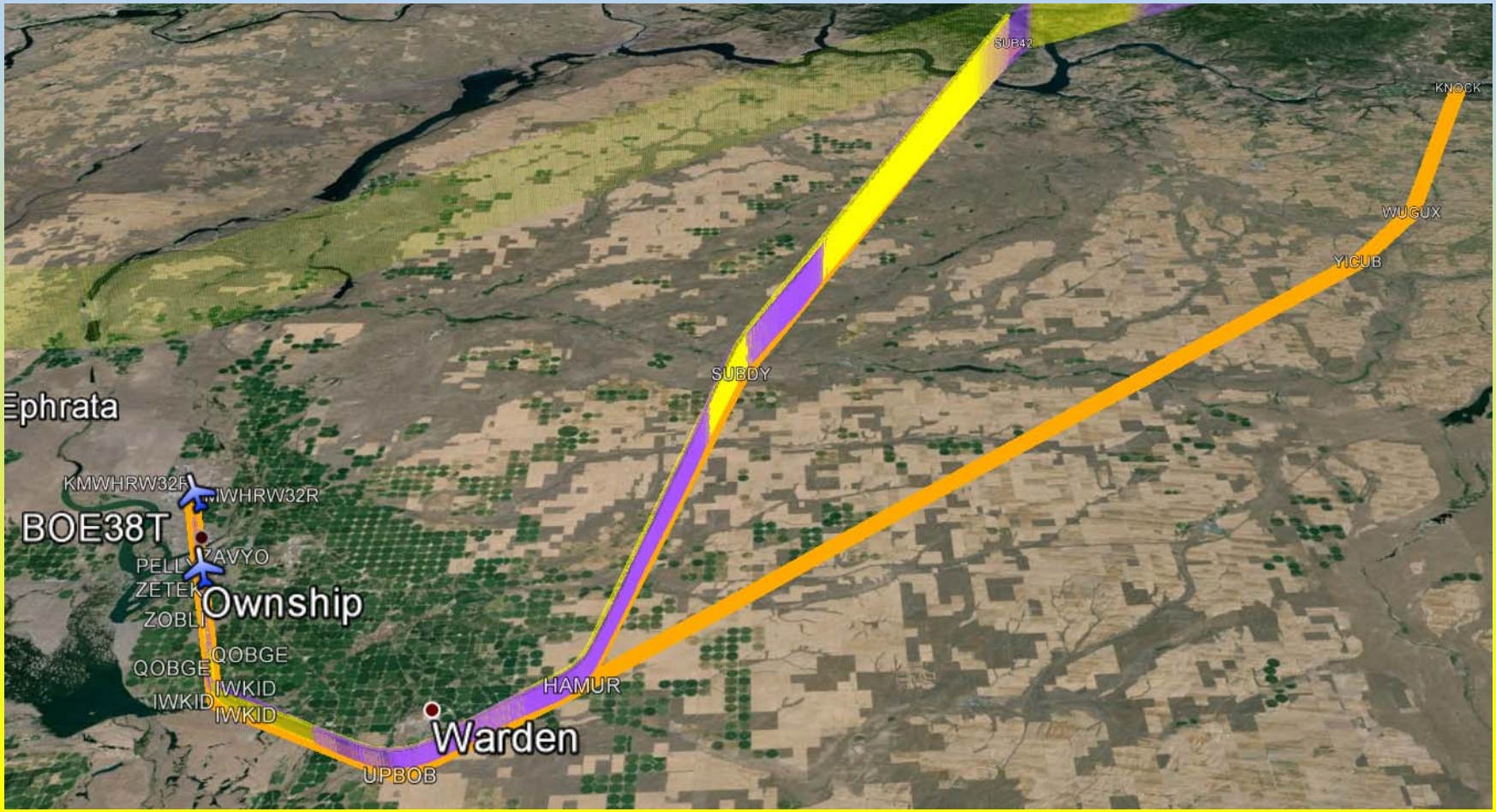
FIM Distance: 94.5 nm

FIM Time: 20 min 11 sec



Performed go-around at 11:54:55

Run 1 Profile



Run 1

- 3 speed inversions
- 13 speed commands (1 command/1 min. 33 sec)
- B787 performed a go-around b/c T-38 was on runway

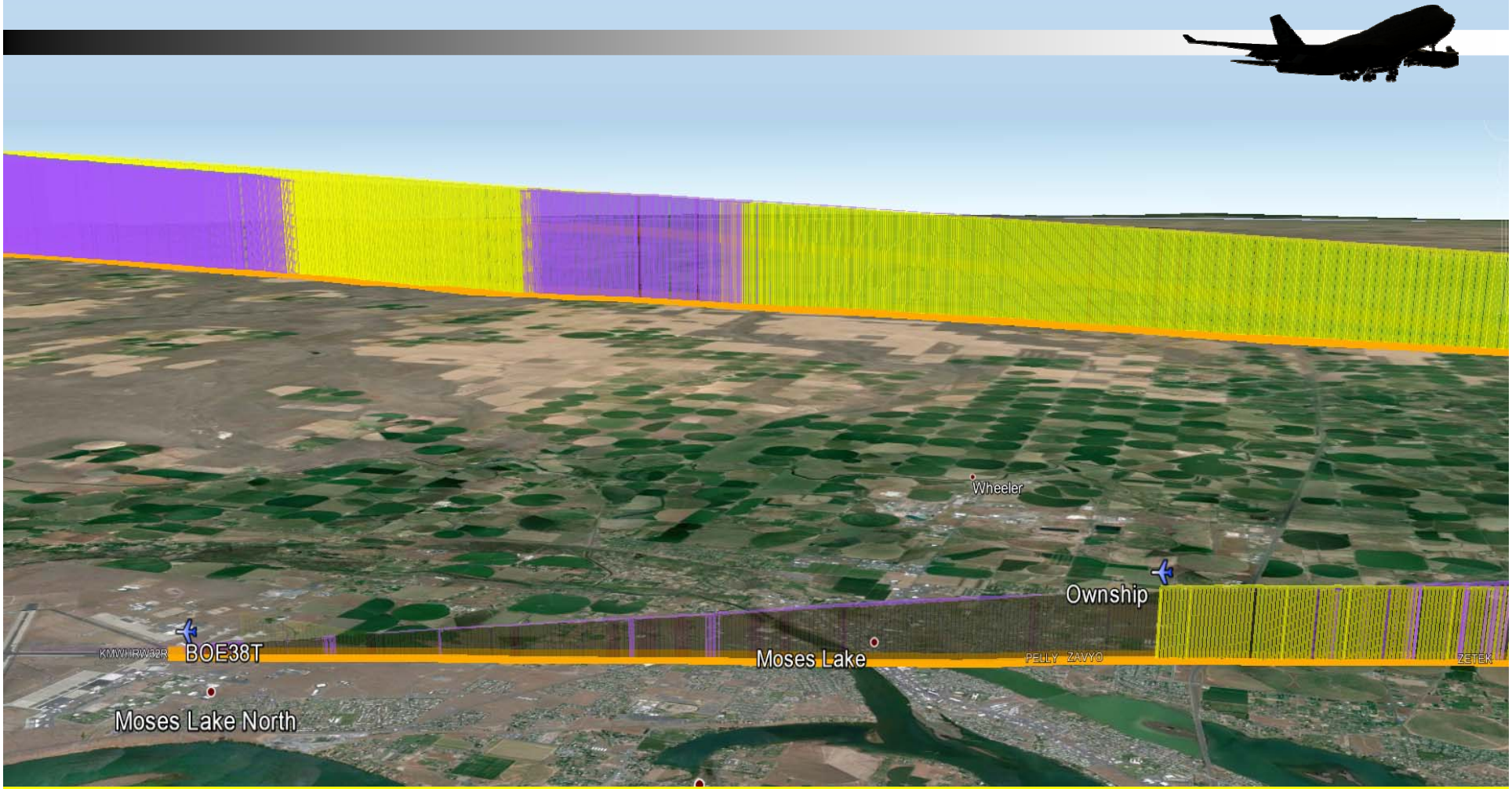
Grant County International Airport, Moses Lakes, WA

Run 1: Joining SUBDY Arrival

Run 1: Turn at UPBOB

Run 1: Turn to Final

Run 1 Final

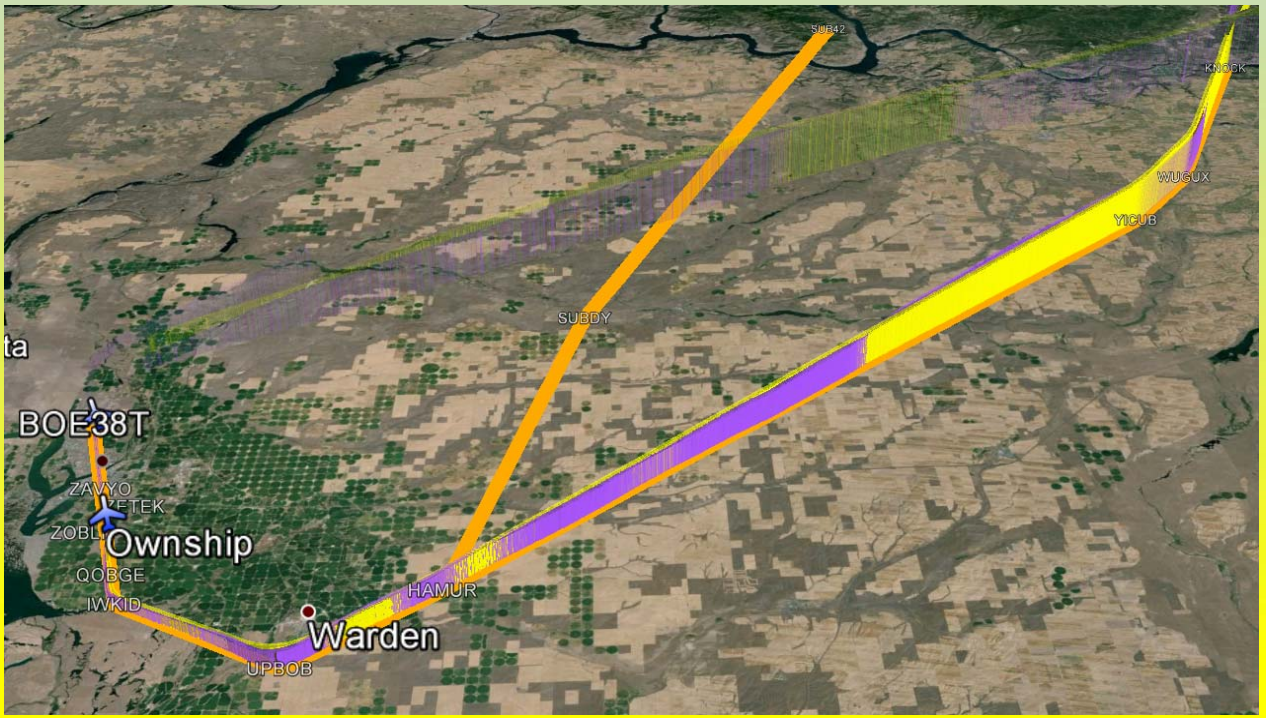

Wheeler
Ownship
BOE38T
KMWH RW32R
Moses Lake
PELLY ZAVYO
ZETEK
Moses Lake North

Run 2: Delivery Accuracy +1.5 sec. late

- Both aircraft on KNOCK Arrival
- 16 nm separation planned (24.12 nm actual)
- 120 seconds planned, 150 sec. actual (151.5 @ FAF)

FIM Distance:
89.9 nm

FIM Time:
17 min 54 sec

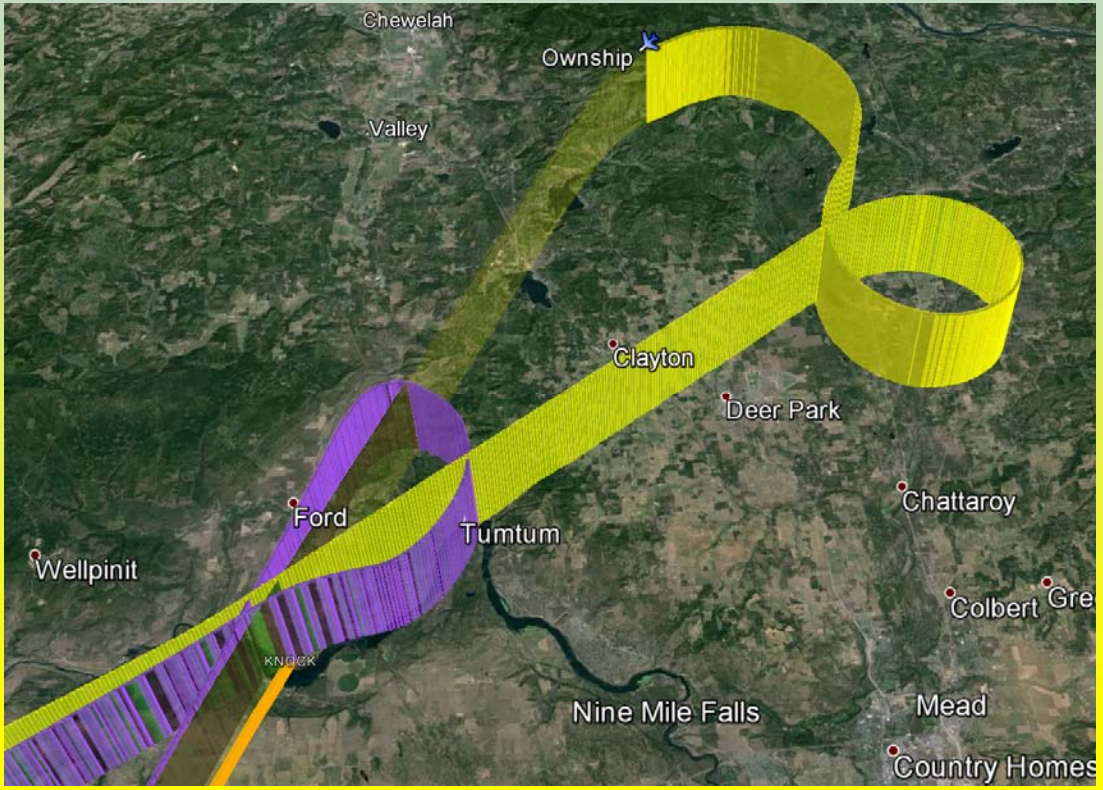


Run 2

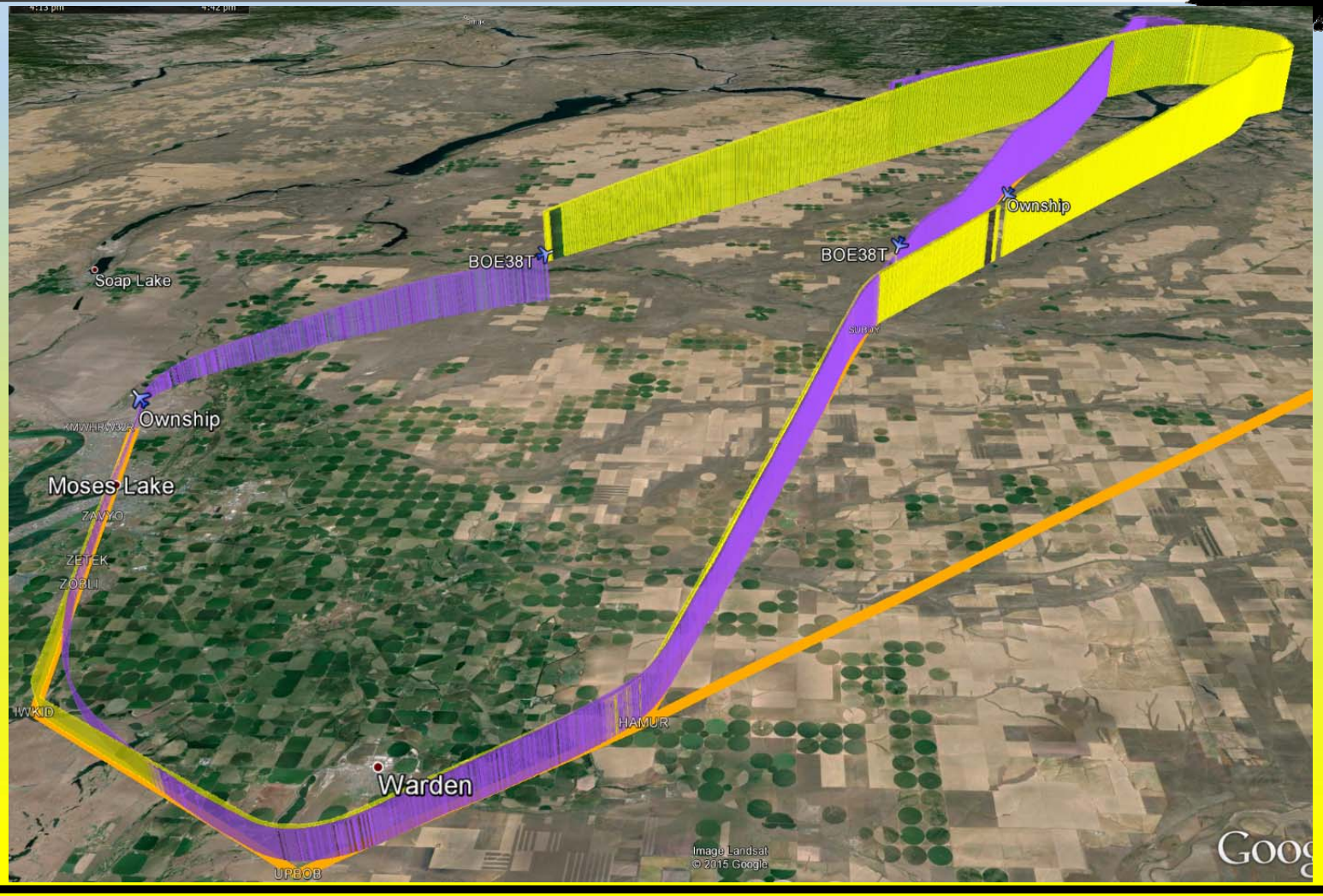
- 3 speed inversions
- 14 speed commands (1 command / 1 min. 17 sec.)

Ownship departs ahead of T-38 and holds, but gets disoriented for the initial setup. T-38 performs a teardrop entry.

Causes ownship to get behind schedule, maintains 340 kts. airspeed to try to make up the distance.



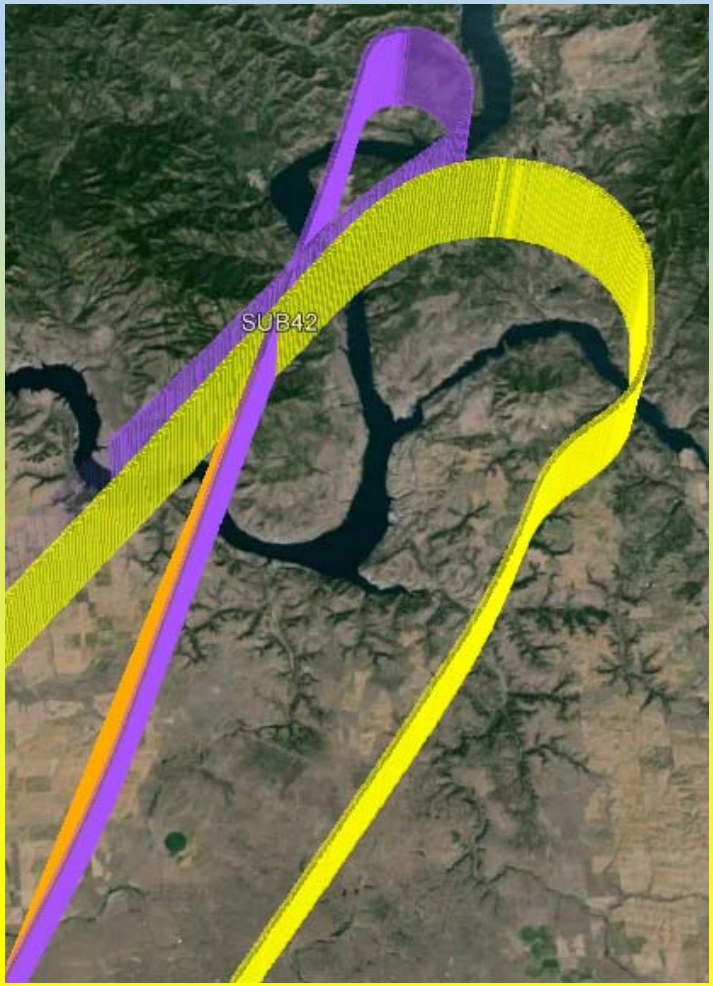
Run 3 & 3A


Soap Lake
BOE38T
Ownship
BOE38T
Ownship
Moses Lake
ZAVYO
ZETEK
ZOBLI
WWKID
HAMUR
Warden
UPBOB
Image Landsat
© 2015 Google

Run 3

Poor setup prior to run

- ASTAR on ~8 min. with no pairing
- OWNSHIP OFF PATH message
- Cockpit stated B787 was on path
- Paired 8 sec. prior to shutdown
- 6.14 nm separation at shutdown

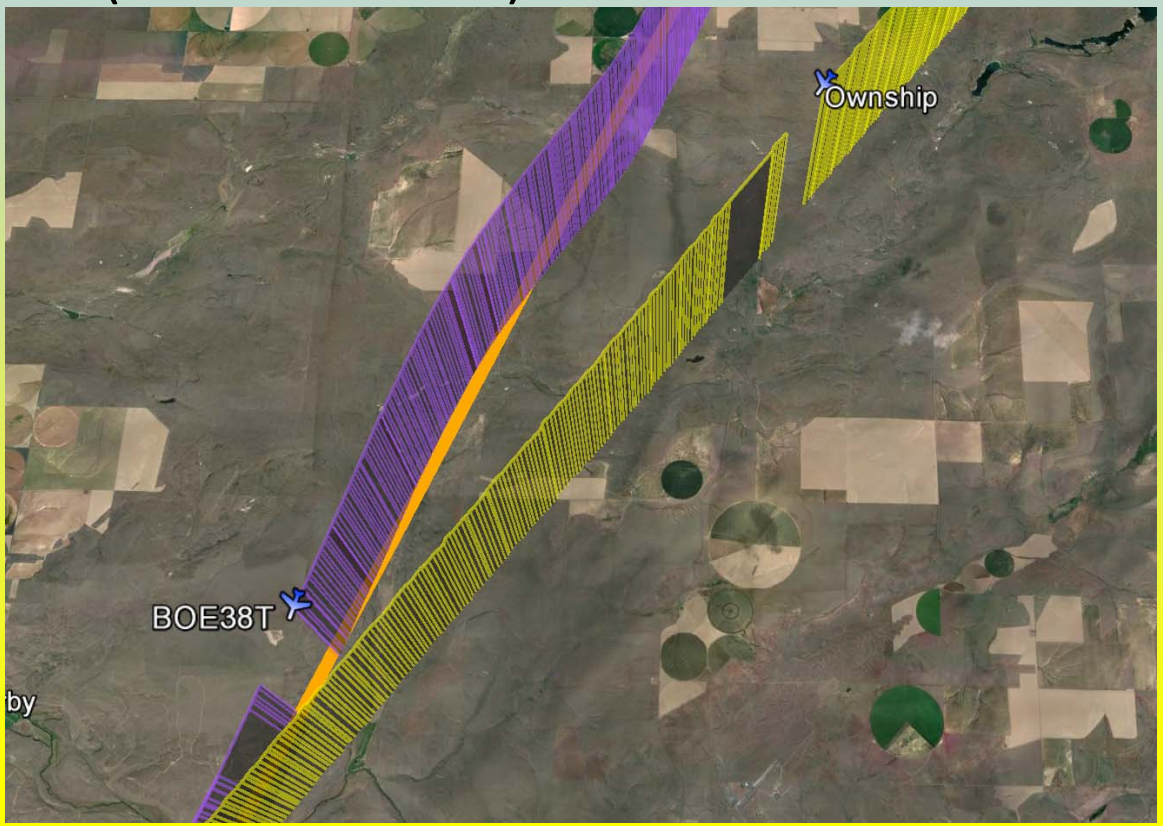


Run 3A: Delivery Accuracy +1.4 sec. late

- Both aircraft on SUBDY Arrival
- 10 nm separation planned (6.23 nm actual)
- 120 seconds planned,
  (121.4 sec @ FAF)

FIM Distance: 43.78 nm

FIM Time: 10 min 48 sec



Run 3A

Run 3A

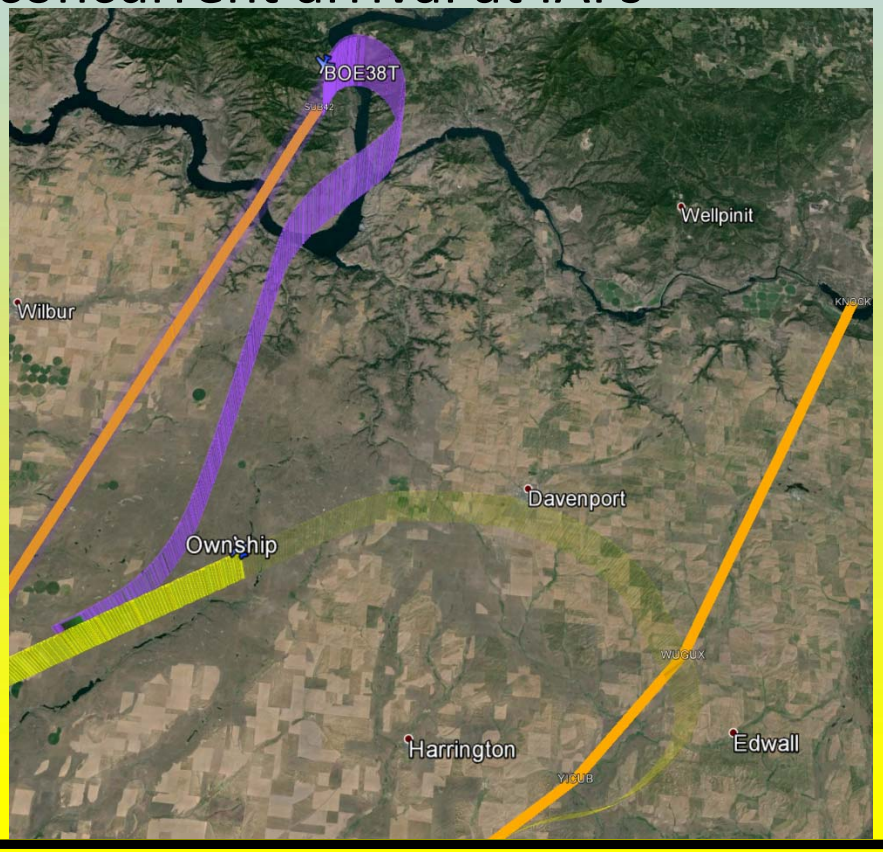
- 1 speed inversion
- 7 speed commands (1 command / 1 min. 17 sec.)
- Forecast winds were not entered on this run due to time constraints

Run 4: Delivery Accuracy +2.0 sec. late

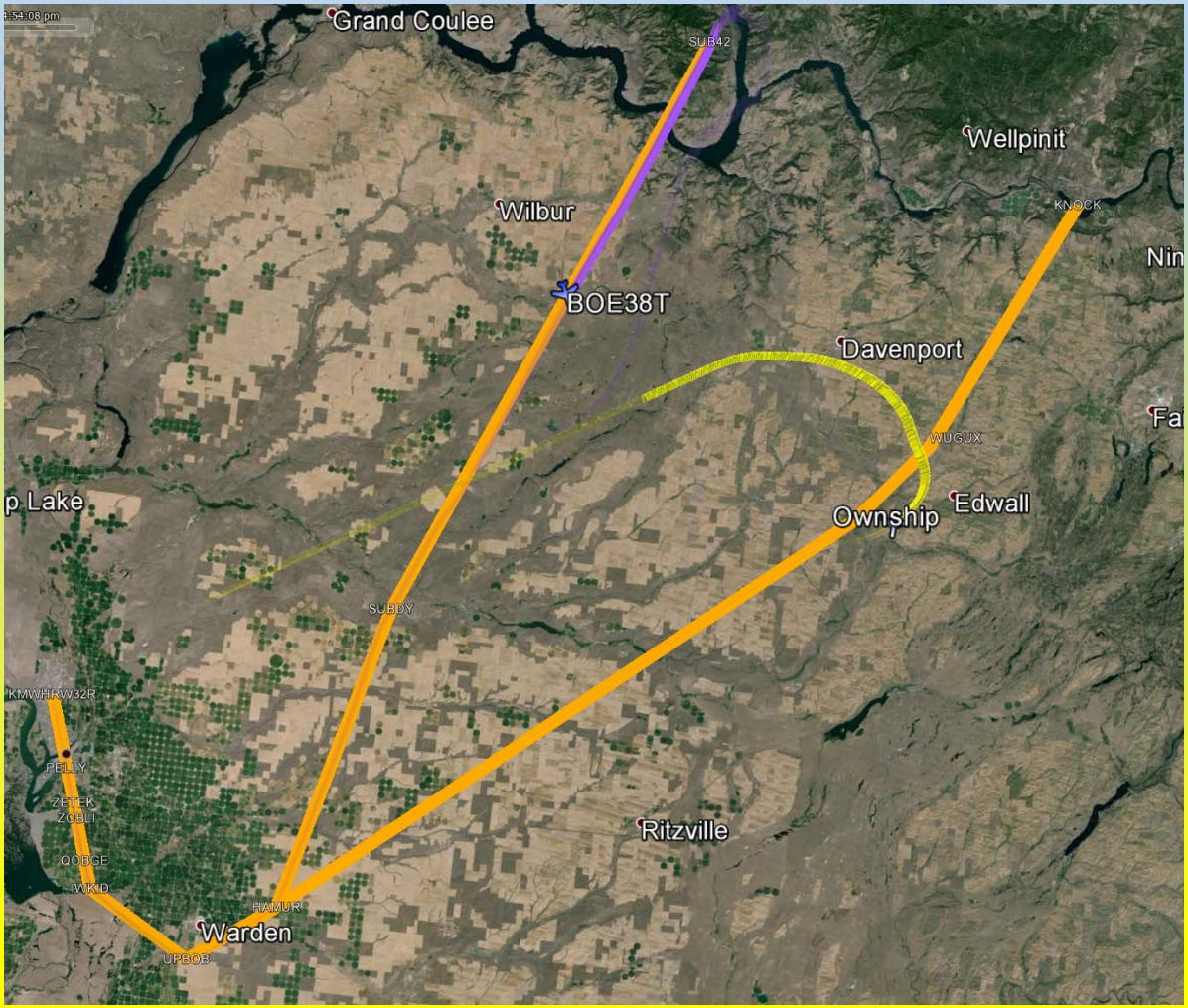
- T-38 Target on SUBDY Arrival, B787 Ownship on KNOCK Arrival
- 7.5 nm separation planned with concurrent arrival at IAFs
- Poor initial setup
- 1.63 nm along route separation
- 120 seconds planned
  (122 @ FAF)

FIM Distance: 71.59 nm

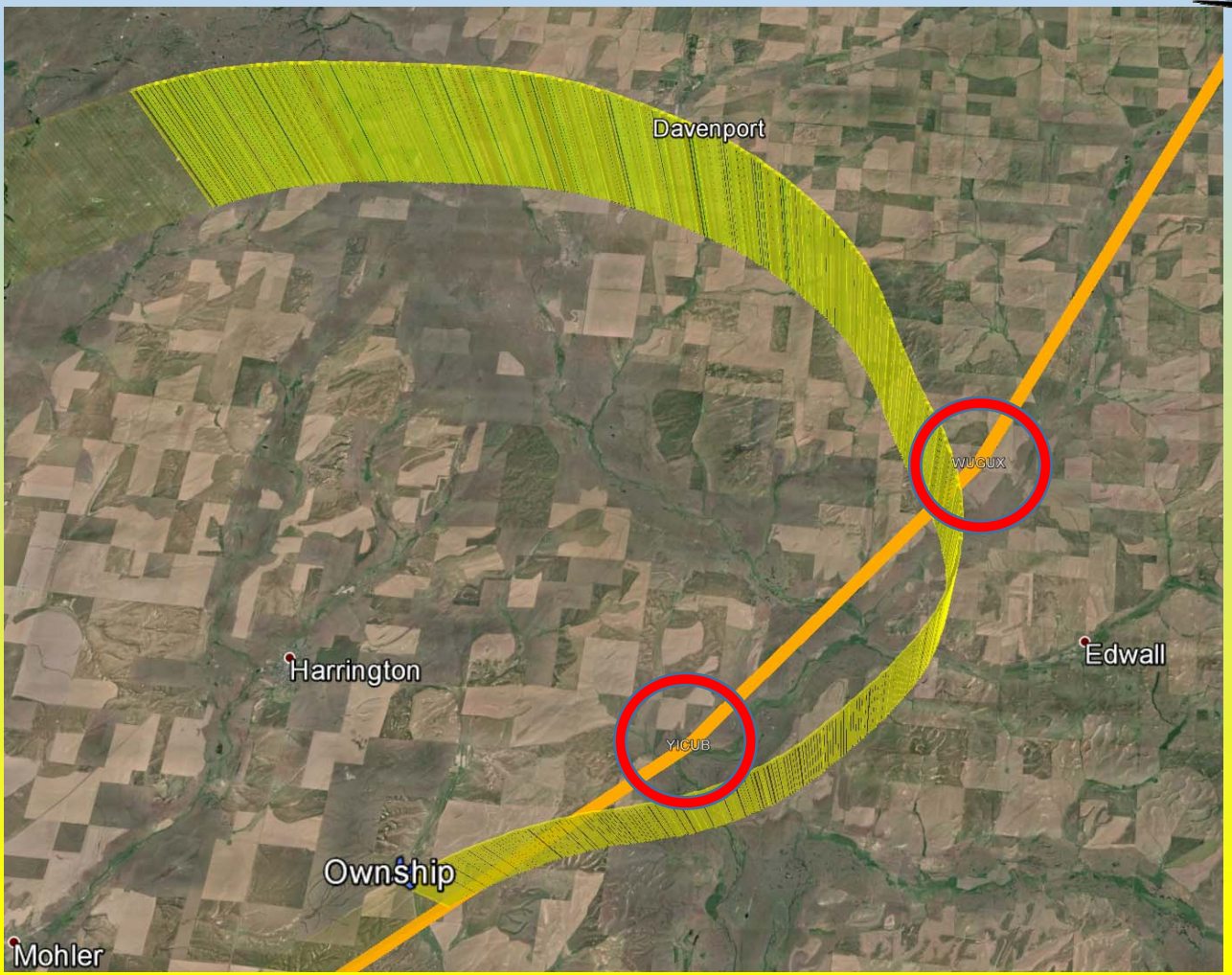
FIM Time: 17 min 40 sec



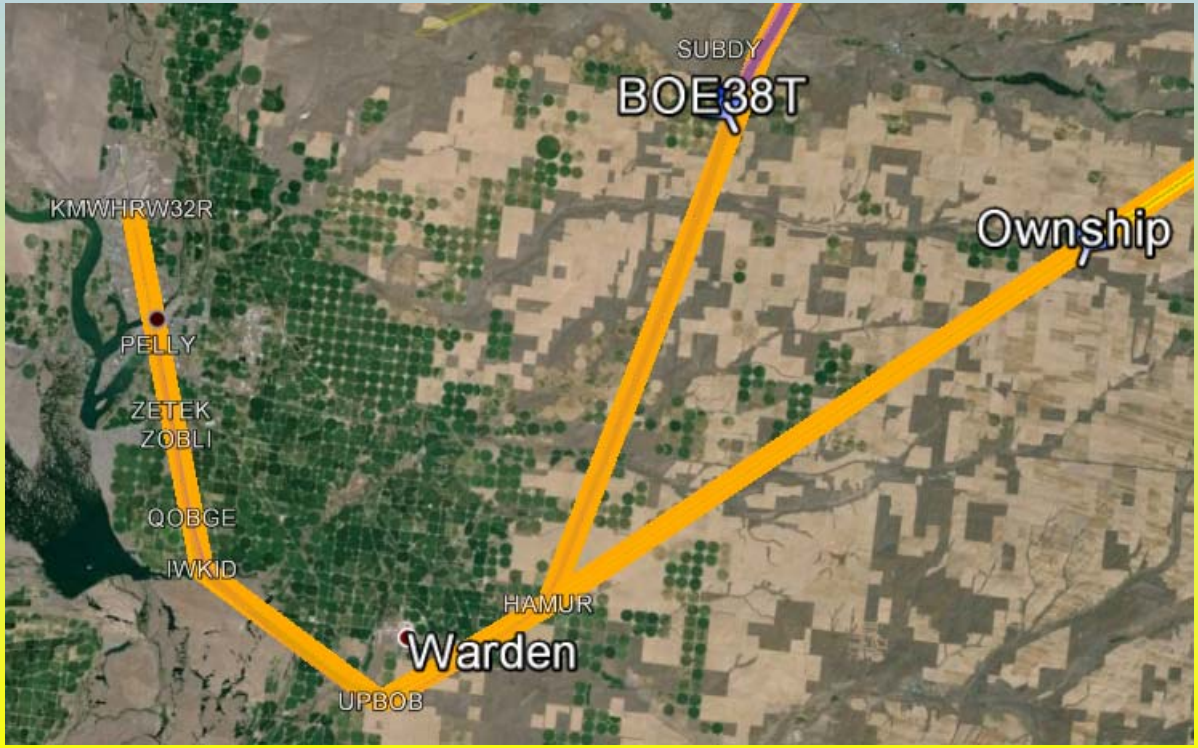
Run 4


Grand Coulee
SUB42
Wellpinit
Wilbur
KNOCK
BOE38T
Davenport
WUGUX
Edwall
Ownship
SUBDY
KMWHRW32R
PELLY
ZETEK
ZOBLI
QOBGE
WKID
HAMUR
Warden
UPBOB
Ritzville

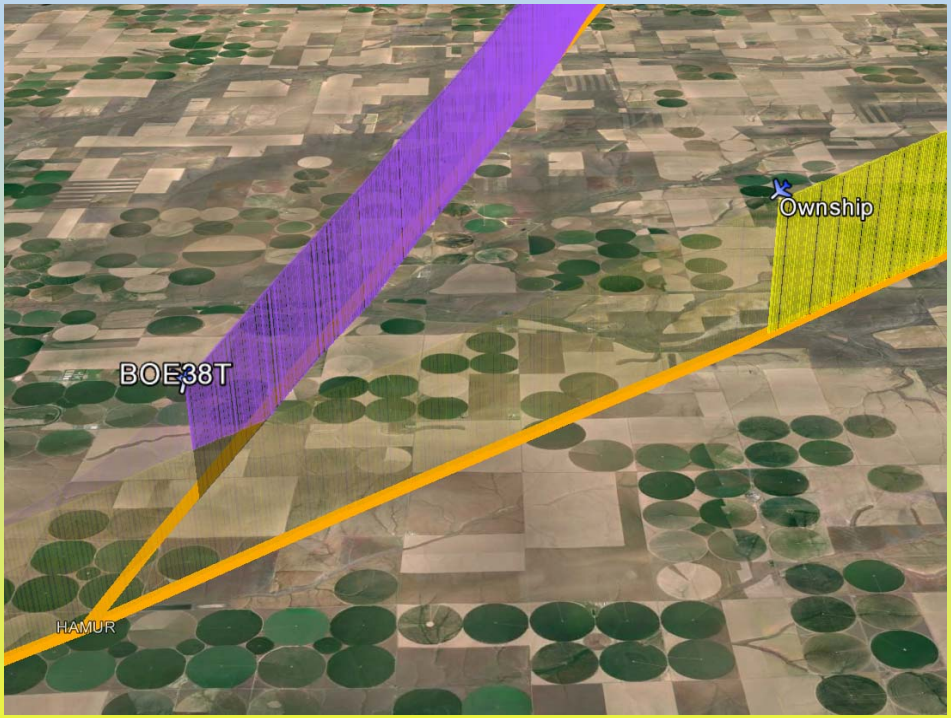
Run 4



Run 4


SUBDY
BOE38T
KMWHRW32R
Ownship
PELLY
ZETEK
ZOBLI
QOBGE
IWKID
HAMUR
Warden
UPBOB

Run 4



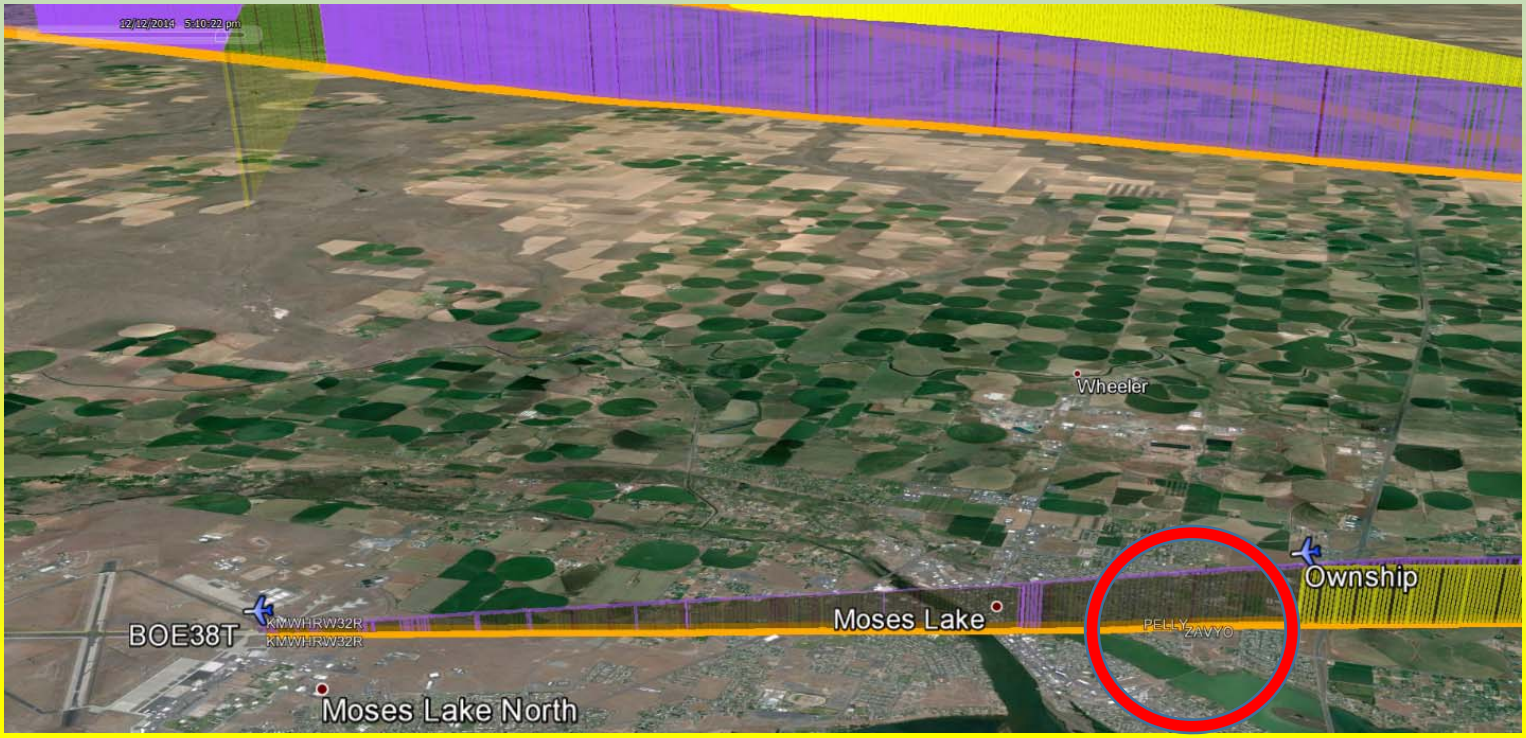
About where we achieved 3 nm spacing

Run 4

Unpaired for
5 seconds,
right here

Run 4

- 4 speed inversions
- 13 speed commands (1 command / 1 min. 26 sec.)

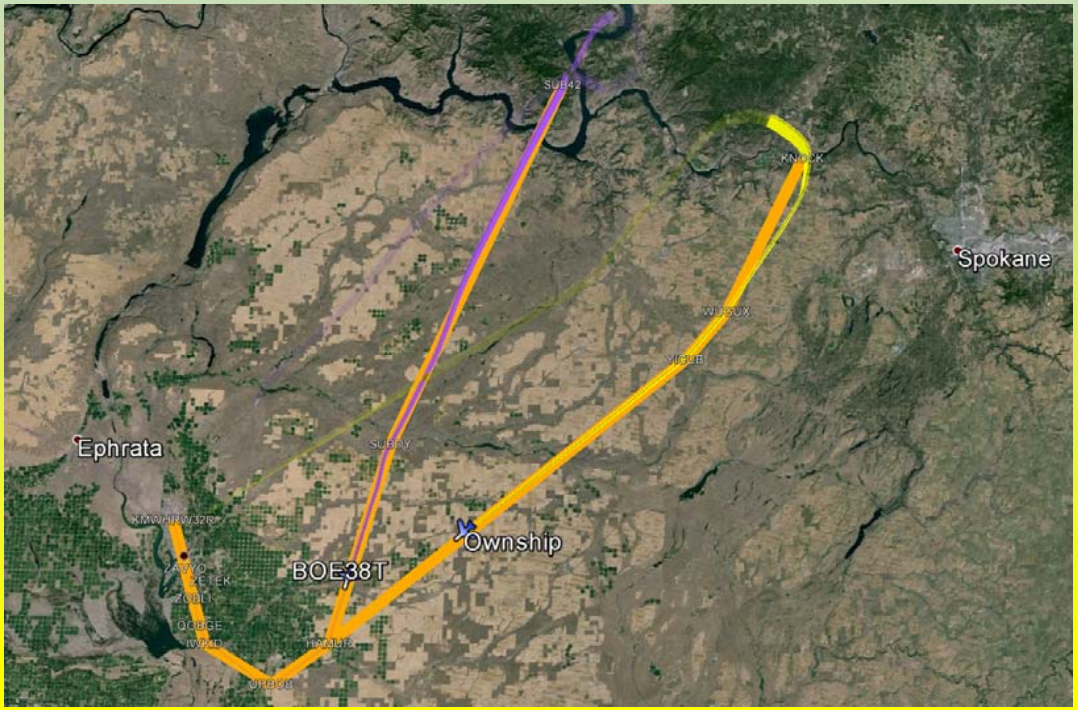


Run 5: Delivery Accuracy -3.5 sec. early

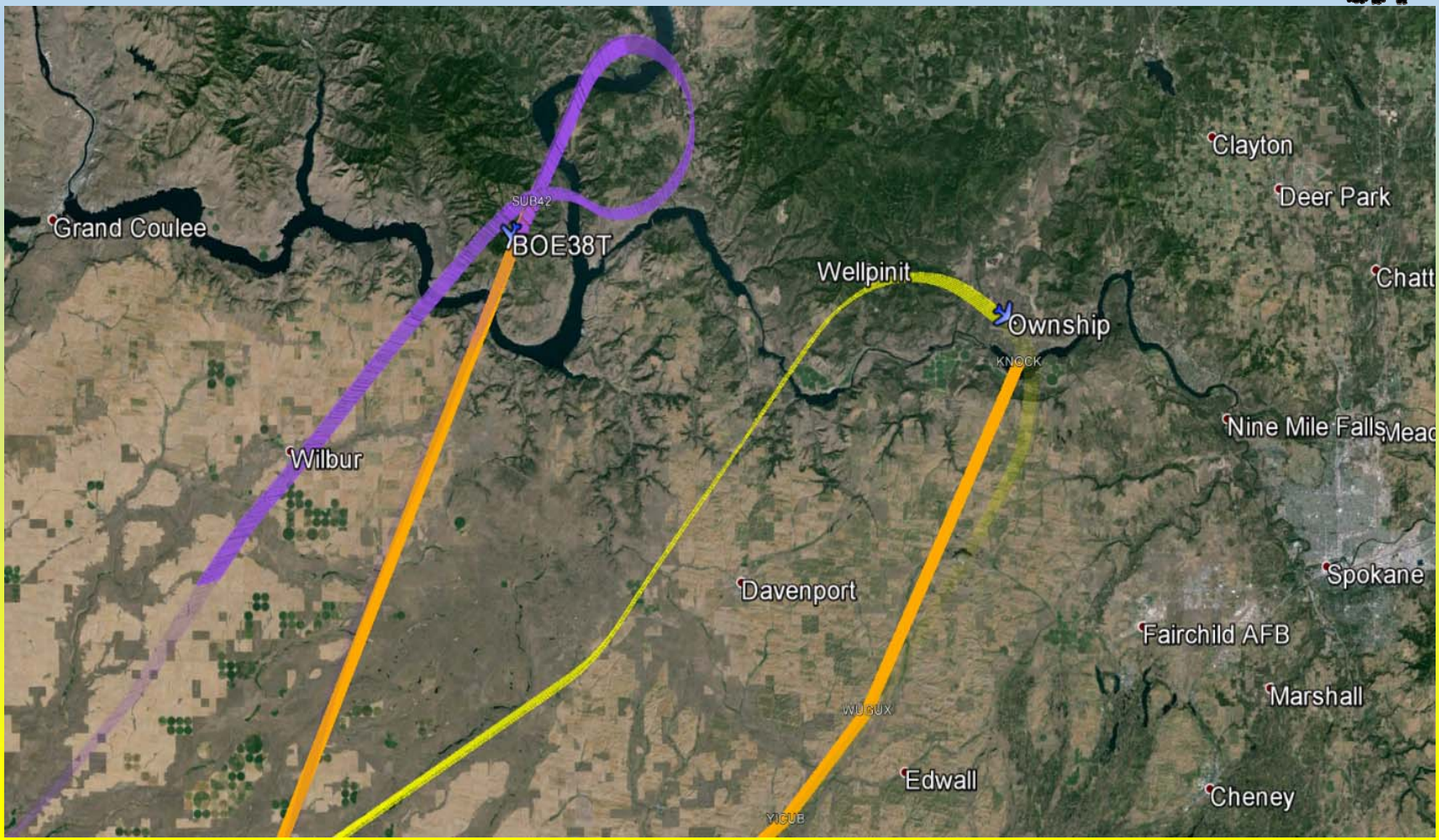
- T-38 Target on SUBDY Arrival, B787 Ownship on KNOCK Arrival
- 7.5 nm separation planned with concurrent arrival at IAFs
- 10.83 nm along route separation
- 120 seconds planned
  (116.5 @FAF)

FIM Distance: 85.88 nm

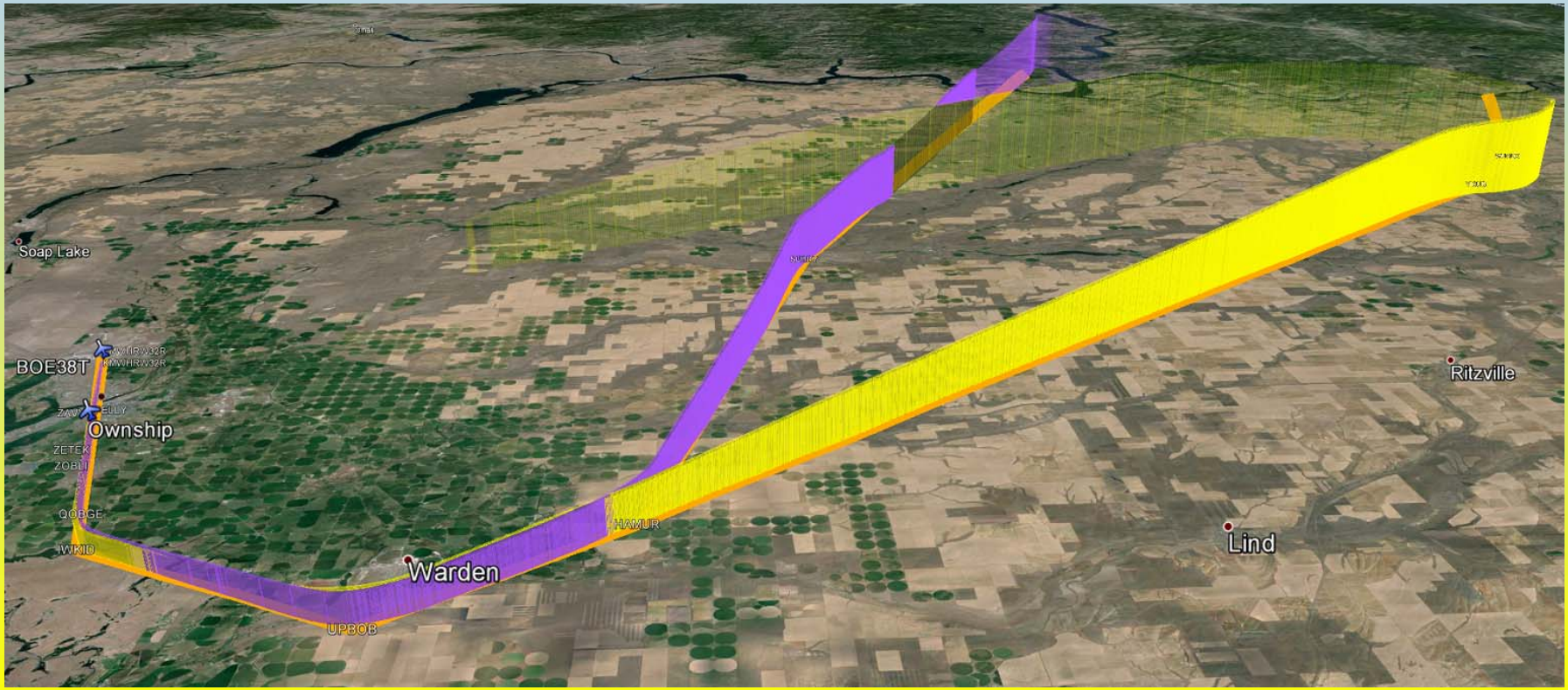
FIM Time: 18 min 33 sec



Run 5


Clayton
Deer Park
Grand Coulee
SUB42
BOE38T
Wellpinit
Ownship
KNOCK
Nine Mile Falls
Wilbur
Davenport
Spokane
Fairchild AFB
Marshall
WUGUX
Edwall
Cheney
YICUB

Run 5


Soap Lake
BOE38T
Ownship
ZETEK
ZOBLI
QOBGE
WKID
Warden
UPBOB
HAMUR
Lind
Ritzville

Run 5

Run 5

- 3 speed inversions
- 14 speed commands (1 command / 1 min. 20 sec.)

Altitude and Distance

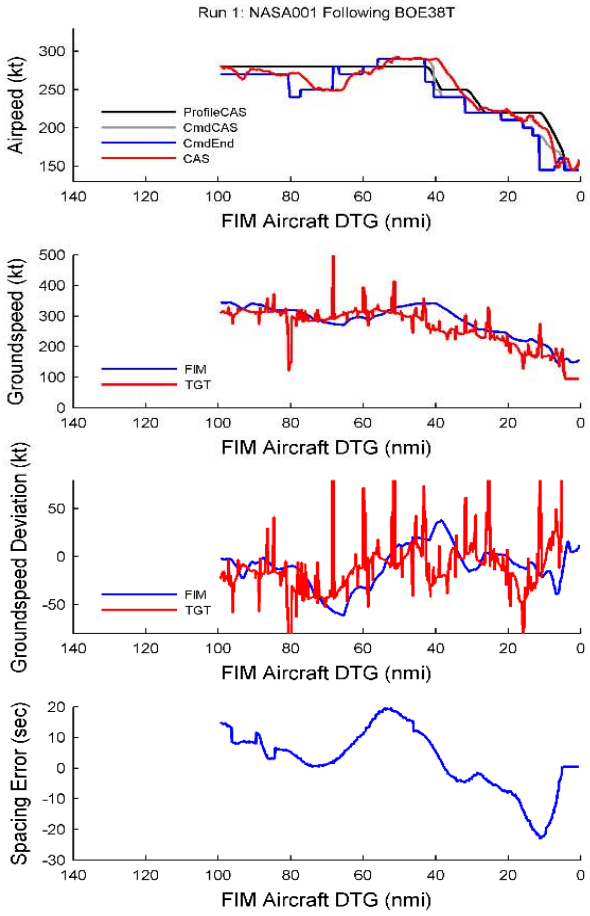
Run #	Initial Speed	Initial Altitude	T-38 @ FIM Start	B787 @ FIM Start	Planned In-Trail Distance	Actual In-Trail Distance
1	280	FL220	21875	22998	13 nm	12.51 nm
2	280	FL220	16625	22388	16 nm	24.12
3	280	FL220	11425	12908	10 nm	6.23
4	280	FL220	19050	22739	7.5 nm	1.63
5	280	FL220	20825	22313	7.5 nm	10.83

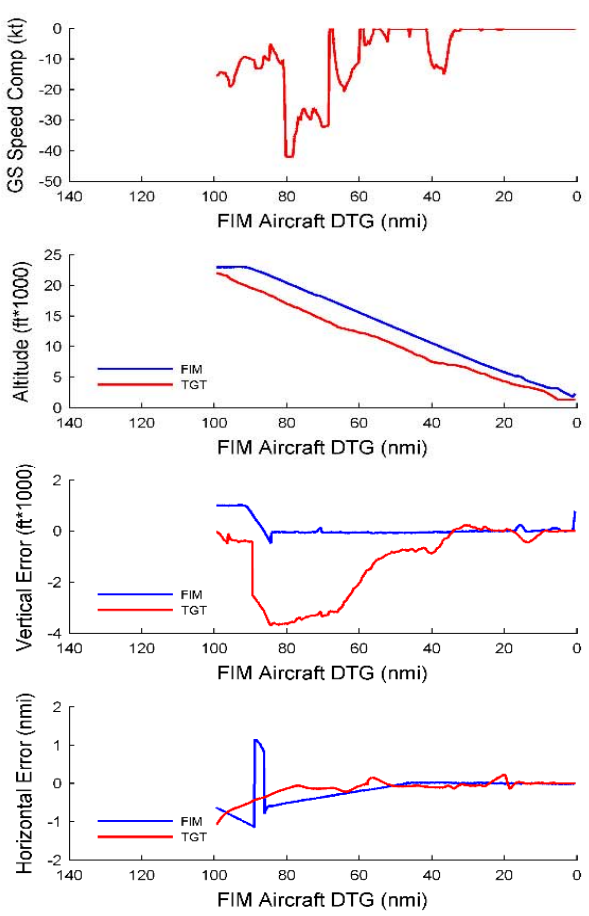
FIM Distance

- Objective was to get between 80-100 nm of data

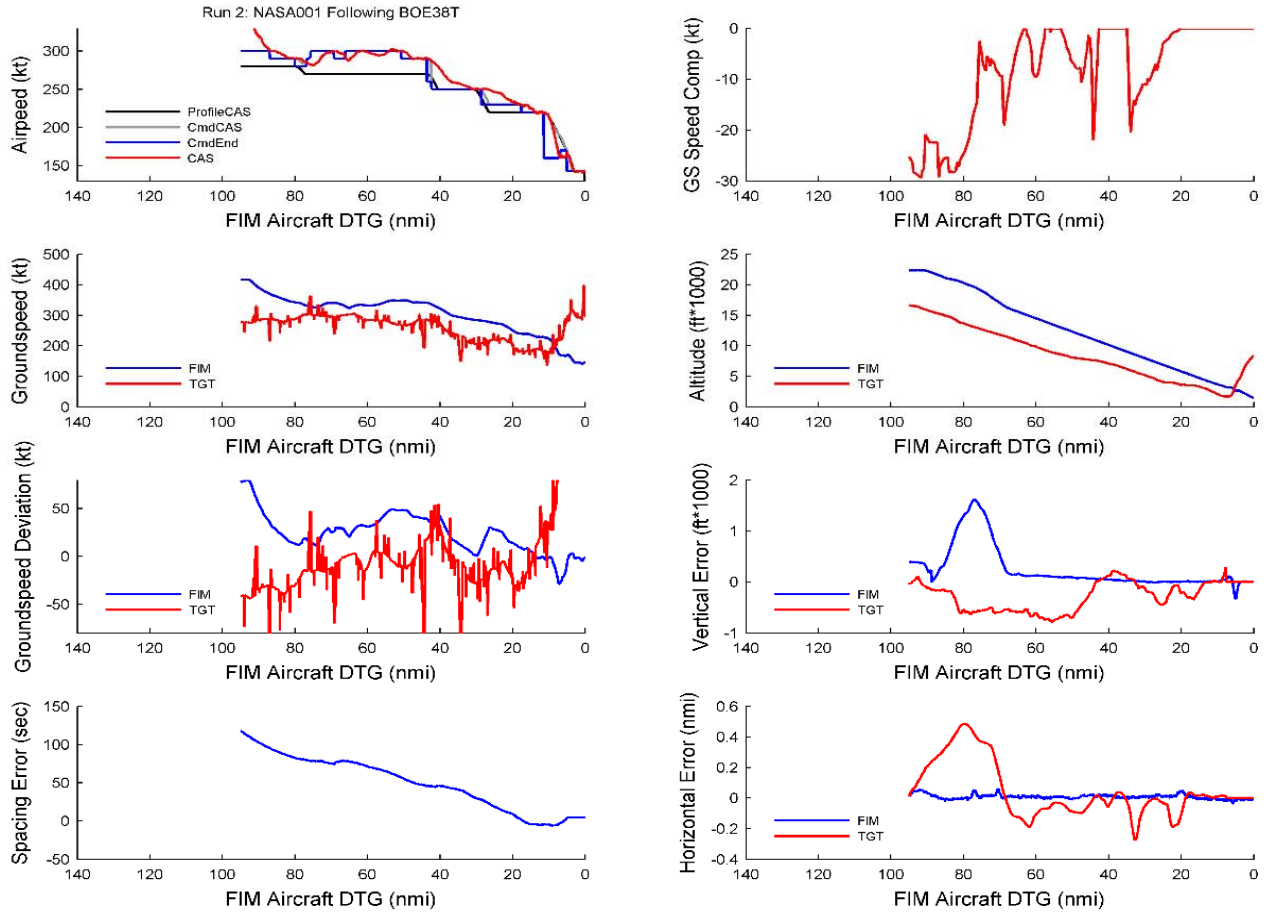
Run #	FIM Distance
1	94.5
2	89.9
3	43.8
4	71.6
5	85.9
Average	77.14

Run 1

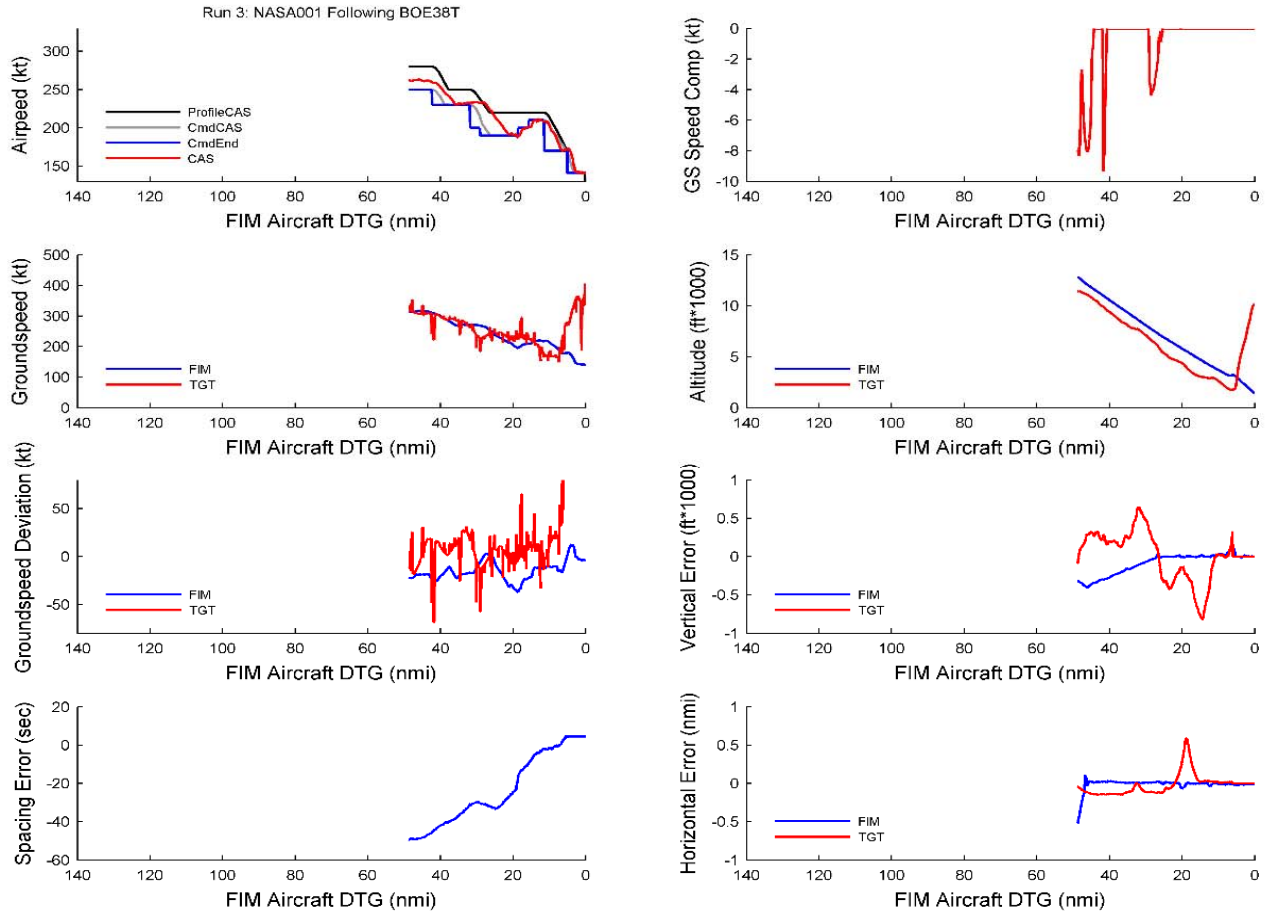

Run 1: NASA001 Following BOE38T
Airpeed (kt)
ProfileCAS
CmdCAS
CmdEnd
CAS
FIM Aircraft DTG (nmi)
Groundspeed (kt)
FIM
TGT
FIM Aircraft DTG (nmi)
Groundspeed Deviation (kt)
FIM
TGT
FIM Aircraft DTG (nmi)
Spacing Error (sec)
FIM Aircraft DTG (nmi)


GS Speed Comp (kt)
FIM Aircraft DTG (nmi)
Altitude (ft*1000)
FIM
TGT
FIM Aircraft DTG (nmi)
Vertical Error (ft*1000)
FIM
TGT
FIM Aircraft DTG (nmi)
Horizontal Error (nmi)
FIM
TGT
FIM Aircraft DTG (nmi)

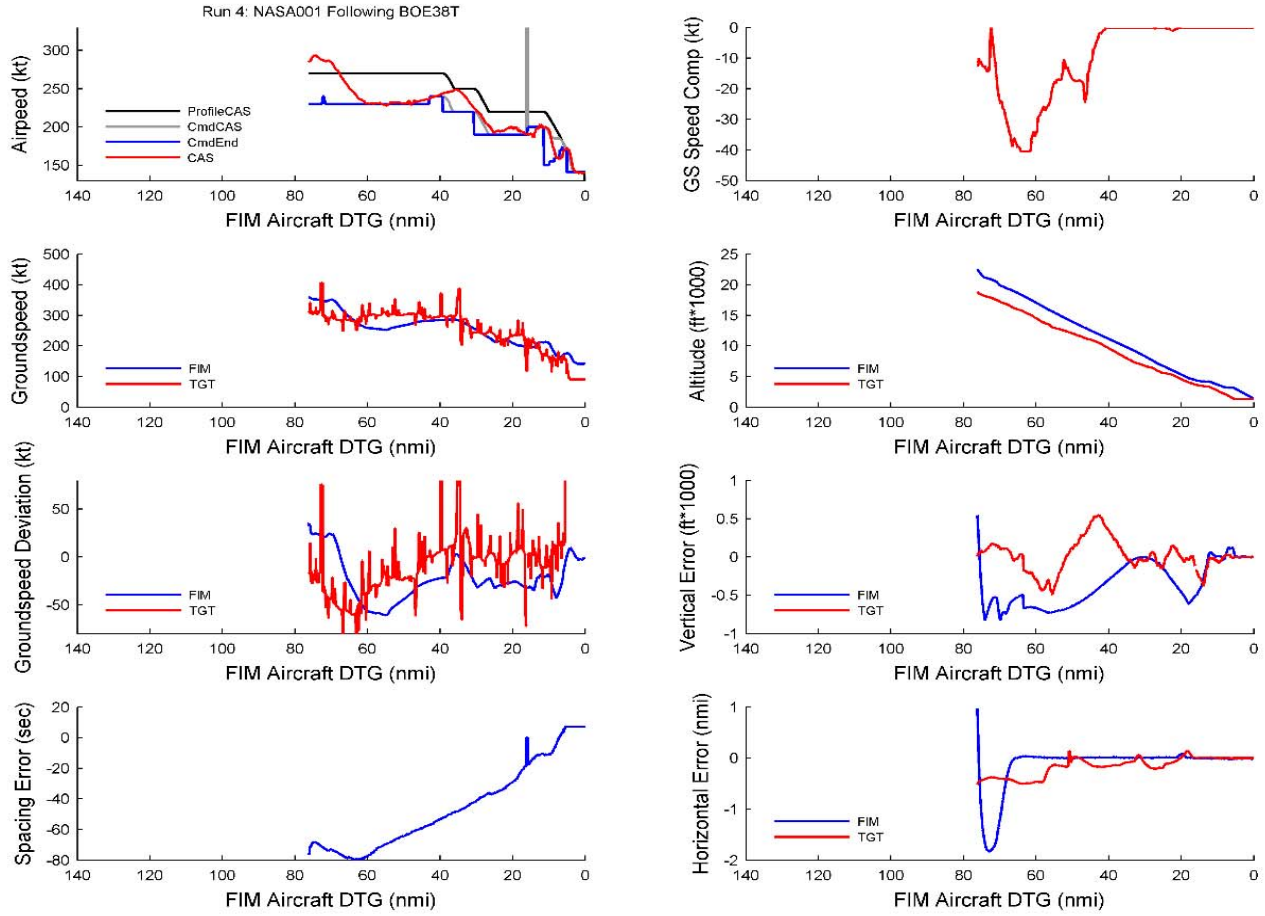
Run 2


Run 2: NASA001 Following BOE38T
Airpeed (kt)
ProfileCAS
CmdCAS
CmdEnd
CAS
FIM Aircraft DTG (nmi)
GS Speed Comp (kt)
FIM Aircraft DTG (nmi)
Groundspeed (kt)
FIM
TGT
FIM Aircraft DTG (nmi)
Altitude (ft*1000)
FIM
TGT
FIM Aircraft DTG (nmi)
Groundspeed Deviation (kt)
FIM
TGT
FIM Aircraft DTG (nmi)
Vertical Error (ft*1000)
FIM
TGT
FIM Aircraft DTG (nmi)
Spacing Error (sec)
FIM Aircraft DTG (nmi)
Horizontal Error (nmi)
FIM
TGT
FIM Aircraft DTG (nmi)

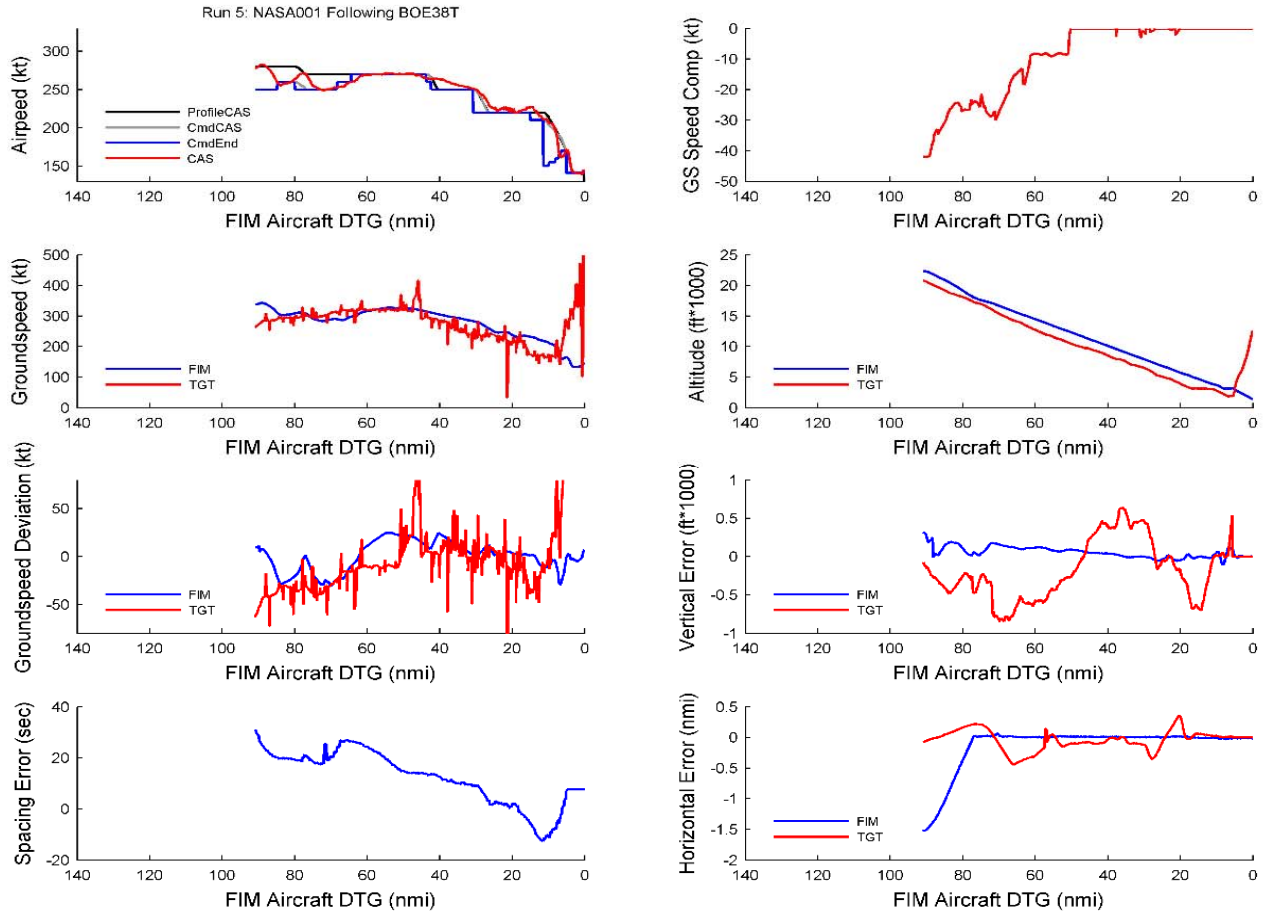
Run 3A


Run 3: NASA001 Following BOE38T
Airpeed (kt)
ProfileCAS
CmdCAS
CmdEnd
CAS
FIM Aircraft DTG (nmi)
GS Speed Comp (kt)
Groundspeed (kt)
FIM
TGT
Altitude (ft*1000)
Groundspeed Deviation (kt)
Vertical Error (ft*1000)
Spacing Error (sec)
Horizontal Error (nmi)

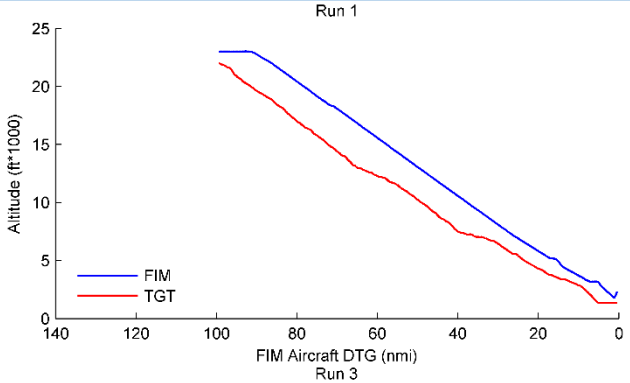
Run 4

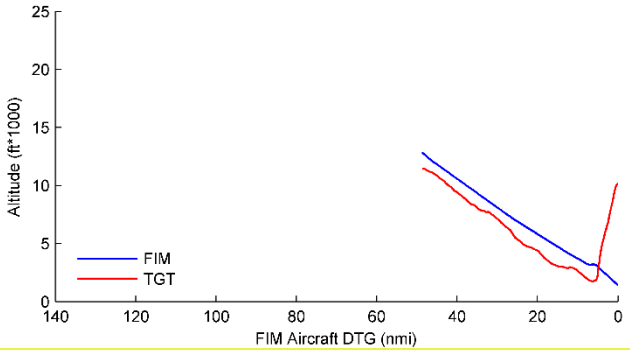

Run 4: NASA001 Following BOE38T
Airpeed (kt)
ProfileCAS
CmdCAS
CmdEnd
CAS
FIM Aircraft DTG (nmi)
GS Speed Comp (kt)
FIM Aircraft DTG (nmi)
Groundspeed (kt)
FIM
TGT
FIM Aircraft DTG (nmi)
Altitude (ft*1000)
FIM
TGT
FIM Aircraft DTG (nmi)
Groundspeed Deviation (kt)
FIM
TGT
FIM Aircraft DTG (nmi)
Vertical Error (ft*1000)
FIM
TGT
FIM Aircraft DTG (nmi)
Spacing Error (sec)
FIM Aircraft DTG (nmi)
Horizontal Error (nmi)
FIM
TGT
FIM Aircraft DTG (nmi)

Run 5

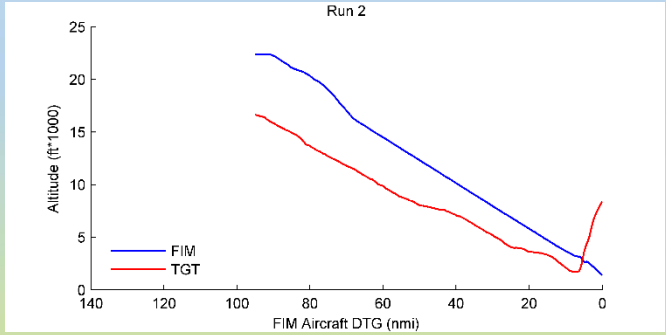

Run 5: NASA001 Following BOE38T
Airpeed (kt)
ProfileCAS
CmdCAS
CmdEnd
CAS
FIM Aircraft DTG (nmi)
GS Speed Comp (kt)
FIM Aircraft DTG (nmi)
Groundspeed (kt)
FIM
TGT
FIM Aircraft DTG (nmi)
Altitude (ft*1000)
FIM
TGT
FIM Aircraft DTG (nmi)
Groundspeed Deviation (kt)
FIM
TGT
FIM Aircraft DTG (nmi)
Vertical Error (ft*1000)
FIM
TGT
FIM Aircraft DTG (nmi)
Spacing Error (sec)
FIM Aircraft DTG (nmi)
Horizontal Error (nmi)
FIM
TGT
FIM Aircraft DTG (nmi)

Altitude



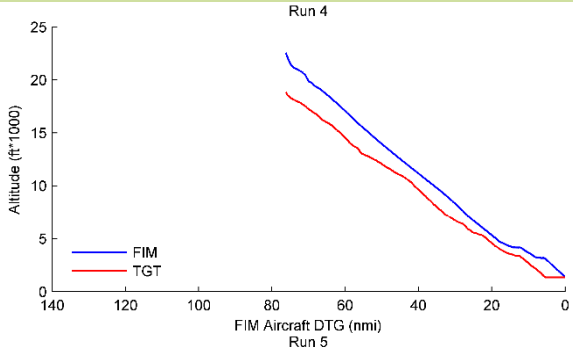


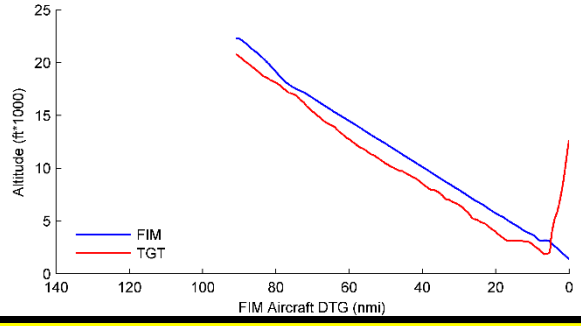
SUBDY Arrival



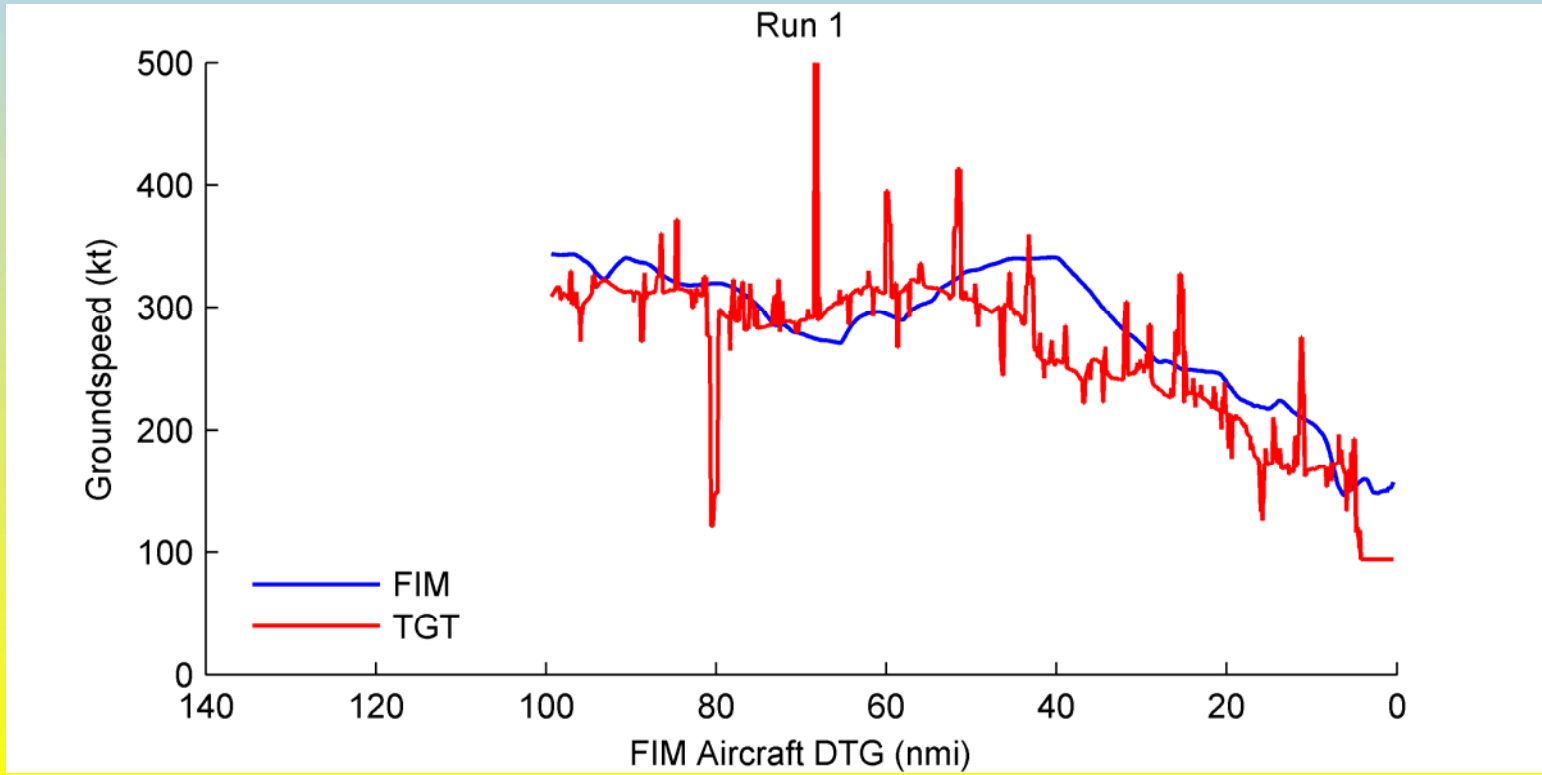
KNOCK Arrival

Dual Route

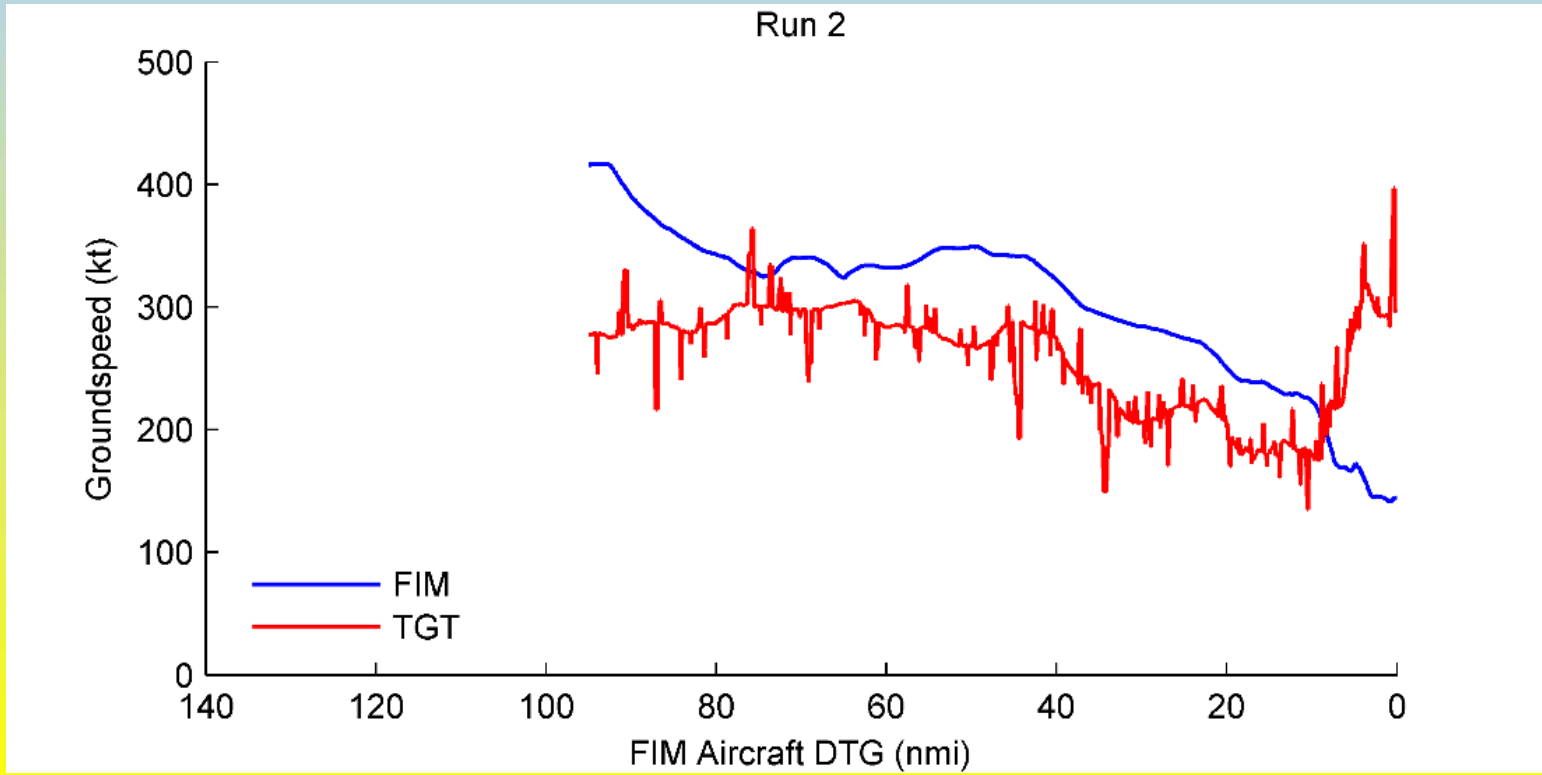




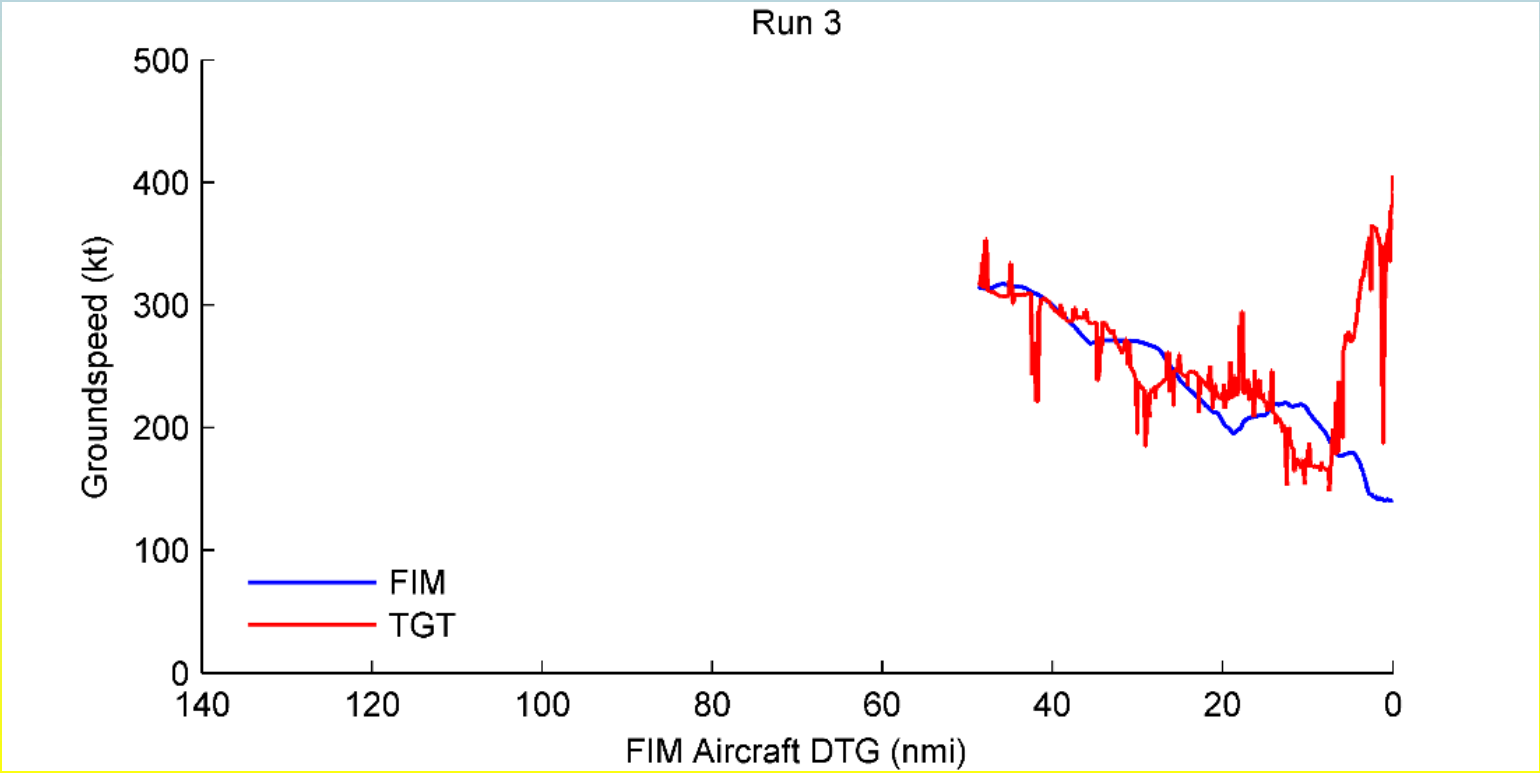
Groundspeed 1



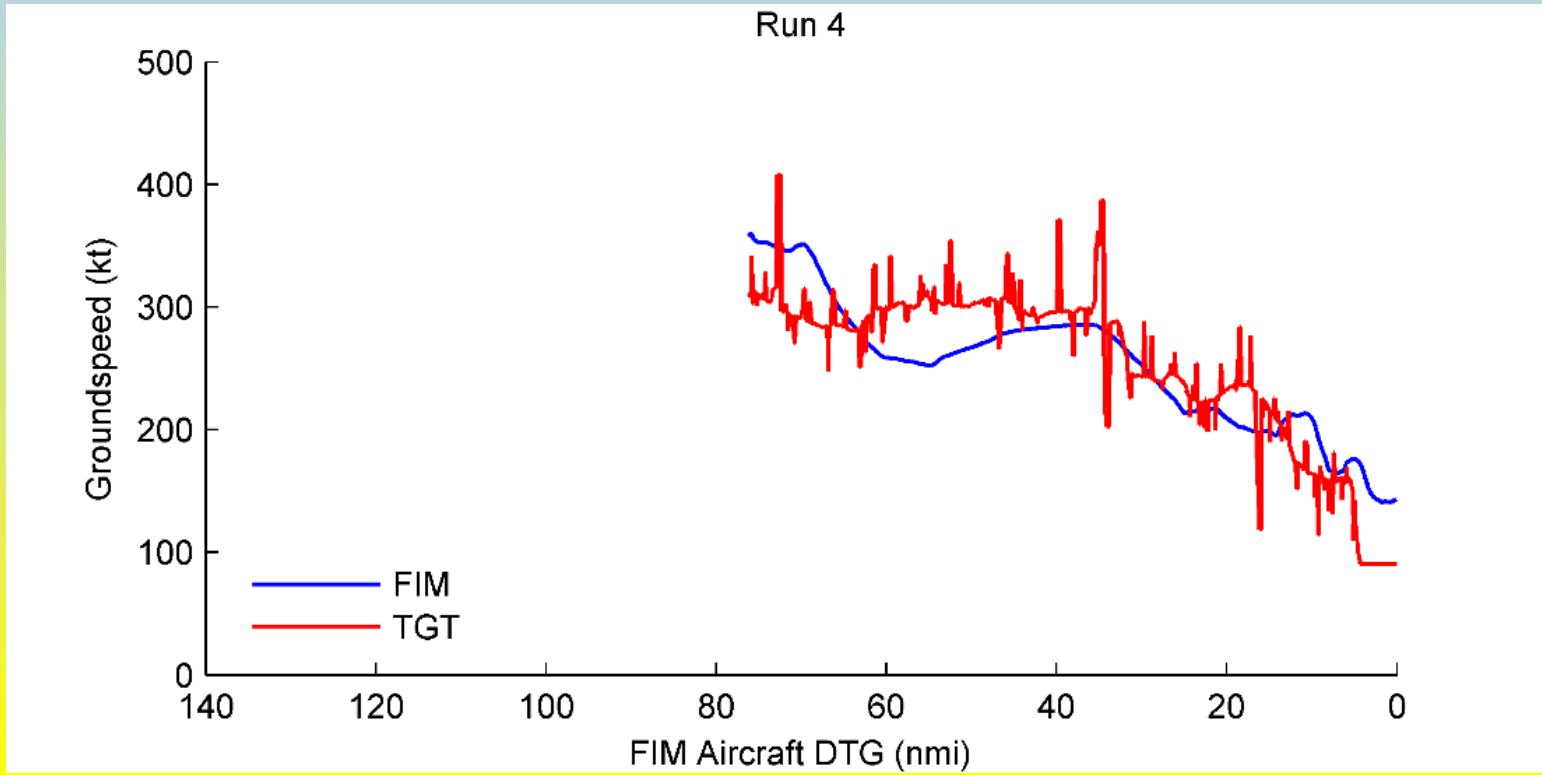
Groundspeed 2



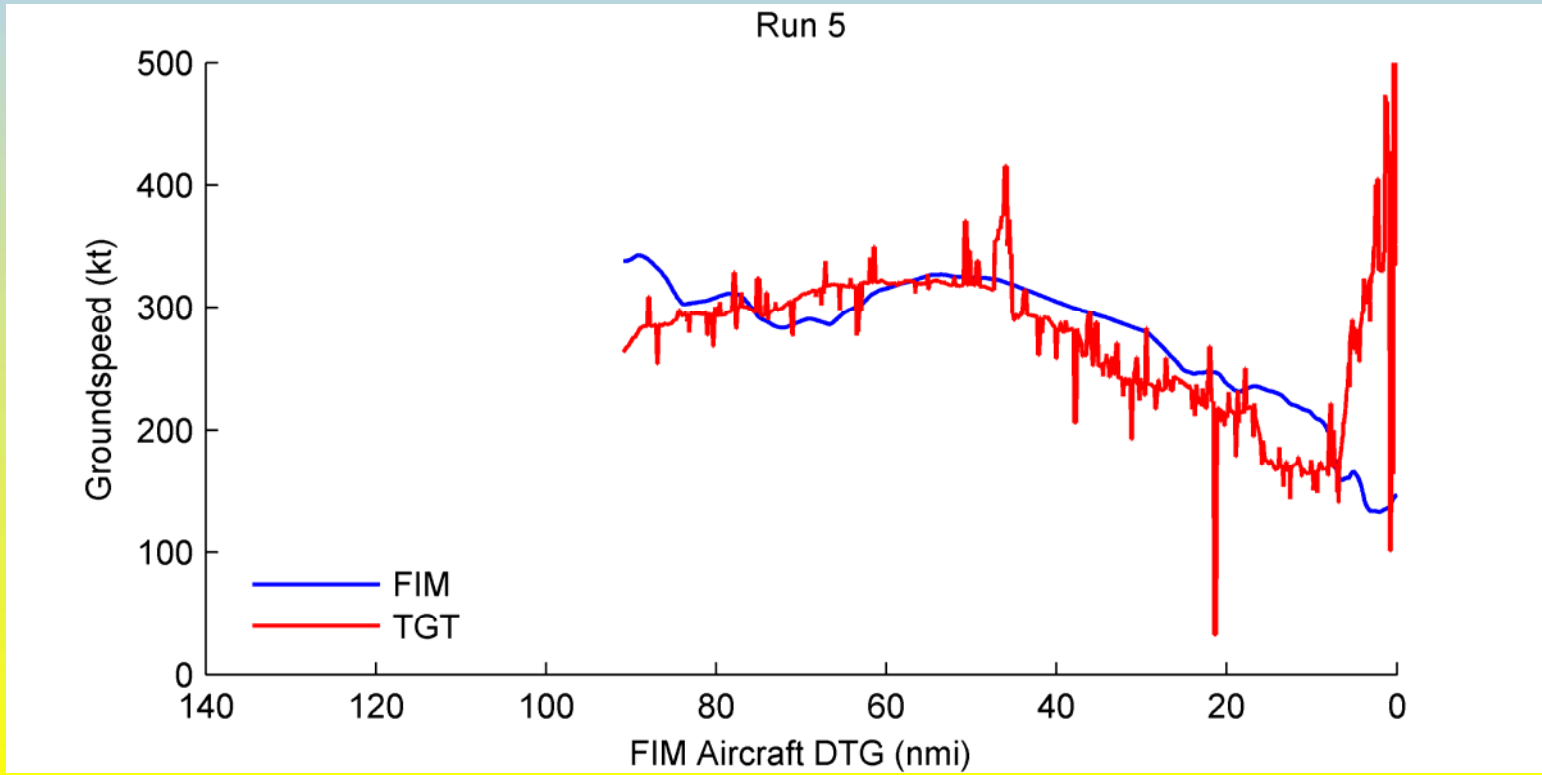
Groundspeed 3



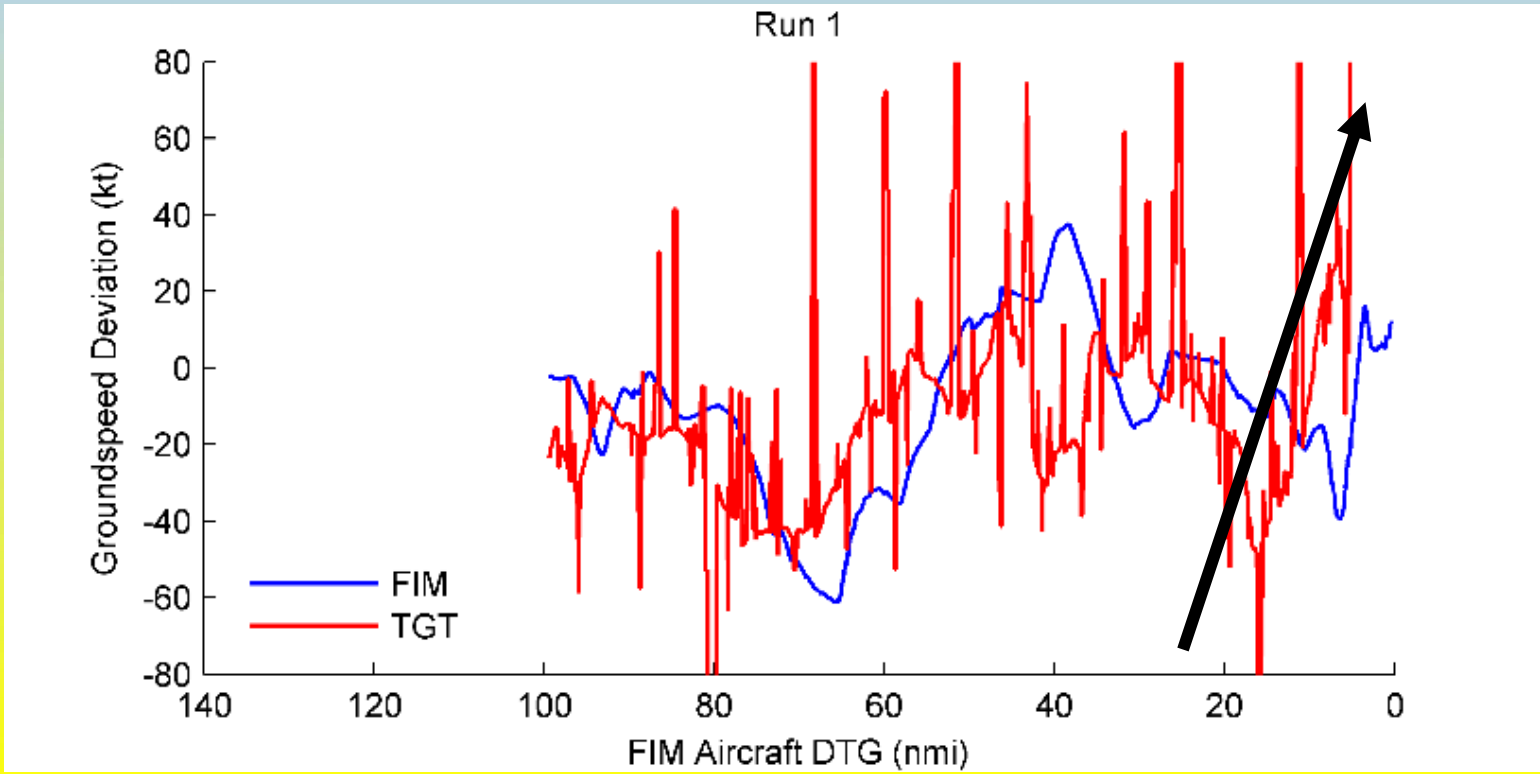
Groundspeed 4



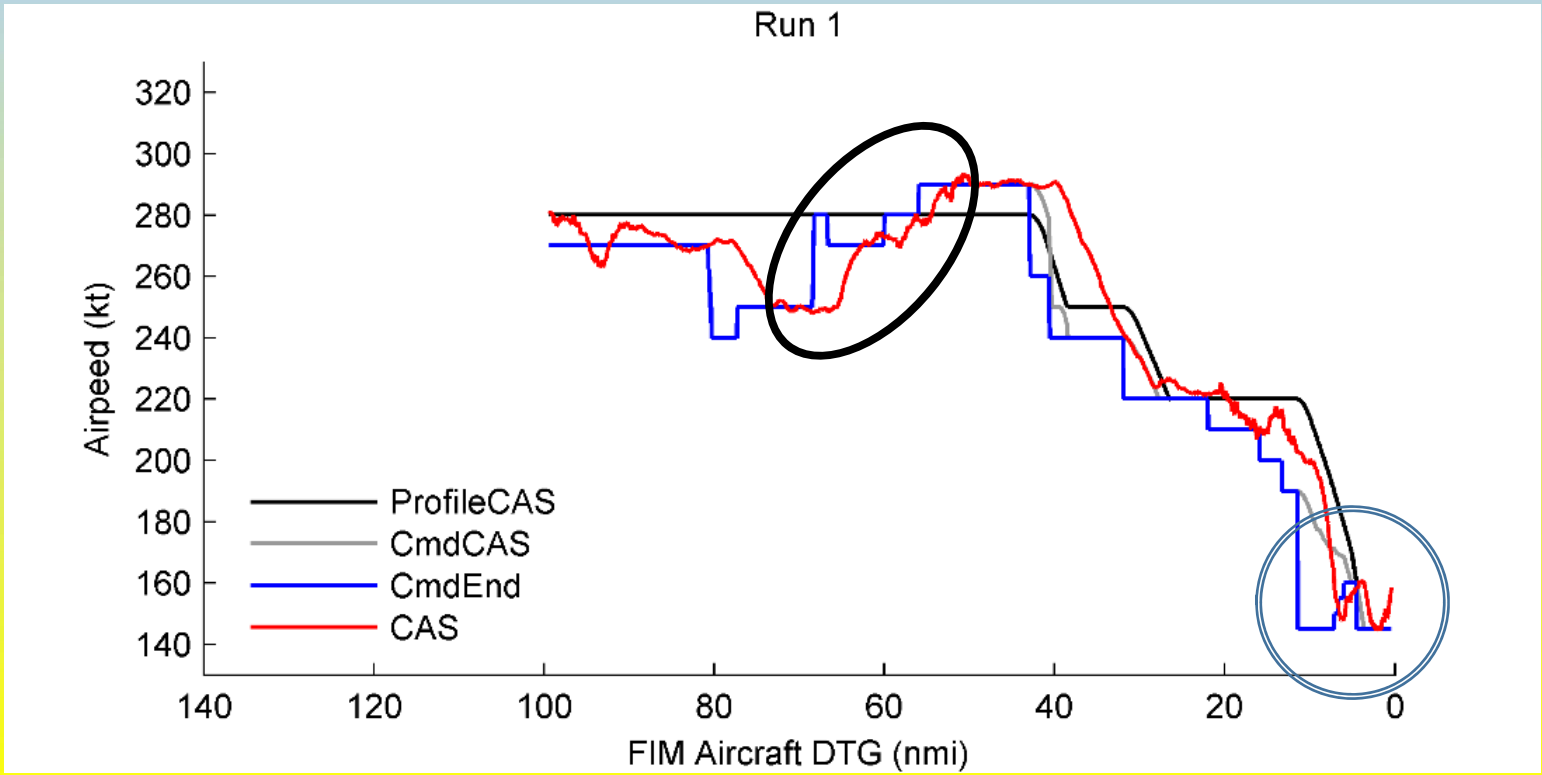
Groundspeed 5



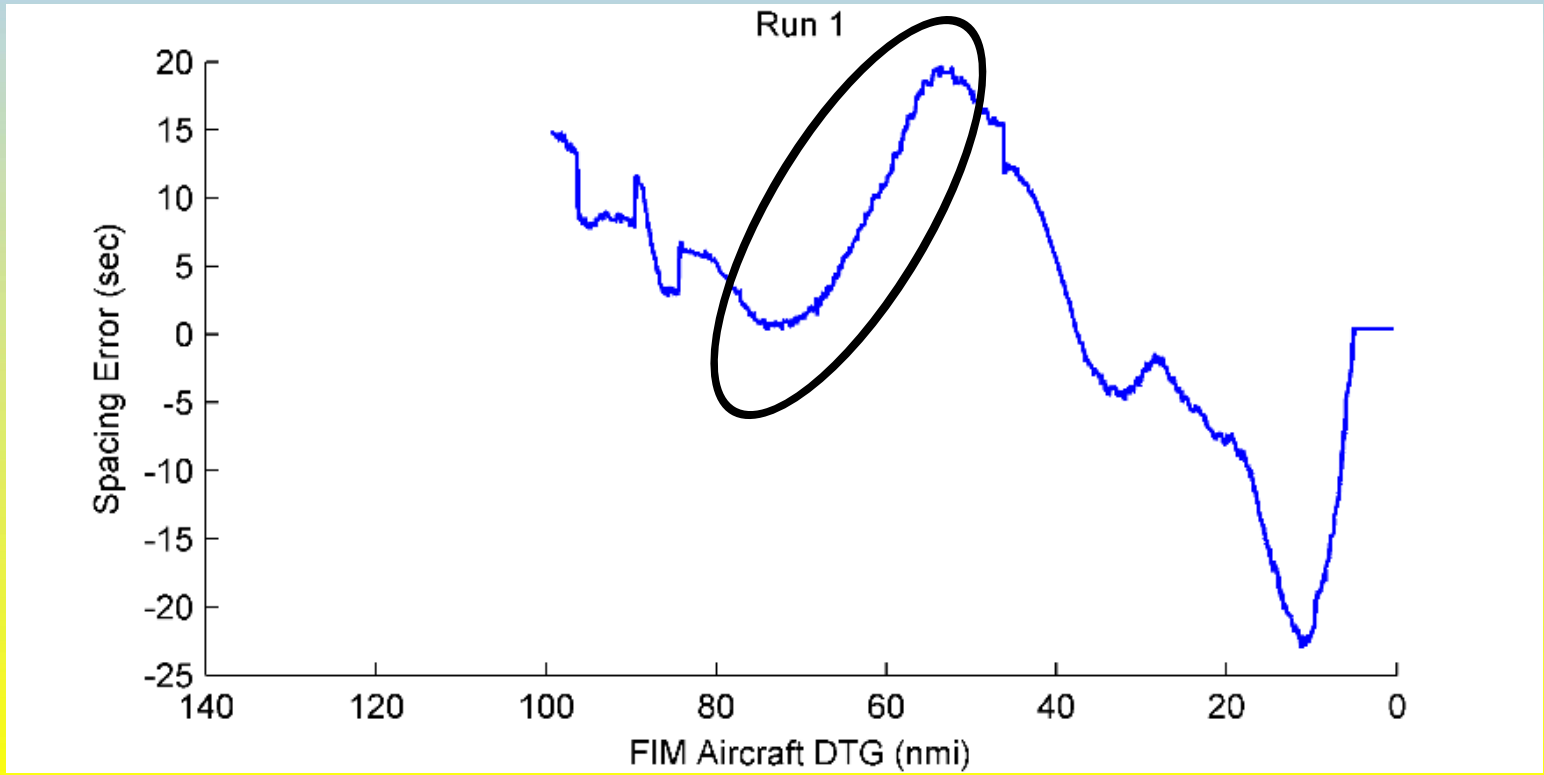
Groundspeed Deviation 1



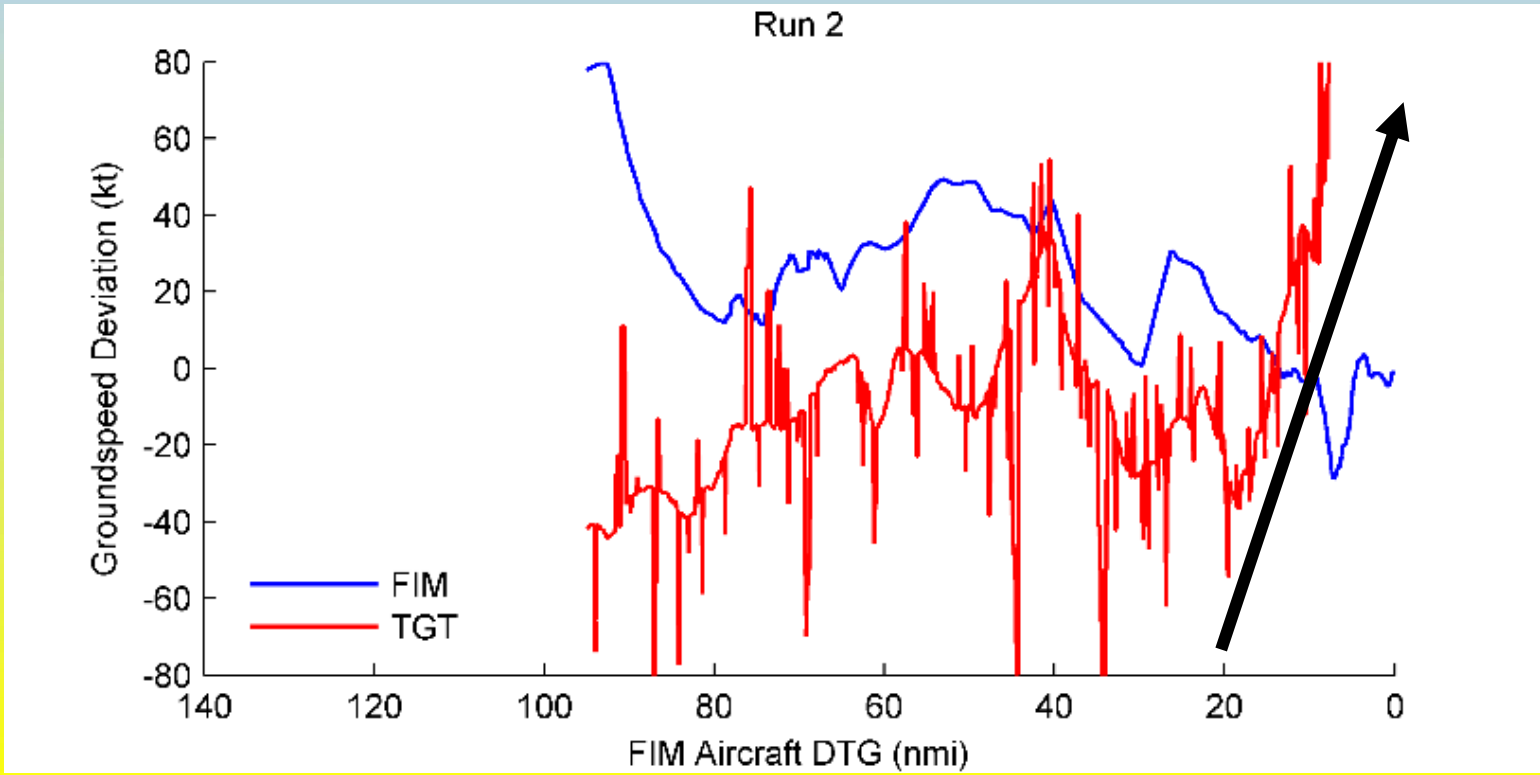
Airspeed 1


Run 1
Airpeed (kt)
320
300
280
260
240
220
200
180
160
140
ProfileCAS
CmdCAS
CmdEnd
CAS
140
120
100
80
60
40
20
0
FIM Aircraft DTG (nmi)

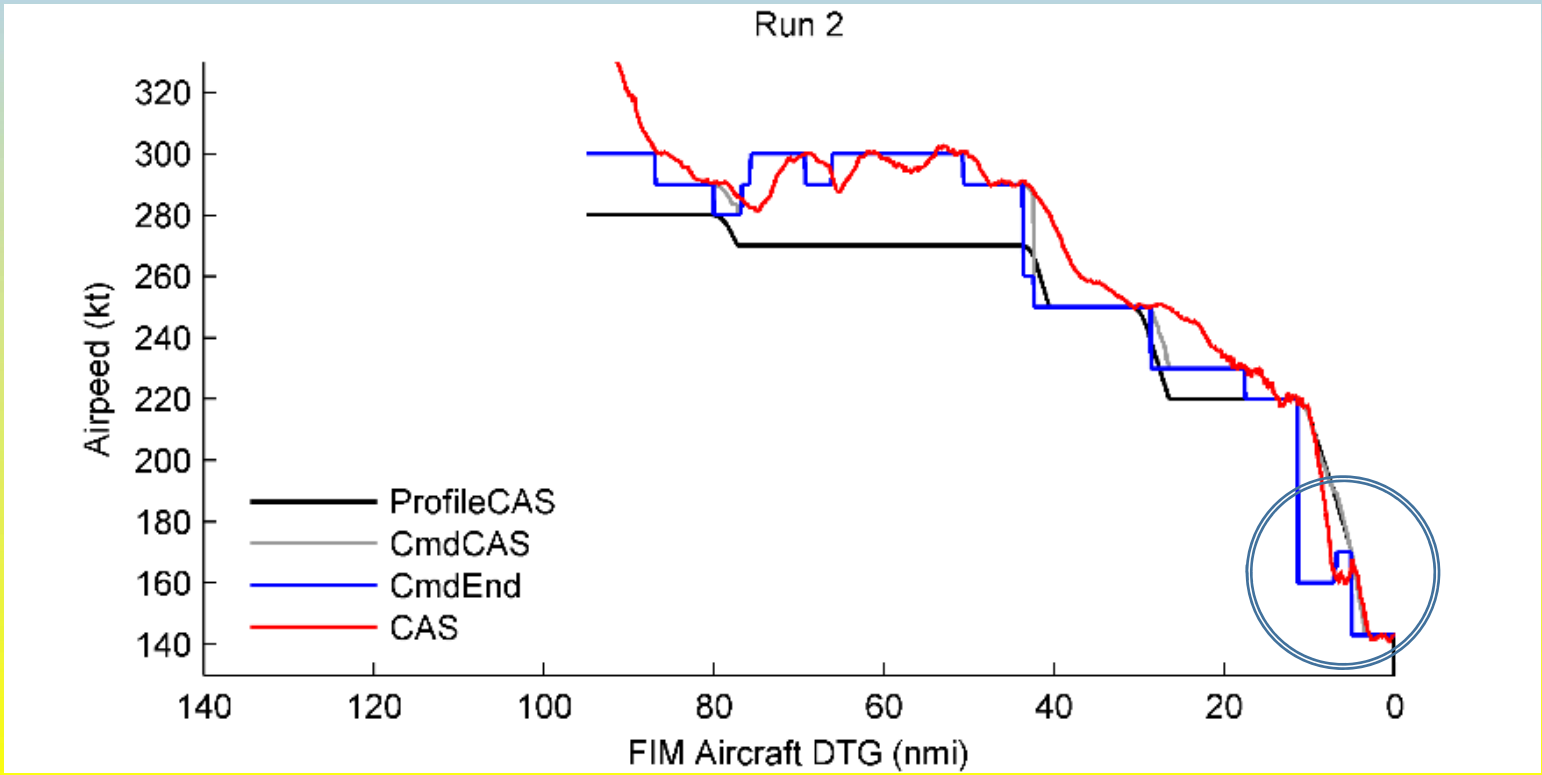
Spacing Error 1



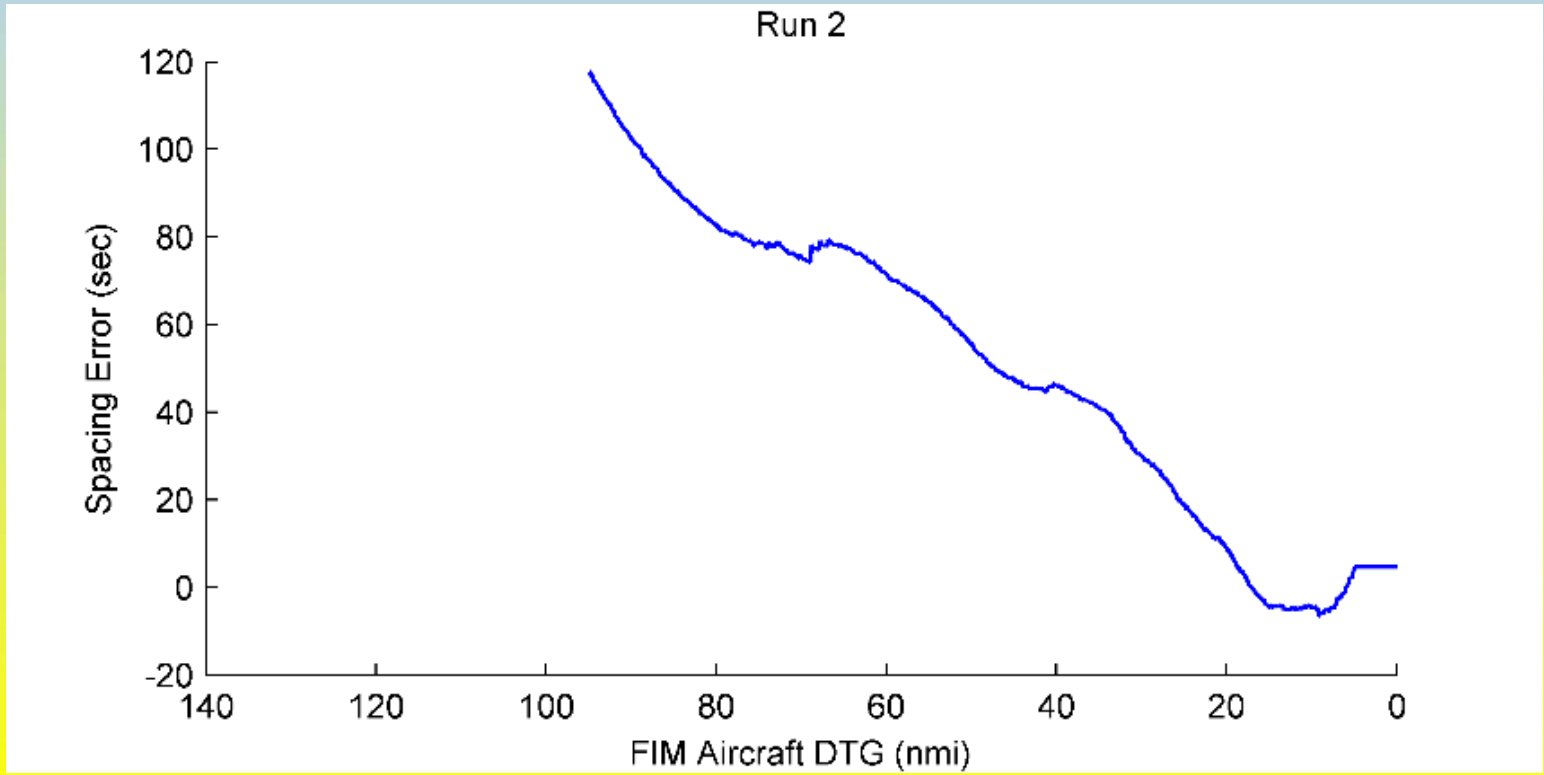
Groundspeed Deviation 2



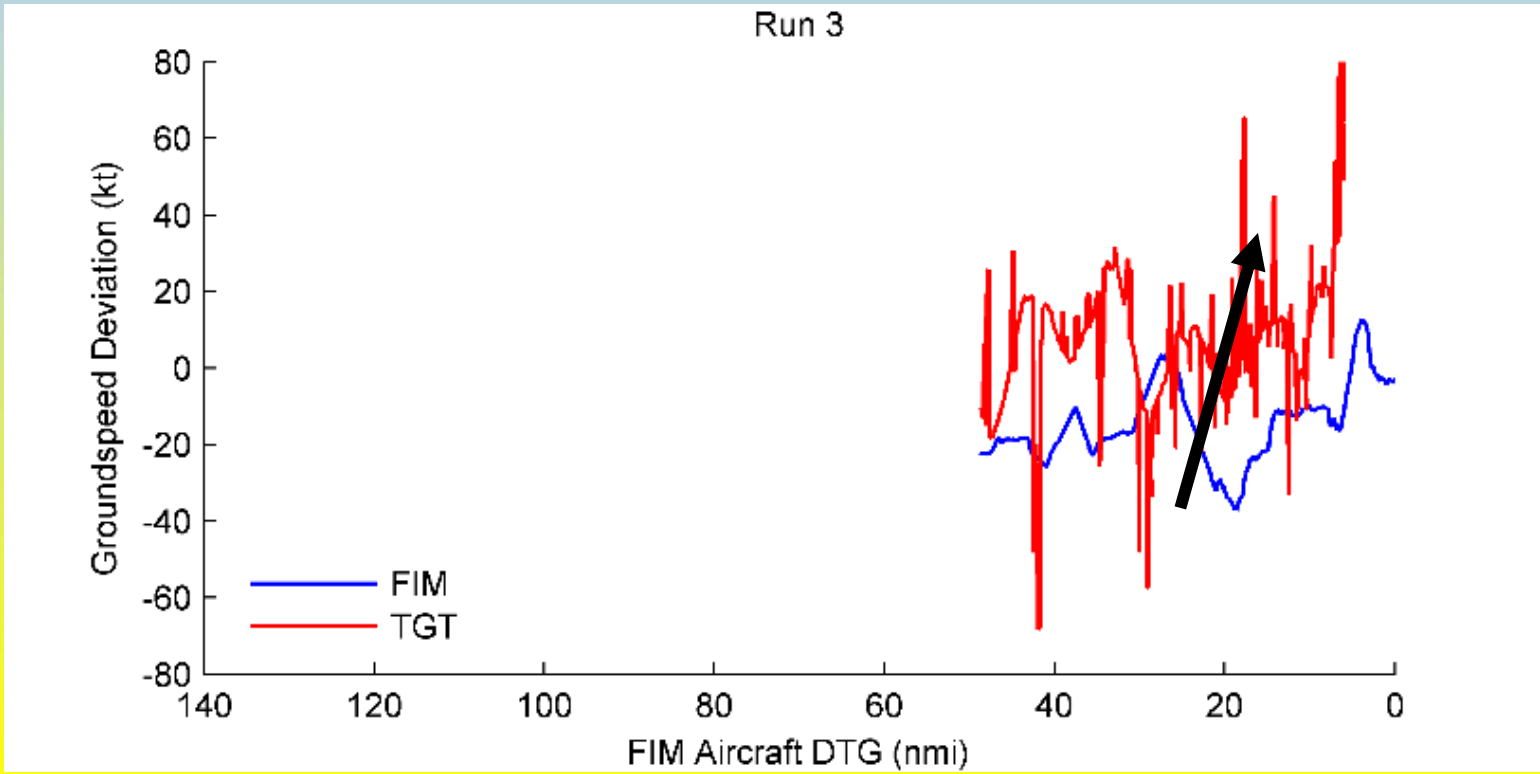
Airspeed 2


Run 2
Airpeed (kt)
320
300
280
260
240
220
200
180
160
140
ProfileCAS
CmdCAS
CmdEnd
CAS
140
120
100
80
60
40
20
0
FIM Aircraft DTG (nmi)

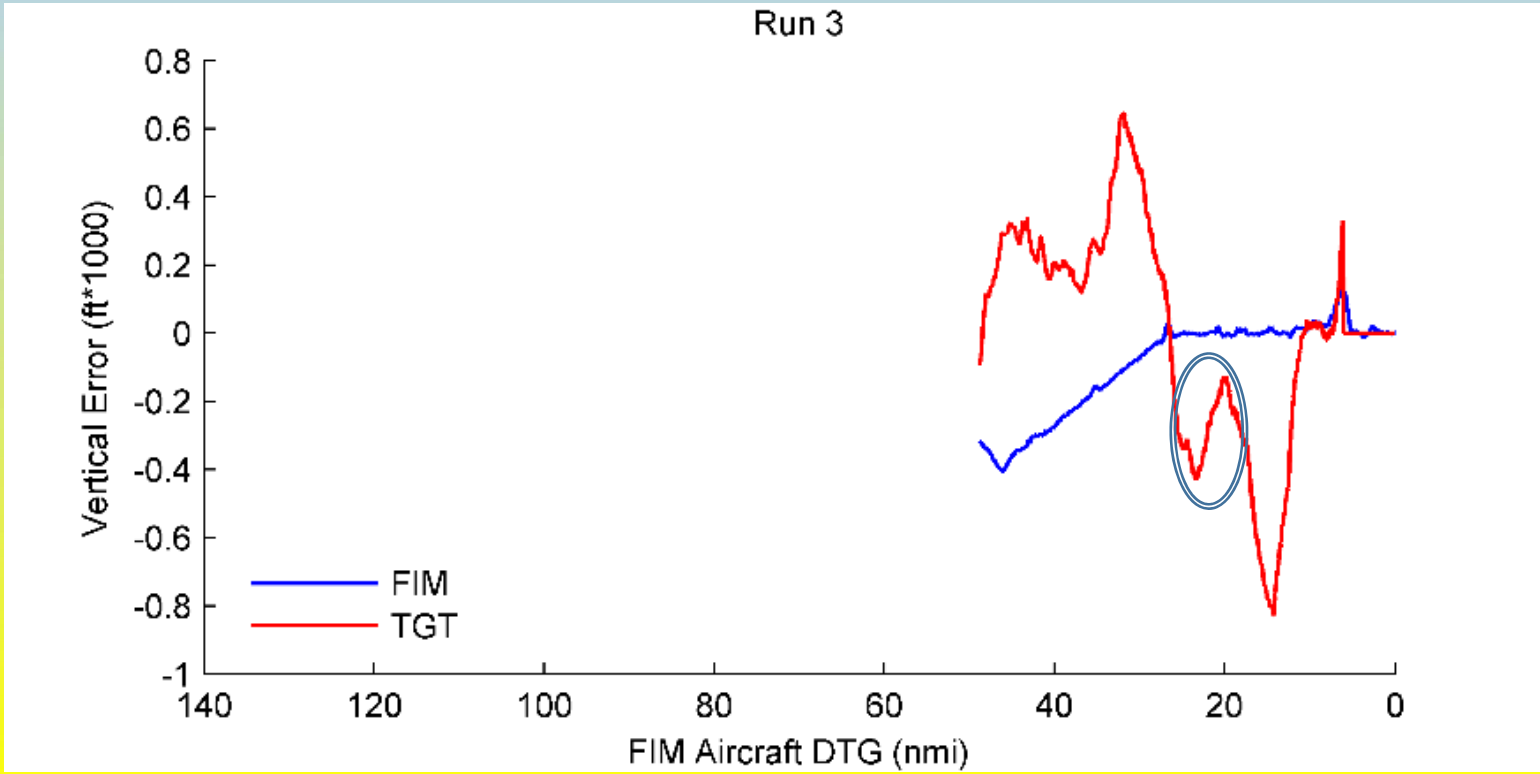
Spacing Error 2



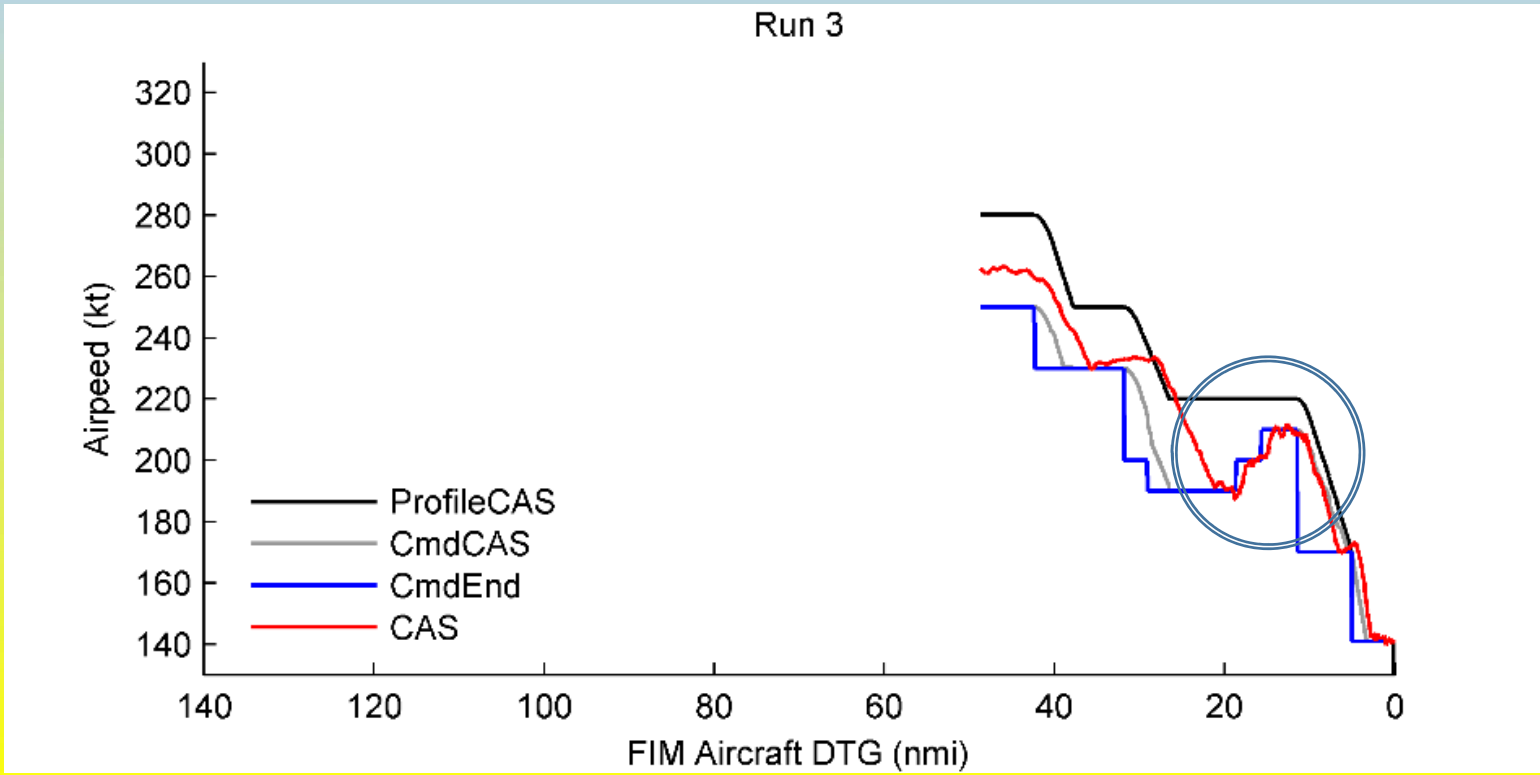
Groundspeed Deviation 3



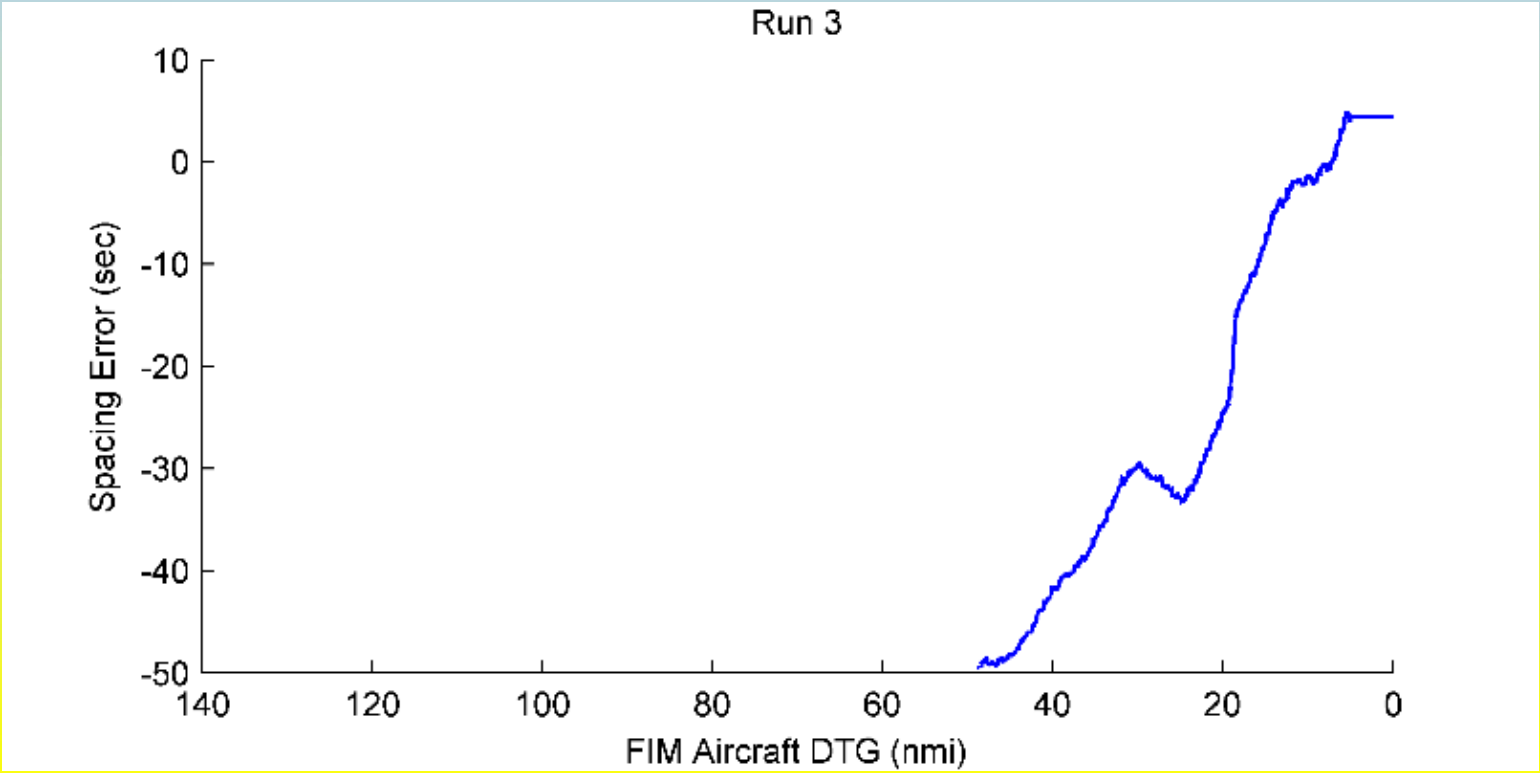
Vertical Track Error 3



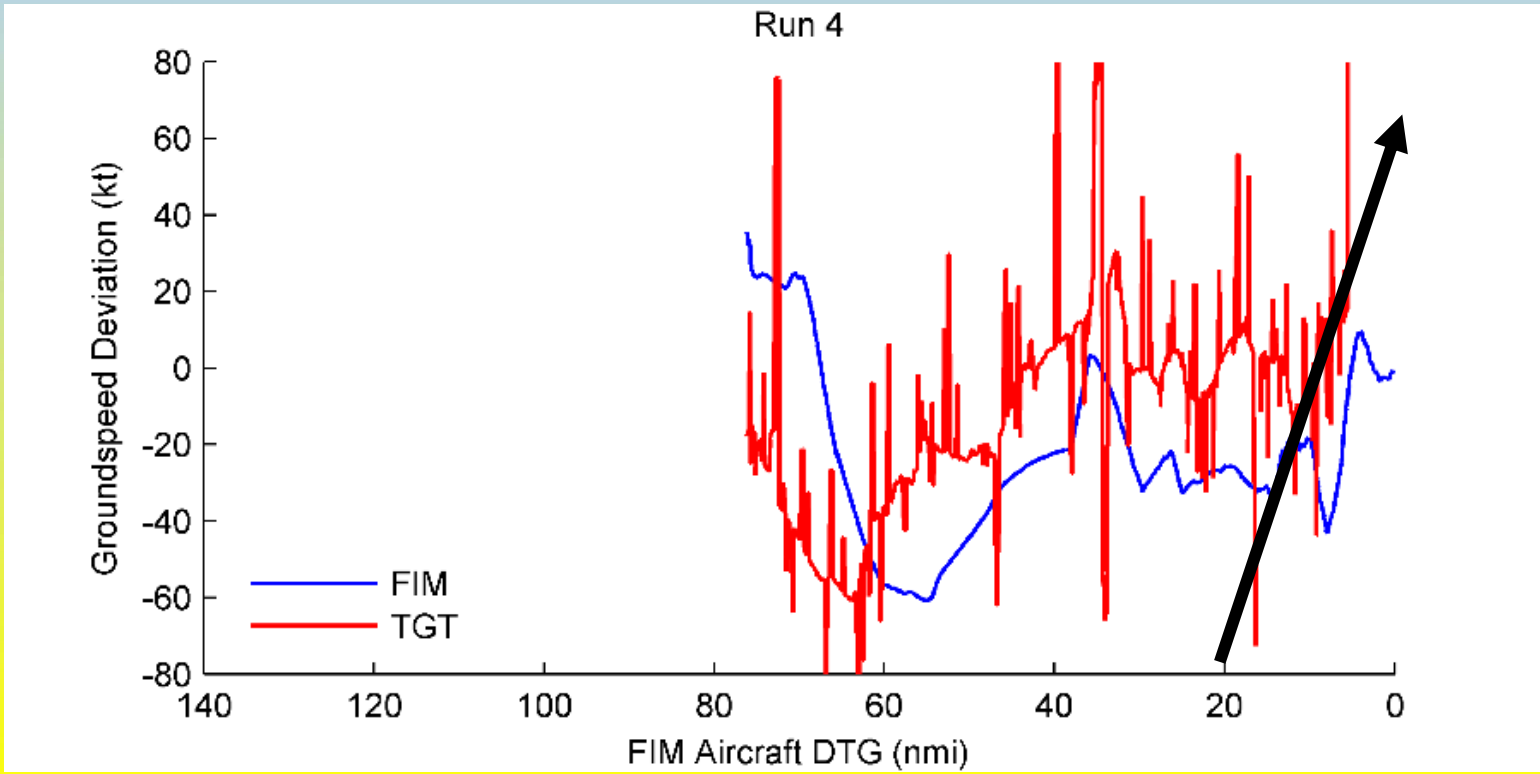
Airspeed 3


Run 3
Airpeed (kt)
320
300
280
260
240
220
200
180
160
140
ProfileCAS
CmdCAS
CmdEnd
CAS
140
120
100
80
60
40
20
0
FIM Aircraft DTG (nmi)

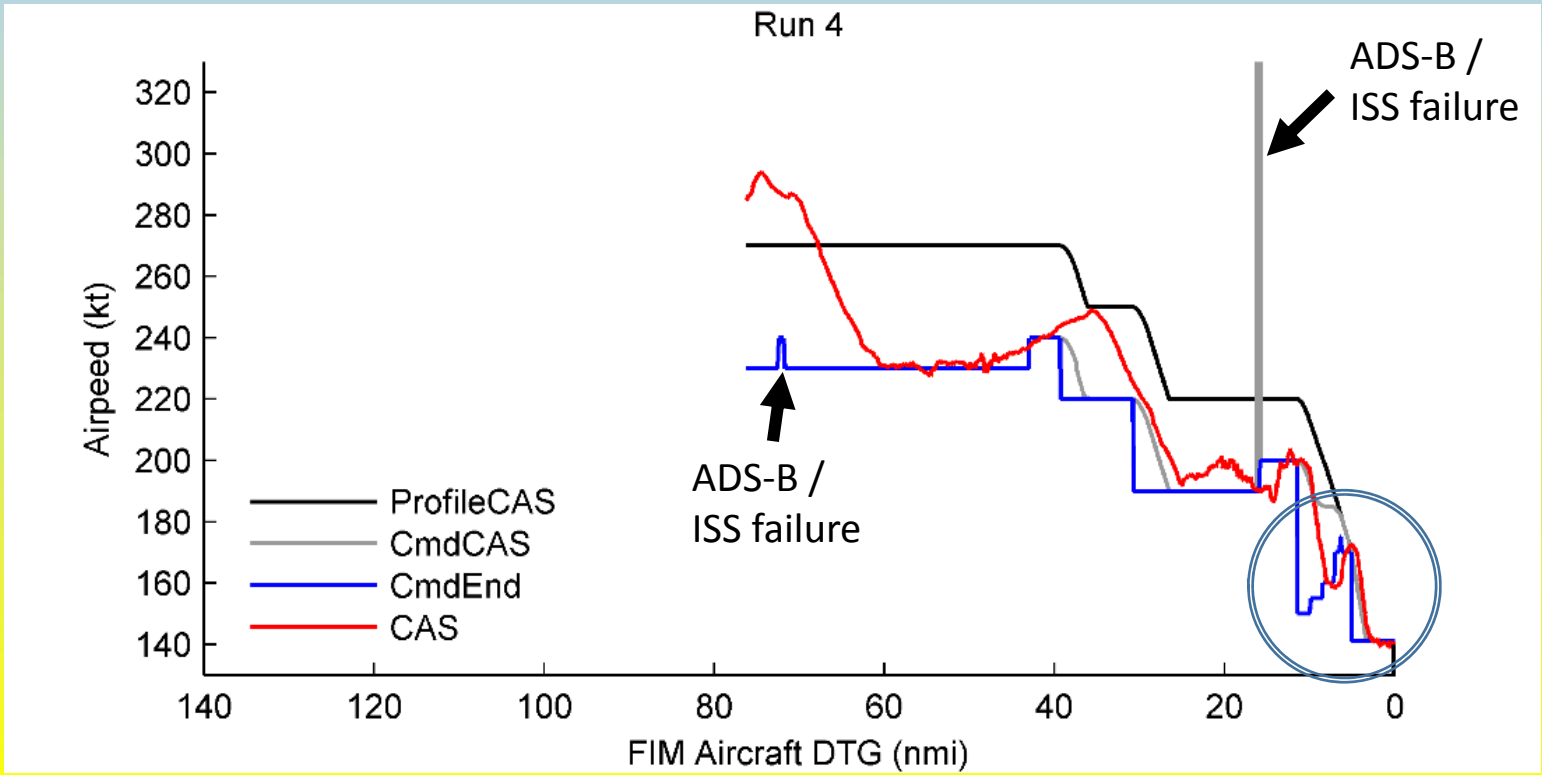
Spacing Error 3



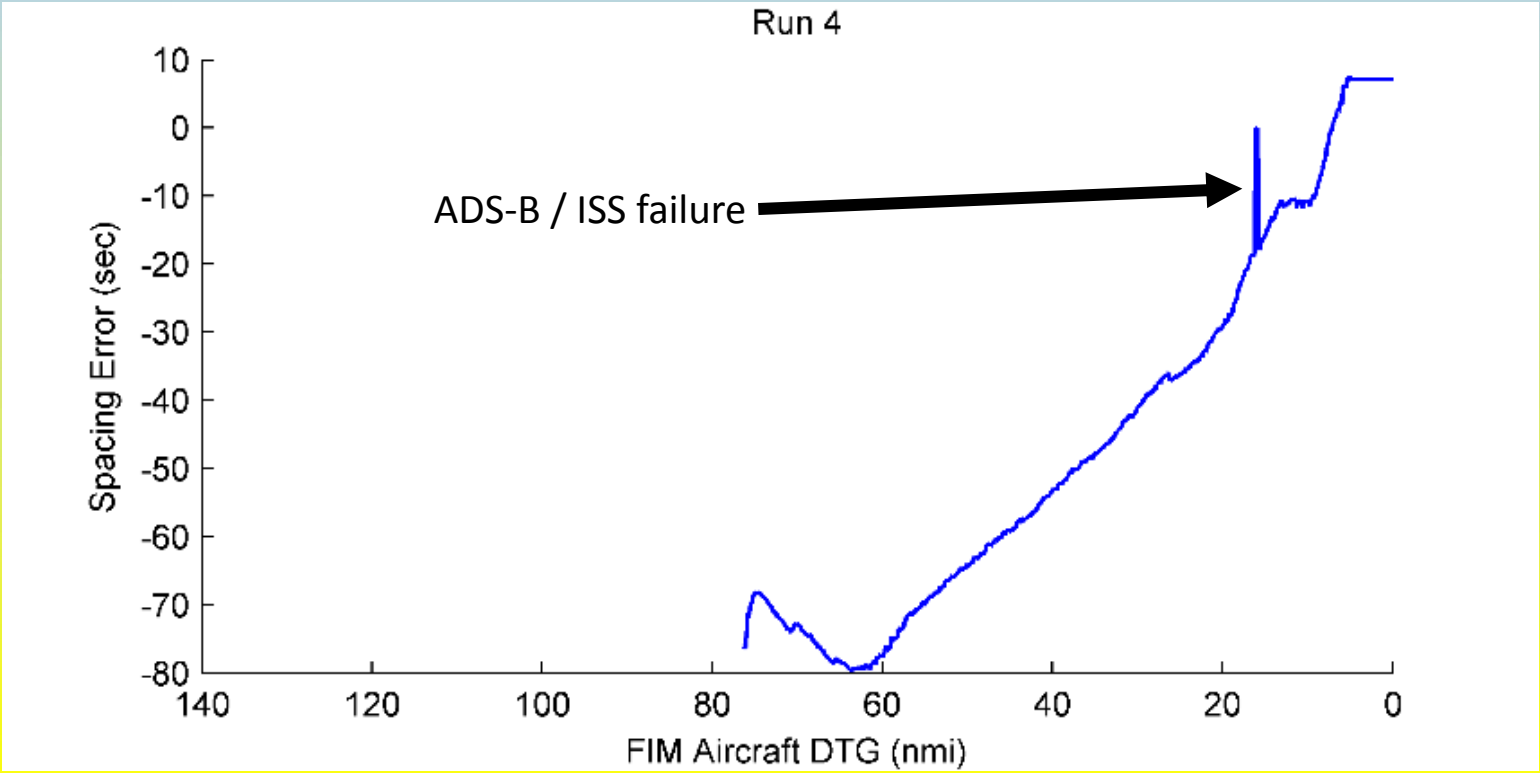
Groundspeed Deviation 4



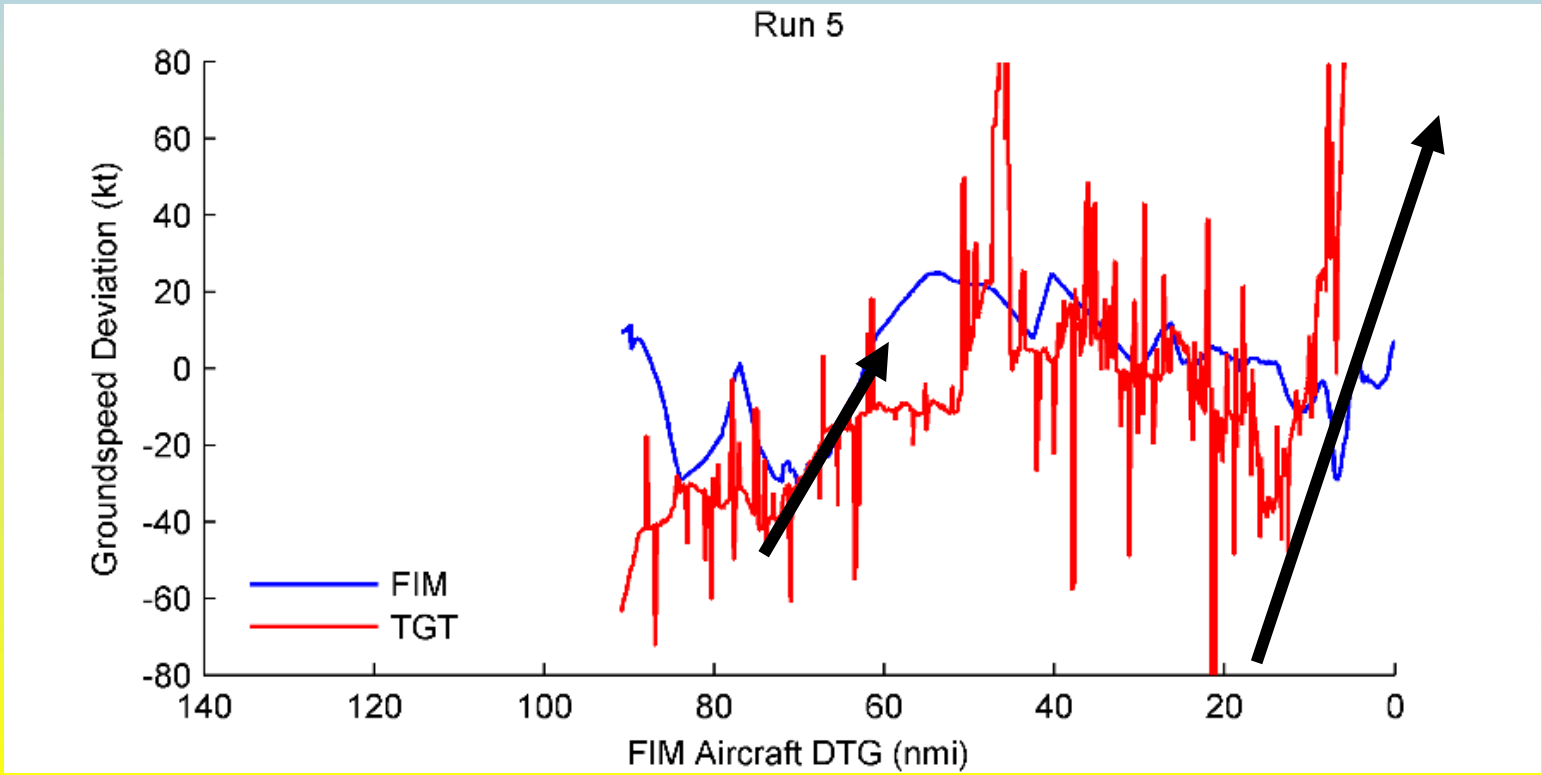
Airspeed 4


Run 4
ADS-B /
ISS failure
ADS-B /
ISS failure
Airpeed (kt)
320
300
280
260
240
220
200
180
160
140
ProfileCAS
CmdCAS
CmdEnd
CAS
140
120
100
80
60
40
20
0
FIM Aircraft DTG (nmi)

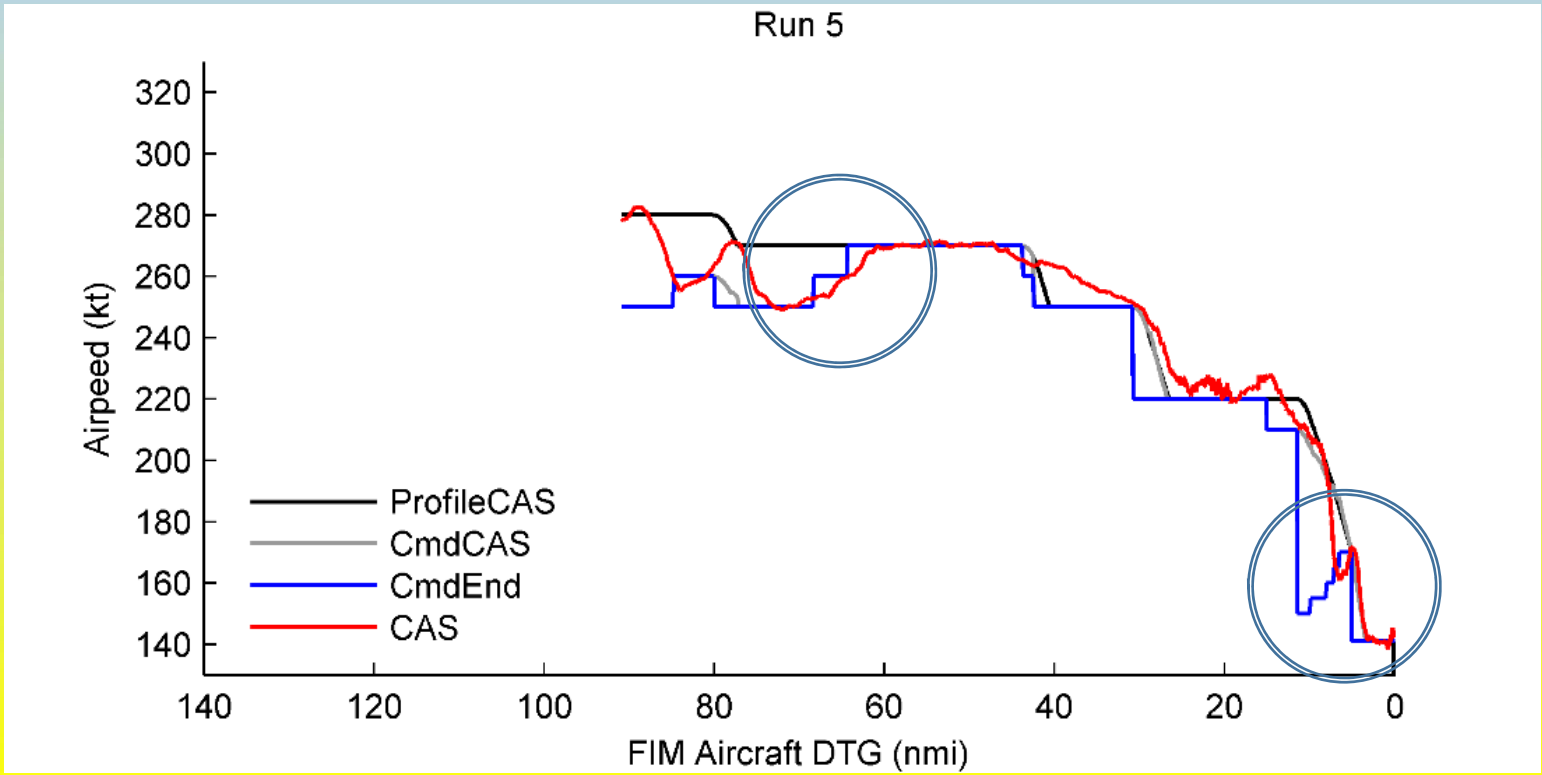
Spacing Error 4



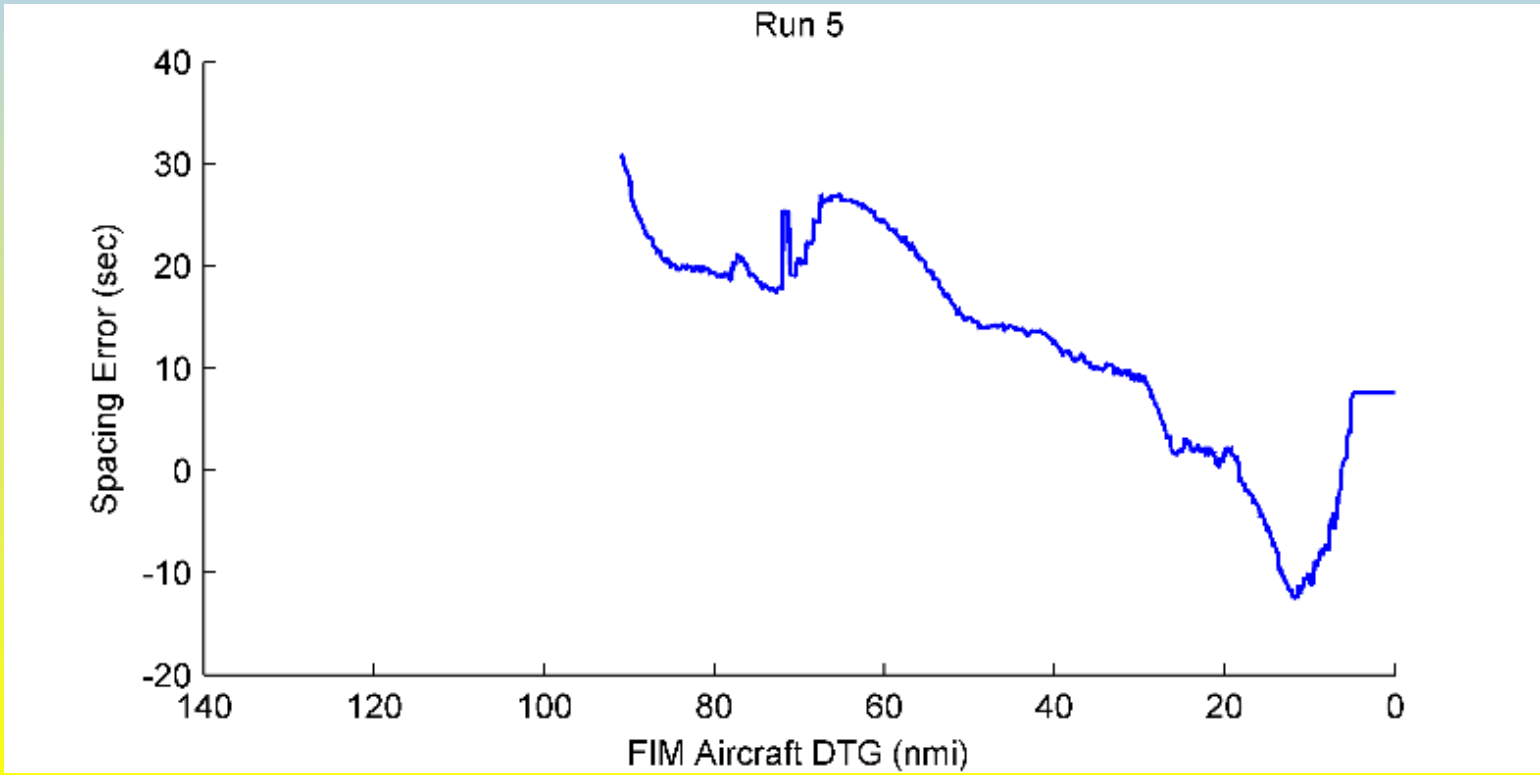
Groundspeed Deviation 5



Airspeed 5

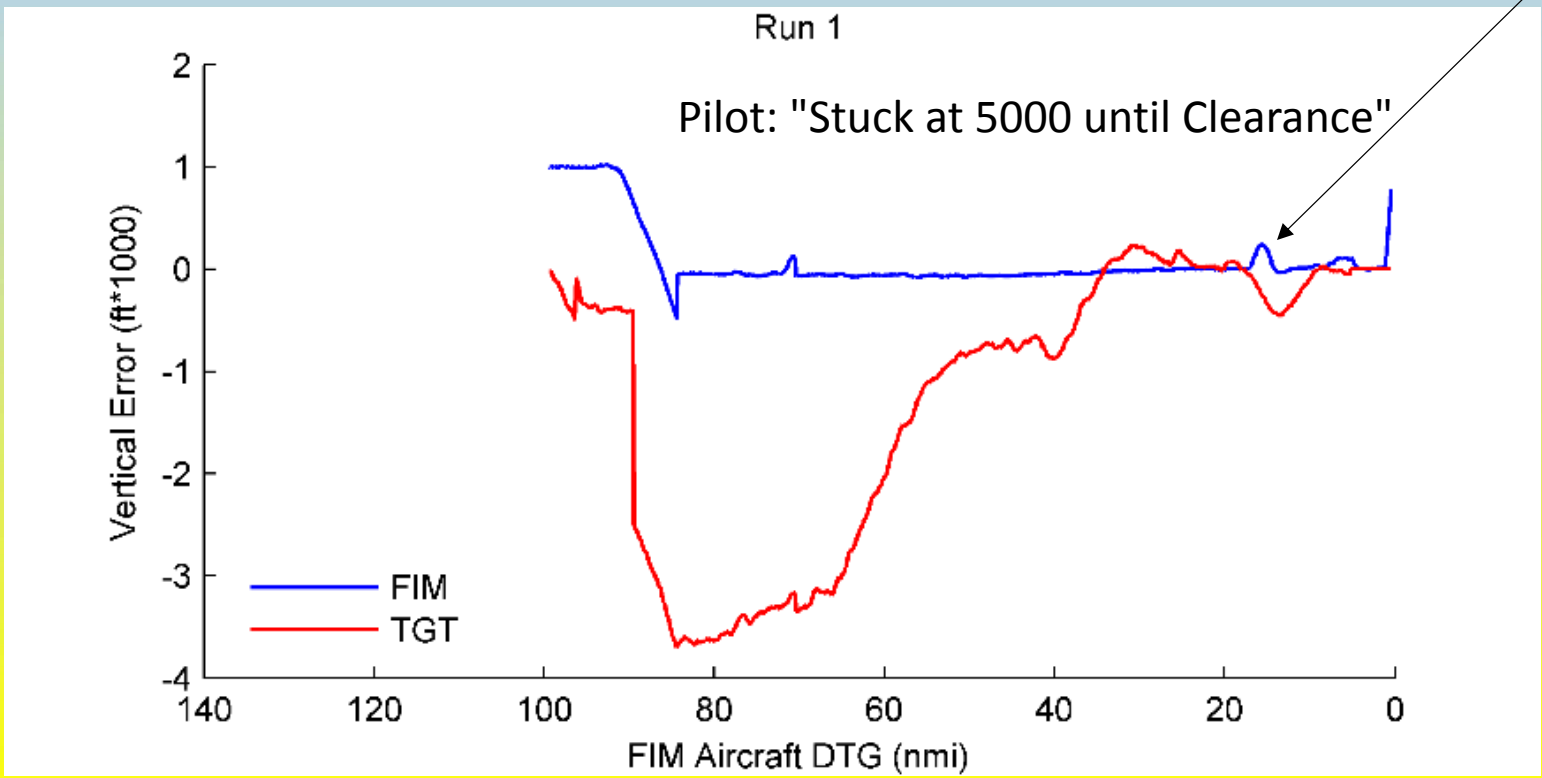

Run 5
Airpeed (kt)
320
300
280
260
240
220
200
180
160
140
ProfileCAS
CmdCAS
CmdEnd
CAS
140
120
100
80
60
40
20
0
FIM Aircraft DTG (nmi)

Spacing Error 5

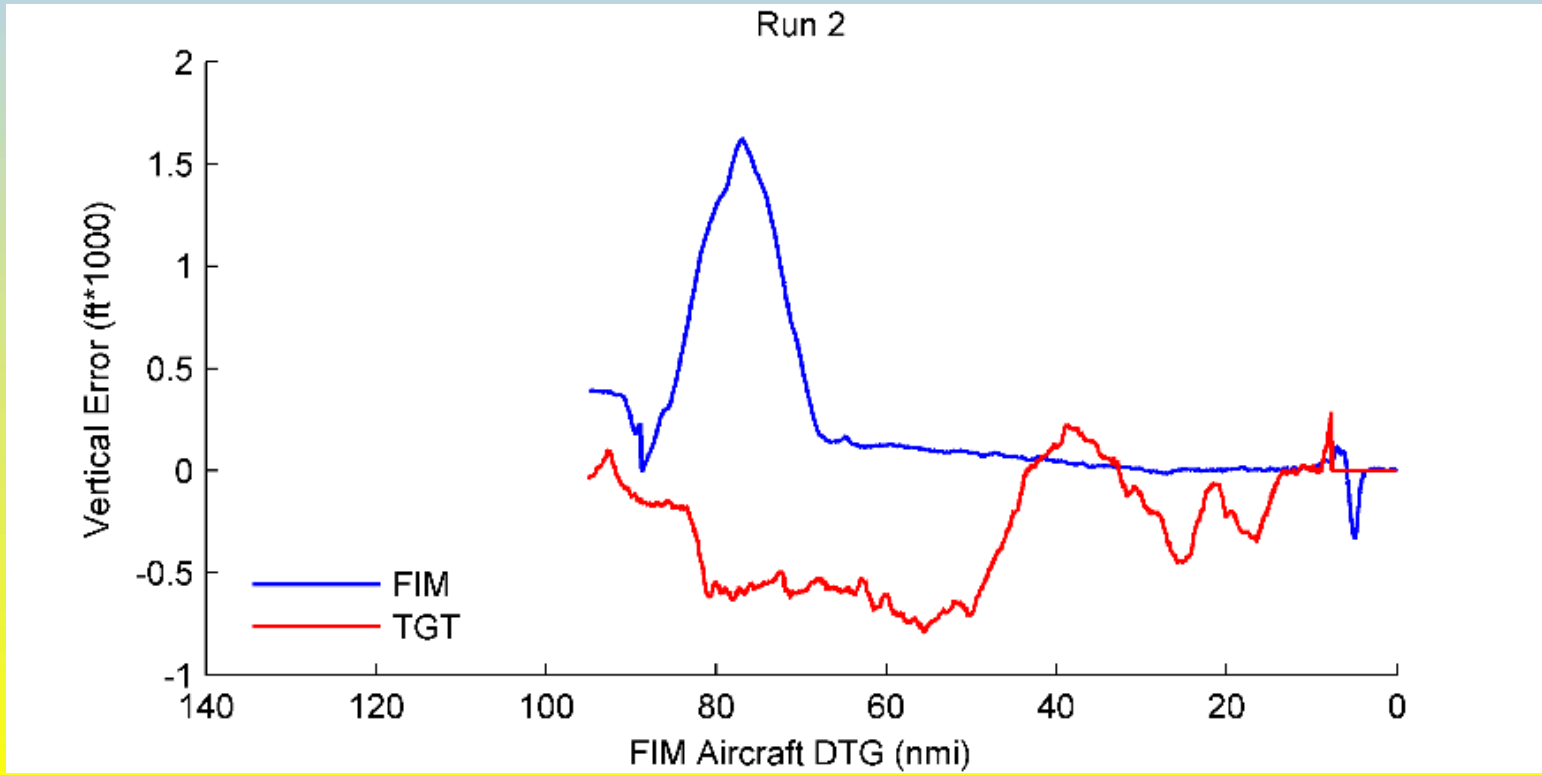


Vertical Track Error 1

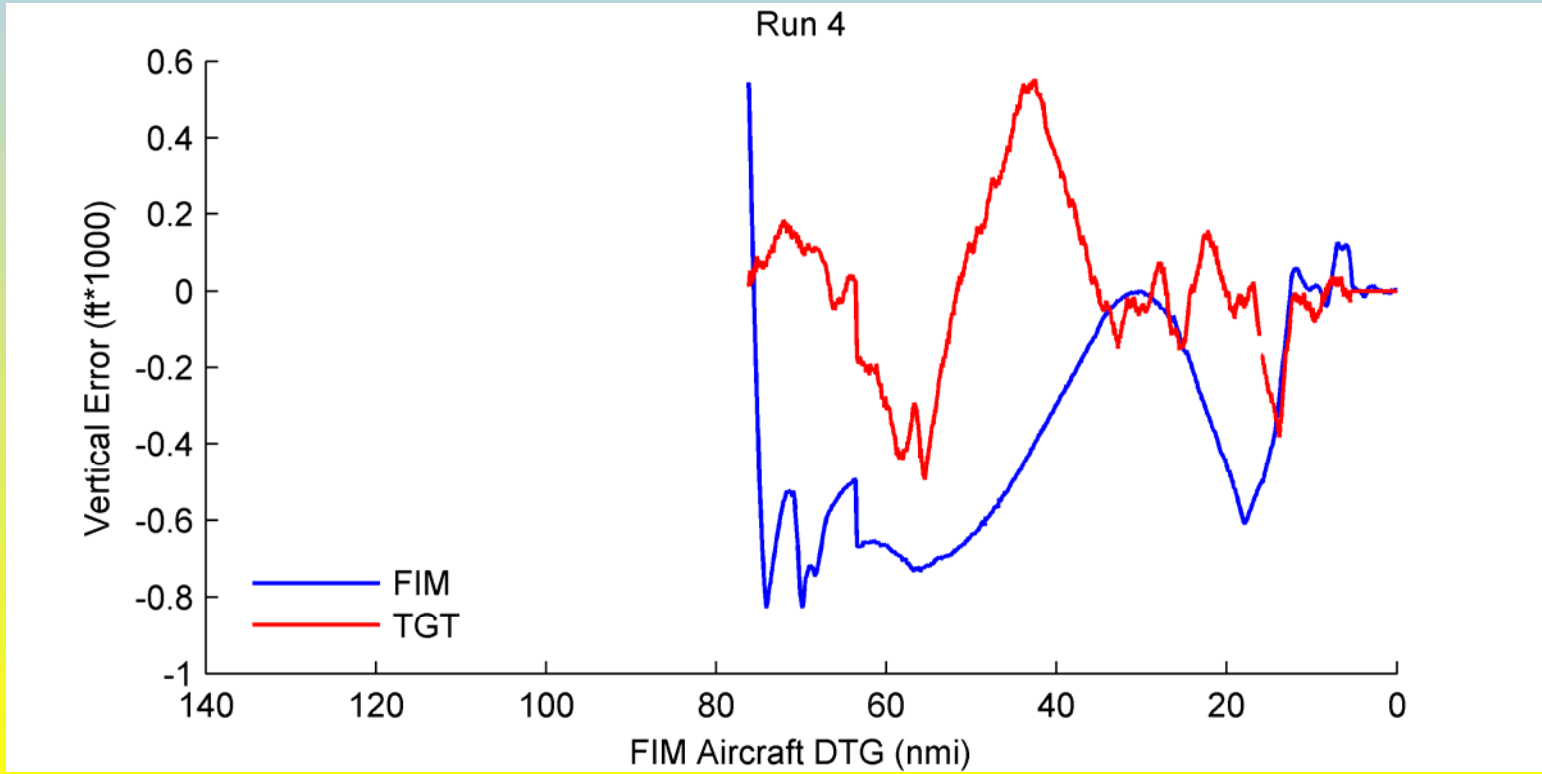
"Cleared SUBDY descent down to 5000"



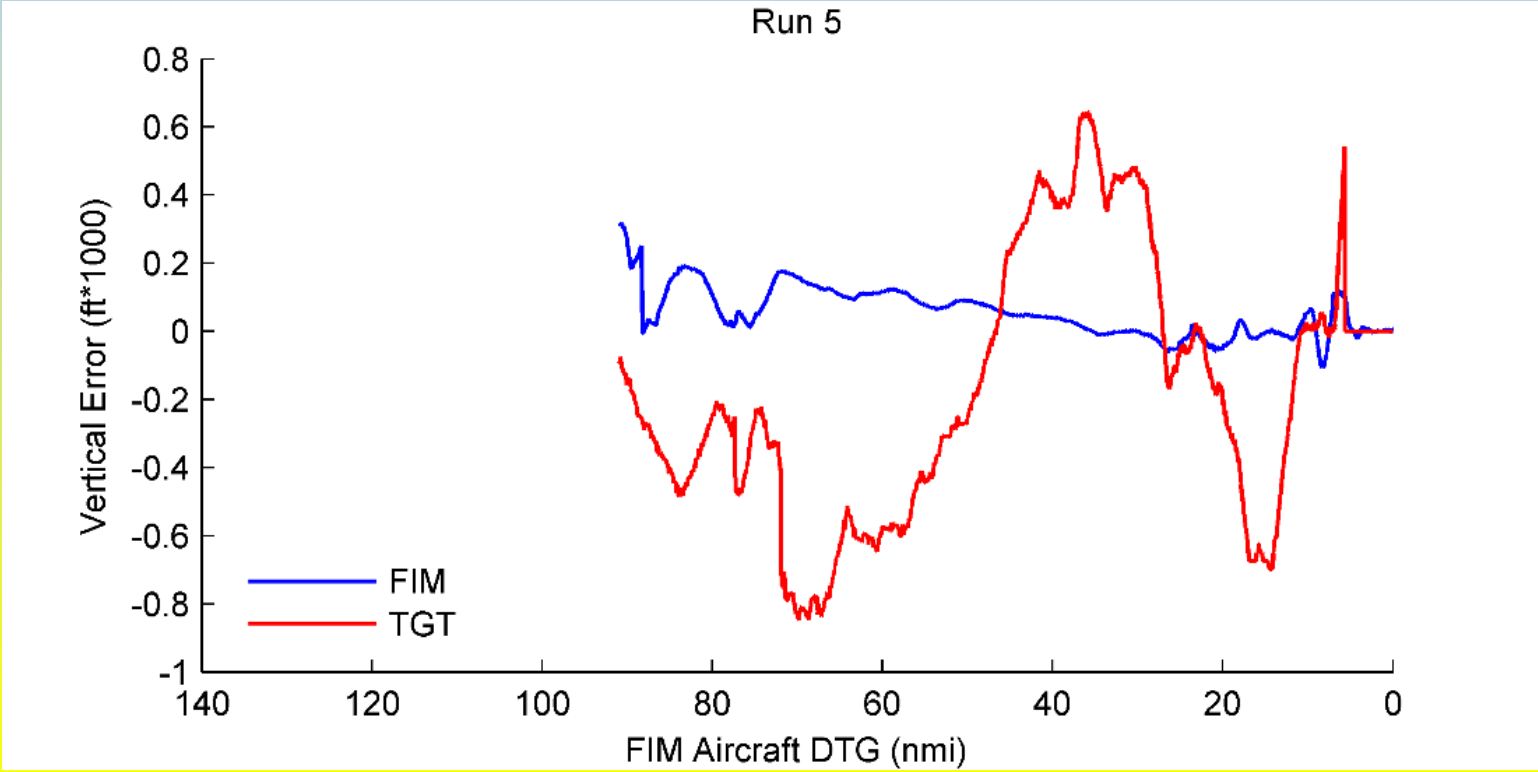
Vertical Track Error 2



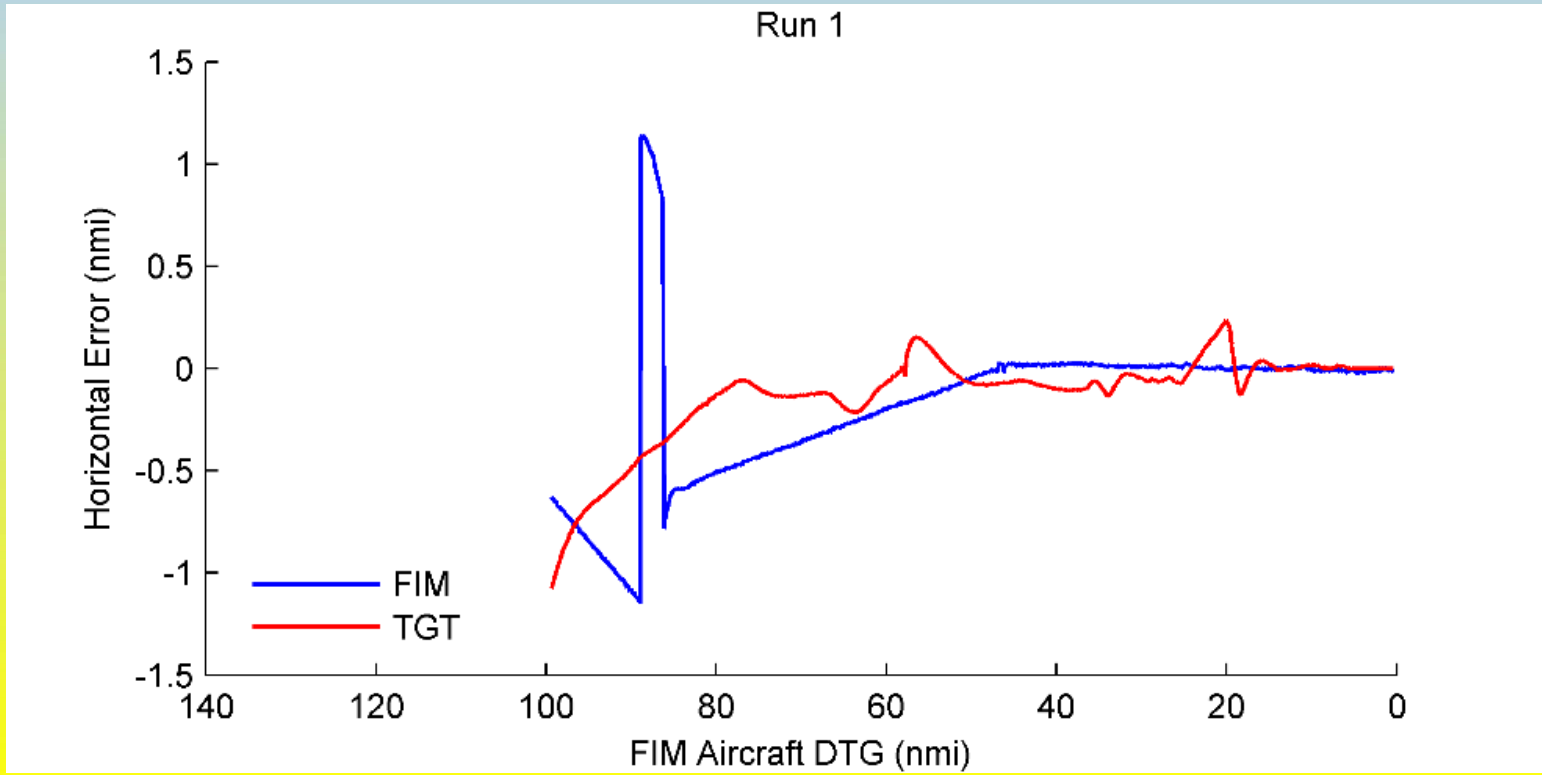
Vertical Track Error 4



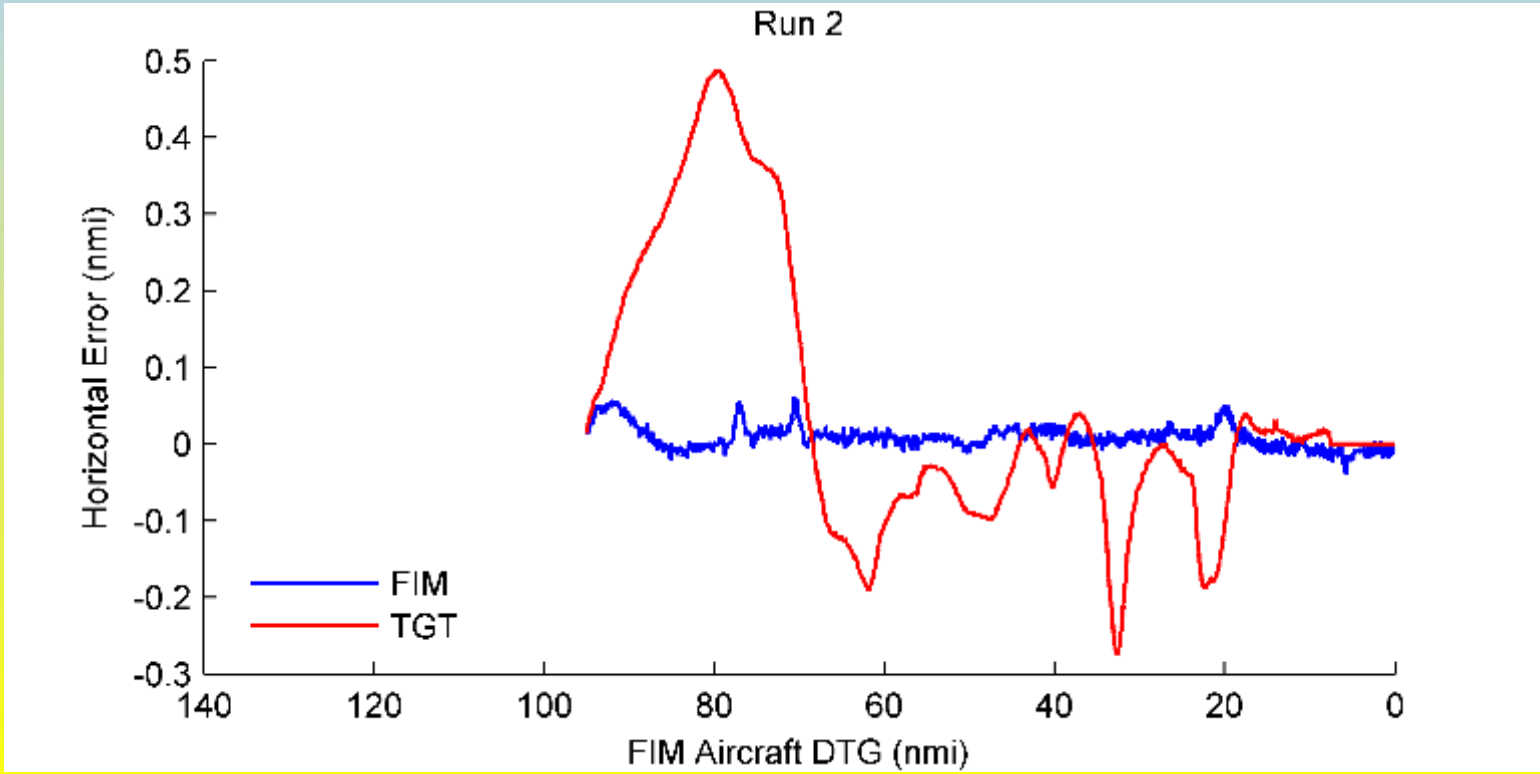
Vertical Track Error 5



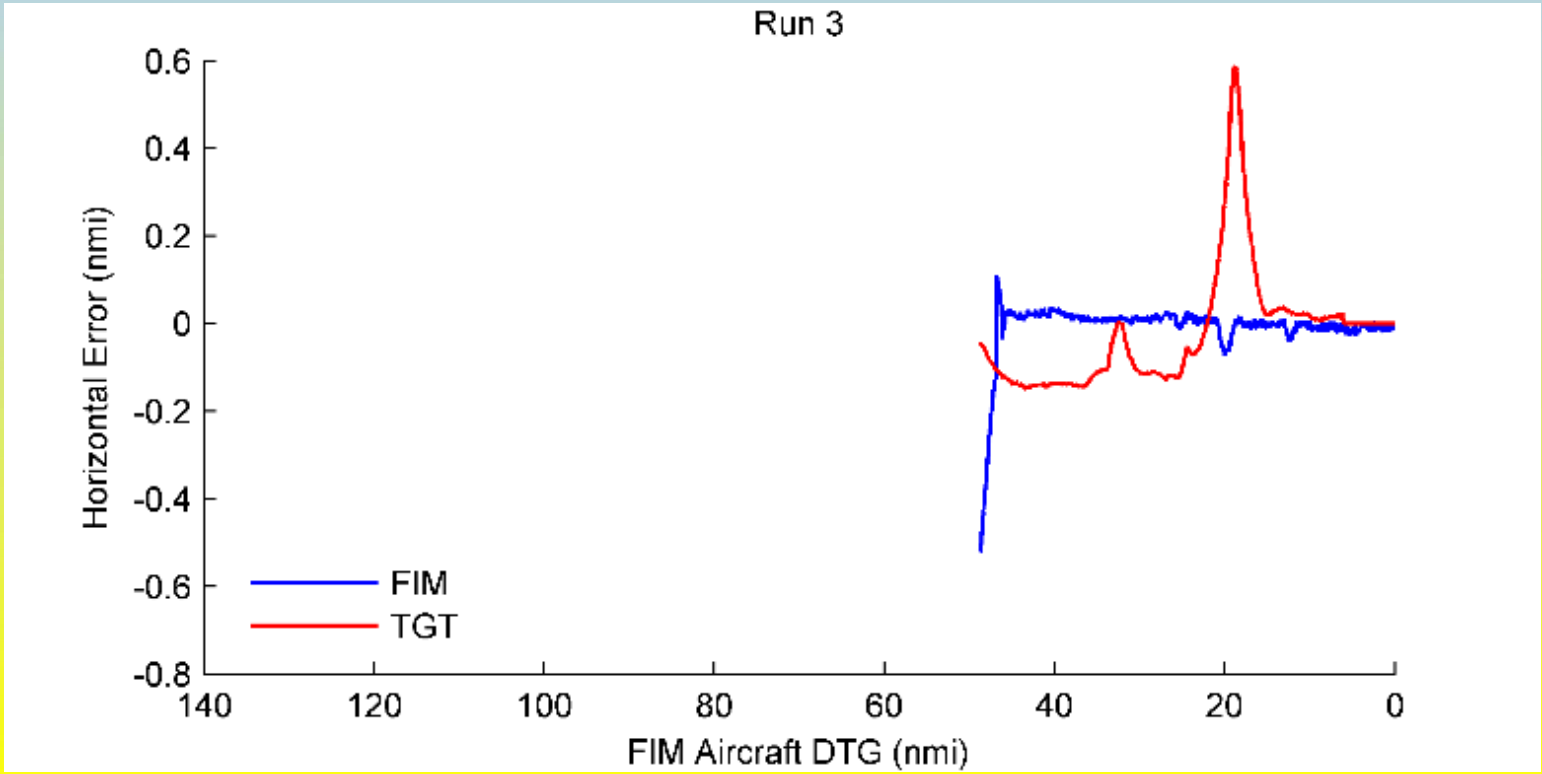
Horizontal Track Error 1



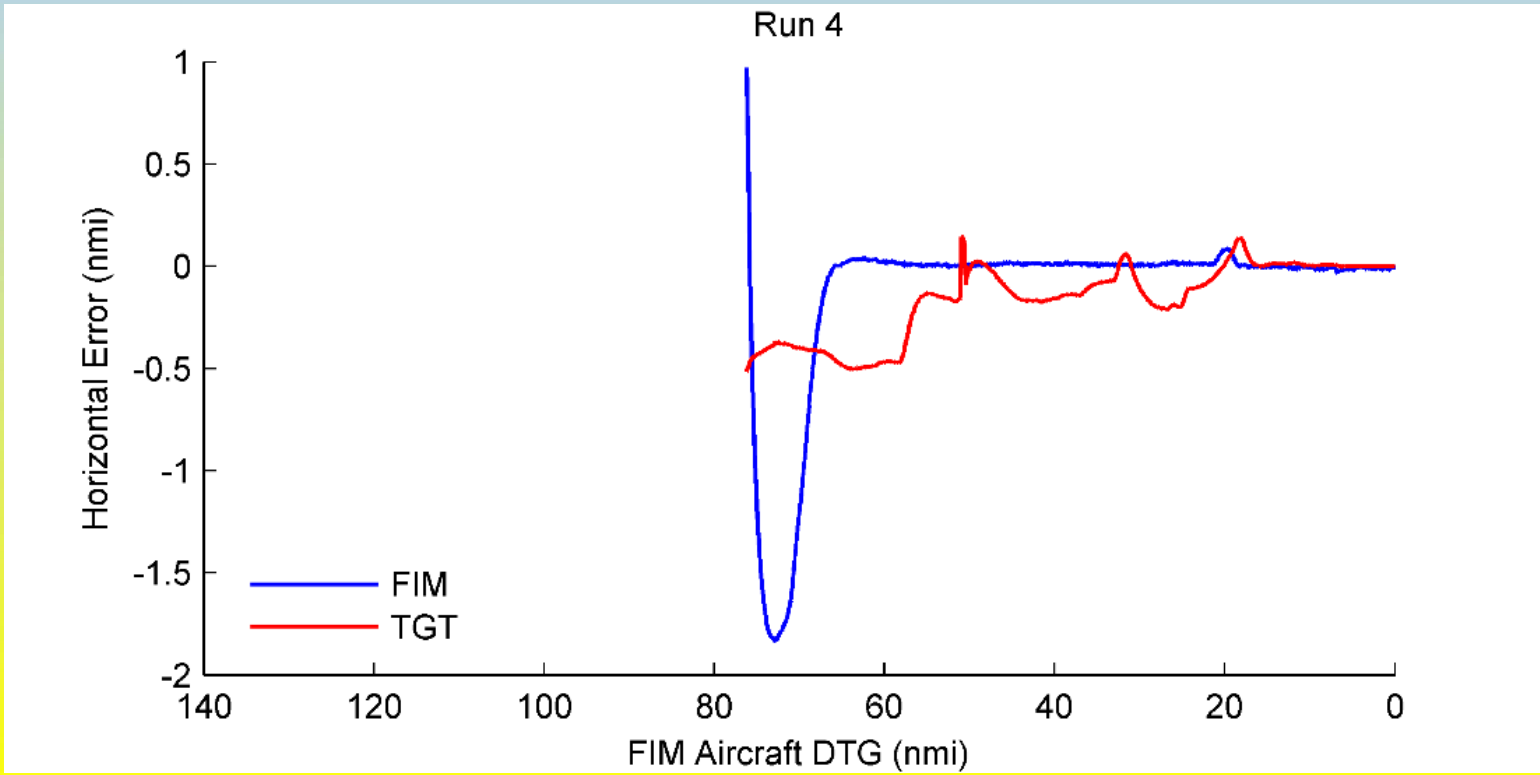
Horizontal Track Error 2



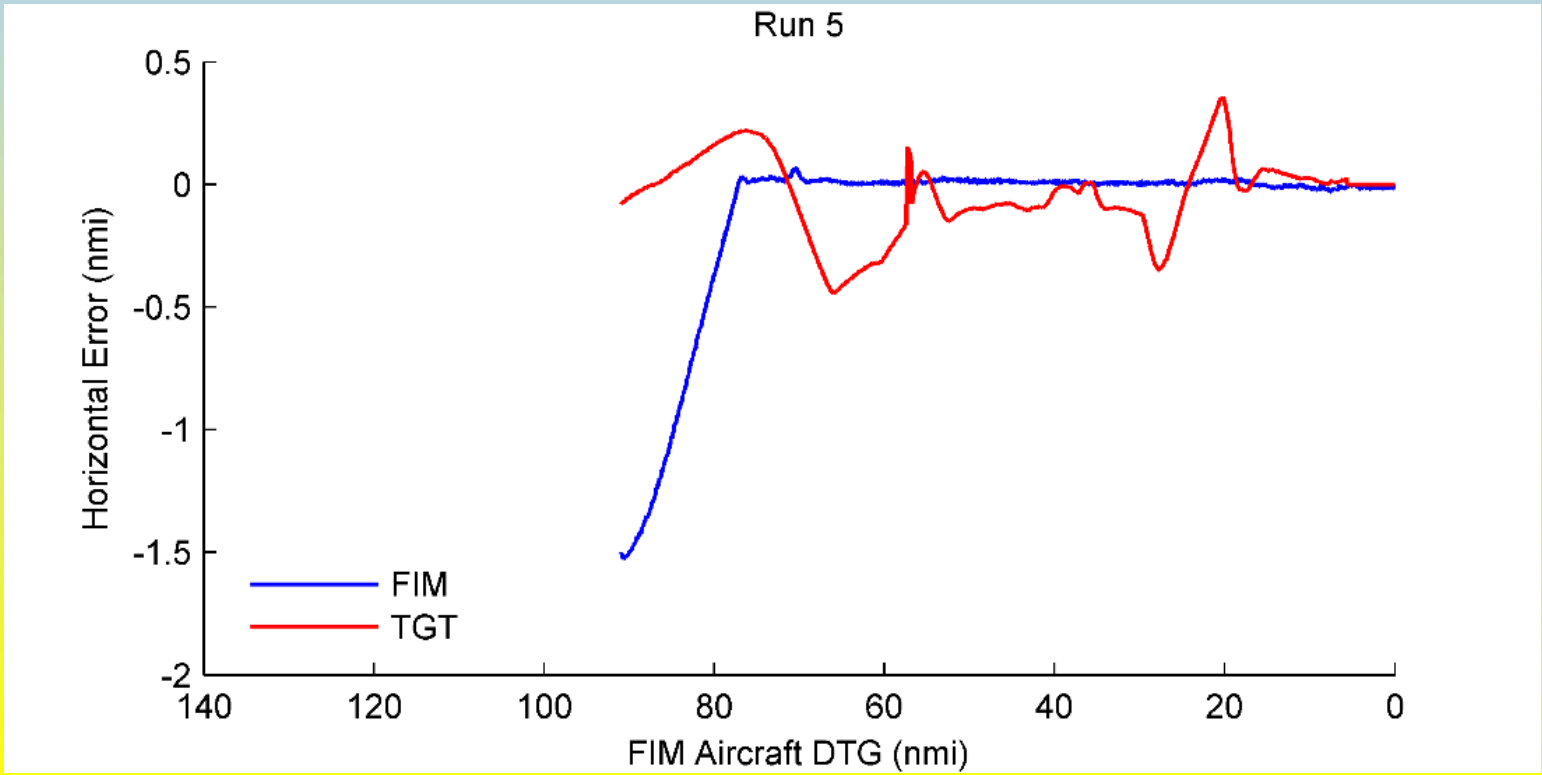
Horizontal Track Error 3



Horizontal Track Error 4



Horizontal Track Error 5



Test Issues

- ADS-B was experimental and circuit breaker had to be reset just prior to testing (day of concurrent testing)
- Floating point issue with the Rockwell ISS unit
- Cmd speeds on inbound track sometimes below landing airspeed limitation for B787 (155 CMD v. 165 Stall for config.)
- T-38 fuel limited: Shortcut the route and time he had available to fly – affected aircraft positioning and decision making
- T-38 was vertically challenged to dodge icing and stay within the algorithm performance
- Winds aloft were not given until in the air.
- In-trail distances ranged 22.6 nm instead of 8.5 nm (We went almost three times the planned in-trail distance range – FIM can handle slop.)

Test Issues

- Substitute pilots the day of the demonstration.
- Pilots have no reference to perform FIM, no training – compare to simulation testing in RAPTOR/CA 5.3.
- T-38 performed teardrop entries, B787 didn't
- T-38 was GPS limited: Entered MWH, not KMWH to prevent flight plan termination. No time/ability to re-input everything.
- ATC re-input new flight plans after every run - High workload.
- Other conversations on a single party line meant waiting to issue speed commands, sometimes 20-30 seconds.
- B787 overly aggressive with the speed brakes on initial run, then under aggressive on subsequent runs.
- Simulation studies designed the simulated aircraft to fly route to the runway. Unintended consequence: No summary log if the aircraft doesn't land.

Safety Issues

- Fuel leak in one of the wings, while being fixed a second leak was discovered. Boeing suggested they would fly off the gas in the other wing and central tank. (not discussed in prebrief)
- Icing along route using an aircraft not equipped with deice
- 1 out of 2 radios lost at startup on T-38 – Pilot could either communicate with ATC or the B787, but not both. He decided if he declared it, the test would get cancelled.
- Resulted in ATC confusion, because T-38 was communicating when not expected. (B787 was communications leader)
- B787 was eager to get to same frequency with T-38 because it was the only way either could know what the other a/c was doing (or else T-38 had to leave ATC frequency)

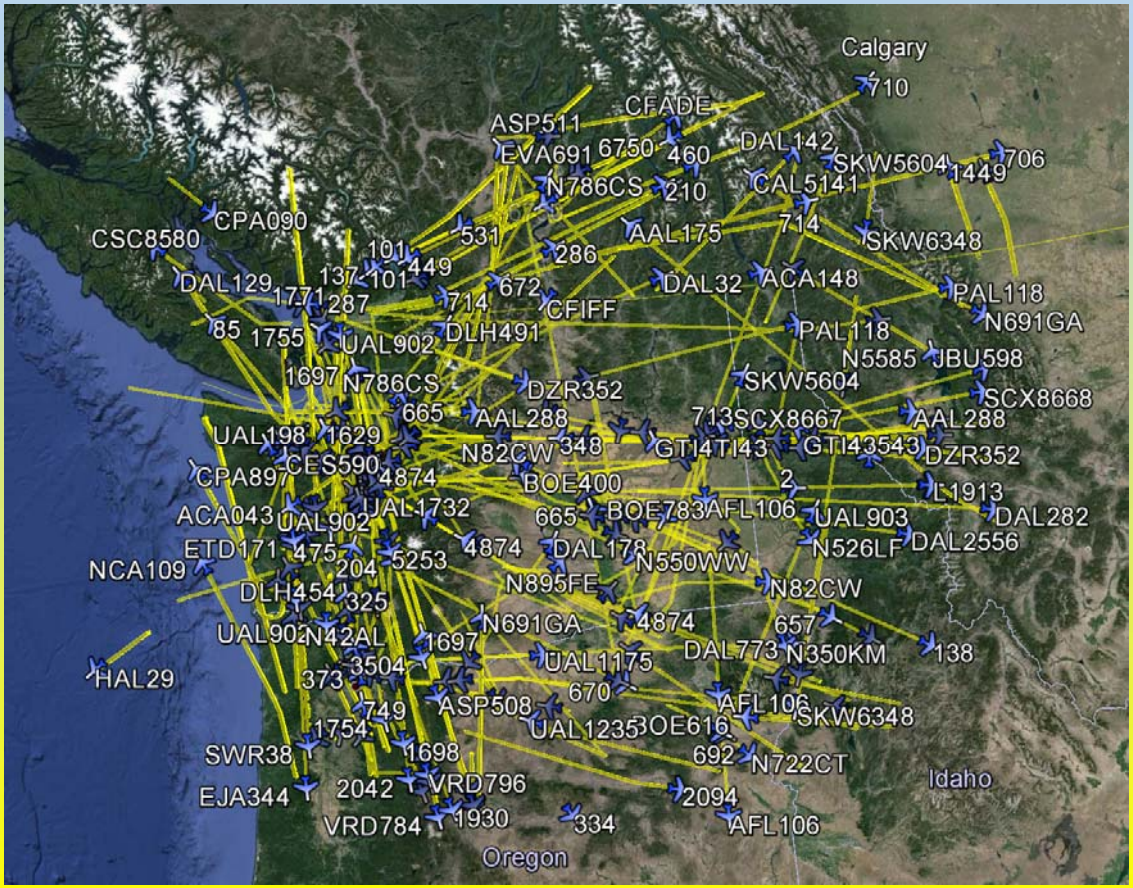
Lessons Learned

- Key logging for the Flight Test Gateway output (when we check to see where aircraft are located in reference to us)

  -Allows for a point of reference

- Streamline route building, testing, and packaging
- Realtime .kmz graphics on Google Earth
- Color coordination on the .kmz files to recognize On/Activate/Execute periods graphically
- Large database for queries to pull in different data sets
- Training – Better pilot understanding of FIM and test setup. If one does teardrop, then “follow the leader”.
- Summary logs without Weight-on-Wheels

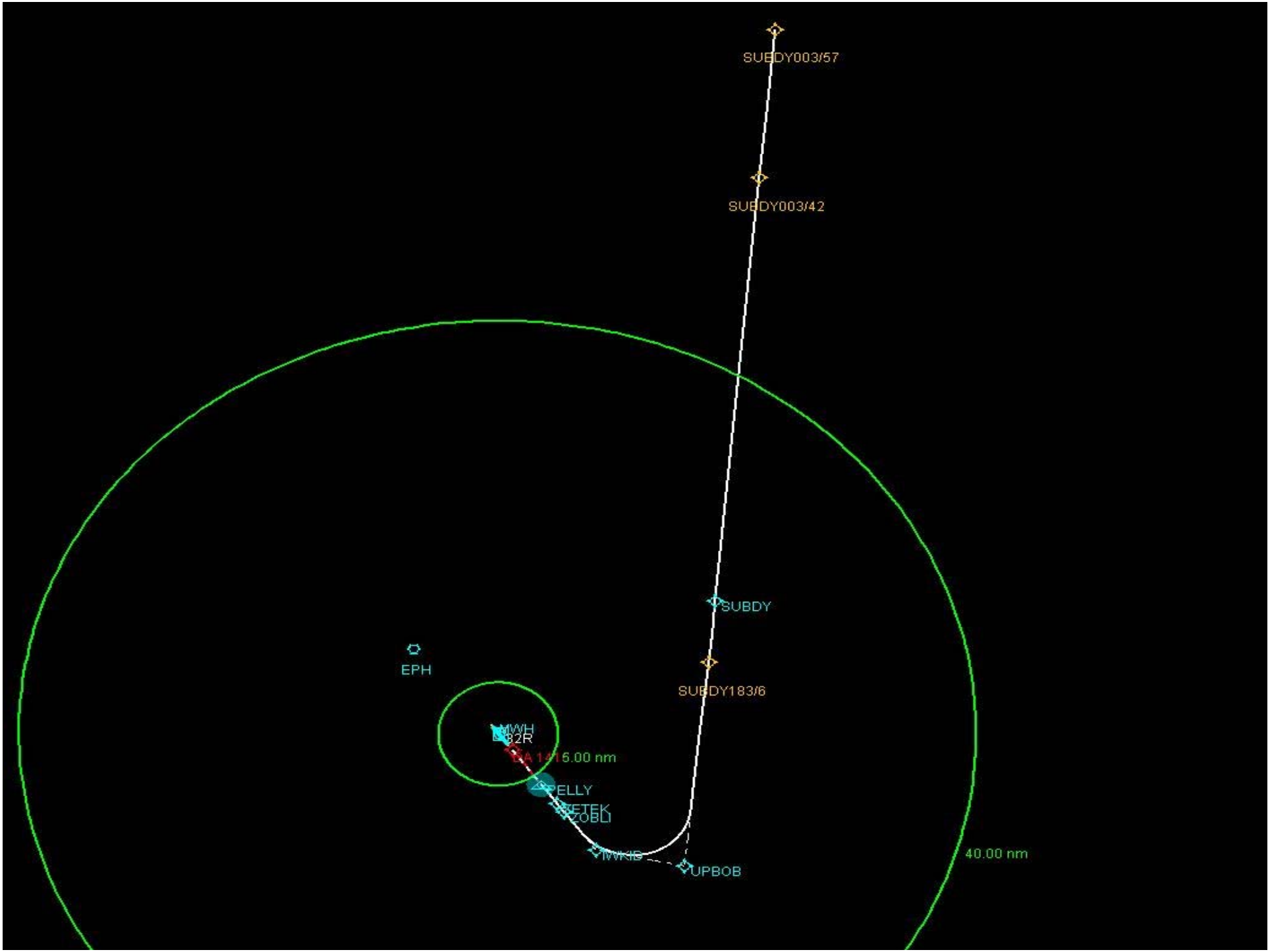
Lessons Learned



- We have all the ADS-B data for other aircraft while we flew.
- We can build new custom routes that allow us to FIM behind them in simulation and further verify our software and algorithm.

Lessons Learned

- ASTAR In/Out data
- ERAM displays from Seattle Center
- Boeing providing flight deck display videos and timestamp
- Analysis meeting scheduled Friday, Jan. 30, 2015 to discuss gathered data


SUBDY003/57
SUBDY003/42
SUBDY
SUBDY183/6
EPH
MWH
32R
16.00 nm
ELLY
ETEK
ZOBLI
WRKIB
UPBOB
40.00 nm