30th Digital Avionics Systems Conference
Seattle, October 16-20, 2011

Trajectory Synchronization between Air and Ground Trajectory Predictors

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Trajectory Based Operations (TBO)

- Trajectory-based control requires accurate 4D trajectory (4DT) predictions of the entire flight
- 4D trajectory is the estimated path a moving aircraft will follow through the airspace (AP16)
  - Mathematical representation: time-ordered set of trajectory change points (TCPs)
    - Time, Lat, Lon, altitude, speed (at a minimum; all available in the ADS-C EPP)
    - Rate of climb/descent (ROCD), accelerations, uncertainties, ETA bounds, etc. (ancillary data)

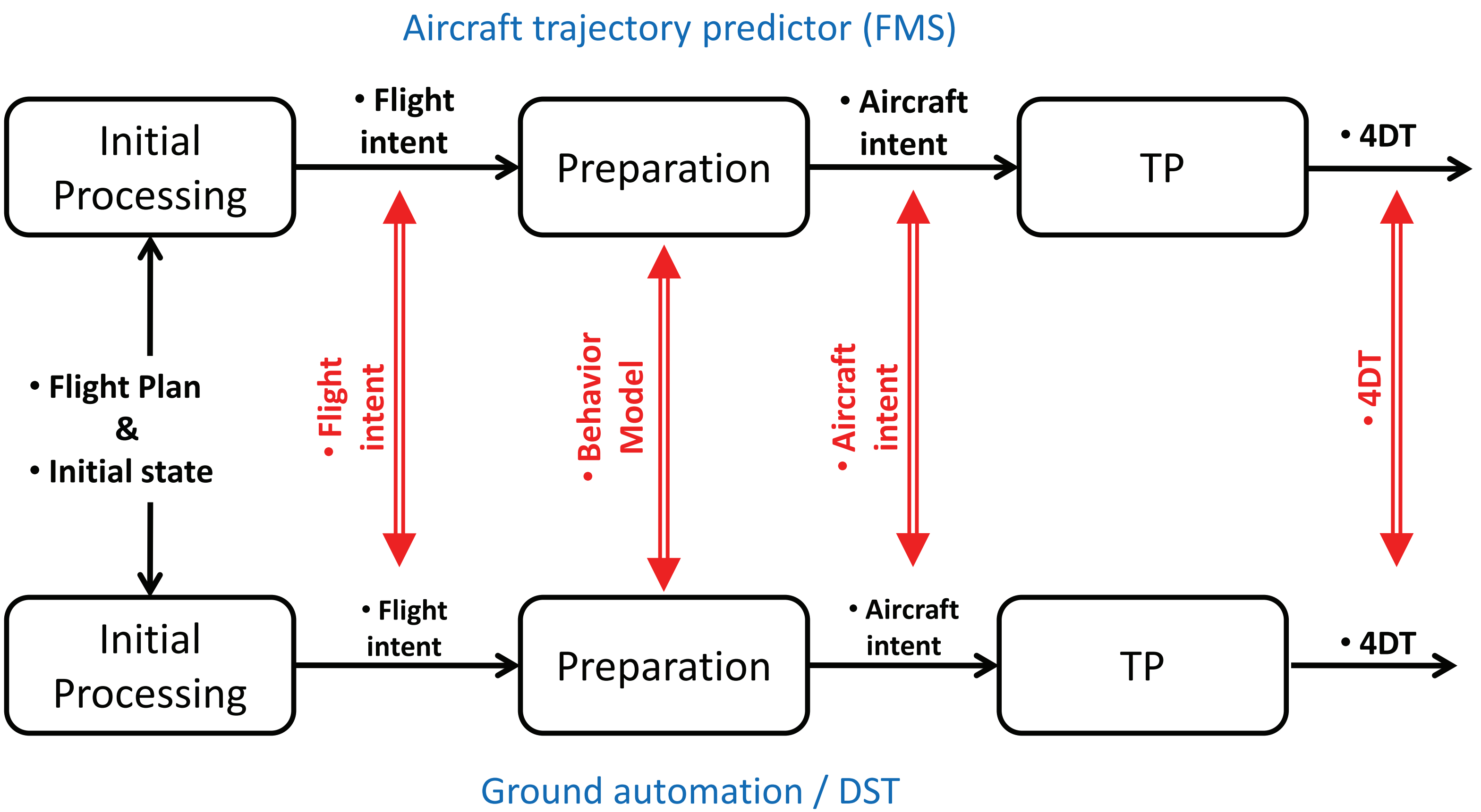
Trajectory Synchronization (I)

- Preferred trajectory (business trajectory) reflects user's preferences
  - A key concept in TBO
- Flight management systems (FMS), ground automation systems and decision support tools (DSTs) operate using their own version of the 4DT
  - In TBO air and ground systems must have a consistent 4DT of the flight
- Different systems have different objectives, hence the concept of a shared "common trajectory" is not practical
  - Differences in trajectories built by disparate systems generate interoperability issues, and
  - Prevents the business trajectory to be fully realized
- Trajectory synchronization and negotiation address both problems

Trajectory Synchronization (II)

- Trajectory synchronization
  - Process of resolving trajectory discrepancies such that any remaining differences are operationally insignificant
- Focus on air-ground trajectory synchronization
  - Air (FMS) trajectory directly reflects user's preferences, and
  - is used for close-loop guidance
- Goal of trajectory synchronization
  - Increase the likelihood of flying the business trajectory

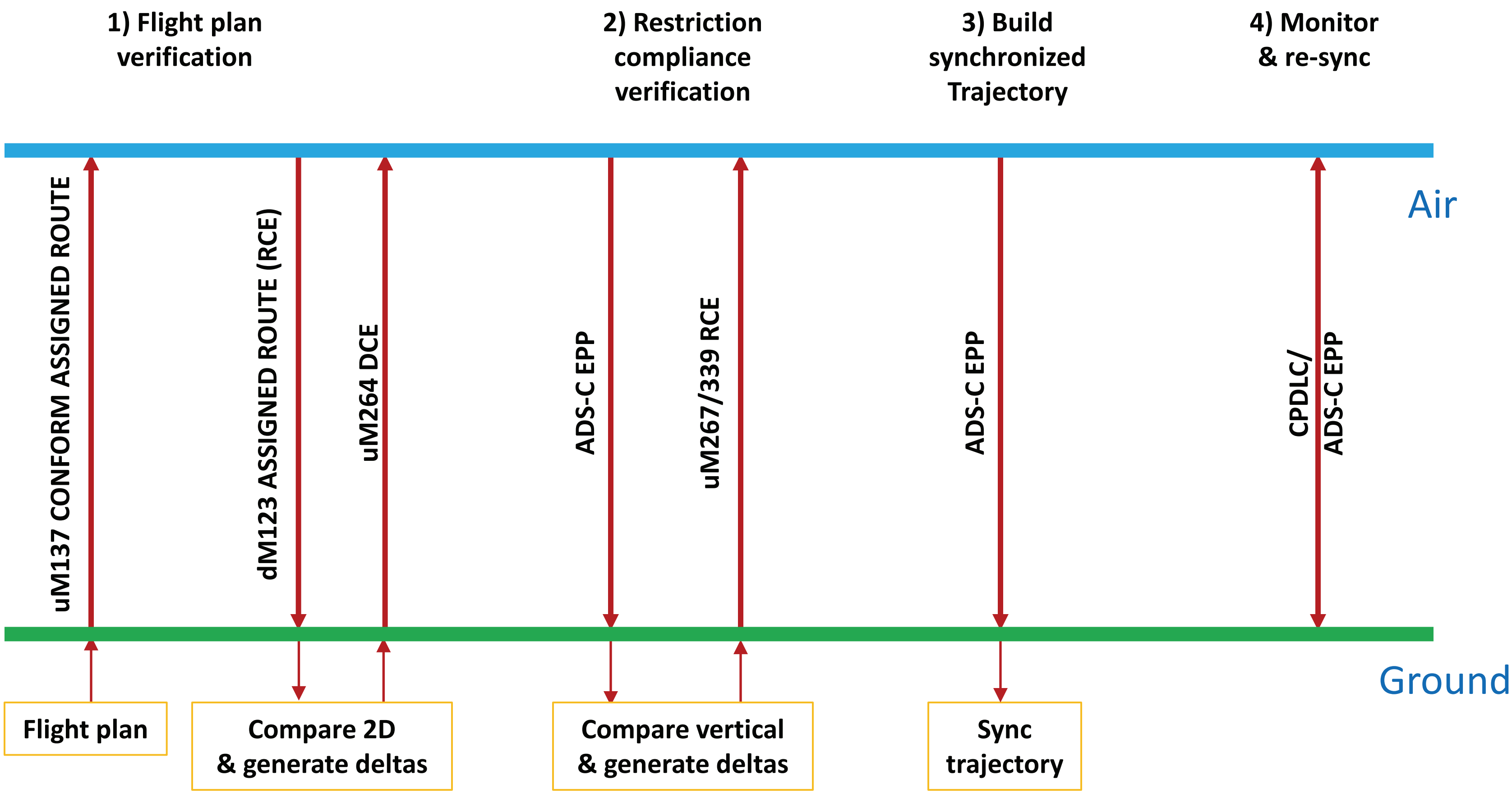
Air-Ground Data Exchange Mechanisms for Trajectory Synchronization



Air-Ground Data Exchange for Trajectory Synchronization

- Pre-departure synchronization
  - TBO trajectory-based pre-departure clearances requires solving discrepancies
  - Core synchronization operation
- Dynamic synchronization
  - Required to maintain synchronization whenever conditions change the predicted trajectory
  - Flight initiation, route amendment, conflict resolution maneuvers, etc

Pre-Departure Synchronization Steps

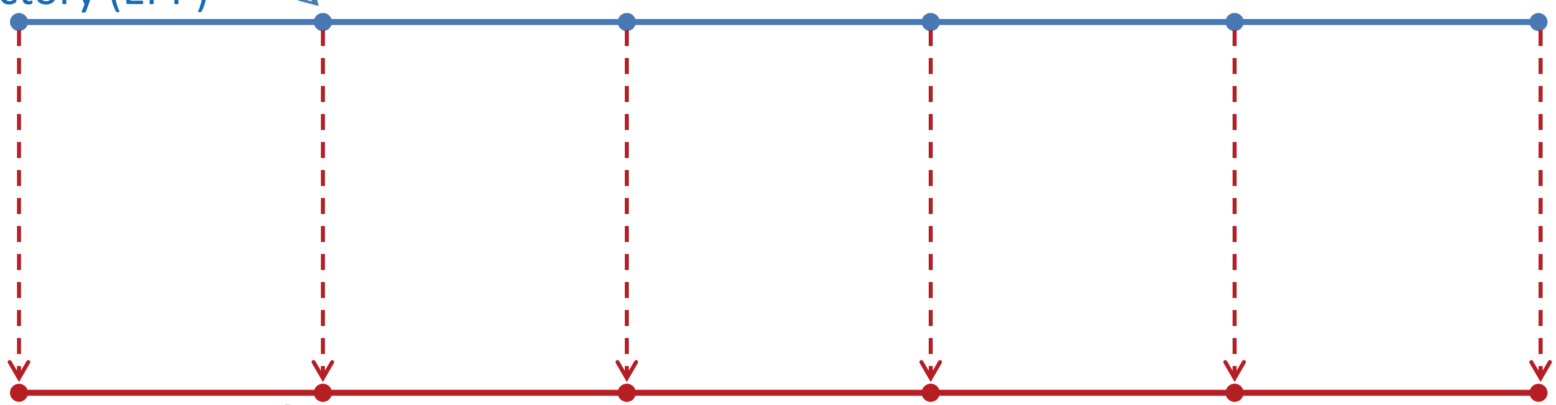


Indicated CPDLC messages are loadable to the FMS

Building the Synchronized Trajectory

Trajectory Change Point (TCP)
- time
- position (lat/lon)
- altitude
- speed

FMS trajectory (EPP)



Synchronized trajectory

1. TCP info copied from EPP
- time
- position (lat/lon)
- altitude
- speed

2. Build trj segments using native data structures and EPP info

Segment acceleration is implied (assumed constant). System is overdetermined:

$$a = \frac{2(L - V_0 T)}{T^2}$$

$$a = \frac{V_1 - V_0}{T}$$

ROCD is implied/derived (assumed constant)

3. Check for wind data discrepancies

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Sampling Errors of Synchronized Trajectory

With,
T = segment duration,
b = da/dt = acceleration rate of change

$$\varepsilon_v = \frac{bT^2}{6}$$

Speed error at the end of segment when implied acceleration is not constant

$$\varepsilon_x = \frac{2bT^3}{81}$$

Maximum longitudinal error at the segment mid point when implied acceleration is not constant

$$\varepsilon_x = \frac{\sigma_v T}{4}$$

Longitudinal error due to speed uncertainty (σ_v) at start of segment

$$\sigma_h = \frac{a_h T^2}{8}$$

Altitude error when ROCD is not constant (a_h = vertical acceleration)

Interpolation errors can be maintained below a given threshold by controlling segment duration (or length)

Differences in Earth models (air vs ground) is another source of errors

Use of Aircraft Intent and FMS 4DT for Trajectory Synchronization

Pros	Cons	Approach
FMS 4DT		
Captures accuracy of APM used by FMS	Usefulness decreases when aircraft state deviates outside conformance bounds or intent is amended	Maintain a dynamic synchronization control loop that triggers a synchronization cycle when out of conformance is detected
Contains (directly or derived) some amount of aircraft intent (i.e. speeds)	Accuracy subject to sampling errors	Sampling errors can be maintained below operationally acceptable levels by controlling segment size (via insertion of Along Track Waypoints allowed by route clearance enhanced CPDLC messages)
	A 4DT is one realization of the FMS trajectory predictor. Not usable for "what-iffing"	Some aircraft intent is directly provided in the FMS 4DT; additional aircraft intent can be derived from the FMS 4DT
Required data exchange can be accommodated in existing or planned Data Comm standards (CPDLC & ADS-C EPP) - Use of EPP considered in SC-214 4DTRAD Service	Accuracy affected by wind forecast errors used by FMS	Wind data could be uploaded to the FMS
Aircraft Intent		
Completely defines the maneuvers that the aircraft intends to follow	Prediction depends on fidelity of aircraft performance model (APM)	
Information can be used for "what-iffing"	Prediction depends on aircraft state and performance parameters that may not be available (i.e. cost index, mass, etc.)	
	Not all of the aircraft intent data items required to build a trajectory are included in current [or in development] Data Comm standards	

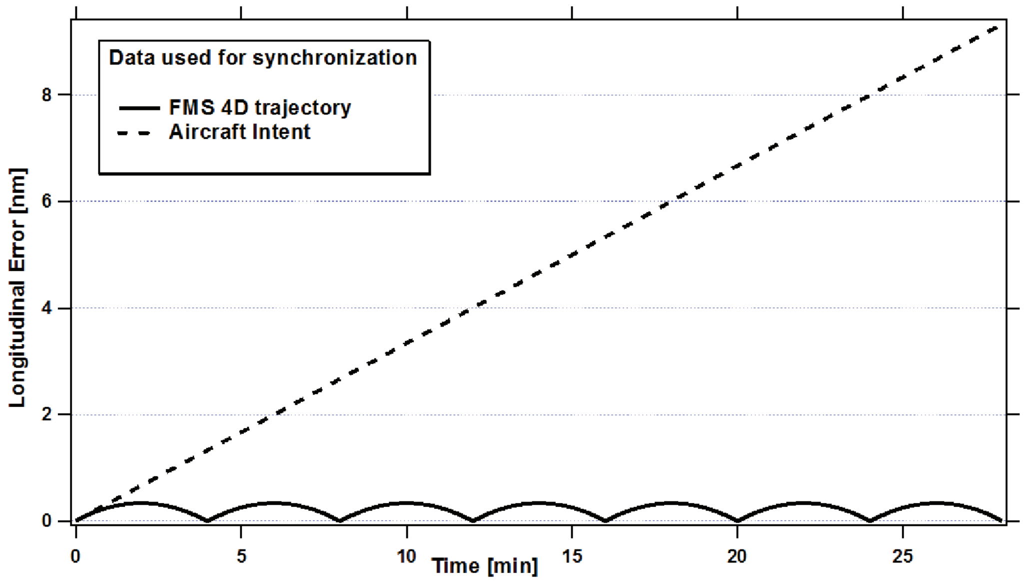
Illustration of Longitudinal Differences Using EPP for Synchronization vs Speed Schedule Alone

Example of air-ground trajectory differences when modeling a cruise phase of 210 nm in length in two cases:

1. Using aircraft intent alone (cruise TAS = 450 knots),
2. Using the EPP to build the synchronized trajectory (as described)

Assume a ground speed uncertainty of 20 knots (for example due to expected speed variation when navigating based on cost index)

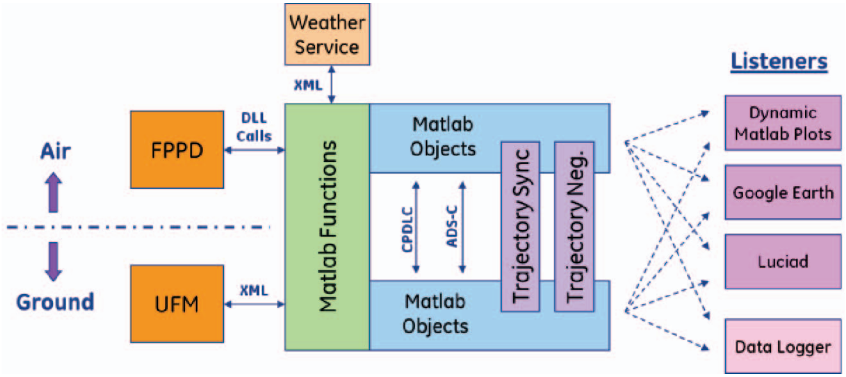
Whereas the synchronized trajectory using the EPP keeps the maximum longitudinal difference below a threshold (that depends on EPP segment duration), using speed alone results in an error that grows linearly with time and it is not bounded



Trajectory Synchronization Case Study

Pre-departure synchronization for a SFO-SEA flight

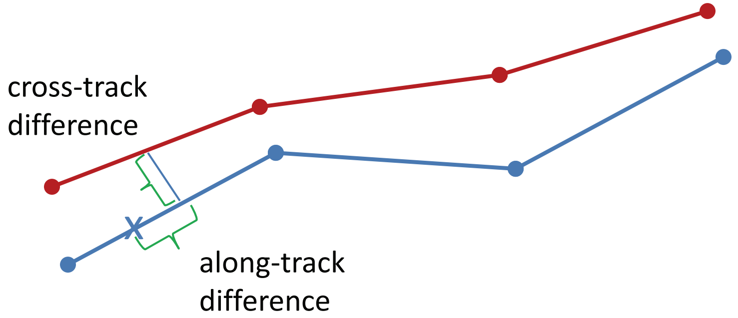
Simulation environment



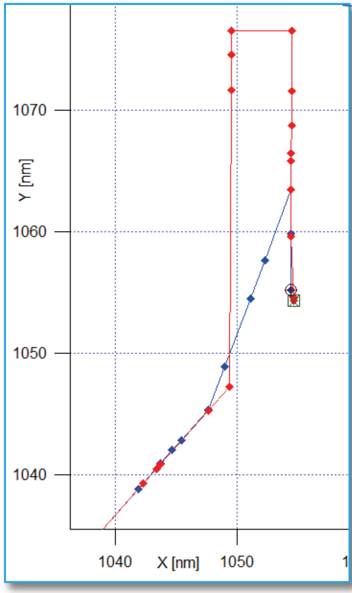
Trajectory comparison metrics (time-based)

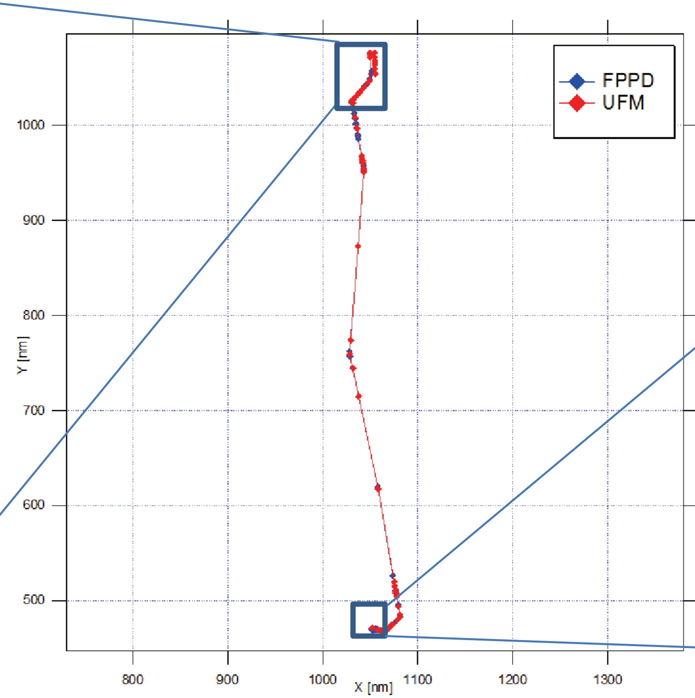
1. Resample trj1 & trj2
2. Project trj1 points on trj2
3. Measure differences in
   - cross-track
   - along-track
   - altitude
   - speed
4. Repeat for trj2 projected on trj1
5. Compute statistics of measurements

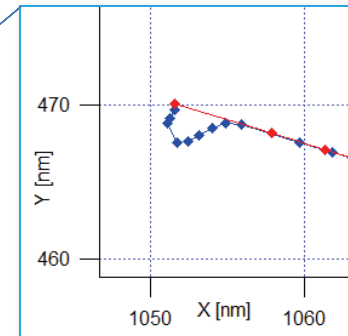
FPPD: Flight Plan Prediction Driver (based on FMS)
UFM: Unified Flight Manager



Pre-Departure Sync - Original

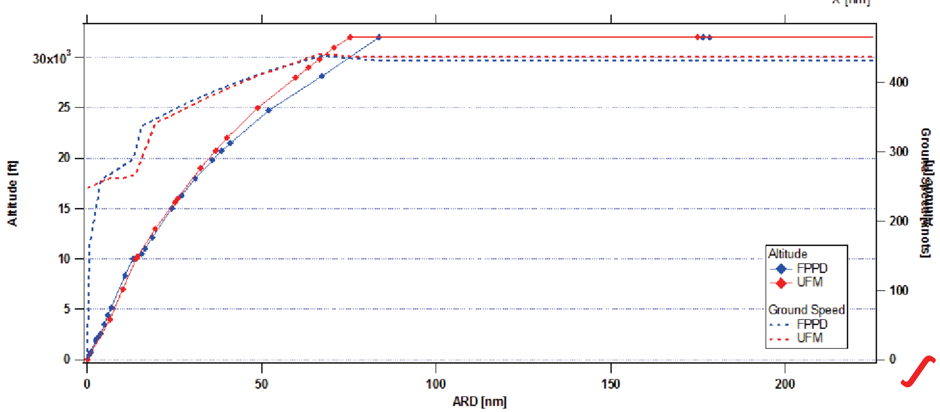


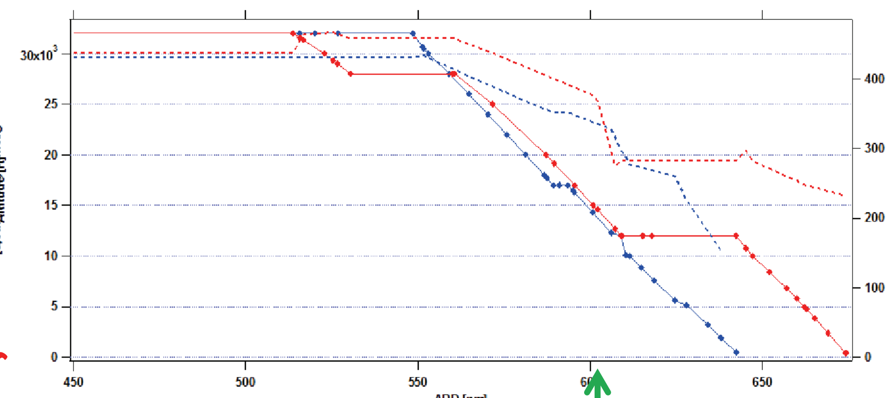




Difference Metrics	Peak	RMS
Along track [nm]	20.1	7.1
Cross track [nm]	13.9	1.8
Altitude [ft]	7297	2148
Time (ETA) [sec]	281	74

(*) metrics apply to entire trajectory using the same departure time

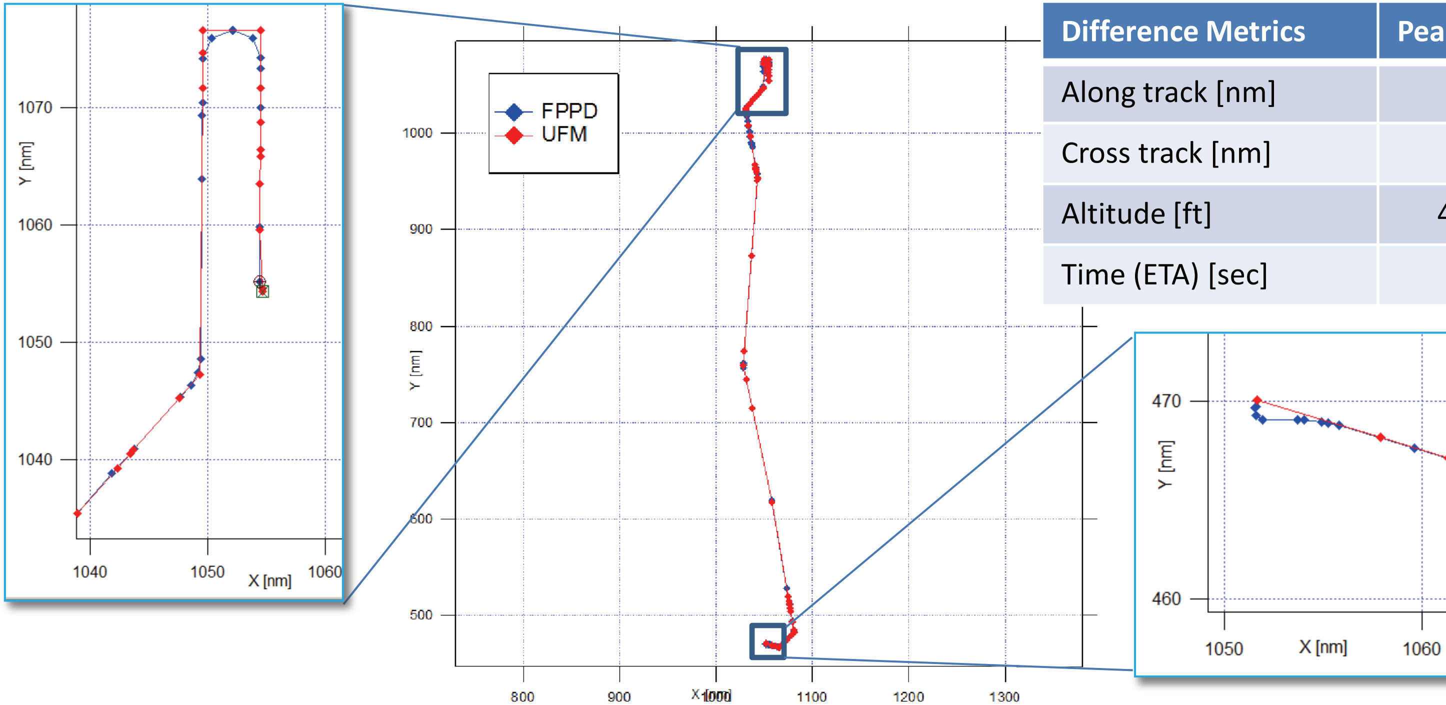


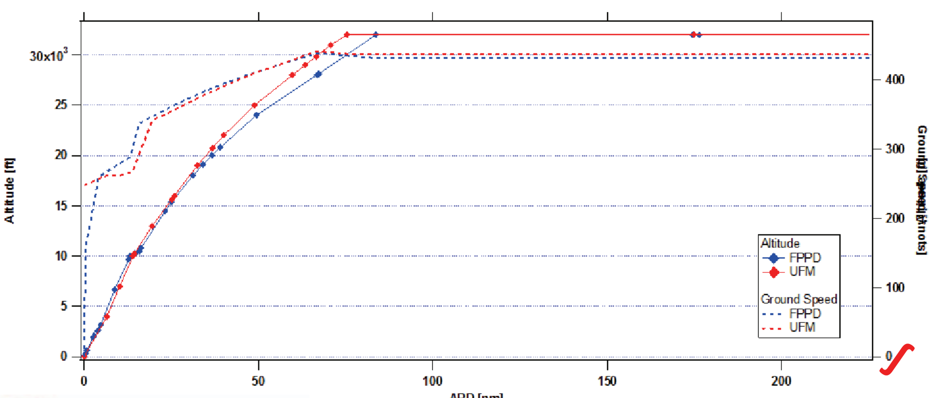


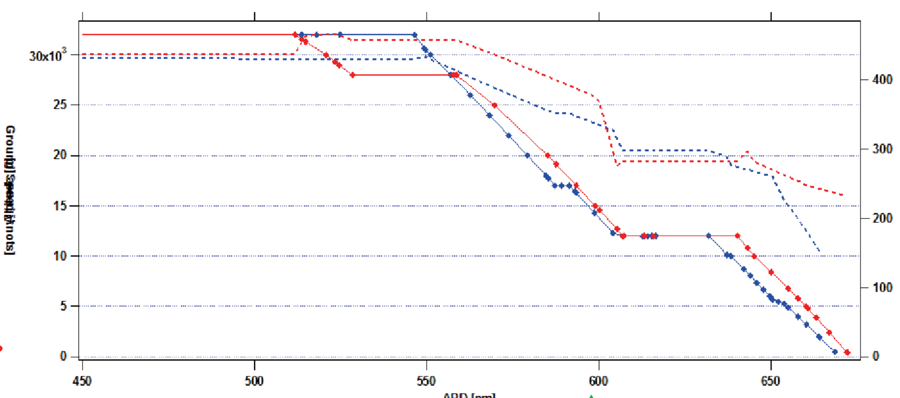
Vertical profiles relative to OLM

Pre-Departure Sync - After Route Amendment

Difference Metrics	Peak	RMS
Along track [nm]	11.9	5.5
Cross track [nm]	1.0	0.1
Altitude [ft]	4000	1240
Time (ETA) [sec]	154	58







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Vertical profiles relative to OLM

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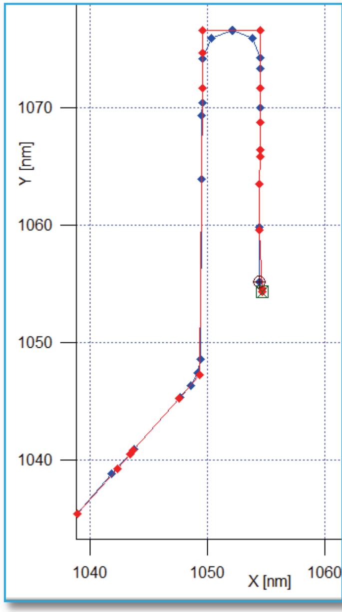
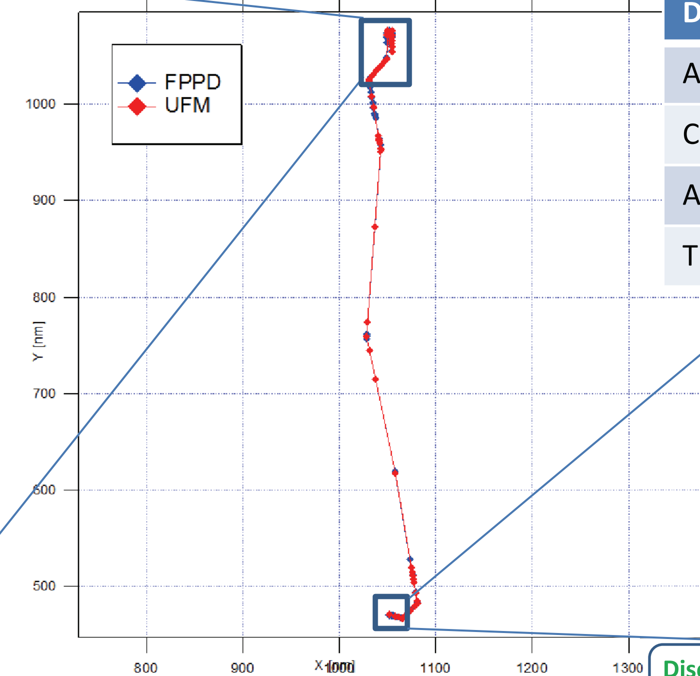
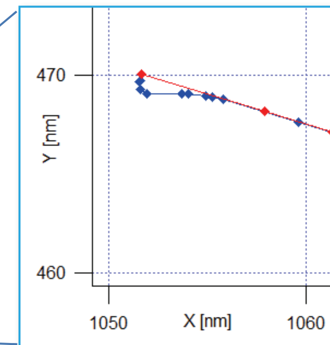
Pre-Departure Sync - After Restriction Compliance

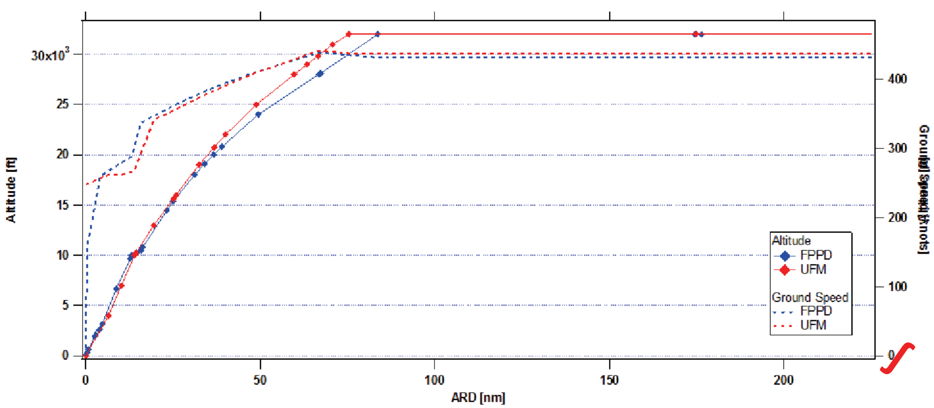


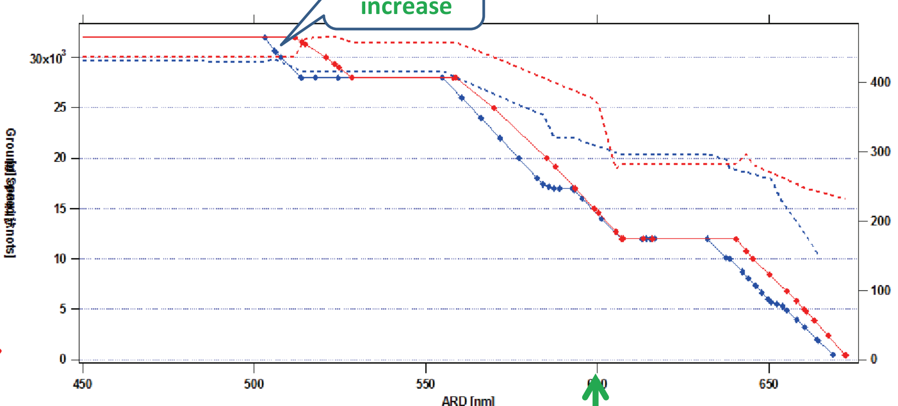


Difference Metrics	Peak	RMS
Along track [nm]	13.6	6.4
Cross track [nm]	1.0	0.1
Altitude [ft]	4737	1032
Time (ETA) [sec]	190	71



Discrepancy increase





Vertical profiles relative to OLM

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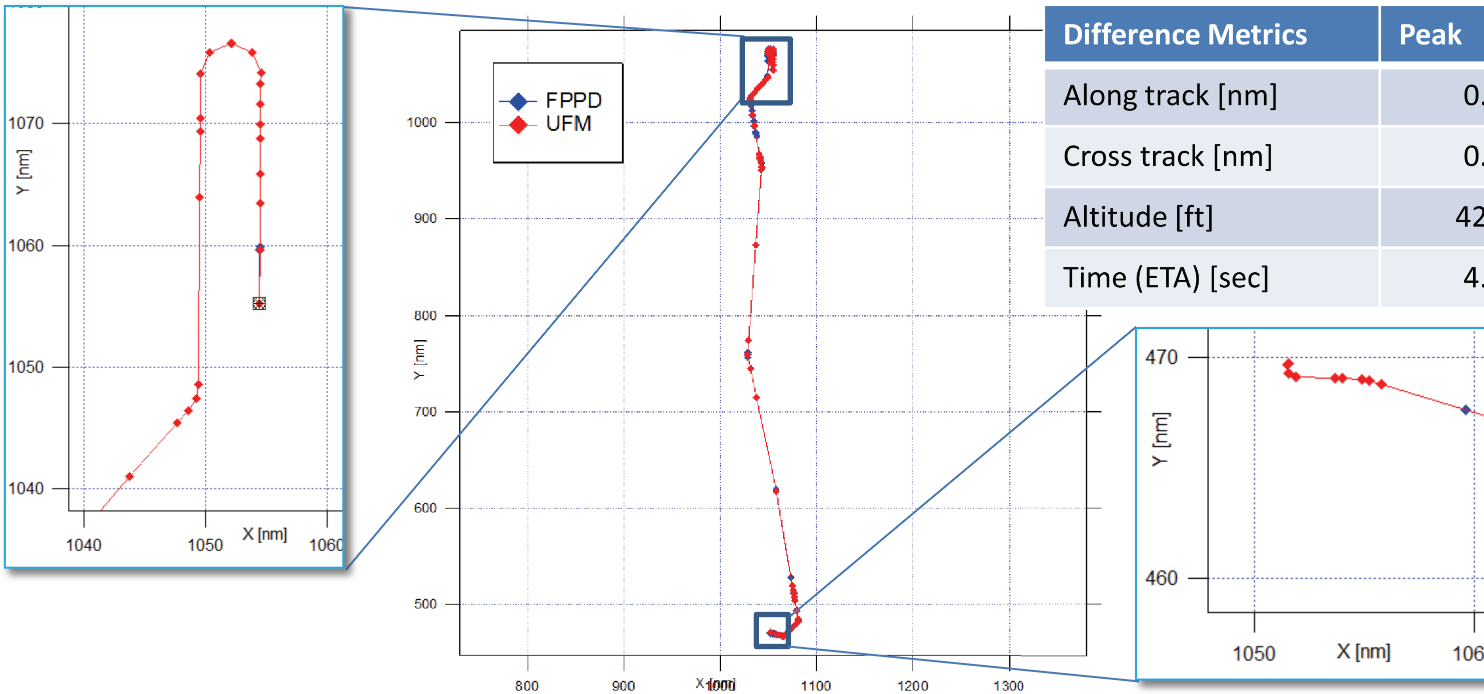
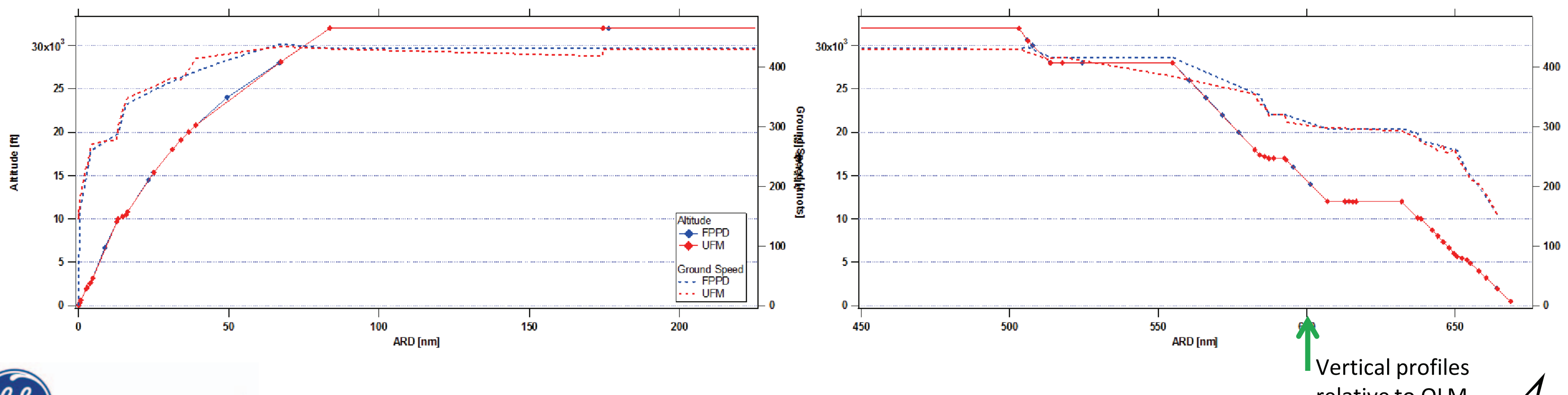
Pre-Departure Sync - Synchronized Trajectory



Difference Metrics	Peak	RMS
Along track [nm]	0.5	0.1
Cross track [nm]	0.3	0.04
Altitude [ft]	421	54
Time (ETA) [sec]	4.8	1



Conclusions

- Use of the FMS 4DT for air-ground trajectory synchronization is shown to be effective
  - The ground trajectory reflects user preferences and the high fidelity modeling afforded by the FMS TP
  - Remaining differences can be controlled by limiting segment size
- Air-Ground trajectory synchronization can be achieved via exchange of CPDLC messages and ADS-C EPP data