

INTELLIGENT TRACKING OF AIRCRAFT IN THE NATIONAL AIRSPACE SYSTEM

Jimmy Krozel, Ph.D.
Metron Aviation, Inc.
131 Elden St., Suite 200
Herndon, VA 20170

Abstract

We present a method of tracking the conformance of aircraft flying in the National Airspace System (NAS). Tracking is based on an intent inference algorithm. In this algorithm, we track an aircraft relative to a filed flight plan (or amended flight plan) and reason about the errors associated with its actual position versus its flight plan. We identify aircraft that are not within normal navigation performance error limits, and identify situations that can be explained by simple explanations (e.g., controller issued a direct-to route to the aircraft). Finally, we discuss how our algorithms can be used to project traffic forward in time and help estimate the future demand of airspace in the NAS.

Introduction

In the NAS, routes are defined as specific paths, determined between Navaids or waypoints, traveled by aircraft that fly primarily in a horizontal plane (flight levels). Airways are defined as the airspace area or corridor whose centerline is defined by routes. Routes are broken down into categories:

- Victor Airways are low altitude routes serving aircraft operating from 1200 ft above the surface of the earth up to, but not exceeding 18,000 ft above Mean Sea Level (MSL). These airways are shown in blue on En Route Low Altitude Charts and are implemented with the use of VOR and VORTAC facilities.
- Jet Routes serve aircraft operating from 18,000 ft up to 45,000 ft MSL. Jet routes are shown in black on high altitude aeronautical charts and implemented with the use of VOR and VORTAC facilities, except in Alaska.
- RNAV Routes are defined as any course, which an aircraft can operate in, within the coverage of a Navaid's reference signal. There are two kinds:
 - *Fixed Routes* are permanent, published routes that can be used for flight planning. Most have been terminated except for some in Alaska.
 - *Random Routes* between two waypoints that are within the area navigation capabilities, and must be radar-monitored by air traffic control. These are known as *direct routes*.

In addition, Standard Instrument Departure (SID) routes and Standard Terminal Arrival Routes (STARs) are published procedures, involving specific routes, headings, runways, speed, and other parameters. A pilot can execute these procedures at certain airports, whether landing or taking-off, in order to simplify clearance delivery procedures. SIDs and STARs also facilitate the air-traffic controller's task to manage a greater number of aircraft without repeating the same procedure to every aircraft. To use SIDs and STARs requires that the pilot has at least the approved textual description or the graphic form (charts) of the SIDs and/or STARs for that particular airport. However, pilots are not required to use SIDs and/or STARs unless otherwise directed by an air-traffic controller.

Several path-corridor correlation measures are developed in this paper to identify if aircraft are properly using published routes. The path-corridor correlation identifies a number between -1 and 1 that corresponds to the degree to which an aircraft is following a route defined by jet routes or victor airways. **Figure 1** illustrates an example. If an aircraft is on or near a jet route, then the path-corridor correlation value is near 1. If an aircraft is veering away from a flight corridor, then the path-corridor correlation will decrease from 1 towards -1.

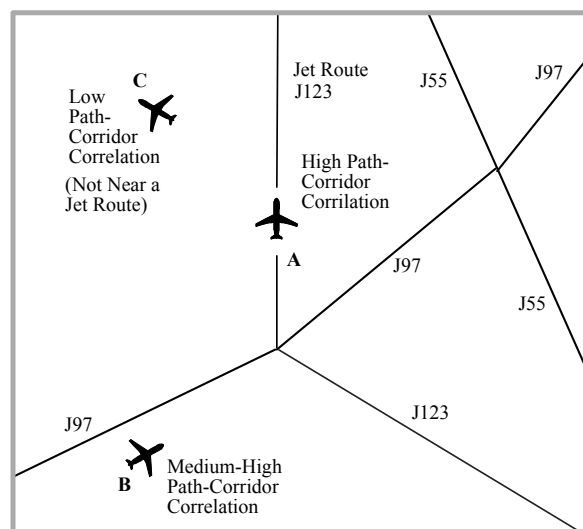


Figure 1. The concept of a Path-Corridor Correlation.

Naturally, the path-corridor correlation will vary as wind uncertainties and navigation errors propagate, however, the path-corridor correlation should statistically be high for aircraft intending to follow standard commercial flight corridors. Aircraft that are not following standard routes can be identified with filters. Monitor alerts can be given to Military or Civilian Air Traffic Control (ATC)².

There are many reasons why an aircraft might not be on a published route. Aircraft might simply be off course, may be directed by an air traffic controller to deviate, may be performing pilot initiated deviate acts (drug runs, hijacking), or may be lost. The biggest reason for major deviations is weather. In Krozel⁴, the author investigates intent inference algorithms that try to explain why a pilot might be deviating given the history of data associated with the aircraft. Zhao⁵, et al, specify several classifications of such pilot intent models, including: motive intent, objective intent, trajectory intent, and cost intent. In Klopfenstein³, et al, the authors study the magnitude and causes of deviations from filed flight plans. We focus this paper on algorithms that automatically detect such deviations in the NAS. Such an algorithm may be quickly applied to many aircraft in the NAS, for instance, in a system like NASA's Future Air Traffic Management Concept Evaluation Tool (FACET)¹, or onboard an AWACS or E2-C aircraft patrolling the nations borders.

Analysis

In this section, we investigate several methods which may be used to automatically monitor the conformance of aircraft to following published routes.

Method 1. The simplest form of path-corridor correlation is based on the proximity of an aircraft from its flight plan. Assume that the filed flight plan follows victor airways and jet routes. The path-corridor correlation measure is derived from a simple geometric analysis. Given jet routes or victor airways that describes segments from one Navaid to another, and an aircraft current location that describes a point in space, the distance the aircraft location is from the route is computed and compared to a standard flight corridor diameter. Let a jet route segment go from one Navaid located at \vec{r}_1 to a second Navaid located at \vec{r}_2 :

$$\vec{r}_1 = [x_1 y_1 z_1] \quad (1)$$

$$\vec{r}_2 = [x_2 y_2 z_2] \quad (2)$$

The aircraft is located at the position \vec{r} :

$$\vec{r} = [xyz] \quad (3)$$

The location relative to the first Navaid is:

$$\vec{r}_A = \vec{r} - \vec{r}_1 \quad (4)$$

From vector algebra:

$$\vec{r}_A \cdot (\vec{r}_2 - \vec{r}_1) = |\vec{r}_A| |\vec{r}_2 - \vec{r}_1| \cos \theta \quad (5)$$

where θ is the angle from the first Navaid to the aircraft, as shown in **Figure 2**.

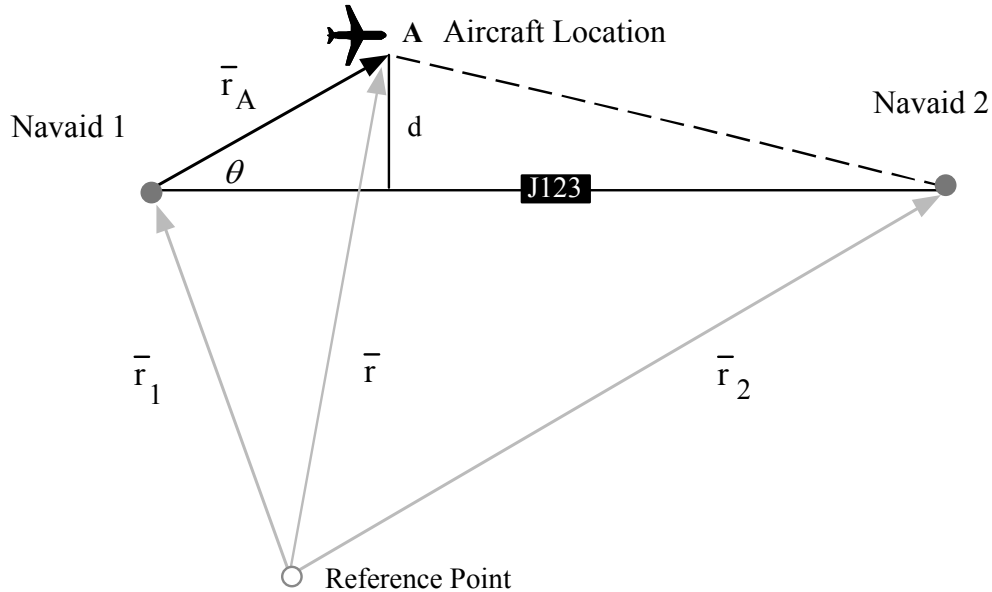


Figure 2. The distance aircraft A is from a jet route (e.g., J123) is found from geometry.

Let the distance d be the distance from the aircraft to the jet route or victor airway. From trigonometry:

$$\sin \theta = \frac{d}{|\vec{r}_A|} \quad (6)$$

Equations (5) and (6) are combined:

$$\sin^2 \theta + \cos^2 \theta = 1 \quad (7)$$

and solving for the only unknown quantity d :

$$d^2 = |\vec{r}_A|^2 - \frac{[\vec{r}_A \cdot (\vec{r}_2 - \vec{r}_1)]^2}{|\vec{r}_2 - \vec{r}_1|^2}. \quad (8)$$

Next, the distance d that the aircraft is from the jet route or victor airway is compared to a standard flight corridor radius R or diameter $D=2R$. While a value for R currently 4 nmi for victor airways and jet routes in the NAS, we still use this flight corridor diameter as a parameter in the path-corridor correlation measure. We adjust R to a value that minimizes false alarms. Using real aircraft data, if a given value of R causes too many false alarms for lack of adherence, then the value of R can be increased. If the aircraft is within the flight corridor radius, then there is no conflict, otherwise a status of “out of corridor” exists. A path-corridor correlation measure μ is defined:

$$\mu_1(d) = \begin{cases} 1 & \text{if } d \leq R \\ 0 & \text{if } d > R \end{cases} \quad (9)$$

Method 2. Similar to Method 1, the distance d the aircraft is from the jet route or victor airway can be compared to a standard flight corridor radius R using a continuous function. A path-corridor correlation measure μ can be defined:

$$\mu_2(d) = \frac{1}{1 + e^{-a(d_0 - R - d)}}. \quad (10)$$

This path-correlation measure function has a behavior that is very close to 1 up until the distance R , then drops off to zero correlation by approximately $2R$, as controlled by the design parameters a for decay rate and d_0 for trigger point. **Figure 3** illustrates a function.

Next, when implementing this path correlation measure, multiple jet routes might be considered. If an aircraft is close to 2 (or more) jet routes, and 2 (or more) distances d_1 and d_2 are computed. In this case, the path-corridor correlation measure μ is defined:

$$d = \min(d_1, d_2). \quad (11)$$

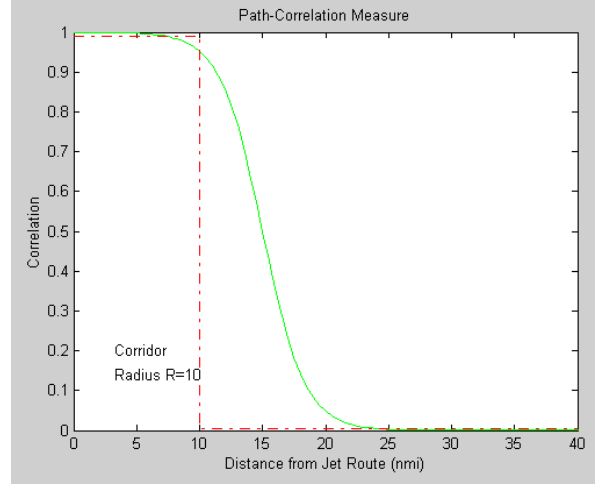


Figure 3. The path-corridor correlation measure based on the distance an aircraft is from a jet route; Method 1 is binary (dashed line) and Method 2 is continuous (solid line).

Method 3. A history of proximity data can also be used to develop a path correlation measure. In this way, the path correlation data will be less sensitive to noisy inputs, and also the rate of change of the path-corridor correlation measure can be monitored. Let the distance d and path correlation measure μ be continuously monitored. Thus, we have functions $d(t)$ and $\mu(t)$, for time t . For a moving window of time ΔT , the moving window path-corridor correlation measure is defined:

$$\mu_3(d, t) = \frac{1}{\Delta T} \int_{r(t-\Delta T)}^{r(t)} \mu_2(d(t)) dt. \quad (12)$$

Here, the path correlation function μ is defined from Method 2, nonetheless, the path correlation function from Method 1 could also be used.

Method 4. For a more advanced analysis, the data of an aircraft can be analyzed to compare the inferred intent⁴ of an aircraft to the filed flight plan intent. If an aircraft is flying way point navigation, then, even if the aircraft is off course, one would expect to see the aircraft heading towards its next way point. For this method, both the aircraft’s position and heading are used to define the path-corridor correlation measure. The aircraft and jet route positions are defined as in equations (1) - (4). The heading vector \vec{h}_A of the aircraft A is defined by a unit vector in the direction of the velocity vector \vec{v}_A for aircraft A:

$$\vec{v}_A = \frac{d}{dt} \vec{r}_A = [v_{Ax} \ v_{Ay} \ v_{Az}] \quad (13)$$

$$\bar{h}_A = \frac{\bar{v}_A}{|\bar{v}_A|}. \quad (14)$$

Next, a unit direction vector that points from the aircraft position to the next waypoint or next Navaid position is defined:

$$\bar{d} = \frac{\bar{r}_2 - \bar{r}}{|\bar{r}_2 - \bar{r}|}. \quad (15)$$

The dot product between the heading vector and the direction vector is an indication of whether or not the aircraft is heading in the direction of the next waypoint or Navaid:

$$\bar{h}_A \cdot \bar{d}. \quad (16)$$

A path-corridor correlation measure is defined by combining the correlation measure from Method 2, denoted $\mu_2(d)$, with this dot product factor:

$$\mu_4(d, \bar{h}_A) = \frac{1}{2} [\mu_2(d) + \bar{h}_A \cdot \bar{d}]. \quad (17)$$

Thus, this correlation is a function of two variables, the distance d from the closest jet route and the heading vector \bar{h}_A of the aircraft.

Method 5. Just as described in Method 3, a history of proximity data can also be used to develop a path correlation measure by using a moving window

running average of the path-corridor correlation from Method 4. In this case, the moving average is:

$$\mu_5(d, \bar{h}_A, t) = \frac{1}{\Delta T} \int_{r(t-\Delta T)}^{r(t)} \mu_4(d(t), \bar{h}_A(t)) dt. \quad (18)$$

Comparison of Methods

A series of experiments was conducted using the five methods of path-corridor correlation. Not all experiments are described in this paper, however, the most interesting ones are described next.

Experiment 1. In the first experiment, the path-corridor correlation measures are compared for a path that diverges from a jet route based on synthetic data. **Figure 4** illustrates the experiment and the results. An aircraft that is expected to fly directly from Navaid 1 to Navaid 2 strays off course. The comparison indicates that the binary Method 1 is the quickest to identify that the aircraft strays outside the corridor. Methods 2 and 3 indicate the aircraft passes out of the corridor in the same general vicinity, which is further along than Method 1. Methods 4 and 5 notice that the aircraft is turning back to the corridor, so they do not indicate an alert that the aircraft is out of conformance.

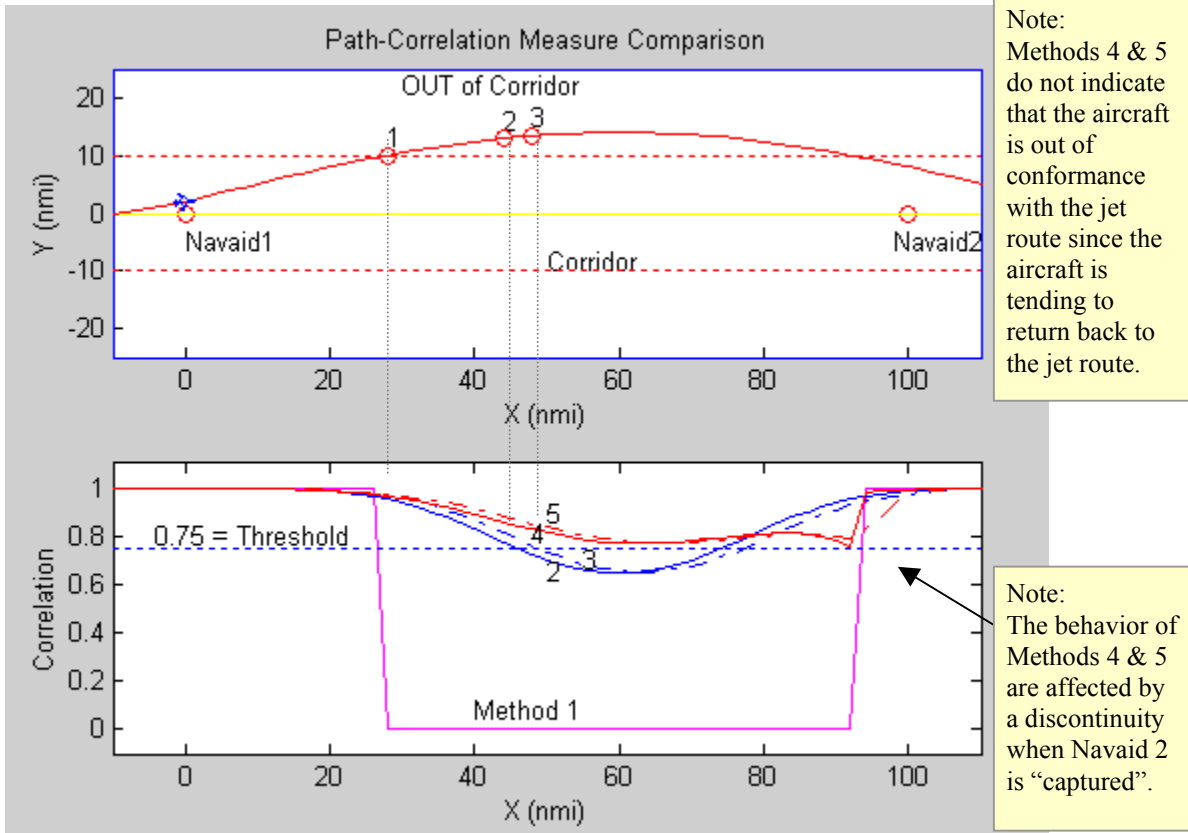


Figure 4. Path-Corridor conformance comparisons between 5 methods.

In our experiments, we have concluded that retaining a moving window average is useful to tracking aircraft in the NAS. Methods 3 and 5 seem to have the advantage that they are more robust to errors in the input data. In the next sets of experiments, we base our work on Method 5.

Experiment 2. In this experiment, we investigate several routes that are based on real-world data from the Enhanced Traffic Management System (ETMS). ETMS provides information to flight planners at the ATCSCC, ARTCCs, TRACONs, and commercial airlines. ETMS provides the data for flight plans, flight plan amendments, and track positions. The update rate for track information in ETMS is 1 minute. **Table 1** shows the ETMS data used in our analysis.

Table 1. ETMS Data used in analysis.

ID	Description	Purpose
FZ	Flight Plan	Flight Plan as filed with the NAS
AF	Flight Plan Amendment	Amendment to flight plan
DZ	Departure	Activation of a flight
UZ	Center Boundary Crossing	Current flight plan data as sent from ARTCC from which flight is leaving to ARTCC which the flight is entering
TZ	Position Update	Current position, altitude, and speed as tracked in the NAS

We look at these data to determine how consistent the path-corridor correlation value will be for aircraft that are seemingly following their flight plans. Our testing shows that a “follow flight plan” path-corridor correlation measure of 0.95 to 1.00 generally corresponds to an aircraft that is closely following its flight plan. As an aircraft drifts off the flight plan or zigzags (for whatever reason), the correlation values drop down to 0.60 to 0.95.

Figure 5 illustrates an example based on ETMS data. In this figure, all the aircraft seem to follow the flight plans fairly well. One trajectory deviates due to “path stretching” by air traffic control. In the “path stretching”, a controller turns an aircraft away from the jet route and then turns the aircraft back in order to space the aircraft further behind another aircraft. This typically occurs at or before metering fixes where a controller may be establishing a Miles-In-Trail (MIT) spacing between aircraft.

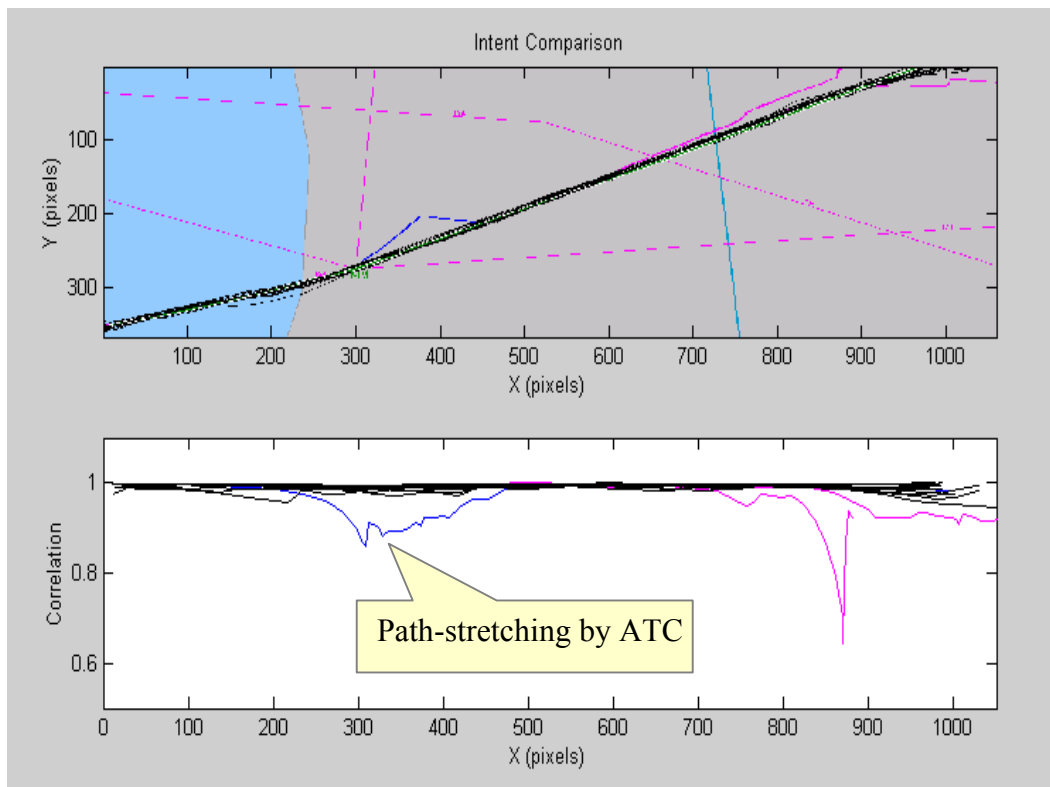


Figure 5. Examples of aircraft following their flight plans with a couple routes indicating low path-corridor correlation values.

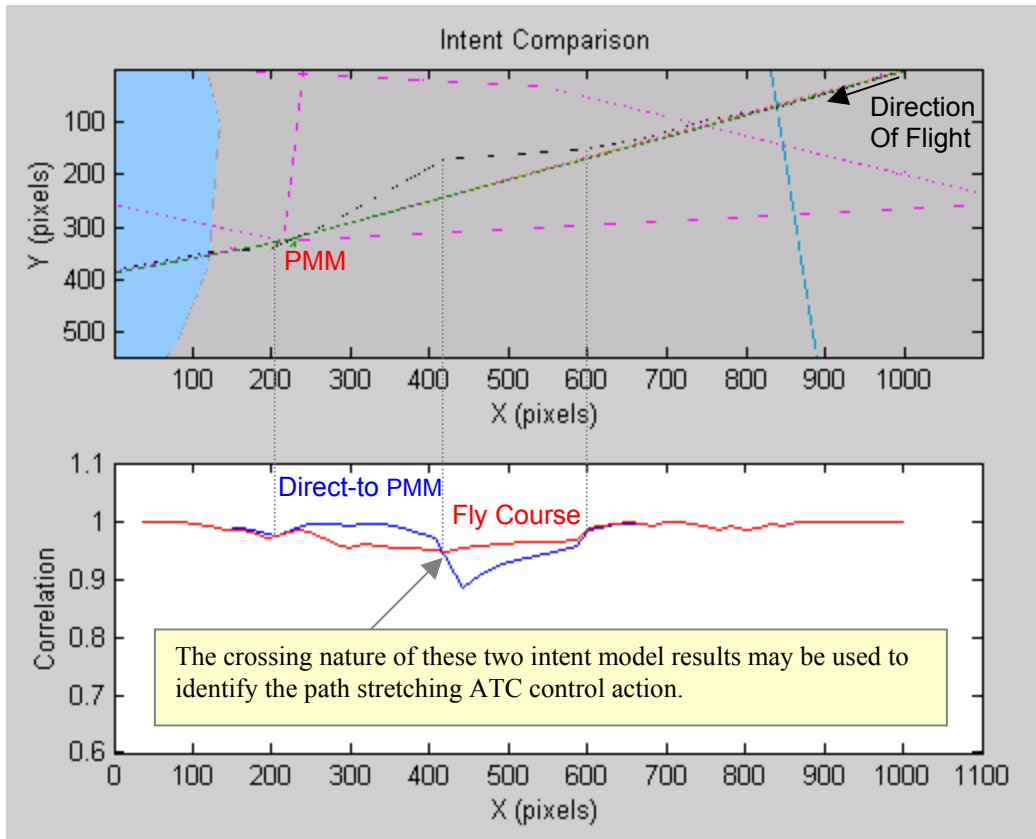


Figure 6. The path-stretching maneuver imposed by ATC is detected by two crossing filters.

Experiment 3. In this experiment, we specifically tried to identify if an aircraft was in the middle of a path-stretching situation. These situations are typical (they occur multiple times every day) and they are not entered into the computer as a change in flight plans. However, it is useful to note that an aircraft is under a path-stretching maneuver and to determine if this should trigger an alert of some sort (for instance, if it is getting outside some bound).

In order to identify the path-stretching maneuver, we used the path-corridor correlation measure for the original flight plan, and we compared it to a new path-corridor correlation measure which assumed that the aircraft is holding course in whatever direction it is currently pointed at. The same equation as the path-corridor correlation value is used, however, we place a “pseudo waypoint” just in front of the aircraft. **Figure 6** illustrates the results that indicate a criss-cross in the two functions. This criss-cross can be used to identify the path-stretching situation.

Experiment 4. In this experiment, we further investigate the situation of aircraft that are deviating from their flight plans. It is reasonable to expect that some of these deviations are expected (observed to happen every day in the NAS) and can be classified to

actions that are typical in the NAS. For instance, we investigate in this experiment aircraft that are given a “direct-to” route. In a direct-to route, an aircraft is allowed by air traffic control to skip a way point and proceed “direct-to” a way point upstream in the flight plan.

In order to implement this tracking logic, we perform a similar comparison as was done for the “path-stretching” maneuver. In order to identify if an aircraft is in a “direct-to” route, we look ahead in the flight plan and build a list of the next several way points (usually 2 or 3 suffices). We then assume that the aircraft is on a flight plan that skips the next way point and goes “direct-to” some future way point. We found this method to be quite effective in identifying direct-to routes.

Figure 7 illustrates an example of the identification of a “direct to” route based on ETMS data. Our algorithms indicate a separation between the path-corridor correlation value sufficient to verify the assumption of the “direct-to” route. In the next section, we discuss the prediction of the route into the future, given that the assumption is valid.

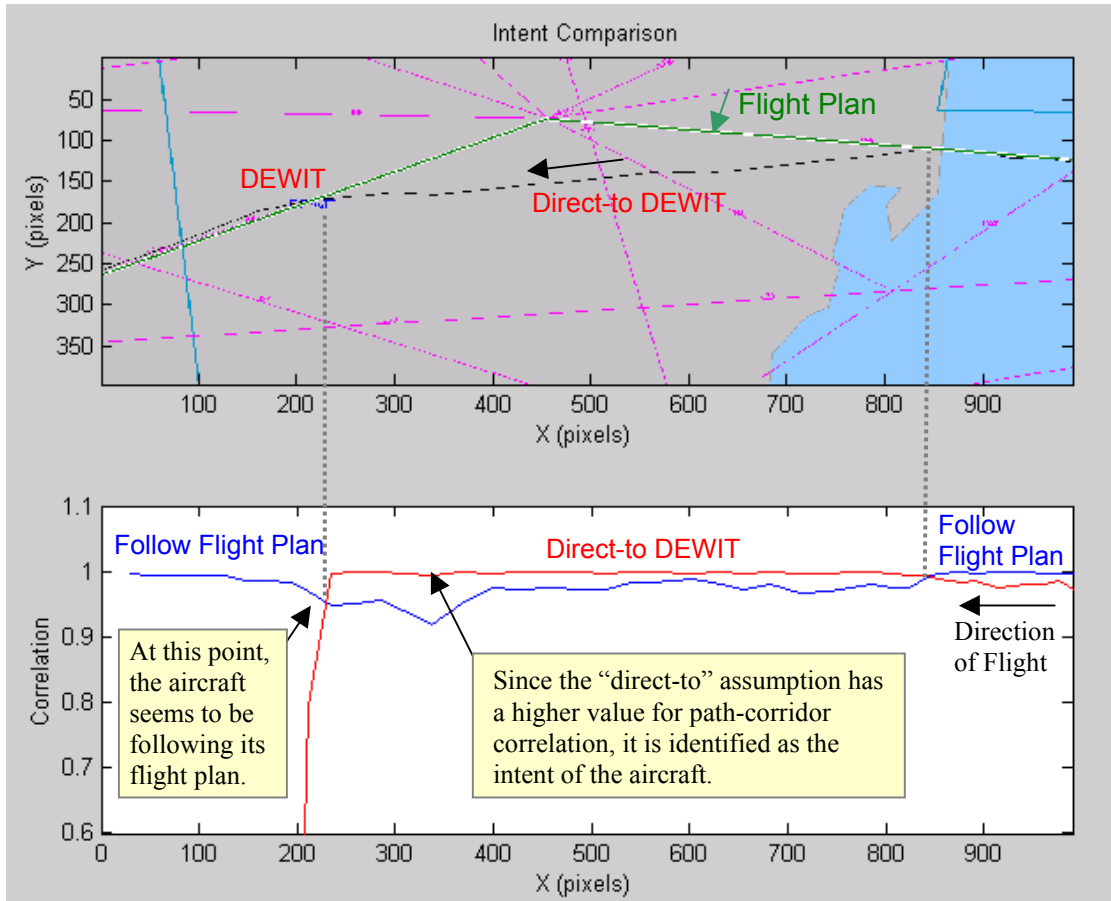


Figure 7. Example comparison between a filed route and a direct-to route to DEWIT.

Discussion

Both safety as well as capacity issues are addressed by including a tracking system like the one in this paper into the NAS:

- Safety is enhanced since there is no reason to alert to an aircraft that is executing a maneuver that fits in with normal operations. However, when no reasonable intent is matched or when the aircraft is following an intent that is not in accordance to NAS rules, nearby pilots, air traffic controllers, and even the airlines should be alerted.
- Capacity can be enhanced by allowing for trajectory predictions to take into account better estimates of where an aircraft will be in the future, better estimates of time of arrival, and better information for maximizing traffic flows.

Prediction of the future motion of the aircraft is handled as follows. After an aircraft is identified to closely match an intent, e.g., the filed flight plan or a direct-to route, we use the assumed intent to project the trajectory forward. The assumption for prediction is

that if the aircraft is not on the flight plan, then the aircraft will eventually return to the filed flight plan.

Figure 8 illustrates an aircraft that is on a direct-to route, and the path prediction that is based on the assumption that the aircraft will follow the direct-to route until it can return back to its flight plan. Because of the structure imposed by jet routes, the predicted future motion is quite good.

Adjustments to the predicted speed are not currently made in our algorithm. However, the speed should be adjusted so that the timing of the aircraft returning onto a jet route must fit in with the traffic flow. The speed should be adjusted so that the aircraft is placed in a gap between two aircraft already in a stream, or, if there is a very large gap, the speed may be assumed constant.

Trajectory prediction and its practical limitations are topics of future research.

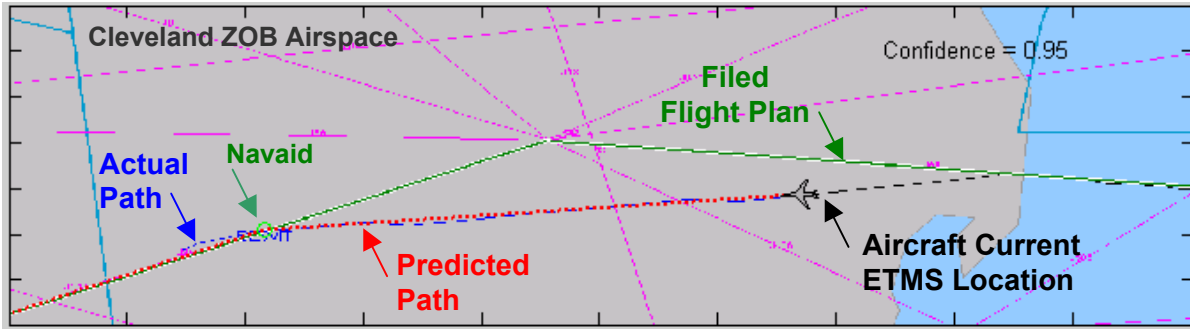


Figure 8. An inferred intent to fly “direct-to” is used to correctly predict the future motion of an aircraft by predicting that the aircraft will re-join the flight plan after flying by the direct-to point.

Future Work

In future work, we have considered adding further intent models for actions that we observe in the NAS from ETMS data. The following list of intents have been considered in our current research (not all are illustrated in this paper):

- follow flight plan,
- return to flight plan,
- fly direct-to routing,
- path-stretching from ATC
- hold altitude,
- hold heading, and
- execute a holding pattern.

In the case of a holding pattern, we created a “template”, that is mapped onto the observed motion of the aircraft, as shown in Figure 9. The degree to which the template matches the motion of the aircraft has produced good and bad results, depending on the data we test. For instance, Figure 10 illustrates an example where we were able to get a good match (case (a)) and a bad match (case (b)). Future work is needed to identify when an aircraft is in a holding pattern. Furthermore, we have not begun to explore how we might be able to predict when an aircraft might exit a holding pattern.

In the future, we would like to add further intent models to our list of filters:

- Low Altitude Arrival and Departure Routes
- Turning short of a Navaid
- Conflict avoidance between two aircraft
- Avoiding Turbulence
- Avoiding SUA
- Avoiding Weather
- Hijacked Aircraft
- Drug traffic situations (sparse data sets)

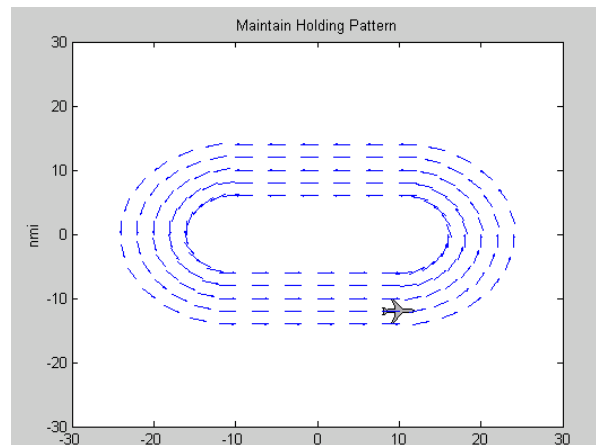
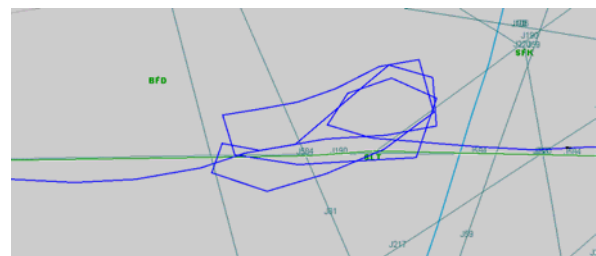


Figure 9. A template used to identify when an aircraft is in a holding pattern.



(a) Holding Pattern matches the template well



(b) Holding pattern does not match the template well

Figure 10. Examples of when the template does a good job (a) and a bad job (b) identifying if an aircraft is in a holding pattern.

By having a full set of models for intent, we hope to build a software system that monitors the NAS for conformance to published jet routes and to conformance to standard ATC control instructions. The work presented in this paper presents the start towards that objective.

Conclusions

In this paper we present several methods to track aircraft flying in the NAS. Tracking is performed based on reasoning about the decisions that pilots are making subject to the constraints imposed by the current ATC system. We identify competing intents that might explain the motion of the aircraft, and then select the intent model that best explains the motion. This method allows us to transition a trajectory predictor from one assumed intent to another, even if the intent differs from the filed flight plan. For the majority of traffic in the NAS, we observe path-corridor correlation values that indicate conformance to the filed flight plan.

Acknowledgments

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