OVERVIEW AND FLIGHT-BY-FLIGHT ANALYSIS OF TRAJECTORY PREDICTION SYSTEMS USING A 2D GALAXY VISUALIZATION

Confesor Santiago[1], Dr. Adrian Rusu[2], Linda Falconi[2], Bryan Petzinger[2], Andrew Crowel1[l]

Abstract

A new graphic visualization tool, Trajectory Galaxy Visualization (TrajGalaxyViz) has been developed that significantly enhances analysts' ability to determine the accuracy of flight trajectory predictions, i.e. the anticipated route of an aircraft. The partnership between the Federal Aviation Administration's Conflict Probe Assessment Team (CPAT) and the Software Engineering, Graphics, and Visualization (SEGV) research group at Rowan University has enabled the development of TrajGalaxyViz. TrajGalaxyViz is a system developed in Java that enables CPAT to measure the accuracy of flight trajectory prediction methods as well as perform comparisons of different flight trajectory methodologies. This paper explores the development and implementation of TrajGalaxyViz as well as its integration with a previously developed system, Trajectory Graphical User Interface (TrajGUI). TrajGalaxyViz greatly improves the ability to analyze the voluminous amount of data generated by the evaluation of a new air traffic control system.

Introduction

Air traffic density in the United States National Airspace System (NAS) is expected to increase to the extent that it will overpower the capabilities of the current aviation systems. To mitigate this problem, the Federal Aviation Administration (FAA) is upgrading its entire air transportation system from ground based technology and voice communications to satellite based technology and trajectory based operations (TBO). This upgrade will allow an increase in air traffic and improve safety and efficiency. A major component of this Next Generation Air Transportation System (NextGen) [1] is the En Route Automation Modernization (ERAM) [2] which will replace the current system that processes flight radar data, provides communications support, and generates display data to air traffic controllers. ERAM's trajectory predictor (TP) will support NextGen's new standards in flight separation that will allow an increase in air traffic capacity. Trajectory prediction is based upon the four dimensional path (latitude, longitude, altitude, and time) of an aircraft and is calculated using flight position, aircraft data, clearance, and weather information. This enables air traffic controllers to maintain minimum flight separation standards and forecast potential conflicts. TP accuracy is a primary concern and the basis of the overall functionality of the new system. The Conflict Probe Assessment Team (CPAT) at the FAA William J Hughes Technical Center has established a set of metrics to measure the accuracy of TPs using the difference between actual and predicted path of the aircraft [3, 4]. During a typical six hour scenario, various measurements are recorded on actual flight data and predicted trajectories and are uploaded into a set of relational databases. The comparison between the actual flight data and predicted trajectories comprises the TP errors and are input into the trajectory metrics database table. Analysis of the immense volume of data generated by these calculations is a huge undertaking. This examination is made manageable by the development of the Trajectory Analysis Graphical Suite by Rowan University's Software Engineering, Graphics, and Visualization (SEGV) research team. In the following paper we discuss the two programs that comprise this suite. TrajGUI has been introduced in earlier publications [5] and will be discussed briefly. We will then introduce the next step in the suite, Trajectory Galaxy Visualization.

Trajectory Graphical User Interface

The SEGV group at Rowan University, in conjunction with CPAT at the FAA, created TrajGUI to enable analysts to evaluate the data in the trajectory metrics database. TrajGUI was written in Java using the Java Database Connectivity (JDBC) Application Program Interface (API) to retrieve flight data,

[1] Federal Aviation Administration William J Hughes Technical Center, Atlantic City International Airport, NJ.
[2] Rowan University Department of Computer Science, Glassboro, NJ.

trajectory predictions and trajectory errors in the metrics database tables. The JOGL API (Java Bindings for OpenGL), which provides access to the OpenGL libraries, is utilized to present the data in a visual display. The analyst has the ability to create multiple two-dimensional plots comparing the actual path of an aircraft to its predicted trajectory. The graph created shows the actual flight path and its predicted trajectories plotted out according to chosen axes. The analyst has the option to choose from the four dimensions that comprise a trajectory (latitude, longitude, altitude, and time) as well as the error measurements in the metrics database. The plots can contain multiple flight paths, and each flight path may contain many trajectories that were calculated at different times during the flight. This allows for comparison of the accuracy of the trajectories to the actual flight path and to each other. TrajGUI is intended to be the 'micro' scale analysis tool, giving researchers the ability to peer deeply into the details of a few flights of interest.

Trajectory Galaxy Visualization

The Trajectory Galaxy Visualization (TrajGalaxyViz) application was developed to expand upon the capabilities of TrajGUI, providing a method for the rapid and clear visual representation of the trajectory predictions for many flights across one or two sets of error data simultaneously. The data generated from a scenario is grouped into clusters that represent one or more factors of the trajectory. Many flights could potentially be grouped together in this fashion. This will complement TrajGUI, allowing for evaluation of the data that will aid analysts in recognizing trends in trajectory error predictions as well as their significance.

Selection Screen

The selection screen is the first screen displayed when the system is launched (Figure 1). Here the analyst selects specifically what data is to be used and how it will be plotted. The first option is to choose a database from a drop down list to parse for the desired flight information. The analyst must then choose an Air Route Traffic Control Center (ARTCC) from another drop-down list. In Figure 1 the analyst has chosen the faasegv1 database, ZDC which is the Washington DC ARTCC and the ROWANV7 scenario which is the ERAM trajectory predictor.

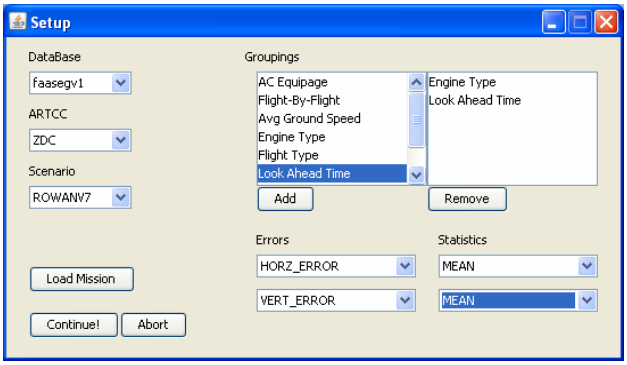

Figure 1. Selection screen

The database is then parsed to populate the drop-down list for scenarios available within the ARTCC chosen. In the example in Figure 1, the analyst has selected the ROWANV7 scenario.

The groupings list determines how the data is grouped into stars. For example if Engine Type is selected then each star will represent all the flights of a particular engine type, i.e. aircraft with jets will be plotted separately from those with piston engines. Multiple groupings can be selected in which case there will be a star for each combination of groupings. Available groupings include AC Equipage, Flight-By-Flight, Average Ground Speed, Engine Type, Flight Type, Look Ahead Time, Max Reported Altitude and End Time.

Errors are graphed on the X and Y axis and therefore a maximum of two errors can be represented. Error types include horizontal, vertical, latitudinal, longitudinal, along track, cross track, slant range, time and k-value. These errors may be calculated according to various statistics including the mean, first quartile, median, third quartile, inner quartile range, minimum, maximum, range, variance, standard deviation and mean square root. In Figure 1 the mean of the horizontal and mean of the vertical error have been selected and will be displayed on the X and Y axes, respectively.

After the selections are complete, the analyst can use the button "Continue!" to launch the next screen. There is also the option to "Abort" which will cancel the system, or "Load" which will load a previously saved session.

Advanced Filtering

Due to the vast amount of data available an advanced filtering screen has been implemented as the metrics databases are so large that the amount of available RAM could be insufficient for some of the queries. This screen allows the analyst to exclude data that is not pertinent to their current session which allows for easier analysis after the plot is created. Figure 2 and 3 show the Advanced Filtering window, the bar at the bottom of the screen shows the percentage of RAM that the system is using with the current choices. As the analyst includes or excludes data the bar will adjust accordingly automatically if the "Auto-Calculate" button is checked. The analyst may choose to uncheck the button and calculate manually by pressing the "Calculate" button. The screen divides the data in to nominal and quantitative data.

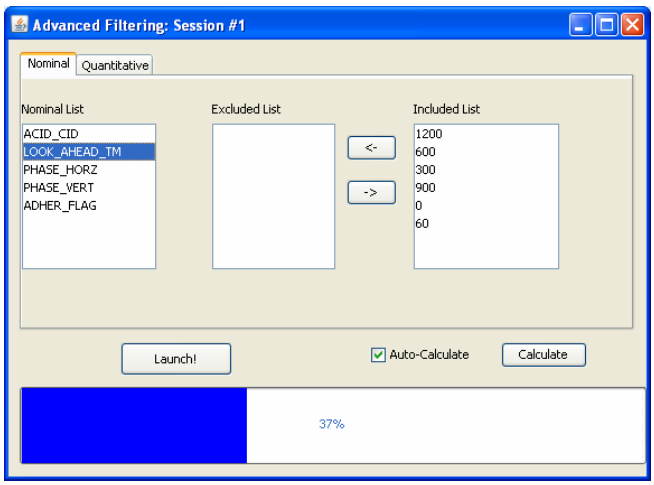

Figure 2. Advanced filtering – Nominal

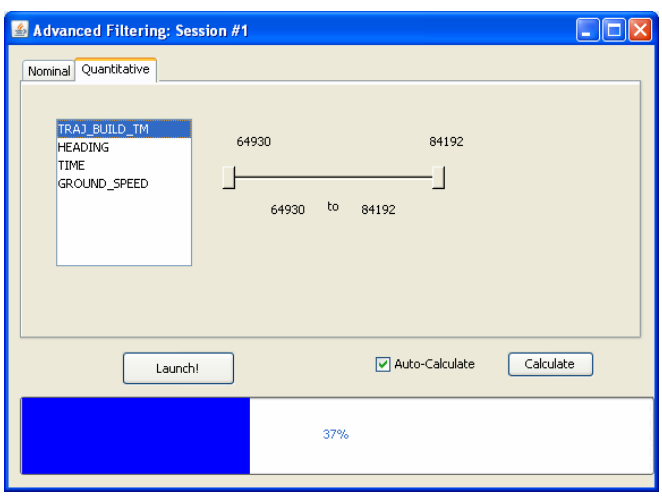

Figure 3. Advanced filtering - Quantitative

Nominal data has specific categories and the analyst can choose to eliminate one or more of these categories for one or more types of data, they include the ACID CID, look ahead time, phase horizontal, phase vertical and adherence flag.

Also provided is the functionality to sort by quantitative data which do not have specific categories. The included ranges are represented on the screen in Figure 3 by the sliding bar. Quantitative data may be sorted by trajectory build time, heading, time and/or ground speed.

Galaxy Plot

When selecting for two errors the data is graphed as a bubble plot, or "Galaxy Plot" (see Figure 4), with errors displayed on each axis and the size of each data point proportional to the amount of data collected. TrajGalaxyViz represents the data as "stars" where each star is a cluster of data based upon the grouping factors chosen in the selection screen.

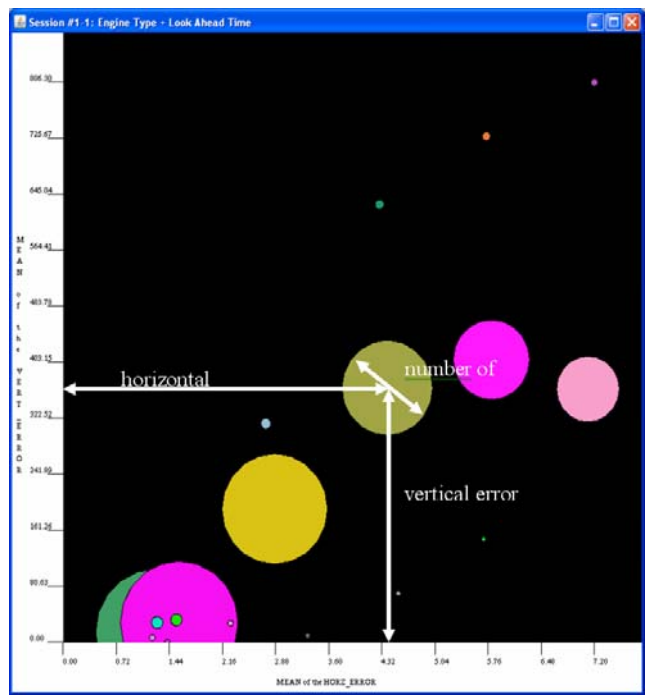

Figure 4. Galaxy Plot

"Engine-Type" and "Look Ahead Time" were the chosen grouping factors in the example in Figure 4, so each star will represent a different engine type and look ahead time. The X-axis is the first statistic-error chosen, mean of the horizontal error, and the Y-axis is the second statistic-error chosen, mean of the vertical

error. From this plot the analyst is quickly able to determine the accuracy of the data as the stars that are clustered together contain comparable accuracy measurements with those closest to the origin (0, 0) being the most accurate. The stars that are set apart on the graph show a deviation in the data, the significance of which can be quickly determined by the radius. The location of each star on the plot is therefore significant in representing how accurate the cluster of metrics data is. Stars that gather together will have similar accuracy measurements while outliers indicate deviations.

Histogram

When plotting data against a single error a standard histogram (Figure 5) is used where the error is represented on the y-axis and the stars are represented as individual bars on the x-axis. By default the bars are sorted according to amount of data collected, with the bars on the left containing the most data points and the bars on the right the fewest, allowing the analyst to easily determine the significance of any given bar in relation to the rest of the data.

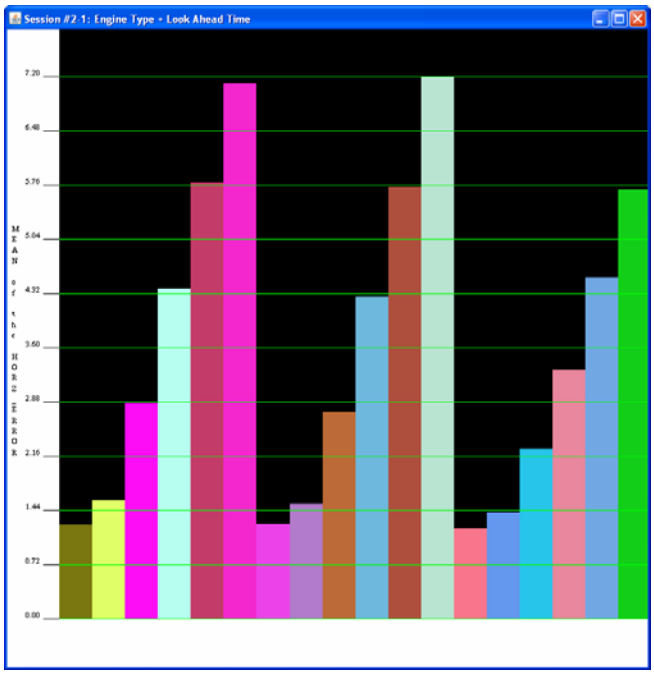

Figure 5. Histogram plot

Compare Plots

TrajGalaxyViz implements a method of comparing two plots by creating a new plot that contains every data point the original two plots have in common and using their difference as the error measurement.

Plot Features

TrajGalaxyViz employs a wide range of features that are intended to aid the analyst in their ability to visually process the data. The toolbar is the main window of TrajGalaxyViz from which all functionality is accessed. A more detailed glimpse of each “Star” is possible by clicking on it. A “Star Chart” is displayed that contains specific information such as “Bin Name” which is the categories from the groupings, diameter, and the exact points on the X and Y axes.

Plots can display an additional dimension via the color of the stars in a Galaxy Plot, or bars in a Histogram. TrajGalaxyViz provides the option to resize the axes through either a continuous adjustment via dragging along the axes or by right clicking the plot and selecting “set axis range” which will bring up a dialog allowing the analyst to specify a discrete range for each axis. By choosing the move option the analyst can click anywhere on the plot and drag the mouse to re-center the plot.

The application employs a method of “expanding” stars. This option creates a Flight-by-Flight view of a new plot using the same parameters as the original plot and populates the graph with only flights contained within the selected star and then groups the data by individual flight. A flight-by-flight plot is a special case of the normal plot types where each star is an individual flight.

If a star is then expanded while in Flight-by-Flight view it opens that flight in TrajGUI for closer inspection. A star in a flight-by-flight plot cannot be expanded in TrajGalaxyViz any further because each star represents a single flight. Therefore this action results in TrajGUI being opened with the preselected database, ARTCC, scenario and flight fields.

The ability to selectively hide and display stars allows the analyst to further customize their viewing options to allow for data to be pictured in the most optimal configuration. This is useful with large data sets where there are many overlapping stars that may be obscuring other data points. All of these features will be demonstrated in a later section when a case study is presented.

Design Overview

TrajGalaxyViz uses object oriented design to separate the application and the graphics from the database, and to allow the user the flexibility needed for analysis (Figure 6).

The Initialization module consists of three sub modules that initialize the application, connect to a database and allows the user to determine what data to be displayed. This module encapsulates the setup functions within one module and allows for greater portability for other projects. All of the database functionality is contained within the Database module which is composed of three lower level modules which acquire the database statistics, set the database parameters and establishes a connection to the selected database. This allows all of the tasks attributed to the database to be in one module.

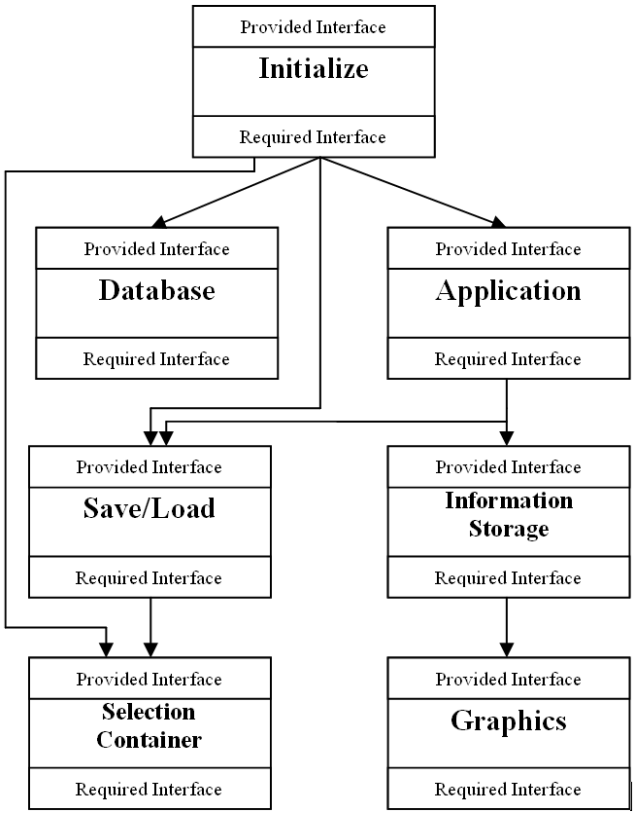

Figure 6. UML of TrajGalaxyViz design

The Application module manages active sessions by providing communications between different parts of the application and providing the tools necessary for manipulation of the plots. The Information Storage module represents the application data in an object oriented fashion. The sessions are represented by Space objects which in turn contain Star objects. Star objects contain all of the information for a particular star and interacts with the Star Chart module which displays the star's statistics.

The Save/Load module interfaces with the Selection Container module to save and load the information selected by the user to be able to save the current session and load previous sessions. The Graphics module was created to encapsulate all of the JOGL and event handlers. All of the graphic capabilities are within this module such as displaying the plots and stars. This module also controls all of the events that occur when a plot is resized or a star is clicked on.

Case Study – URET & ERAM

One of the primary uses of TrajGalaxyViz is comparing different scenarios to analyze their performance relative to each other. This usually comes in the form of regression testing [6], i.e. comparing a new incarnation of an existing trajectory predictor to ensure that each version is better than the last, or analyzing two different trajectory predictors.

In this case the analyst is attempting the latter, selecting scenarios from the two trajectory predictors URET and ERAM (designated ROWANV6 and ROWANV7 respectively). The flight data collected for these trajectory predictors has been grouped by engine type and look ahead time and the data is graphed by the root mean square of the horizontal and vertical errors. The grouping engine type indicates the type of engine the aircraft has (e.g. piston, jet) and the look ahead time is an indication of how many seconds into the future the predictor is working. It is common for the error to increase with the look ahead time and certain types of engines are more difficult to predict and are expected to have greater error as well (e.g. piston aircraft). The root mean square statistic accounts for both positive and negative values and focuses the mean around zero, which allow the data points to be compared against their distance from the origin.

The Galaxy Plots for these scenarios are displayed in Figure 7. In these plots the vertical error data is displayed on the y-axis in feet and the horizontal error data is displayed on the x-axis in nautical miles. By adjusting the axis range of each plot to the same values it is clear that the vertical error data is similar but there

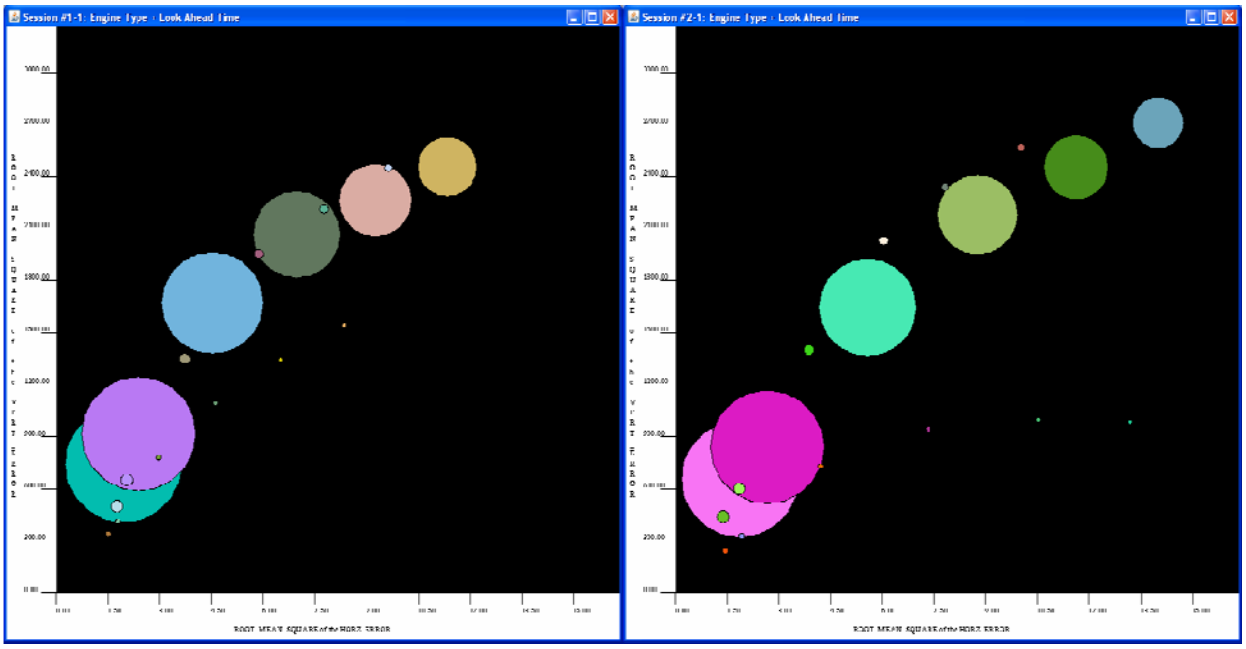

Figure 7. URET (left) and ERAM (right) Galaxy Plots

is enough of a difference of the horizontal error to warrant a closer inspection.

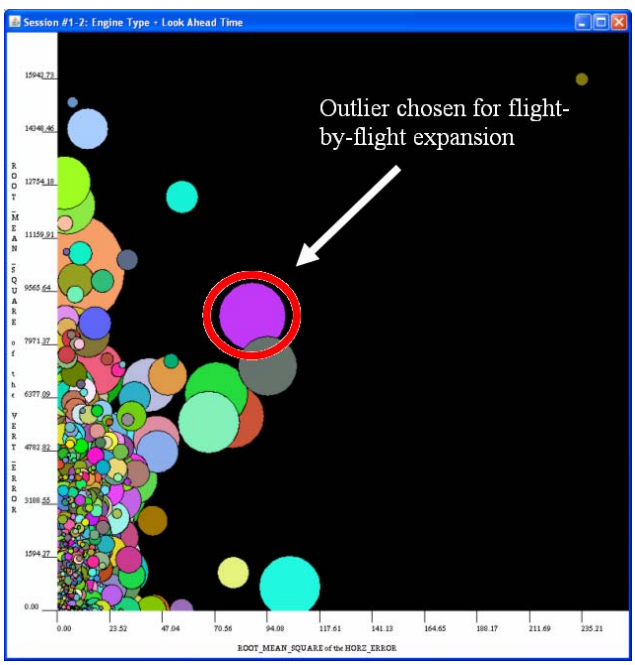

Figure 8. ERAM Flight-by-Flight Galaxy Plot

Expanding the furthest significant outlier (engine type J, look ahead time 1200) into a flight by flight view (Figure 8) we can see the distribution of the individual flights. After opening the flight-by-flight view we can see that there are several flights with a large degree of horizontal error. Utilizing the TrajGUI integration to further explore one of these flights (AIR0642_420) may help determine the cause for the error.

Upon opening the flight in TrajGUI (Figure 9) the reason for the error is immediately apparent. The flight, indicated in red, made an unpredicted loop which resulted in the large amount of trajectory error. Switching to a time and altitude graph in TrajGUI reveals that at the approximate time of the loop the trajectory predictor decreased altitude and the track followed after several seconds. This suggests the loop was made while the flight waited for clearance to change altitude. We can determine other causes for error in a similar fashion, by looking at the data from a high level perspective and then filtering down to eventually find problems at the level of individual flights.

Conclusion

TrajGalaxyViz presents analysts with data that could represent hundreds or thousands of flights and trajectories in a manner that is easy to interpret and further provides functionality to filter through this data in a meaningful way to determine the underlying significance of the data and cause for errors in a given

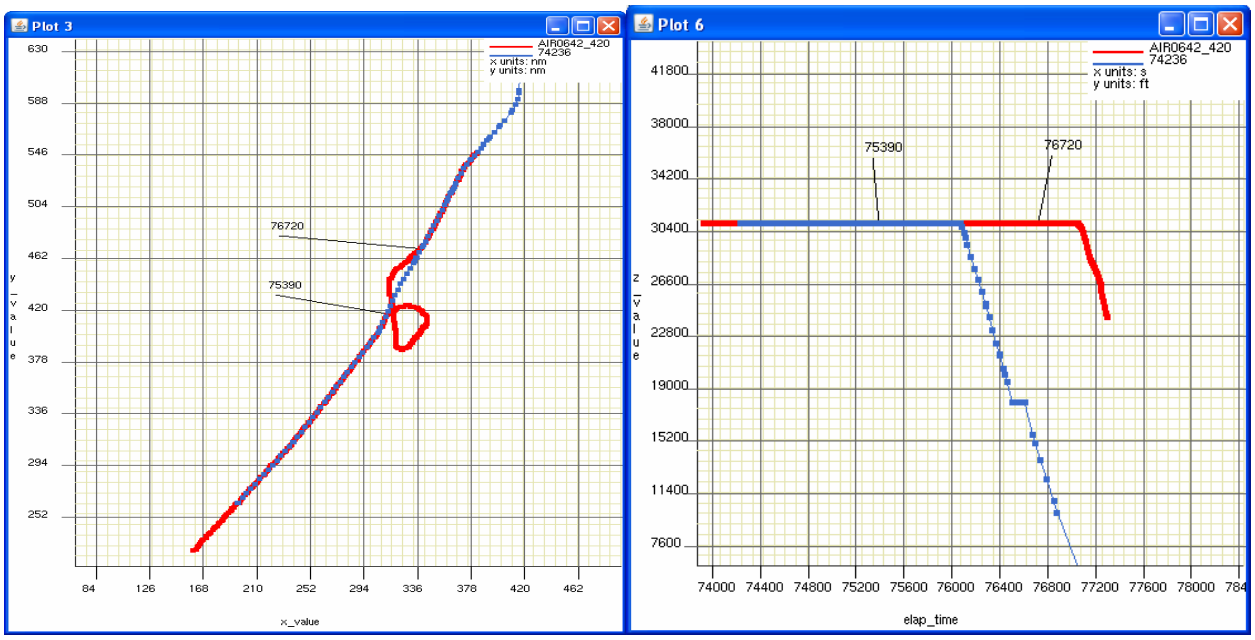

Figure 9. TrajGUI analysis of the outlying flight

scenario. TrajGalaxyViz is the latest application in a suite of developed by SEGV in collaboration with CPAT to assist in the analysis of the copious amounts of air traffic data that are collected. This analysis is critical in the regression testing of trajectory predictors, both ensuring that each new iteration is better than the last and also for finding where any weak points may exist for improvement in future versions.

While TrajGalaxyViz is latest application currently in use by the FAA, SEGV is continuing research on a three dimensional extension of the galaxy plot used by TrajGalaxyViz, as detailed in a recent publication [6].

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