AIAA Aircraft Technology, Integration, and Operations Conf., Chicago, IL, Sept., 2004.

Aircraft ADS-B Data Integrity Check

Jimmy Krozel, Ph.D.[*]
Metron Aviation, Inc., Herndon, VA, 20170

Dominick Andrisani, II, Ph.D.[†], Mohammad A. Ayoubi[‡], Takayuki Hoshizaki, Ph.D.[§]
Purdue University, W. Lafayette, IN, 47906

Chris Schwalm[**]
Metron Aviation, Inc., Herndon, VA, 20170

Automatic Dependent Surveillance – Broadcast (ADS-B) promises to provide significant operational enhancements to military and civilian applications. However, as currently designed, ADS-B will not necessarily provide guaranteed, uninterrupted state and intent data from ADS-B equipped aircraft. Data dropouts, erroneous inputs, and deception may degrade data integrity. To assure ADS-B data integrity, a system has been built to provide continuous real-time state estimates of the aircraft being tracked and a verification that the aircraft is following the ADS-B broadcast intent. This system uses a suite of Kalman filters to smooth out noise within measured ADS-B signals, identify and suppress erroneous data, coast between data dropouts, and provide the current best state estimates. Continuous Geometric Conformance and Intent Conformance metrics are defined to analyze ADS-B intent verification. Geometric Conformance analyzes the aircraft states to verify that the aircraft lies within the horizontal and vertical Required Navigation Performance (RNP) limits. Intent Conformance compares the aircraft motion and the broadcast intent in horizontal, vertical, and speed dimensions. Examples demonstrate data integrity checks with simulated ADS-B data signals.

Acronyms and Abbreviations

ADS-B	=	Automatic Dependent Surveillance – Broadcast
CF	=	Certainty Factor
MASPS	=	Minimum Aviation System Performance Standards
NAS	=	National Airspace System
Nm	=	Nautical Mile
RNP	=	Required Navigation Performance
RTCA	=	RTCA, Inc. (formerly Radio Technical Commission for Aeronautics)
SSR	=	Secondary Surveillance Radar
TCAS	=	Traffic Alert and Collision Avoidance System
TC	=	Trajectory Change
TCP	=	Trajectory Change Point
TTG	=	Time-To-Go

I. Introduction

AIRCRAFT-based Automatic Dependent Surveillance – Broadcast (ADS-B) promises to provide significant operational enhancements to military and civilian applications: a greater degree of surveillance accuracy, improved situational awareness, shared separation responsibility (at far greater range than Traffic Alert and

[*] Chief Scientist, Research and Development Division, 131 Elden St., Suite 200, AIAA Associate Fellow
[†] Associate Professor, School of Aeronautics and Astronautics, AIAA Senior Member
[‡] Ph.D. Candidate, School of Aeronautics and Astronautics
[§] Post-Doctoral Researcher, School of Aeronautics and Astronautics
[**] Software Analyst, Research and Development Division, 131 Elden St., Suite 200

Collision Avoidance System (TCAS)), more accurate parallel landings, and better surface surveillance – these ultimately will lead to increased safety and capacity in the National Airspace System (NAS). With these benefits, ADS-B is beyond the conceptual stage; systems are currently being developed and deployed in experimental operations (e.g., the Capstone Project in Alaska and Ohio Valley Operational Evaluation in the Midwest), and there will soon be both military and civilian markets with widespread operational use.

However, as currently designed, ADS-B will not necessarily provide guaranteed, uninterrupted state and intent data from aircraft equipped with ADS-B transponders. Data dropouts, erroneous inputs, and even deception may degrade data integrity. In civilian applications, traditional Secondary Surveillance Radar (SSR) obtains aircraft information through a rotating radar that interrogates aircraft transponders. In the terminal area around an airport, update rates of once per four to five seconds are typical, and in en route airspace the update rate is once per twelve seconds. However, not all airspace in the NAS is covered by SSR. Mountainous regions and remote regions (e.g., Alaska) are not well covered, and in these areas, ADS-B will likely be the sole source of surveillance information. Thus, we cannot assume that SSR will always be available to verify ADS-B signals. This paper investigates a verification technique which is intended for airborne use and is independent of a secondary source of tracking information.

A. ADS-B Specifications

This research is based on the RTCA's ADS-B Minimum Aviation System Performance Standards (MASPS)[1]. Required Navigation Performance (RNP) Area Navigation (RNAV) standards are specified by the RTCA's RNP RNAV MASPS[2]. Note that MASPS for ADS-B do not address the choice of data link technology.

B. Related Work

There are two primary fields of related work that we rely on for the basis of this algorithm. First, Kalman filtering is described in texts by Gelb[3], Maybeck[4], and Mendell[5]. The use of path correlation measures for correlating the motion of an aircraft with an intent is introduced in Krozel[6] and Krozel and Andrisani[7]. Second, the problem of automated conformance monitoring has appeared in the literature to address issues of security and alerting in NAS decision support tools. Krozel[8] has presented the intent inference approach as a viable conformance monitoring system for the NAS, and the topic has also been studied at M.I.T. by Reynolds, et al[9,10,11]. Research on how to use intent information in the cockpit of the future (e.g., for airborne separation assurance systems) is being researched by Wing, et al[12], Magill[13], and Ruigrok and Valenti[14].

II. Approach

Next, we describe the algorithms used for state and intent verification.

A. State Verification

The first part of the ADS-B Data Integrity Check is to receive ADS-B data and process the aircraft state variables into continuous real-time signals that describe the motion of the aircraft. This involves several steps:

- Unwrapping Data – Certain ADS-B data elements will make discontinuous jumps. For instance, headings that instantaneously change from 0 to 360 degrees are identified and corrected by replacing the data with a continuous function that automatically advances up (down) without limit, i.e., from 0 to 360 to 720, or from 360 to 0 to -360 to -720, etc. Time of applicability is provided on the ADS-B data bus as time in seconds from last midnight. This means that at midnight time will jump from 86400 seconds to 0 seconds. Additionally, longitude resets from –180 to 180 approximately when the aircraft crosses the International Data Line. Such jumps must be prevented in order for our algorithms to reason about the continuous motion of aircraft.
- Units Conversions – ADS-B data is converted to a consistent set of units for reasoning about all the state and intent variables as a set of logically related variables.
- Bad Data Flagging – A flag is set for data that exceeds a bound on the state or derivative of a variable. If the state value or derivative value exceeds the bounds, the flag is set and the data will be ignored by the Kalman filters.
- Missing Data Identification – Data dropouts, regardless of cause, are identified when the time stamp on ADS-B inputs do not follow the nominal one second update.

Table 1. ADS-B Data.

ADS-B State Vector Data
Barometric Altitude
East Velocity
Geometric Altitude
Latitude
Longitude
North Velocity
Surface Ground Speed
Surface Heading
Vertical Rate
Time of Applicability

The next step in state verification is to create continuous signals for the aircraft state variables. A set of nine measurements (Table 1) are used to track a single aircraft using a set of nine separate uncoupled Kalman filters. The main objectives of Kalman filtering are:

- Bad Data Point Elimination
- State Estimation
- Noise Filtering
- Coasting over Missing Data Points

The ADS-B signal may have missing data points where there is initially a signal, then no signal, and then the signal appears again for an aircraft. This may occur because the aircraft goes out of range briefly, the ADS-B signal is turned off briefly, there is jamming or interference, or some other reason (we do not need to know why). In between missing data points, the Kalman filter is designed to "coast" as illustrated in Figure 1. The Kalman filter estimates state values during the coasting time period. This occurs up to a maximum amount of time T_{COAST} (30 seconds) and after this time, the algorithm assumes that the vehicle is no longer going to re-appear. After coasting T_{COAST} amount of time, the algorithm purges the aircraft from memory. If the aircraft appears again, it is considered a new aircraft and the Kalman filter must re-initialize with zero memory of the aircraft motion. The end result of the State Verification process is a set of continuous real-time state estimates of the aircraft being tracked.

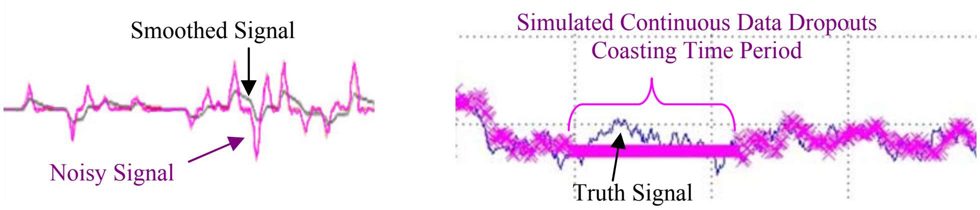


Figure 1. Kalman filters smooth noisy input data and coast between data dropouts.

B. Intent Verification

The intent of the aircraft is revealed in the ADS-B Trajectory Change (TC) Report. The Trajectory Change Point (TCP) is described in terms of horizontal, vertical, and speed (time) dimensions. The purpose of Intent Verification is to determine if the aircraft is flying to the TCP within the Required Navigation Performance (RNP).

To perform Intent Verification, we first define correlation functions as mathematical tools. Then, Geometric Conformance and Intent Conformance will be introduced which perform Intent Verification utilizing the correlation functions.

1. Correlation Functions

Correlation functions evaluate quantitatively the correlation between the aircraft motion and the ADS-B intent. The continuous forms will be introduced first followed by the discrete forms.

Local Correlation

The local correlation analyzes the correlation between the aircraft motion and the ADS-B intent locally at a given instant:

$$\text{Local Correlation} = L() \tag{1}$$

L() is a function of aircraft state estimates and the information from ADS-B. *L()* can be a function of independent variable time (t) or path position (s) and is defined uniquely in each Geometric Conformance and Intent Conformance as described below.

Global Correlation

The local analysis is extended to a global analysis by considering the recent history of the local correlation. Several types of global correlation functions are possible.

The basic form of the global correlation continuously integrates the local correlation over the observed flight path:

$$\rho = \frac{1}{k} \int_{flight\ path} L(s)\, ds \tag{2}$$

where ds is a differential element along the flight path and k is a non-dimensionalization constant based on the cost of flight. A good value for k is simply the arc distance between the current location of the aircraft and some characteristic domain location (e.g., the first location in the time window history):

$$k = \int_{flight\ path} ds \tag{3}$$

In computing global correlation functions, control over the time history of data is important as well as the weighting given to past data. A general strategy for handling the computation of ρ is to compute the correlation recursively. Two methods were implemented:

It is also plausible to compute the global correlation with a moving window as shown in Figure 2 which is analyzing the horizontal aircraft motion as an example. In this example, *L()* is a function of the aircraft Current Ground Track and the Direction of Intent Model given by the TCP information. This will be described shortly in the Horizontal Correlation subsection.

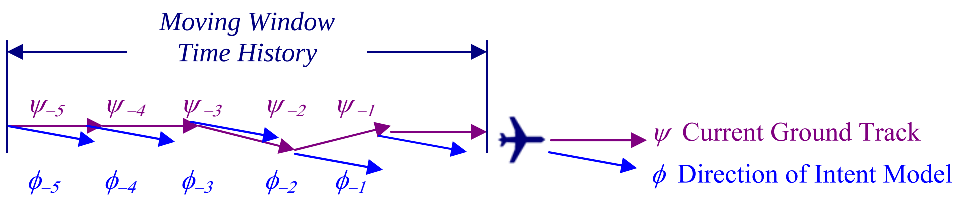


Figure 2. Global Correlation functions incorporate present and previous data.

The global correlation function applicable to a moving window of size l_w is described by:

$$\rho(l, l_0) = \frac{1}{k}\int_{l_0}^{l} L(s)\, ds \quad \text{where } k = \int_{l_0}^{l} ds \tag{4}$$

and $l_0 = \max\{0, l - l_w\}$. In addition to the moving window, the fading memory global correlation function can also be used, as introduced only by the discrete form in the next section. The global correlation measure has a range: $-1 \le \rho \le 1$.

<u>Discrete-Time Global Correlation Functions</u>

Next, we describe the Basic, Moving Window, and Fading Memory Global Correlation Functions in discrete form (suitable for software implementation).

- *Basic Global Correlation Function*
  The basic form of the Global Correlation Function, $\rho(N)$, at time $t=N\Delta$ (the N-th time increment of duration Δ), is computed from the local correlation function $L(i)$ as follows:

$$\rho(N) = \frac{1}{N}\sum_{i=1}^{N} L(i) = \frac{N-1}{N}\left\{\rho(N-1) + \frac{1}{N-1}L(N)\right\} \tag{5}$$

  In this representation, the local correlation $L(i)$ is defined by $L(t)$ with $t = i\Delta$.

- *Moving Window Global Correlation Function*
  Only data between time $(N-M+1)\Delta$ and $N\Delta$ are included in the summation (M terms):

$$\rho_M(N) = \frac{1}{M}\sum_{i=N-M+1}^{N} L(i) = \frac{N}{M}\rho(N) - \frac{N-M}{M}\rho(N-M) \tag{6}$$

- *Fading Memory Global Correlation Function*
  Past data points are weighted less and less. The fading memory factor f ($f = 1$ for no fading, $0 < f < 1$ for some fading) is used to exponentially reduce the weighting on past data points:

$$\rho_f(N) = \frac{1}{G_N}\sum_{i=1}^{N} f^{N-i} L(i) = \frac{G_{N-1}}{G_N}\left\{ f\rho_f(N-1) + \frac{L(N)}{G_{N-1}}\right\} \tag{7}$$

where: $$G_N = \sum_{i=1}^{N} f^{N-i} = G_{N-1} + f^{N-1} \tag{8}$$

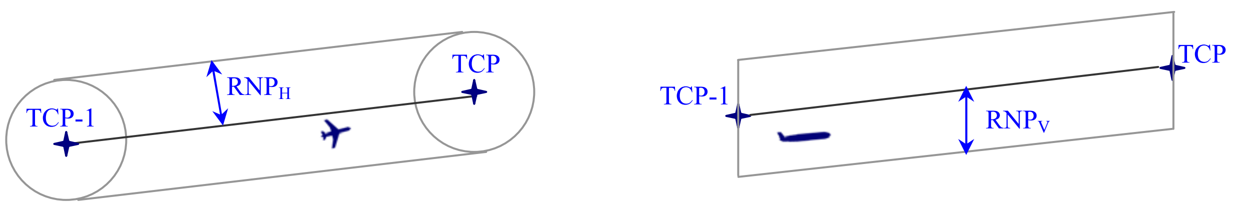
and initially, $G_1 = 1$.

The RNP will vary based on the equipage of the aircraft; RNP-1, for instance, would specify that the RNAV system is certified to stay within one nm of the intended lateral routing at least 95% of the time, including the time during turns. In order to determine if this is the case, the following sections define *L()* specifically for RNP-1.

2. Geometric Conformance

The first measure for Intent Verification is to identify if the aircraft is geometrically within the horizontal and vertical RNP limits. The horizontal RNP limit, labeled RNP_H, requires that the aircraft is within the horizontal distance RNP_H (e.g., RNP_H = 1 nm) away from the flight leg defined by TCP-1 (the previous TCP prior to the current TCP) and TCP. (Note: TCP-1 and TCP are "updated" as new ADS-B messages indicate that TCP is captured and the pilot/aircraft is moving on to the next TCP (TCP+1)). The vertical RNP limit, labeled RNP_V, requires that the aircraft is within the vertical distance RNP_V (e.g., RNP_V = 1 nm) away from the flight leg defined by TCP-1 and TCP. Figure 3 illustrates these geometric requirements. The local correlation function *L()* is defined by a binary function:

{ If the aircraft is within RNP_H and RNP_V for the leg from TCP-1 to TCP, Then *L()=1*
Elseif the aircraft is within RNP_H and RNP_V for the leg from TCP to TCP+1, Then *L()=1*
Else, *L()=0*



(a) Horizontal Requirement (b) Vertical Requirement

Figure 3. The horizontal and vertical RNP.

Geometric Conformance is executed with the moving window global correlation function in order to measure the success / failure to meet the requirement of a 95% conformance with respect to RNP:

Conformance: $$\rho_M(N) = \frac{1}{M} \sum_{i=N-M+1}^{N} L(i) = \frac{N}{M}\rho(N) - \frac{N-M}{M}\rho(N-M) > 0.95 \tag{9}$$

where *L()* is defined above. Because *L()* is binary, the conformance will vary from 0 to 1 (or 0% to 100%). Note that Geometric Conformance is independent of the speed along the flight path.

3. Intent Conformance

In addition to Geometric Conformance, we track the intent of the pilot to fly from TCP-1 to TCP. The motion of the aircraft is analyzed in terms of comparing the motion to a plausible intent model in each dimension:

- Horizontal
- Vertical
- Speed

Horizontal Correlation

As shown in Figure 4, the horizontal parameters that determine the path correlation are a unit vector $\hat{\psi}$ in the direction of the ground track ψ and a unit vector $\hat{\phi}$ in the optimal direction to proceed according to the horizontal intent model ϕ. The local correlation is defined by the dot product:

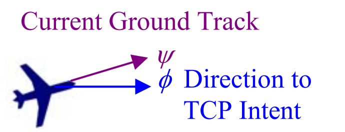


Figure 4. The local horizontal path correlation.

$$L(t) = \hat{\psi}(t) \cdot \hat{\phi}(t) \tag{10}$$

The local correlation will indicate (locally) if the aircraft is heading towards the direction of the intent model (dot product of 1) or in some sense opposite of the intent model (dot product –1). This dot product acts as a good measure of correlation (providing a number between –1 and 1) between the current aircraft motion as indicated by the current ground track and the intent to fly according to the logic of the intent model.

The global correlation functions of Basic, Moving Window, and Fading Memory are applicable to this local correlation function.

Vertical Correlation

As shown in Figures 5 and 6, the vertical parameters that determine the path correlation are a unit vector $\hat{\psi}$ in the direction of the current climb vector ψ and a unit vector $\hat{\phi}$ in the optimal vertical direction to proceed according to the vertical intent model ϕ. The local correlation is defined by the dot product:

$$L(t) = \hat{\psi}(t) \cdot \hat{\phi}(t) \qquad (11)$$

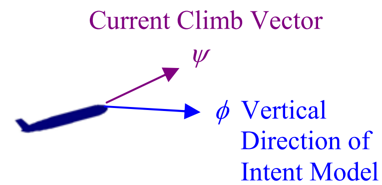


Figure 5. The local vertical path correlation.

This dot product acts as a good measure of correlation (providing a number between –1 and 1) between the current aircraft motion as indicated by the current climb vector and the intent to fly according to the logic of the vertical intent model.

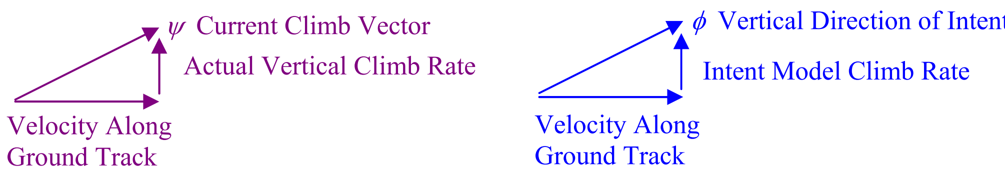


Figure 6. The vector components of the local vertical path correlation.

The global correlation functions of Basic, Moving Window, and Fading Memory are applicable to this local correlation function.

Speed Correlation

The speed state variable used to define local speed correlation is the ground speed signal available from ADS-B data, denoted as V_{actual}. Each intent model dealing with speed will also have an intent speed, denoted as V_{intent}. Both of these speeds will be a function of where the aircraft is on the path. The local speed correlation is defined by:

$$L() = \frac{V_{\text{actual}}}{V_{\text{intent}}} \qquad (12)$$

This function will always be positive, since speeds are always greater than zero. However, the function may be greater or less than one. If the actual speed is the same as the intent speed the function will have value one. As a consequence, the global correlation will be a number between zero and infinity, with one indicating that the vehicle has a speed consistent with the intent model.

In making this choice for the local correlation, we have recognized that speed is inherently different than the other variables used to define horizontal or vertical path correlation functions. Speed is a scalar function, while the quantities used in the horizontal or vertical path correlation functions were two-dimensional vectors. With vectors, a dot product is appropriate to capture if two path directions are aligned. With scalars, the simple division is appropriate to indicate if the scalar is at or near the intent value. The dot product provides normalization to ±1. With a scalar there is still a normalization to one but the local correlation may be greater or less than one and is always positive.

If an aircraft is following the flight plan, the V_{intent} will come from the TCP Ground Speed ADS-B data record. When V_{intent} at TCP is different from V_{intent} at TCP-1, we assume that the aircraft's intent speed can be linearly interpolated over the path from TCP-1 to TCP.

The global correlation functions of Basic, Moving Window, and Fading Memory are applicable to this local correlation function.

4. Certainty Factor in RNP-based Intent Integrity

In order to combine the requirements of horizontal, vertical, and speed dimensions, "Primitive" intent models are considered for each dimension (as listed in Table 2). The primitive intent models are used to define a set of rules to classify the integrity of the ADS-B intent information. The approach taken is to create a continuous Certainty Factor (CF) that ranges from -1 to 1 (or 0 to ∞ in the speed dimension) rather than to indicate a binary verified or not verified solution.

Table 2. Plausible Criteria for Primitive Intent Models.

Horizontal, Vertical, or Speed Intent Description	Dimension	Intent Status
Direct to TCP	Horizontal	Steady State
Return to Flight Leg	Horizontal	Steady State
Hold Coordinated Turn Left (-1.5°/sec or -3°/sec turn rate)	Horizontal	Transient
Hold Coordinated Turn Right (1.5°/sec or 3°/sec turn rate)	Horizontal	Transient
Hold TCP Altitude	Vertical	Steady State
Climb/Descend to TCP Altitude	Vertical	Steady State
Speed to Meet TCP Time-To-Go (TTG) Requirement	Speed	Transient

The following logic is used to determine the CF value. The logic assigns an intent model to each region within the horizontal and vertical dimension as illustrated in Figure 7.

Horizontal:

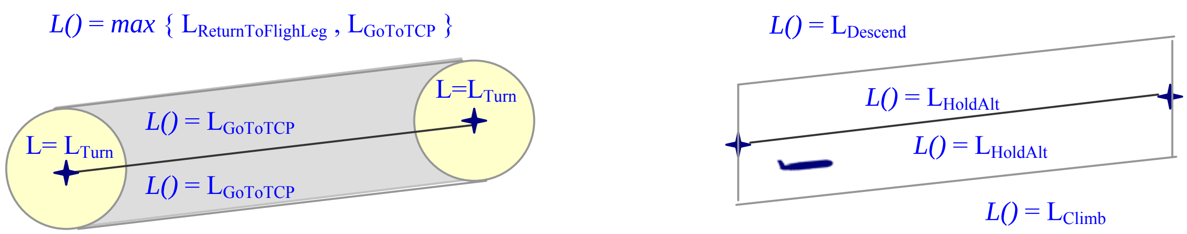
1. If within the RNP_H, Then…
   a. If within the RNP_H from TCP (i.e., the right-most circle in Figure 7a), use Turn Intent Model (Turn Left vs Right determined by TCP+1 location relative to TCP)
   b. Otherwise use Go To TCP Intent Model.
2. If outside the RNP_H, Then: use either the Return To Flight Leg Intent Model or the Go To TCP Intent Model, whichever is better.

Vertical:

1. If within the RNP_V, then use the Hold Altitude Intent Model (Note: The hold altitude intent model is based on the altitude required to meet a straight line interpolation between the TCP-1 altitude and TCP altitude).
2. If outside the RNP_V, then:
   a. If below the RNP_V altitude requirement, use the Climb Intent Model
   b. If above the RNP_V altitude requirement, use the Descend Intent Model.

Speed:

Use Speed to Meet Time-To-Go (TTG) Intent Model.



(a) Horizontal Requirement (b) Vertical Requirement

Figure 7. Regions labeled by the Primitive Intent Models relative to the TCP-1 and TCP.

Given these rules, there are several intent models (Table 2) that are evaluated each time step. We compute:

- *L()* based on Direct To TCP (Intent direction is determined by vector from the current aircraft location to the TCP location, as illustrated in Figure 8)
- *L()* based on Return to Flight Leg (Intent direction is determined by a vector from the current aircraft location to the flight leg along a 45 degree intercept, as illustrated in Figure 8)
- *L()* based on Turn Right or Turn Left (Intent direction is determined by a vector that turns with a rate of a standard 1.5 deg/sec or 3 deg/sec turn rate)
- *L()* based on Climb to TCP Altitude
- *L()* based on Descend to TCP Altitude
- *L()* based on Hold TCP Altitude
- *L()* based on Speed to Meet TTG

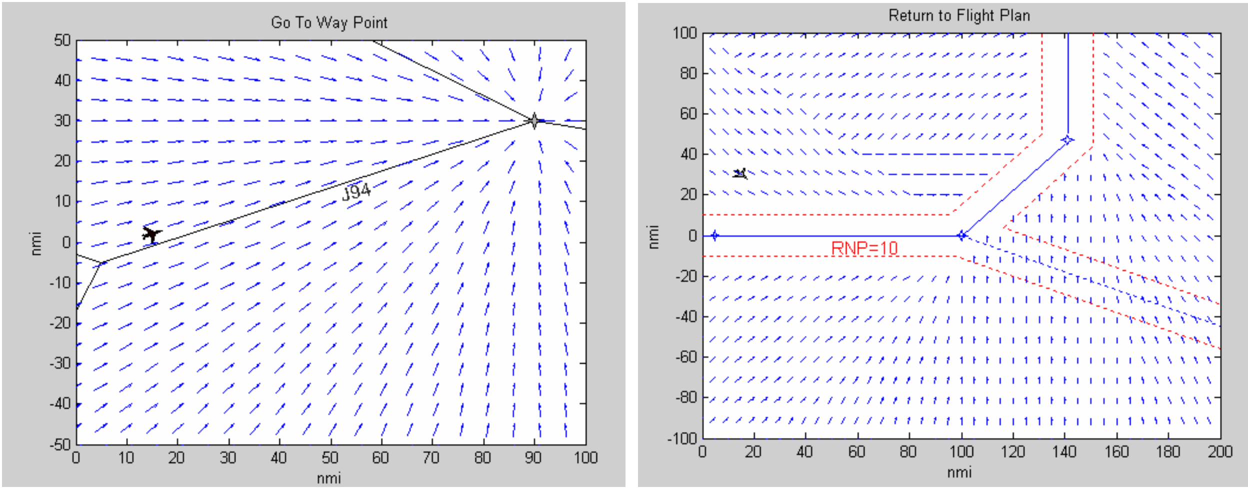


Figure 8. Example Direct To TCP and Return to Flight Leg Intent Model.

The local correlation functions above are used to compute the global correlations ($\rho_{Horiz}, \rho_{Vertical}$, and ρ_{Speed}). Finally, Certainty Factor (CF) is defined as:

$$CF_{Path} = \frac{1}{2}\left[\rho_{Horiz} + \rho_{Vertical}\right] \tag{13}$$

and

$$CF_{Speed} = \left|\rho_{Speed} - 1\right| + 1 \tag{14}$$

where the global correlation functions may be computed with either of Moving Window or Fading Memory. CF_{Path} has a range from -1 to 1. CF_{Speed} is greater than or equal to one.

III. Simulation Results

The following examples demonstrate our algorithms checking state and intent integrity.

Figure 9 illustrates a comparison of several flight paths that demonstrate Geometric Conformance and Intent Conformance in horizontal and vertical dimensions. Red circles on each path indicate that the aircraft is out of Geometric Conformance (falls in the non-conformance status); $\rho \leq$ 0.95. For instance, Path 4 is out of Geometric Conformance almost all of the time because the vertical flight path keeps violating the vertical RNP even though the horizontal flight path is almost always inside the horizontal RNP. Note that Geometric Conformance does not depend on the timing of the update of ADS-B TCP points, nor on the timeliness of the speed profile (ahead or behind the TTG to a TCP). On the other hand, Intent Conformance must reason about the intent of the aircraft to fly to the TCP, to begin a turn early or late, or to proceed to the next TCP. The timing of the ADS-B update and the timing of turns at TCPs becomes an issue in Intent Conformance.

The benefit of Intent Conformance is that it can indicate that the intent of the pilot is to acquire the TCP while the pilot is out of Geometric Conformance. Intent Conformance provides additional information because it reasons about the heading of the aircraft, not just where the aircraft is located (inside vs. outside the RNP). When Geometric Conformance is in the non-conformance status (below 0.95), Intent Conformance identifies if the pilot is attempting to bring the aircraft back into conformance or not. As shown in Figure 9, when comparing the flight paths 1, 3, and 5, there is no attempt for the pilot flying flight path 3 to return to the TCP, and the Intent Conformance continues to decrease well below 1.0. However, for the pilots flying flight path 1 and 5, the pilot seemingly is attempting to return to the flight plan after falling out of Geometric Conformance. So the Intent Conformances of flight paths 1 and 5 increase toward 1.0 even though the aircraft is out of Geometric Conformance for a great deal of time.

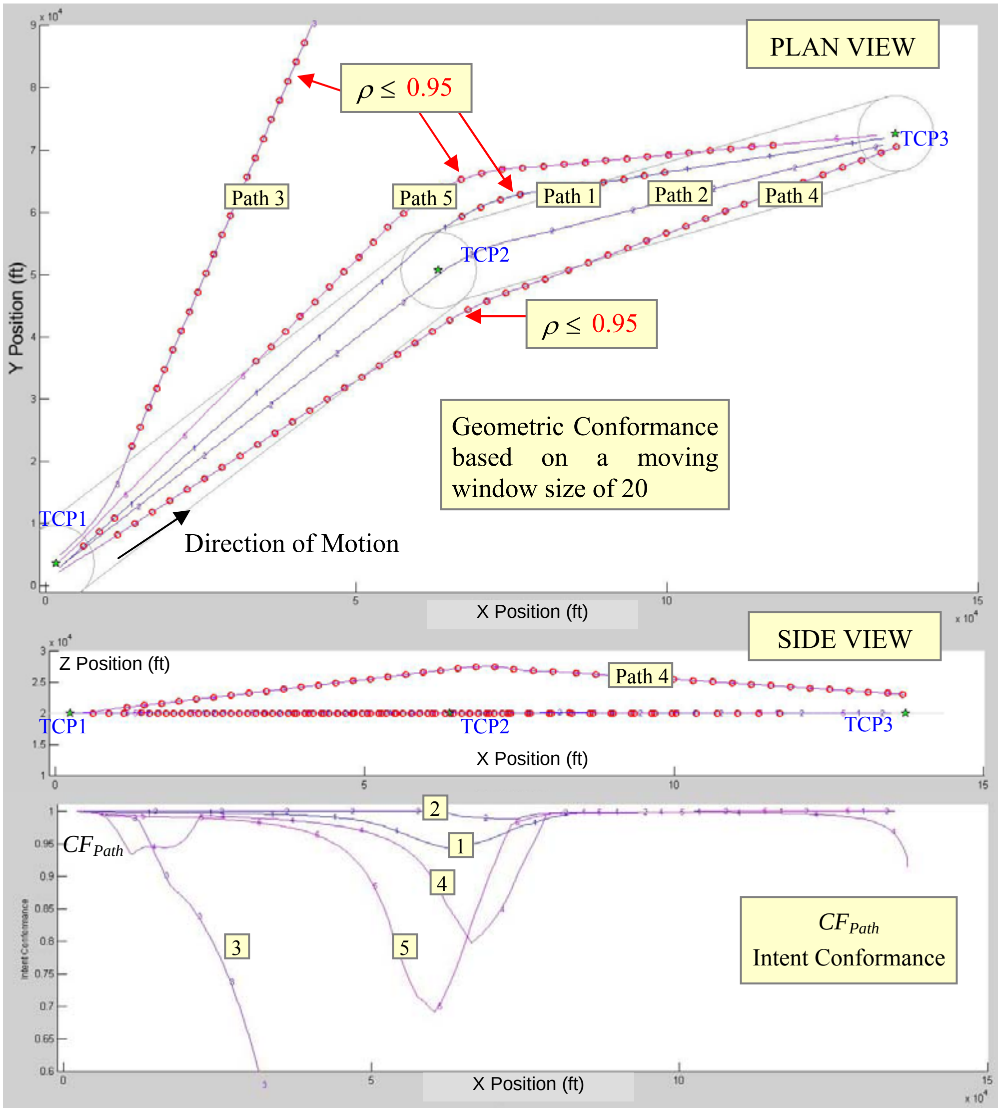


Figure 9. Geometric Conformance and Intent Conformance examples.

Figure 10 demonstrates how Geometric Conformance depends on the moving window size. Note that even though the threshold for Geometric Conformance is fixed at 0.95, the point at which Geometric Conformance is in non-conformance will vary with the moving window size and with the data content of the moving window. If the moving window size is one, then whenever one data point in the moving window history is out of conformance, the algorithm will trigger non-conformance. If the moving window size is ten, then whenever two data points in the moving window history are out of conformance, the algorithm will return non-conformance. In Figure 10, when the aircraft starts out at TCP 1, the moving window average includes a history of all data points in conformance. When a moving window size of one is used, the point of non-conformance is at the RNP boundary (grey line), and when a moving window size is greater than one is used, this point of non-conformance moves away from the NRP boundary as the moving window size is increased. On the other hand, when the aircraft is returning to the flight plan near TCP 3, the moving window is completely full of data in non-conformance. So the aircraft has to re-enter the RNP boundary and remain within the RNP limit long enough (based on the 0.95 threshold) before conformance is regained.

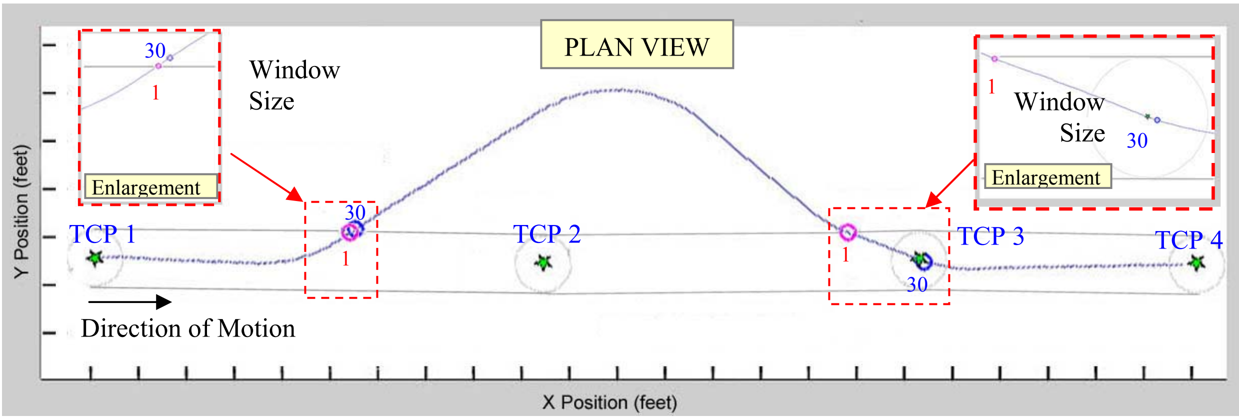


Figure 10. Geometric Conformance depends on the moving window size.

Figure 11 demonstrates how Intent Conformance varies with the degree to which the pilot deviates (wanders) from perfect point-to-point navigation. The flight path 3 represents perfect conformance for an aircraft that flies perfect point-to-point navigation; the Geometric Conformance and the Intent Conformance are both 1.0. For the flight path 1, the aircraft remains in Geometric Conformance, but because the aircraft wanders within the RNP limits, the Intent Conformance varies between 0.97 and 1.0. At the extreme, the flight path 2 wanders out of Geometric Conformance twice, but each time the pilot turns back and returns to the flight plan, the Intent Conformance will return to values above 0.98 before the aircraft returns to Geometric Conformance.

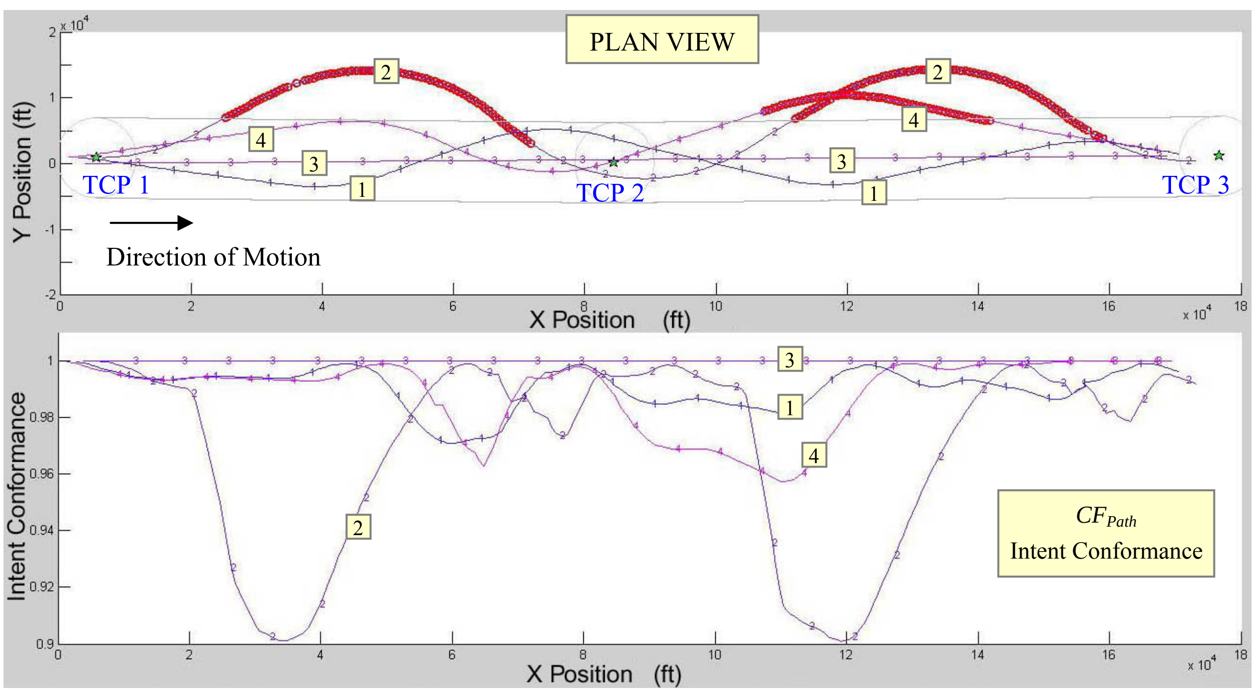


Figure 11. Intent Conformance and Geometric Conformance show different information.

These examples illustrate a need to reason about both Geometric Conformance as well as Intent Conformance for ADS-B integrity checking. In certain applications, there may be a benefit to setting different threshold values for Intent Conformance as well as Geometric Conformance and to reason about both values. In one application, it may be useful to have a first level warning when an aircraft goes out of Geometric Conformance and to subsequently generate a higher level of warning when that aircraft stays out of Intent Conformance for a certain length of time. Furthermore, the moving window size and the choice of a fading memory vs. a moving average may have different impacts in different applications.

IV. Conclusions

The purpose of this research is to verify the aircraft ADS-B data integrity. The approach taken is to estimate the aircraft state in the presence of ADS-B data dropouts, errors, or noise. Given the best aircraft state estimates as determined by a suite of Kalman filters, the ADS-B intent is analyzed to determine if the aircraft is within the RNP limits (a geometric analysis) and/or if the pilot is attempting to follow the broadcast intent (e.g. go to TCP). Real-time metrics are introduced to measure the conformance based on a moving window size. The moving window size is an important parameter since non-conformance depends on the moving window size. Results indicate a promising data-driven approach to verifying the ADS-B data integrity without reliance on a secondary source of surveillance data.

V. Acknowledgments

This research was funded by NASA Langley Research Center under the Small Business Innovative Research (SBIR) Program contract NAS1-02101. The guidance of our NASA Technical Monitor, Edward Johnson, Ph.D. is greatly appreciated; his guidance helped direct and focus the effort.

VI. References

[1]RTCA, *Minimum Aviation System Performance Standards for Automatic Dependent Surveillance Broadcast (ADS-B)*, RTCA/DO-242A, Washington, DC, June 25, 2002.

[2]RTCA, *Minimum Aviation System Performance Standards: Required Navigation Performance for Area Navigation,* RTCA/DO-236A,Washington, DC, 2000.

[3]Gelb, A., *Applied Optimal Estimation*, MIT Press, 1974.

[4]Maybeck, P.S., *Stochastic Models, Estimation, and Control*, Academic Press, New York, NY, 1982.

[5]Mendel, J.M., *Lessons in Estimation Theory for Signal Processing, Communications and Control*, Prentice Hall, 1995.

[6]Krozel, J., *Intelligent Path Prediction for Vehicular Travel*, Ph.D. Thesis, Department of Aeronautics and Astronautics, Purdue University, W. Lafayette, IN, May, 1992.

[7]Krozel, J. and Andrisani, D., "Intelligent Path Prediction for Vehicular Travel," *IEEE Trans. on Systems, Man, and Cybernetics*, Vol. 23, No. 2, March/April, 1993, pp. 478-487.

[8]Krozel, J., "Intelligent Tracking of Aircraft in the National Airspace System", *AIAA Guidance, Navigation, and Control Conf.*, Monterey, CA, Aug., 2002.

[9]Reynolds, T., and Hansman, R., "Analyzing Conformance Monitoring in Air Traffic Control Using Fault Detection Approaches & Operational Data", *AIAA Guidance, Navigation, and Control Conf.*, Austin, TX, Aug., 2003.

[10]Reynolds, T., Histon, J.M., Davison, H.J., and Hansman, R.J., "Structure, Intent, & Conformance Monitoring in ATC", *Workshop on ATM System Architectures and CNS Technologies*, Capri, Italy, Sept., 2002.

[11]Reynolds, T., and Hansman, R., "Conformance Monitoring Approaches in Current and Future Air Traffic Control Environments", *21st Digital Avionics Systems Conf.*, Irvine, CA, Oct., 2002.

[12]Wing, D., Adams, R., Barmore, B., and Moses, D., "Airborne Use of Traffic Intent Information in a Distributed Air-Ground Traffic Management Concept", *4th USA/Europe ATM R&D Seminar*, Santa Fe, NM, Dec., 2001.

[13]Magill, P., "The Use of Aircraft Intent Information in the ATM system; Results of fast-time simulations", *21st Digital Avionics System Conf.*, Irvine, CA, Oct., 2002.

[14]Ruigrok, R., Valenti, C., "The Impact of Aircraft Intent Information and Traffic Separation Assurance Responsibility on En-Route Capacity", *5th FAA/Eurocontrol ATM R&D Seminar*, Budapest, June, 2003.