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Application of Statistical Quality Control Techniques to the Detection of Lateral Adherence to a Flight Plan

M. Paglione, J. Page-Graziano, S. Liu, J. S. Summerill

FAA William J. Hughes Technical Center, Atlantic City International Airport, NJ 08405

***Mike Paglione** is the Conflict Probe Assessment Team Lead in the FAA's Engineering and Integration Services Branch (ACT-250). **Jamie Page-Graziano** is a 2001 summer intern for ACT-250. **Shurong Liu** is a Senior Software Engineer with Signal Corporation. **J. Scott Summerill** is a Systems Engineer with Signal Corporation.*

Abstract
The detection of shifts in a process is not a new problem. In manufacturing, engineers have employed Statistical Quality Control (SQC) to detect shifts in key response variables of production equipment for over seventy years. These same control techniques can be applied to air traffic systems. In this paper, the FAA Engineering and Integration Services Branch (ACT-250) presents SQC charting techniques that perform better than existing simple threshold checking techniques for determining when an aircraft flight is laterally deviating from its flight plan.

Background
To achieve the goals of the Federal Aviation Administration's (FAA) Free Flight Phase One (FFP1) Program, advances in ground and airborne automation are required. The FAA has sponsored the development of two ground based air traffic management decision support tools (DSTs) to aid en route and terminal air traffic controllers. The User Request Evaluation Tool (URET), developed by the MITRE Center for Advanced Aviation System Development, facilitates the controller's management of en route air traffic by identifying potential air traffic conflicts. The Center TRACON Automation System (CTAS), developed by the NASA Ames Research Center, supports the controller in the development of arrival sequencing plans and the assignment of aircraft to runways to optimize airport capacity. A fundamental component of both URET and CTAS is the trajectory modeler, upon which the functionality provided by these tools is based. For example, URET uses aircraft trajectories to predict conflicts; CTAS uses its predicted trajectories to calculate meter fix crossing times. Thus, the deviation between the predicted trajectory and the actual path of the aircraft has a direct effect on the overall accuracy of the tool [5].

Flights that deviate from their known cleared route cause the DST trajectory prediction to become less accurate [1][2][5]. NASA and MITRE researchers have built heuristic algorithms to reduce these errors by estimating the aircraft's intent. These trajectories still produce significant deviations from the known route of flight and have considerably reduced accuracy. Therefore, improvements in the detection of these flight deviations

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can improve both the trajectory prediction, as well as other predictions like conflict notification. The prediction accuracy of ground based DSTs, such as URET and CTAS, are a critical issue to their implementation in the FAA's FFP1 Program and beyond.

The focus of this paper is not on improving the modeling of deviating flights, but on the earlier detection of them. Early detection will reduce the likelihood that an incorrect trajectory will be used in future predictions and therefore improve the total prediction accuracy.

Description of Statistical Quality Control

Aircraft are cleared to fly a particular route of flight. If changes are requested and granted during the flight, flight plan amendments are normally entered into the system. However, there are situations where certain deviations to the original route of flight are granted by the air traffic controller yet do not enter the automation systems including the DST. The trajectory modeler utilizes the known air traffic clearances, especially the flight plan, to accurately build its trajectory and conflict detection predictions into the future. Therefore these occurrences lead to deviations that must be detected before the accuracy is compromised.

Under normal conditions, URET requires an aircraft to deviate laterally by 2.5 nautical miles from its cleared route before it is considered out of adherence and applies its algorithms to build a new trajectory. By applying Statistical Quality Control (SQC) techniques ACT-250 expects to detect deviations sooner than URET's nominal threshold. This study evaluated two different SQC charting techniques against the baseline 2.5 nautical mile threshold. These were the X-Bar and Moving Range Control Charts [4]. These SQC control charts work together to detect shifts or significant deviations in the process mean.

First the Moving Range Control Chart monitors the first difference or recent change in the current lateral deviation. This difference, referred to as the moving range, is defined in Equation 1, where the x_i is the current lateral deviation for aircraft position i and the x_{i-1} is the previous lateral deviation for aircraft position $\mathrm{i}-1$. Therefore, the moving range for position i is the absolute difference between the current lateral deviation and the previous lateral deviation. The Moving Range Control Chart is a plot of these moving range values.

$$\mathrm{MR}_{\mathrm{i}} = \left| x_{\mathrm{i}} - x_{\mathrm{i-1}} \right| \qquad (1)$$

An average of all measurements of the moving range (MR) is proportional to the overall variation in lateral deviation [3]. Over a dozen factors were initially hypothesized to significantly influence this variation. The four factors determined to have the most significant impact include altitude, speed, horizontal phase of flight (e.g. straight or turn),

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and navigation equipage (e.g. flight management system, FMS). The average moving range was calculated for over 1500 aircraft flights for all the combinations of these four factors. One example of the influence of a factor is the navigation equipage. Aircraft with navigation equipage had an average moving range 20 percent less than aircraft without this equipment.

The X-Bar Chart monitors the process by applying a threshold of approximately 3.5 standard deviations from the target mean. The target mean for our aircraft is zero lateral distance, since we are assuming the aircraft's target path is on the cleared route of flight. The following Equations 2 and 3 define the upper and lower control limits of the X-Bar Chart[1] [4]. If an aircraft's lateral deviation is detected outside these control limits, the aircraft would be assumed to be no longer flying on its cleared path.

$$\text{Upper Control Limit} = \text{UCL} = 3.5\left(\frac{\overline{\text{MR}}}{1.128}\right) \tag{2}$$

$$\text{Lower Control Limit} = \text{LCL} = -3.5\left(\frac{\overline{\text{MR}}}{1.128}\right) \tag{3}$$

The $\overline{\text{MR}}$ in the Equations 2 and 3 is defined as the average moving range (i.e. the average first difference). For all similar flights, it is the average value of Equation 1. Therefore by calculating the average moving range for all combinations of the four factors (altitude, speed, horizontal phase of flight, and navigation equipage), the upper and lower control limits of the X-Bar Chart in Equations 2 and 3 expands and contracts accordingly.

Application Example of Statistical Quality Control

This paper illustrates the application of the SQC X-Bar Chart on an overflight commercial aircraft flying in Memphis Air Route Traffic Control Center (ARTCC), recorded on May 26, 1999. This flight referred to in this paper as ABC100 has three flight plan amendments during its transition over the Memphis airspace. As presented in Figure 1, the first flight plan message and thus cleared route is recorded at 14:12:40 hours. For comparison to the flight plan, the actual horizontal path of the aircraft as reported by the Memphis ARTCC's Host Computer System (HCS) is plotted in Figure 1 as well. ABC100 follows the cleared route for about 8 minutes until a second

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[1] Note, the term $\left(\frac{\overline{\text{MR}}}{1.128}\right)$ in Equations 2 and 3 is an estimate of the process standard deviation [4].

amendment is recorded as Cleared Route 2. This second amendment enters the automation at 14:20:54 hours, but ABC100 deviates from Cleared Route 2 to follow Cleared Route 3, which does not enter the automation for about another 13 minutes. For a DST making trajectory predictions from approximately 14:21:00 and 14:33:10 hours, the aircraft is deviating laterally up to 27 nautical miles from the known Cleared Route 2. Until the third amendment enters the automation at 14:33:10 hours, the DST will have difficulty in its trajectory predictions.

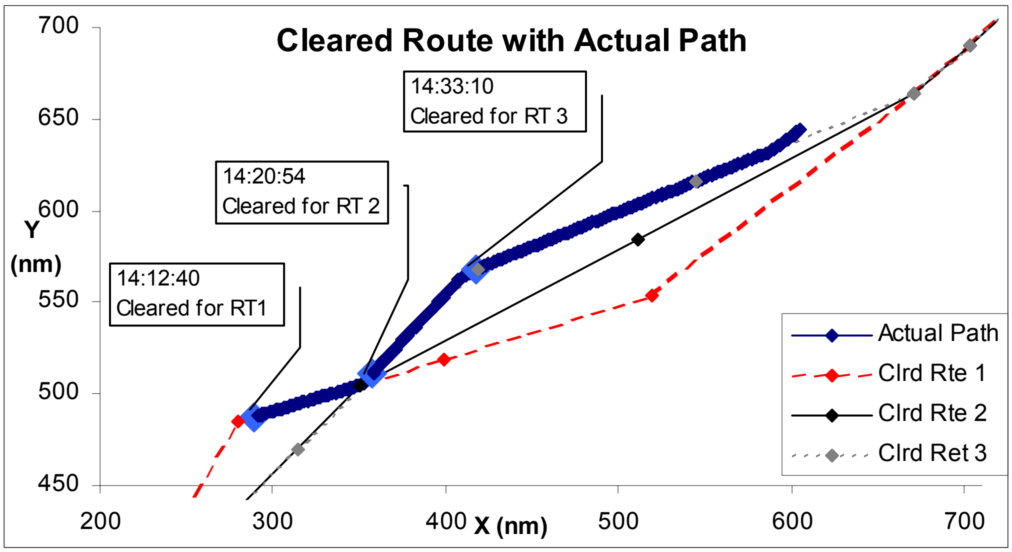

Figure 1: XY Plot of Aircraft Routes and Track Positions

In Figure 2, the X-Bar Chart is presented for ABC100. The X-Bar Chart as described in the previous section is a plot of the lateral deviations as a function of time. Under normal conditions, the ± 2.5 nautical mile thresholds plotted on Figure 2 represent the current methodology that the URET DST uses to determine when an aircraft has deviated from the current trajectory. The upper and lower control limits in Figure 2 range from ± 0.25 nautical miles to about ± 1.5 nautical miles depending on the four parameters discussed in the previous section. The three lateral deviation points marking the transitions between cleared routes are called out in Figure 2. Consistent with Figure 1, the initial lateral deviations in Figure 2 are within both the UCL and LCL and the ± 2.5 thresholds. However, shortly after reaching Cleared Route 2 at point 55, ABC100 deviates beyond the LCL and about a minute later exceeds the -2.5 threshold at point 60. A few minutes after Cleared Route 3 is applied the lateral deviation finally returns to within the UCL and LCL levels. ABC100 remains within both UCL/LCL and the ± 2.5 thresholds until being handed off to an adjacent facility.

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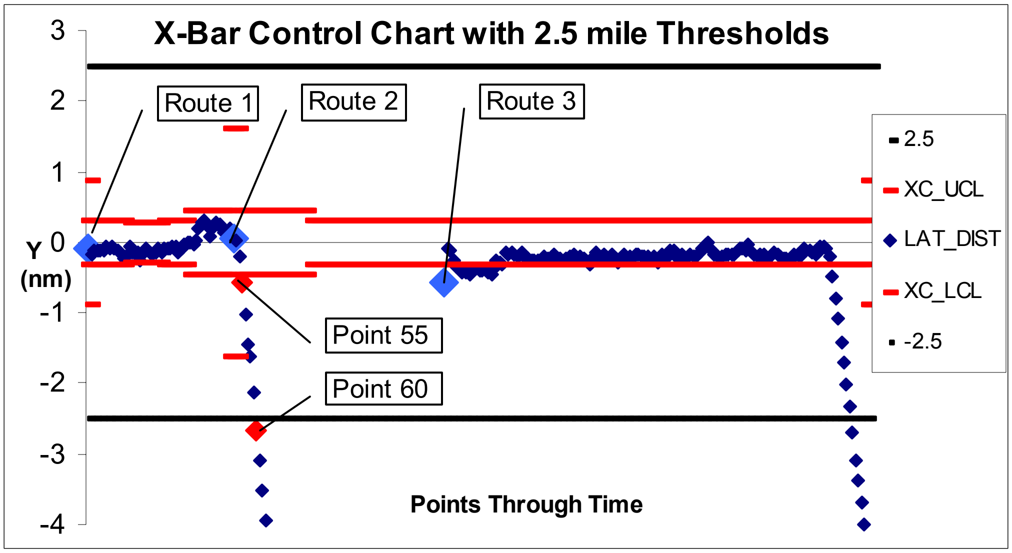

Figure 2: X-Bar Control Chart for Flight ABC100

Conclusion

The X-Bar Control Chart, an SQC technique, was effectively applied to detect aircraft deviating laterally from the known cleared route faster than using a constant threshold. In an example flight, the lateral deviation from the cleared route was detected approximately one minute earlier than the current threshold method. By detecting these deviations earlier, trajectory predictions can be re-built and improve the DST's accuracy as a result. More analysis on many more flights and other SQC charting techniques will need to confirm these findings.

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