Session 139-GNC-49: "Innovations and Support of the National Airspace System at the FAA"

Paper AIAA-2008-7144: "State Vector Based Near Term Trajectory Prediction"

Presented to: AIAA GNC, Honolulu, HI

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Federal Aviation Administration

OVERVIEW (1 of 2)

- New method of trajectory prediction
- Combination of existing methods
- Used when aircraft is not on its planned route
- Advantage for near term predictions (< 5 min)
- Experimental study using field recorded data

Overview (2 of 2)

- Definition of Trajectory Prediction
- Challenge of Trajectory Prediction
- Trajectory Prediction Algorithms
- State Vector Based Algorithm
- Trajectory Accuracy Metrics
- Experimental Study
- Examples
- Results

TRAJECTORY PREDICTION DEFINED

- **Future path of aircraft in 4 dimensions - XYZT**
- **Tactical – Near term – 0 to 2 minutes – no flight plan information**
- **Strategic – Long term - 2 to 20 minutes – flight plan information available**
- **To maintain aircraft-to-aircraft separation and aircraft-to-airspace separation**
- **Alerts the controllers of pending conflicts**
- **Core function of Decision Support Tools**

CHALLENGE: TRAJECTORY PREDICTION

- **Nominally follows filed route**
- **Lack of intent information – where the aircraft is going to fly**
- **Controller directed deviations**
  - For traffic, weather, pilot request
  - Speed
  - Altitude
  - Vector
  - Speed and vector deviations not entered into computer system
- **Pilot directed deviations**
  - Turns – inside or outside
  - Top of Descent
  - Bottom of climb
  - Parallel to route

TRAJECTORY PREDICTION ALGORITHMS

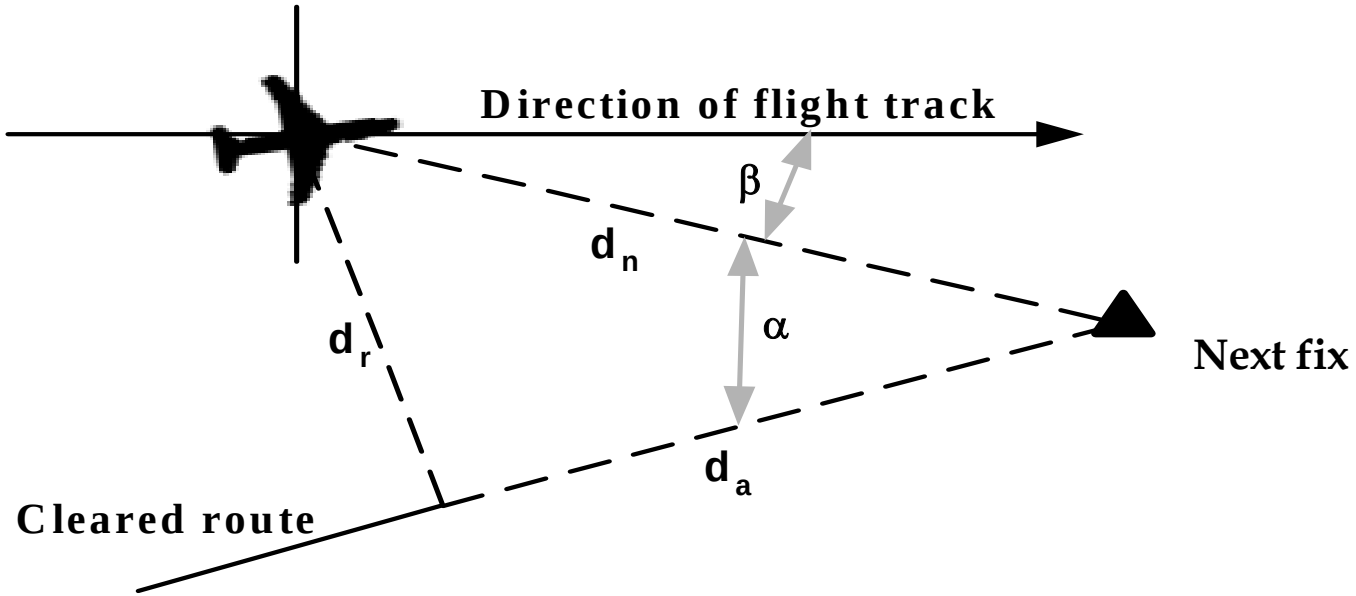
- **CTAS & URET algorithms in use**
- **Based on**
  - flight plans
  - converted routes
  - aircraft performance characteristics
  - airspace adaptation data
  - winds aloft
- **Return to route methods**

STATE VECTOR BASED ALGORITHM

- **Choose 1 of 3 alternatives**
  - 1. Follow flight plan route
  - 2. Continue on current path (dead reckoning)
  - 3. Continue on current path until it intersects flight plan route, then follow flight plan route

- **Alternative chosen determined by**
  - Distance to flight plan route
  - Is aircraft flying towards the next fix
  - Does the extrapolated route intersect the flight plan route

ALGORITHM GEOMETRY



ALGORITHM THRESHOLDS

THRESHOLD PARAMETER	SYMBOL	VALUE
Outer Lateral Threshold	D_2	1.5 nm
Inner Lateral Threshold	D_1	0.5 nm
Heading Offset	P_1	30 degs

$d_r < D_1$ Choose Flight Plan Following

$d_r > D_2$ Choose Dead Reckoning

$D_1 < d_r < D_2$ & $\beta < P_1$ Choose Flight Plan Following

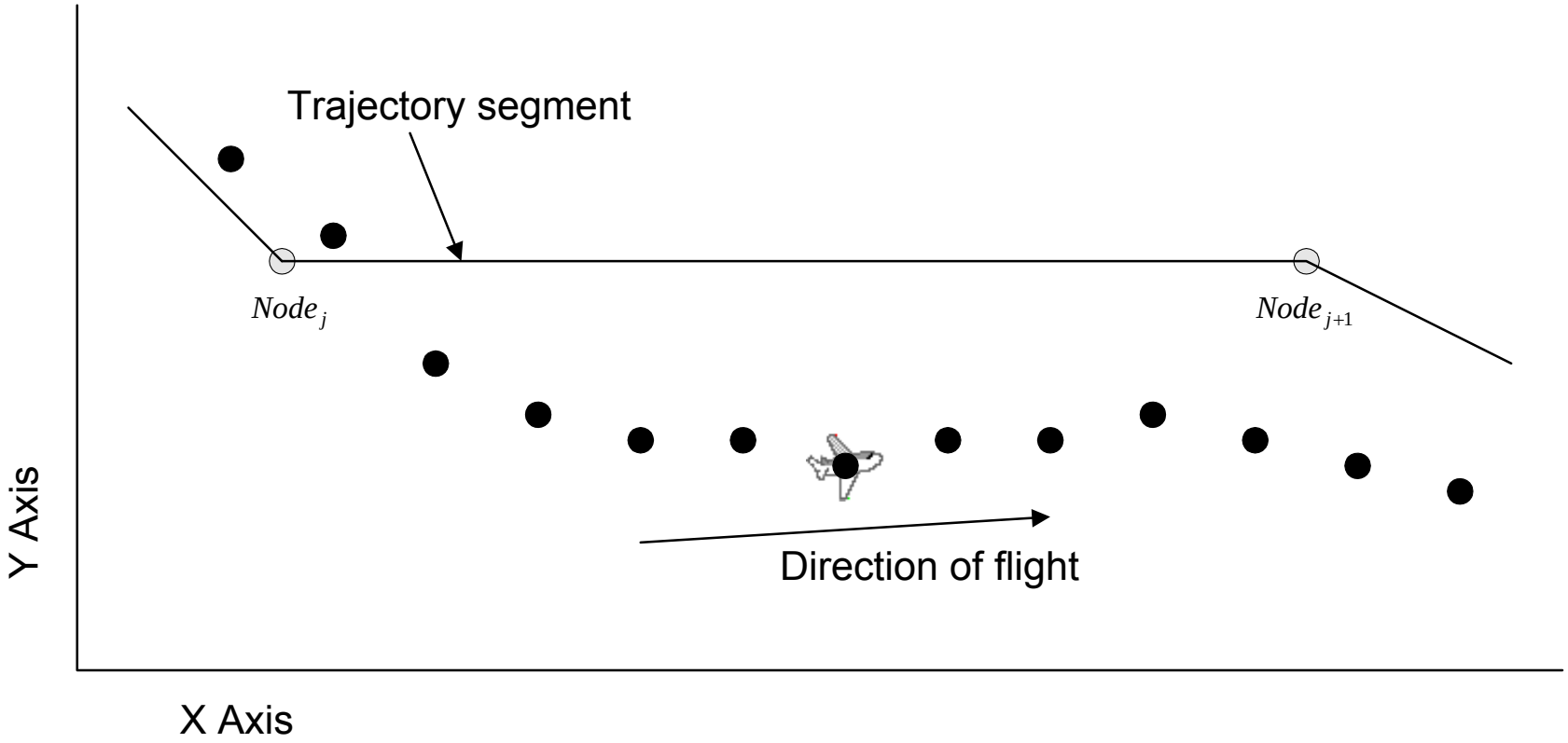
$D_1 < d_r < D_2$ & $\beta > P_1$ Choose Dead Reckoning

TRAJECTORY ACCURACY METRICS

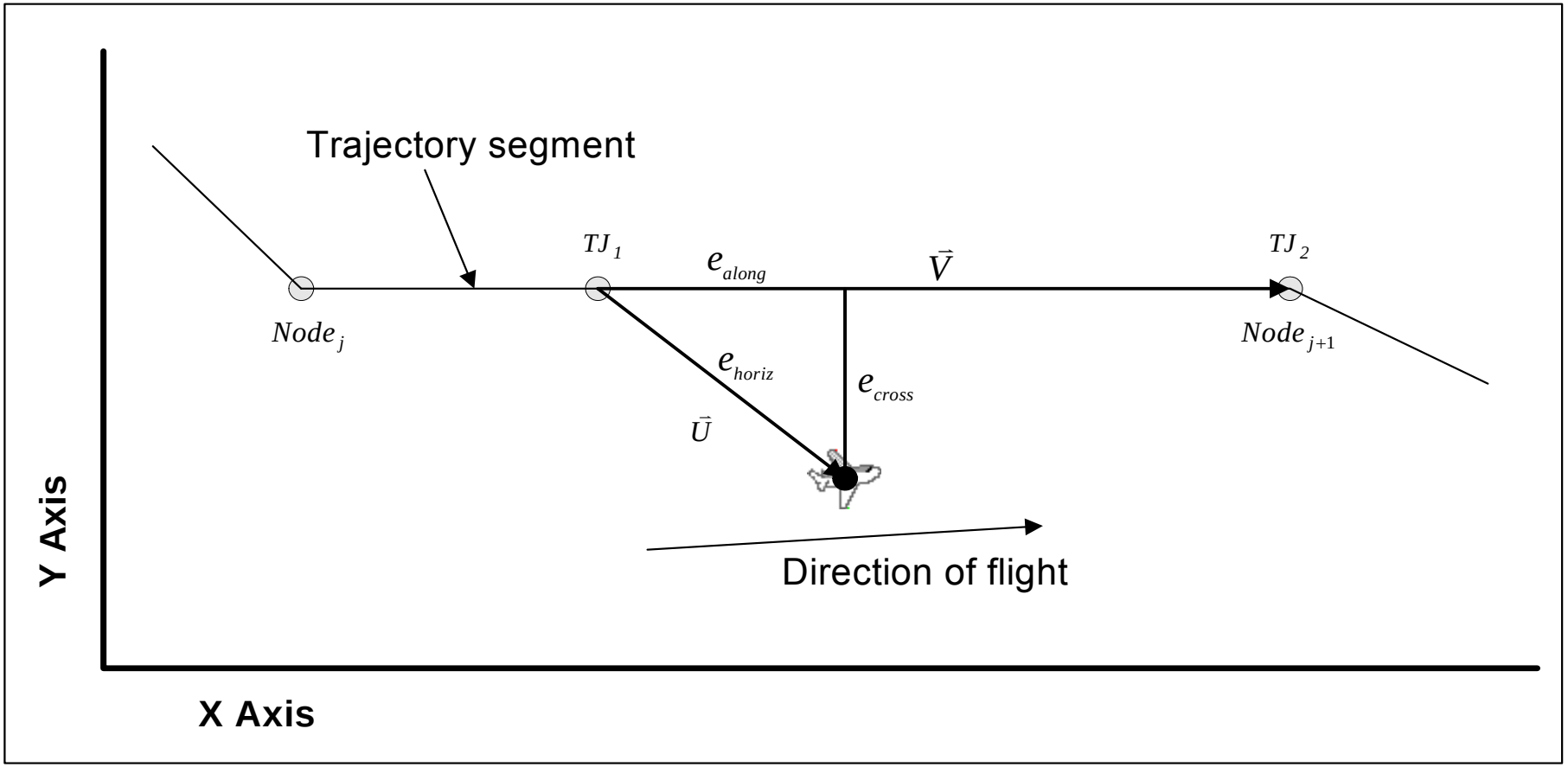
- **Compare trajectory with actual path flown**
- **Along track and cross track differences**
- **Calculated for each track point (10s samples)**

- **Method**
  - Select a point on the track
  - Locate point on trajectory closest to track point
  - Distance between the two points is the cross track error
  - Locate point on trajectory which has the same time tag as the track point
  - Distance along the trajectory from this point to the closest trajectory point is the along track error
  - Horizontal error is the vector sum of the cross track and along track errors

TRACK AND TRAJECTORY



Trajectory Accuracy Metrics: Horizontal Dimension



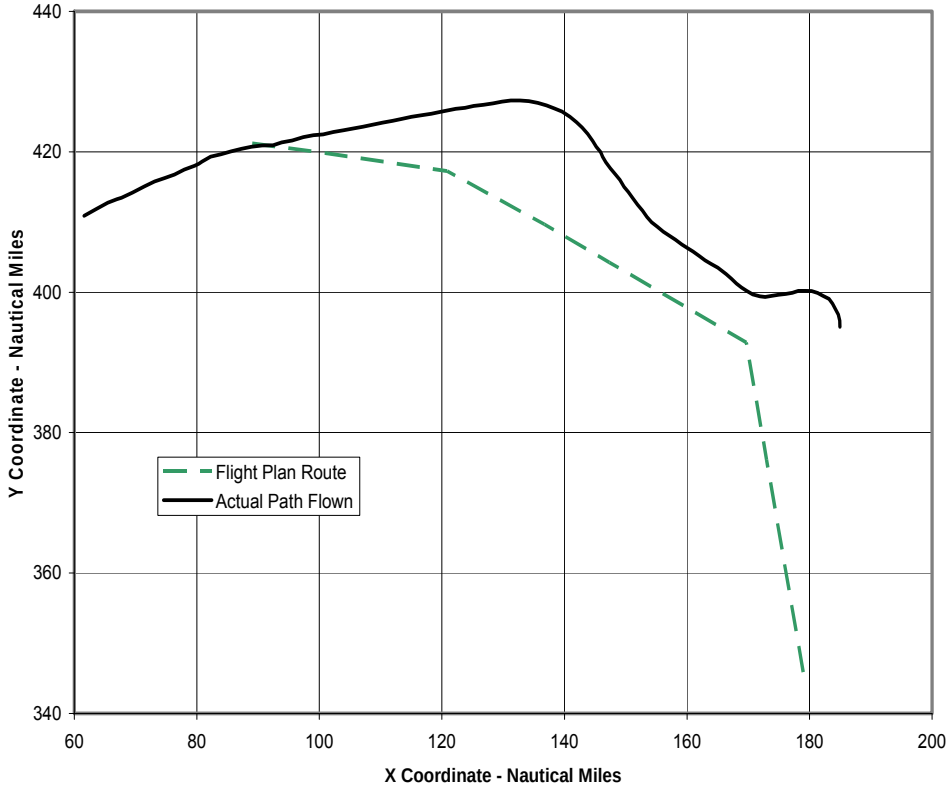
CONFLICT PREDICTION METRICS

- **Another way of measuring trajectory prediction accuracy**
- **Use the trajectories to predict conflicts**
- **Measure accuracy of the predictions**
  - Valid alerts
  - Missed alerts
  - False alerts

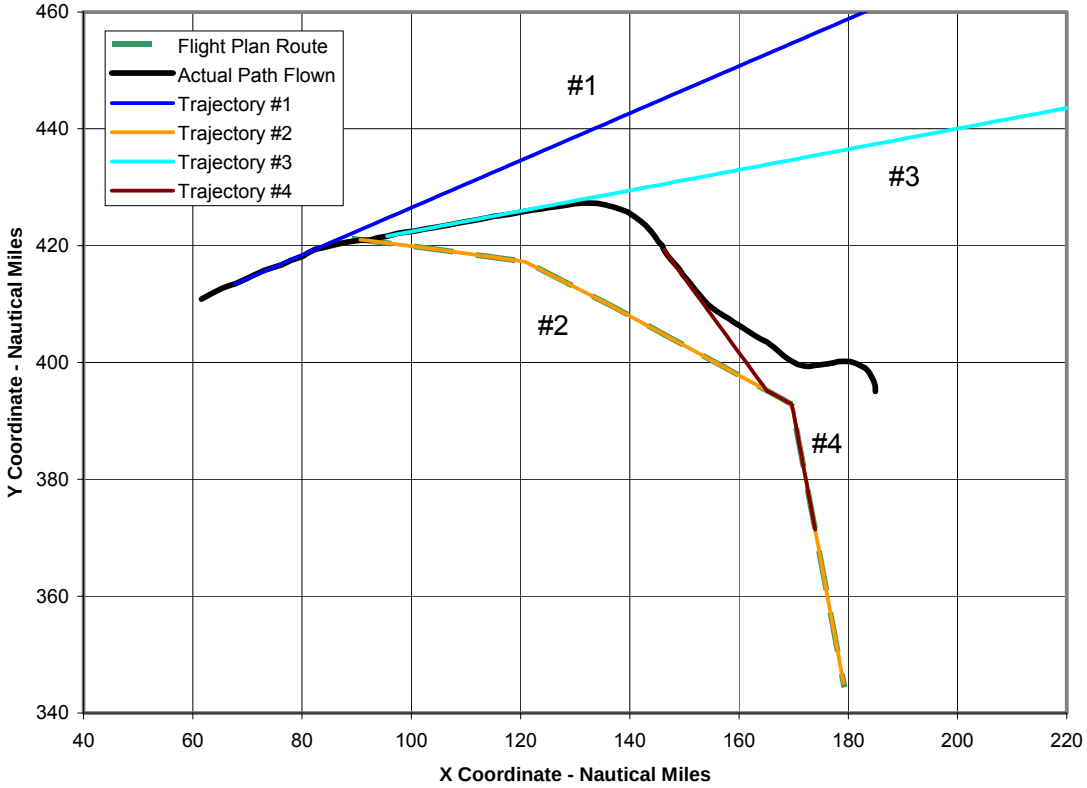
EXPERIMENTAL STUDY SCENARIOS

- **Field recorded air traffic data from ZDC**
  - Flight plans and their amendments
  - Radar tracks
  - 2200 flights
  - 5 hours
- **Scenario 1**
  - 500 flights randomly selected from 2200 flights
  - Processed by Lockheed Martin Laboratory Host Computer System
  - URET trajectories recorded
- **Scenario 2**
  - Time shifted 2200 flights to generate conflicts
  - Selected 418 flights that had conflicts
  - Processed by Lockheed Martin Laboratory Host Computer System
  - URET conflict alerts recorded

EXAMPLE FLIGHT: TRACK & FLIGHT PLAN ROUTE

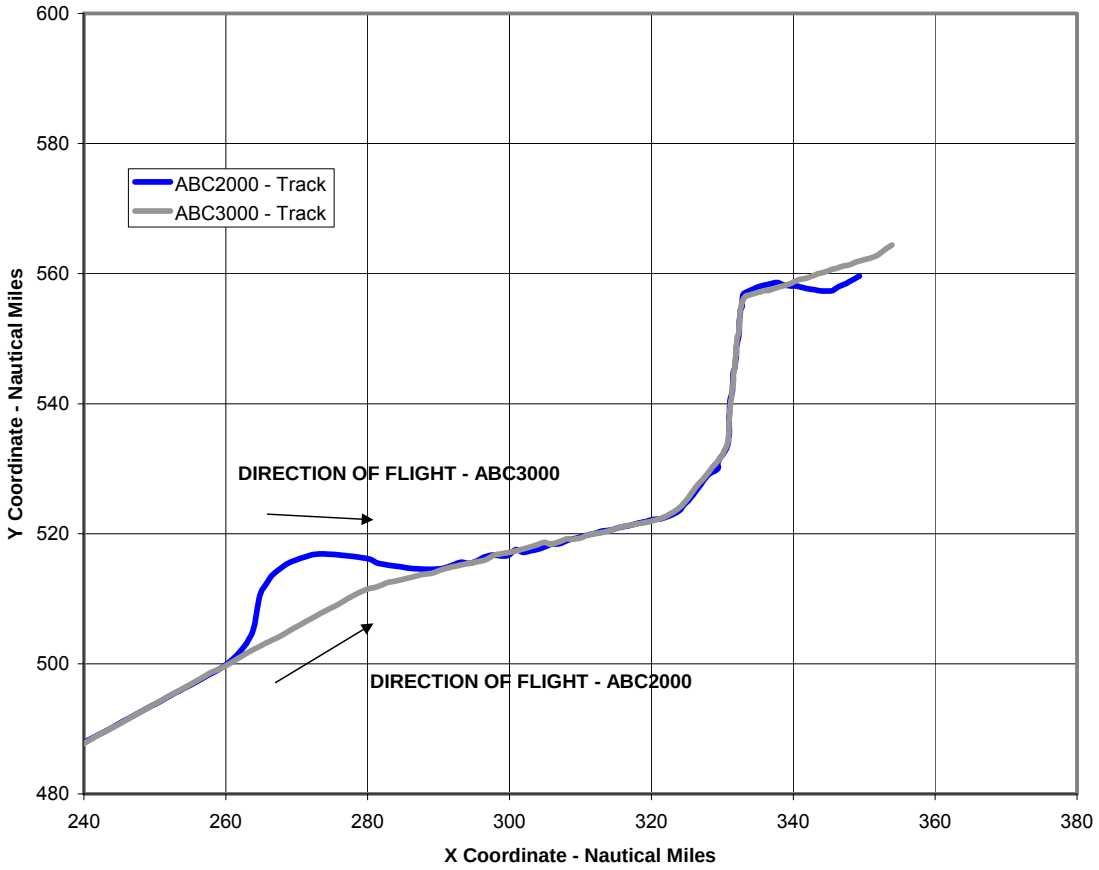


EXAMPLE TRAJECTORIES FOR FLIGHT

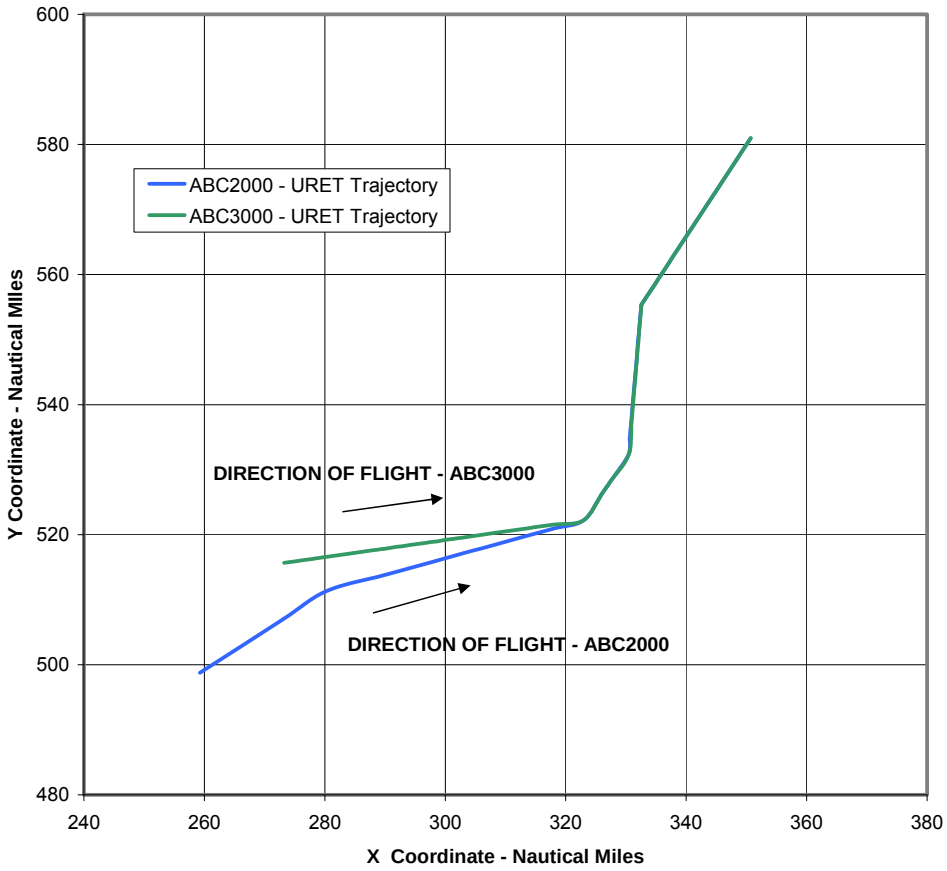


#1 – Dead Reckoning #2 – Flight Plan #3 – Dead Reckoning #4 – Dead Reckoning + Flight Plan

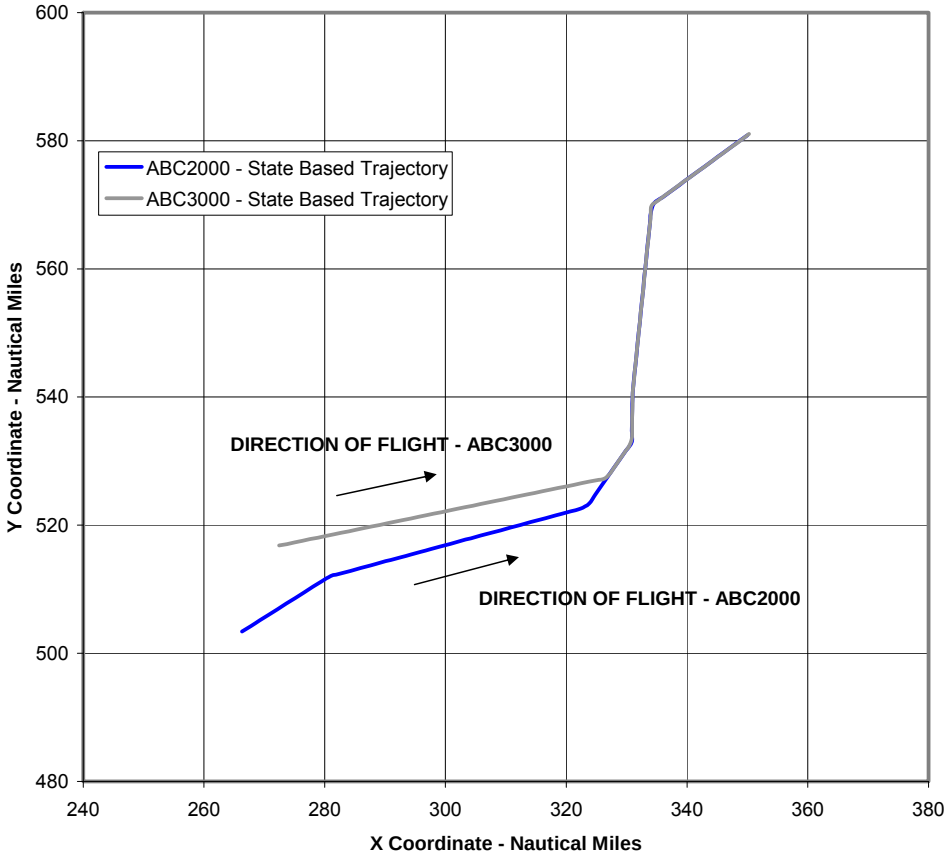
EXAMPLE: POSSIBLE CONFLICT – FLIGHT PATHS



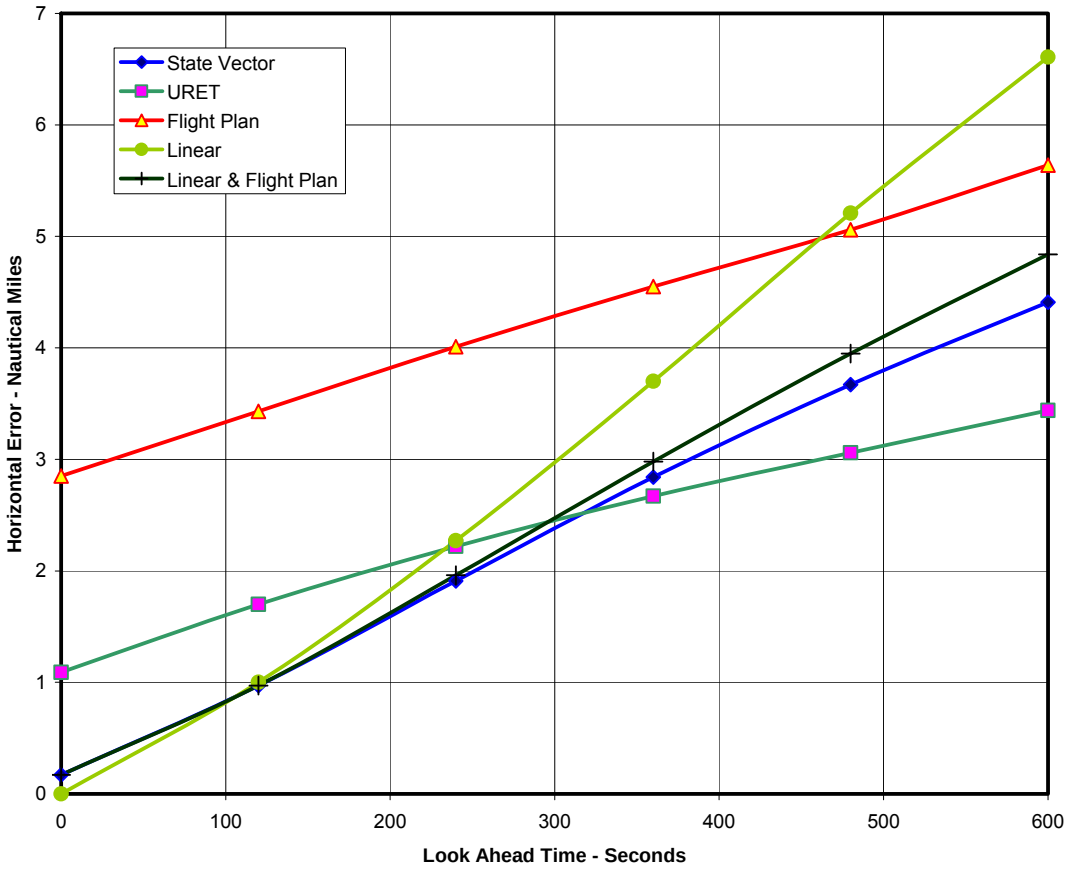
EXAMPLE: POSSIBLE CONFLICT – URET TRAJECTORIES



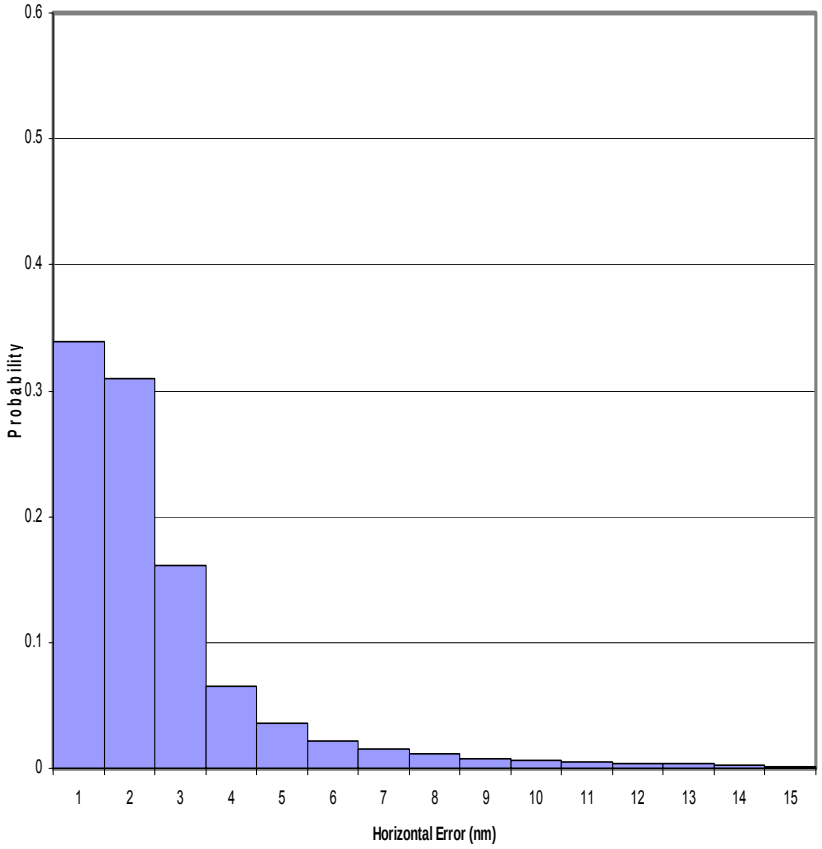
EXAMPLE: POSSIBLE CONFLICT – STATE VECTOR BASED TRAJECTORIES



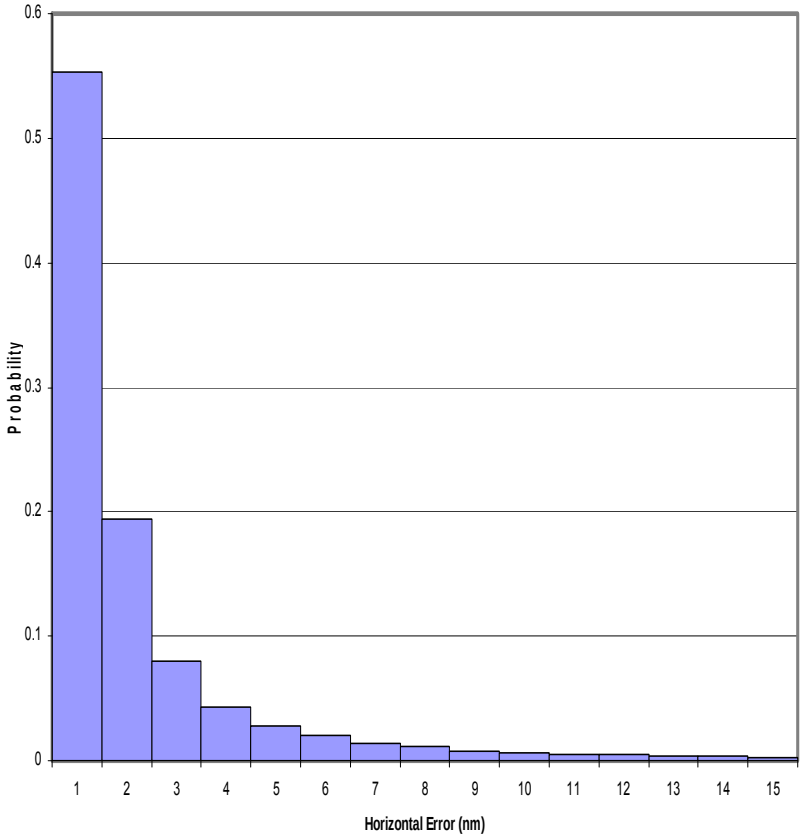
VARIATION OF HORIZONTAL ERROR WITH LOOK AHEAD TIME



HORIZONTAL TRAJECTORY ERRORS



URET



STATE VECTOR BASED

COMPARISON OF CONFLICT ALERTS

URET Action	State Vector Based Action	Count
Missed Alert	Valid Alert	8
Valid Alert	Missed Alert	6
False Alert	No Call	77
No Call	False Alert	12

CONCLUSIONS OF THE TRAJECTORY PREDICTION STUDY

- **Combination of linear prediction (dead reckoning) and flight plan following**
- **In the near term (< 5 minutes)**
- **Combination compared to URET**
  - Generates more accurate trajectories
  - Reduces false alerts
  - Improves conflict detection

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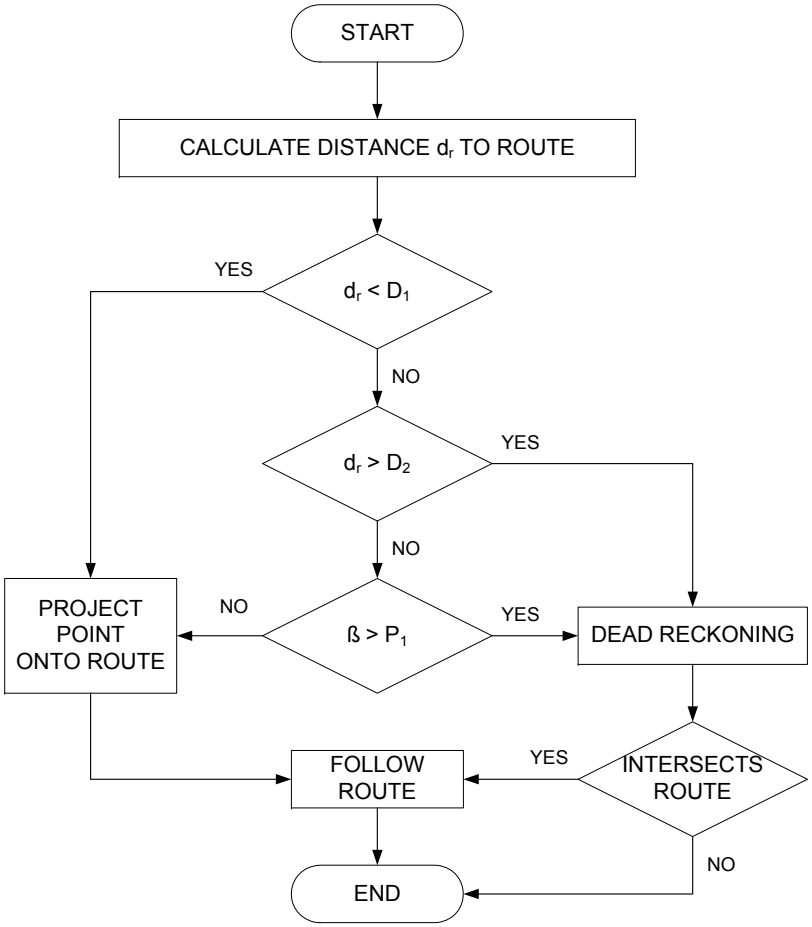
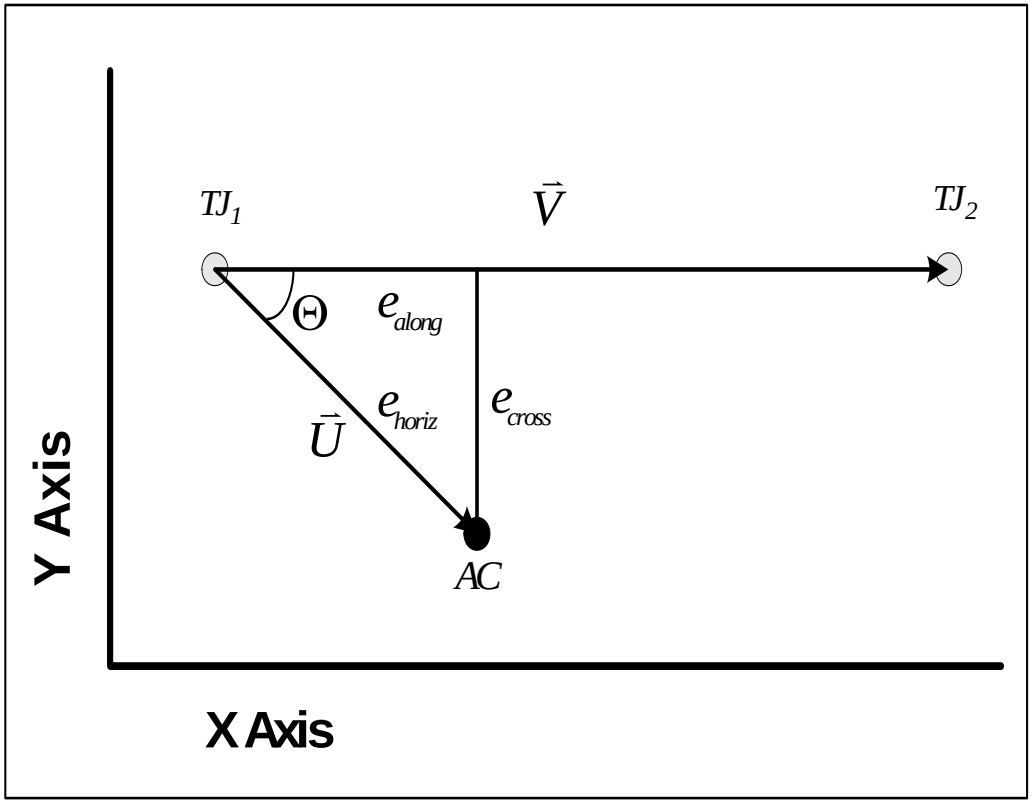
STATE VECTOR BASED TRAJECTORY PREDICTION



Trajectory Accuracy Metrics: Horizontal Dimension

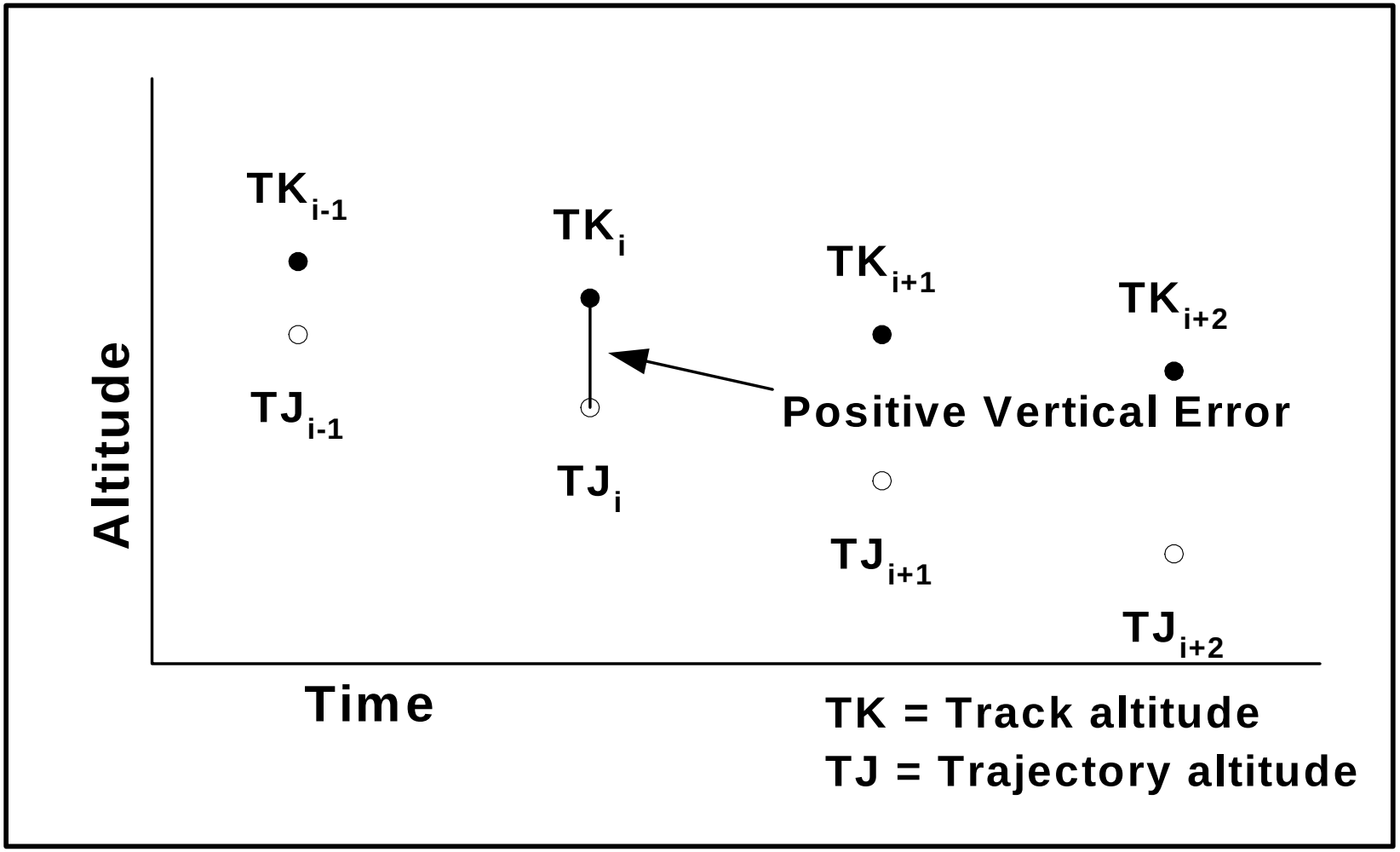


$$e_{horiz} = \left|\vec{U}\right| = \sqrt{u_x^2 + u_y^2}$$

$$e_{along} = \frac{\left(\vec{U} \bullet \vec{V}\right)}{\left|\vec{V}\right|} = \frac{u_x v_x + u_y v_y}{\sqrt{v_x^2 + v_y^2}}$$

$$e_{cross} = \left|\vec{U}\right| \sin\Theta = \frac{\left(\left|\vec{U} \times \vec{V}\right|\right)}{\left|\vec{V}\right|} = \frac{u_x v_y - u_y v_x}{\sqrt{v_x^2 + v_y^2}}$$

Trajectory Accuracy Metrics: Vertical Dimension



TRAJECTORY ERROR RATES

Prediction Method	Error Type	Look Ahead Times – Seconds					
		0	120	240	360	480	600
State Vector	Horizontal Error	0.17	0.97	1.91	2.84	3.67	4.41
	Cross Track Error	0.17	0.52	1.01	1.49	1.86	2.12
	Along Track Error	0.00	0.67	1.31	1.97	2.58	3.12
URET	Horizontal Error	1.09	1.70	2.22	2.67	3.06	3.44
	Cross Track Error	0.62	0.93	1.12	1.23	1.29	1.34
	Along Track Error	0.74	1.15	1.60	2.00	2.38	2.76
Flight Plan	Horizontal Error	2.85	3.43	4.01	4.55	5.06	5.64
	Cross Track Error	2.85	2.36	2.03	1.88	1.78	1.71
	Along Track Error	0.00	1.46	2.52	3.29	3.95	4.65
Linear	Horizontal Error	0.00	1.00	2.27	3.70	5.21	6.61
	Cross Track Error	0.00	0.59	1.56	2.72	3.96	5.10
	Along Track Error	0.00	0.64	1.24	1.85	2.46	3.02
Linear & Flight Plan	Horizontal Error	0.17	0.97	1.96	2.98	3.95	4.84
	Cross Track Error	0.17	0.54	1.15	1.79	2.38	2.87
	Along Track Error	0.00	0.64	1.24	1.85	2.42	2.96