Analysis of Aircraft Turn Trajectory Using SSR Mode S Data

【論文】

Analysis of Aircraft Turn Trajectory Using SSR Mode S Data

Masato Fujita [1]

Abstract

Air traffic control (ATC) systems should accurately predict aircraft trajectories and automatically generate conflict-free trajectories under the trajectory-based operation concept. The turn trajectory data observed by SSR Mode S with the Downlinked Aircraft Parameters were analyzed. We showed that the correlation between turn angle and turn duration is extremely low, but the correlation between the degree of turn and roll angle is high. We also proposed statistical models of the relation between turn angle and roll angle, but they still have residual errors which are not negligible.

Keywords: Air Traffic Management, Trajectory Model, Turn, Downlinked Aircraft Parameter

1 Introduction

Trajectory-based operation (TBO)[1), 2)] is a cornerstone of the future air traffic management system. Under the TBO concept, aircraft follow the planned trajectories developed before their departure. Aircraft and air traffic control (ATC) authorities share their trajectory information during the flights. ATC predicts the trajectories using this shared information accurately. Accurate prediction is expected to realize efficient air traffic flows.

Aircraft operation is roughly categorized into ground operation before takeoff and after landing, climb, cruise and descent operations. We will only consider the cruise operation in this paper though TBO concept covers all the above phases.

The minimum separation between two aircraft is defined in ATC for preventing collisions between aircraft. A “conflict” is the situation where the minimum separation is violated. Aircraft trajectory should be precisely predicted and ATC information systems should automatically compute conflict-free trajectories of multiple aircraft[3)] in order to manage the increasing traffic and realize efficient air traffic.

It will be hard for ATC information systems to compute conflict-free trajectories when a complex trajectory model is used in the systems. A simpler model is preferred as long as it approximates the reality well. For instance, previous works[4),5)] used the piecewise linear trajectory model. Aircraft were assumed to fly straight at constant speeds and change their headings instantaneously in this model.

However, real aircraft cannot change their headings instantaneously. This piecewise linear trajectory model may not approximate the real trajectories sufficiently enough for automatic conflict resolution. When more complex model is considered, dynamic information on turns of actual aircraft is necessary.

We will analyze aircraft trajectory data to understand the actual behavior of aircraft turns in this paper. This paper shows the extremely low correlation between turn angle and turn duration and the high correlation between the degree of turn and roll angle. It also shows that some values of roll angle are preferred. We also proposed statistical models of the relation between turn angle and roll angle, but they still have residual errors which are not negligible. Dynamic information downlinked from aircraft to a Secondary Surveillance Radar (SSR) station is used for the analysis.

This paper is organized as follows. We first explain the data used for the analysis in Chapter 2. Chapter 3 summarizes the analysis results. Finally, we summarize this paper in Chapter 4.

2 Data

Secondary Surveillance Radar (SSR) is used by ATC to monitor aircraft horizontal positions, their flight levels and their identification codes. Aircraft receive interrogation signals from the radar and onboard transponders transmit respond signals. The distance of aircraft is estimated based on the time required to receive the respond signals. SSR with improved surveillance capability and data link function is called SSR Mode S.

The downlinked kinematic/intention parameters such as target altitude, true air speed, true track angle and roll angle are called Downlinked Aircraft Parameters (DAPs). Since jet aircraft cannot change their heading without rolling, roll angle data is useful for the determination of turn initiation time.

Electronic Navigation Research Institute (ENRI) has a SSR Mode S experimental system called Chofu SSR

Received November 29, 2015

1 Japan Coast Guard Academy, masato@jcga.ac.jp

Mode S station, and continuously collects surveillance radar data for research purposes[6]. Figure 1 is Chofu SSR Mode S station and Table 1 summarizes its parameters.

Figure 1 Chofu SSR Mode S Station

Table 1 Parameters of Chofu SSR Mode S station

Parameter	Value
Coverage	250 nautical miles
Rotation period	10 seconds
Device Power	1.5 kW maximum

Data analyzed in this paper was obtained during the following periods from Chofu SSR.

January 1st – 7th, 2012
April 1st – 7th, 2012
July 3rd – 9th, 2012
October 9th – 15th, 2012

Every airframe has its unique Mode S address. Mode S address code is used for the identification of airframes. We computed the required time for turn and maximum roll angle by means of the following procedure. We consider that aircraft fly straight when the downlinked roll angle parameter is not larger than 1.0 degree in magnitude. A turn starts when a datum satisfying the following condition is observed.

1. The parameter value of roll angle is not larger than 1.0 degree in magnitude.
2. The roll angle parameter value of the succeeding observed datum is larger than 1.0 degree.

Aircraft images in Figure 2 represent observation data obtained by SSR Mode S. Since the rotation period of SSR Mode S is 10 seconds, a single aircraft is observed approximately every 10 seconds. In Figure 2, the downlinked roll angle value is 0.8 degrees at 1:00:13 and the next is 3.2 degrees at 1:00:23. Therefore, we consider that the turn is initiated at 1:00:13. A turn ends when the roll angle of observed datum first becomes smaller than 1.0 degree after the turn initiation. The turn is completed at 1:00:53 in Figure 2. The maximum roll angle is defined as the observed roll angle whose magnitude is maximum among the succeeding observed data during a turn. The maximum roll angle is larger than 1.0 degree in magnitude by definition. In the case of Figure 2, the maximum roll angle is 10.2 degrees. The turn duration is 40 seconds. The turn angle is computed from the true track angles of DAPs data at the start and the end of the turn. The true track angles of the aircraft in Figure 2 are 90 and 135 degrees at the time of turn initiation and completion, respectively. The turn angle is 45 degrees in this case.

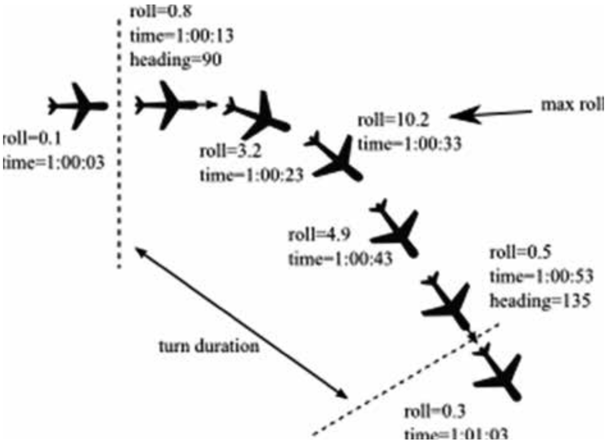

Figure 2 Definition of Turn Duration and Maximum Roll Angle

We generated data consisting of the location of turn, turn duration, turn angle, maximum roll angle and so on from the SSR Mode S observation data by means of the above procedure. We call them turn data. We next extract the turn data whose Mode C code is between 28,500 feet and 41,500 feet to obtain the turn data observed in the cruising phase. Here, Mode C code is the flight altitude measured by atmospheric pressure altimeters. The number of the extracted turn data is 25,402. The downlinked roll angle may exceed the value of 1.0 even though the aircraft does not intend to make a turn. We then extracted the turn data whose maximum roll angle is not smaller than 5.0 degrees in magnitude from the above data. Turns are usually made over the intersections of air routes. The threshold of 5.0 degrees was determined by investigating the locations where turns were observed. The locations of turn is summarized in Section 3.1. The size of this extracted data set is 9,655. We analyze this data set unless otherwise stated in this paper.

3 Analysis Results

3.1 Location of turn

Figure 3 is a heat map illustrating the locations of turns. The darker areas in the figure are the areas where many turns are made. Points in the figure are the geographical points used in the definition of air routes. They are called waypoints. The segments represent air routes. Many turns are made on the waypoints where the route direction changes and also over the sea to the south. It seems to be reasonable because ATC instructs aircraft to make detours in order to delay the arrival of flights at Tokyo International Airport.

3.2 Turn duration

We will analyze turn duration in this section. Since SSR Mode S observation data are available only every 10 seconds, turn duration can be estimated only by a unit of 10 seconds. Turn duration will be overestimated by means of the procedure introduced in Chapter 2 if the roll angle slightly exceeds 1.0 degree in magnitude even after the end of the turn. We computed the Pearson product-moment correlation coefficient between turn duration and maximum roll angle. It was 0.0066, and the correlation between them was extremely weak. The Pearson product-moment correlation coefficient is simply called correlation coefficient in the rest of this paper. The correlation coefficient between turn duration and turn angle is -0.054, and the correlation between them is also weak.

Figure 4 illustrates the histogram of estimated turn duration. The mean of turn duration is 64 seconds and their standard deviation is 43 seconds. The 10 percentile is approximately 30 seconds and the 90 percentile is approximately 110 seconds.

Figure 3　Location of Turn (Heat Map)

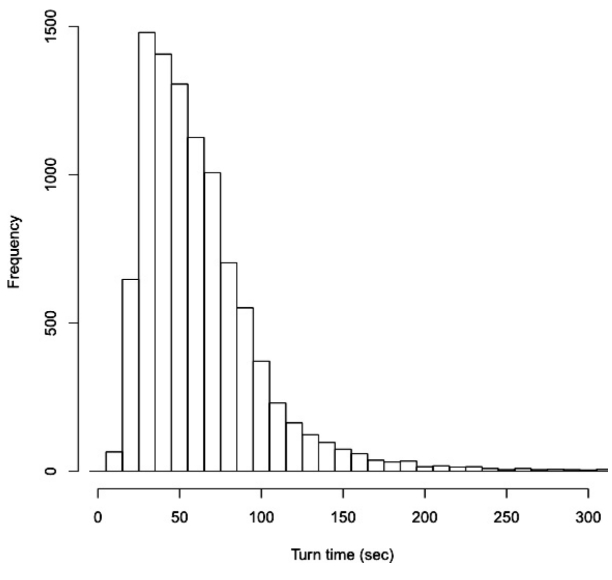

Figure 4　Turn Duration

Consider the case where the observed maximum roll angle is 15 degrees and turn duration is 60 seconds as an example. Various profiles of roll angle can be considered even in this condition. An aircraft may change its roll angle gradually at a rate of 0.5 degrees per second. In this case, at the time of turn initiation, the downlinked roll angle is 0 degrees, the roll angle of 5 degrees is downlinked 10 seconds later, and the downlinked parameters are 10, 15 10, 5 and 0 degrees at 20, 30, 40, 50 and 60 seconds, respectively. The aircraft may change its roll angle rapidly, for instance, it changes its roll angle at a rate of 1.5 degrees per second in the first 10 seconds, then keeps its roll angle constant for 40 seconds, and returns the horizontal position. Then the downlinked parameters are 0, 15, 15, 15, 15, 15 and 0 degrees at 0, 10, 20, 30, 40, 50 and 60 seconds, respectively.

The variations of roll angles of succeeding data during a turn are evaluated so as to investigate the profile of roll angles during turns. We assume that aircraft fly at a constant roll angle when the variation is less than 3 degrees, and compute the duration in which aircraft change their roll angles during their turns. Figure 5 illustrates the results. The threshold of 3 degrees was selected after investigating some typical data.

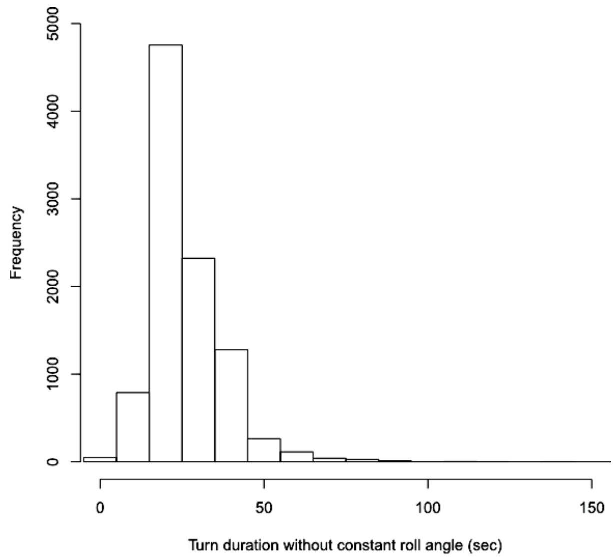

Figure 5　Turn Durations without Constant Roll Angle

The duration in which aircraft change their roll angle is between 20 seconds and 40 seconds in many cases. Aircraft seem to change their roll angle over a maximum of 10 to 20 seconds during their turns, and require the same amount of time to return to their horizontal positions. Observation data are available only every 10 seconds by SSR Mode S, and the number of obtained data during the period of 10 to 20 seconds is only 2 or 3. Therefore, it seems hard to analyze the precise profile of roll angle from aircraft's horizontal position to the position of the maximal roll angle using SSR Mode S data.

3.3　True air speed

We statistically investigate true air speed. The correlation coefficient between maximum roll angles and true air speeds is -0.033, and the correlation between them is weak. Figure 6 illustrates the distribution of true air speeds when maximum roll angles are observed. The mean and standard deviation of this data are 460 knots and 23.3 knots, respectively.

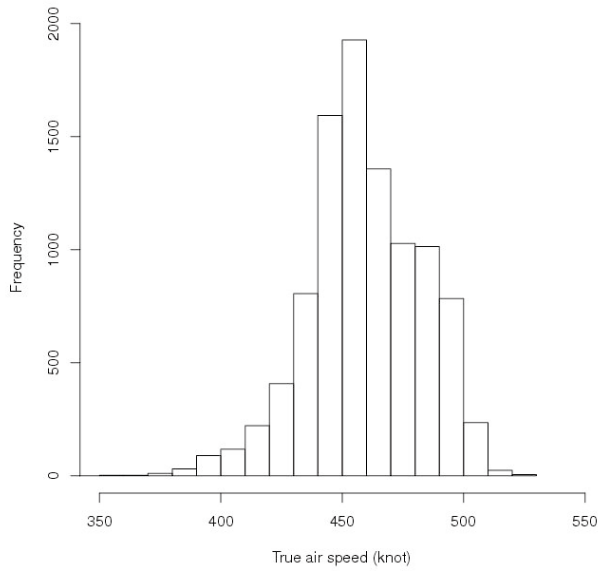

Figure 6 True Air Speed

We also evaluated the standard deviation of true air speed in a single turn. For instance, when four sets of SSR Mode S observation data are obtained in a single turn, we compute the standard deviation of true air speed of these four sets of data. Figure 7 illustrates the distribution of it.

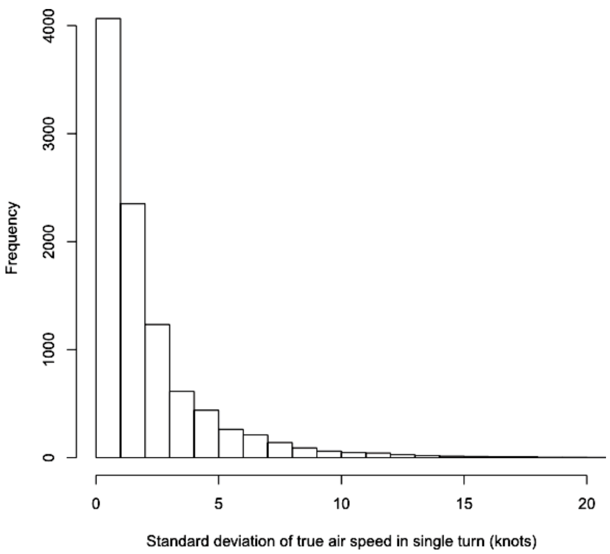

Figure 7 Standard Deviation of True Air Speed in a Single Turn

The mean and standard deviation of this distribution are 1.4 knots and 2.5 knots, respectively. The 90 and 95 percentiles are 5.0 knots and 7.0 knots, respectively. It shows that the speed variation during a turn is small.

3.4 Correlation among turn angle, maximum turn rate and maximum roll angle

We first present the distribution of maximum roll angle in Figure 8. We can see small peaks at 15 degrees and 25 degrees. These values are more often selected than the values close to them. Flight Management Computer is implemented to prefer these values.[7)]

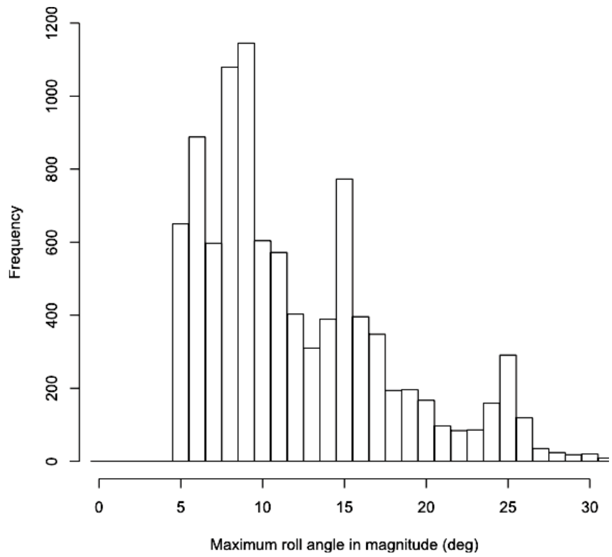

Figure 8 Maximum Roll Angle in Magnitude

We next considered the correlation between maximum turn rate and maximum roll angle. We calculate the turn rate during two sets of continuous observation data as the difference in true track angles of these data and divided them by the difference in observation time. The maximum turn rate is the maximum of these estimated turn rates in a single turn. Since aircraft control their turn rates by controlling their roll angles, we can expect strong correlation between them. Their correlation coefficient is 0.96. In the computation of the correlation coefficient, we excluded the 17 outliers whose maximum roll angles were larger than 40 degrees and maximum turn rates were larger than 3 degrees per second. Table 2 shows the results of linear regression analysis whose regressor is maximum roll angle and whose regressand is maximum turn rate.

Table 2 Linear model of maximum turn rate w.r.t. maximum roll angle.

	Estimate	**Standard Error**
Intercept	0.013	0.0016
Coefficient	0.039	0.00012
Residual Standard Deviation	0.16	

The trajectory is uniquely determined in the uniform circular motion model once speed, turn rate and turn angle are given. Our analysis aims to develop a trajectory model used for conflict detection and conflict-free trajectory generation in TBO. Decisions regarding conflict resolution are made by ATC, and turn angle can be determined by ATC. However, in present-day operation, the turn rate is not instructed by ATC, so ATC should estimate the turn rate selected by the aircraft. Turn rates can be estimated once the relation between turn angles and turn rates are clarified. Figure 9 illustrates the scatterplot of maximum turn rates and turn angles. Obvious correlation is found in Figure 9. The correlation coefficient between them is 0.81.

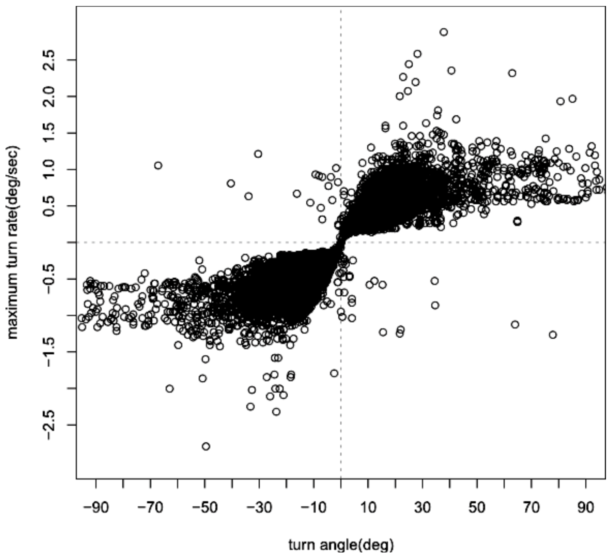

Figure 9　Maximum Turn Rate and Turn Angle

We next consider the relation between turn angle and maximum roll angle. Since maximum roll angle is strongly correlated with maximum turn rate, a similar relation to that illustrated in Figure 9 is expected. Figure 10 illustrates the scatterplot between them. We plotted all the data whose maximum roll angles are greater than 1.0 degree so as to make the distribution of data whose maximum roll angle is roughly 5.0 clearly understandable.

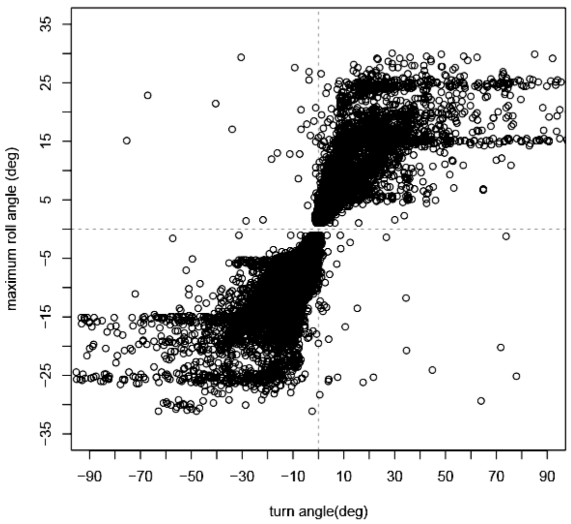

Figure 10　Maximum Roll Angle and Turn Angle

The correlation coefficient between maximum roll angle and turn angle is 0.75. Note that Figure 10 shows the data whose maximum roll angle is larger than 1.0 degree, but the roll angles of the data used for this and the following analyses are larger than 5.0. The correlation coefficient between them is smaller than that between maximum turn rate and turn angle, but we can find special characteristics in Figure 10 which are harder to find in Figure 9. Figure 10 clearly shows linear relations in which maximum roll angle increases when turn angle increases. In addition, we find a relation in which maximum roll angle is constant regardless of the value of turn angle at the multiples of 5 degree roll angles such as 5 degrees, 10 degrees, 15 degrees, 20 degrees and 25 degrees. We first extract the data whose turn angle is smaller than 60 to exclude outliers. We also eliminate the data whose roll angles are the multiple of 5.0 plus/minus 1.0 degrees in this analysis in order to eliminate the influence of data whose roll angles are almost the multiples of 5 degree, and computed the correlation coefficient. The correlation coefficient rose to 0.86. It represents strong linear relation between maximum roll angle and turn angle. It does not contradict Figure 10.

Table 3 shows the results of linear regression analysis whose regressor is turn angle and whose regressand is maximum roll angle. We used the same data set used for the computation of correlation coefficient. The residual standard deviation of 6.3 is large. Data in Figure 10 are widely distributed in the figure even after eliminating the data whose roll angles are the multiple of 5.0 plus/minus 1.0 degrees. The large residual standard deviation means this fact.

Table 3　Linear model of maximum roll angle w.r.t. turn angle (Turn angle is smaller than 60 degrees in magnitude.)

	Estimate	**Standard Error**
Intercept	-0.60	0.091
Coefficient	0.60	0.0051
Residual standard deviation	6.3	

The data analyzed in Table 3 may contain multiple data sets following different linear models due to the mix of multiple aircraft types. We consider the relation between maximum roll angle and turn angle of a single aircraft type. We selected Boeing 737-800 series because the size of turn data is the largest. However, we found similar tendencies in other aircraft types. Figure 11 illustrates the scatterplot between maximum roll angle and turn angle of Boeing 737-800.

We can find two linear relations in Figure 11. We tried to identify the factors determining which aircraft follows which linear model, but failed. The data whose roll angle is the multiple of 5 degrees are often selected and do not follow the linear relations. We then extracted the data whose turn angle is smaller than 60 degrees in magnitude and we eliminated the data whose roll angles are the multiple of 5.0 plus/minus 1.0 degrees. We applied the EM algorithm for the mixed linear regression models introduced in the Appendix assuming that two linear models are mixed in the data. We assumed the same regressor and regressand in Table 3. Table 4 summarizes the results of the mixed linear regression analysis.

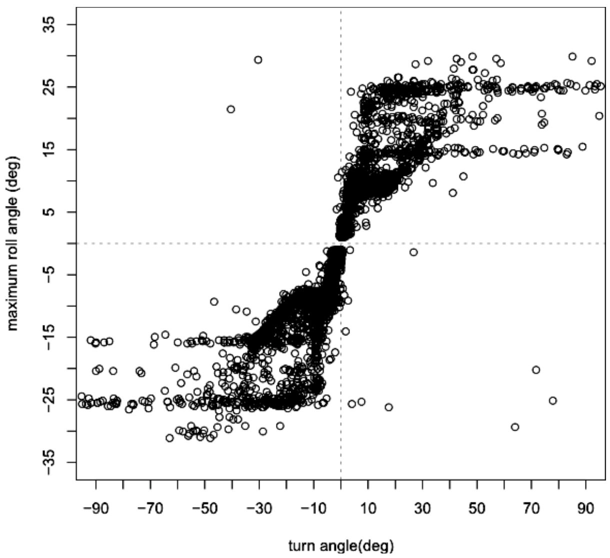

Figure 11 Maximum Roll Angle and Turn Angle (Boeing 737-800)

Table 4 Mixed linear model of maximum roll angle w.r.t. turn angle (Boeing 737-800 series)

Component number	**Mixing Coefficient**	**Estimated Coefficient of Linear Component**	**Residual Standard Deviation**
1	0.57	0.59	5.1
2	0.43	1.48	3.4

Table 4 shows that 57% of the whole data follows the linear model whose coefficient is 0.59, and the remaining 43% follows the model whose coefficient is 1.48. The residual standard deviation of the first component in this model is 5.1 degrees, and it is 1.2 degrees smaller than the residual standard deviation in the case where only one linear relation is assumed in Table 3.

3.5 Consideration

As discussed in Section 3.2, the turn duration is roughly 30 seconds to 110 seconds. An aircraft at a speed of 460 knots flies 4 nautical miles to 14 nautical miles during these periods. For instance, a conflict is defined as when the separation of two aircraft drops to under 5 nautical miles during surveillance by air route surveillance radar (ARSR). Let us consider the 90 degrees turn whose flight distance is 14 nautical miles as an example. Figure 12 illustrates the situation. In the piecewise linear model, the aircraft is considered to fly straight for 7 nautical miles, change its heading by 90 degrees instantaneously and fly straight for another 7 nautical miles. Segments AB and BC represent the trajectory under this model. Aircraft arrives at the point C by the turn. On the other hand, in the uniform circular motion model, aircraft fly 14 nautical miles along an arc of 90 degrees. The turn trajectory is the arc AD in Figure 12. The radius of arc is 8.9 nautical miles. The final arrival points C and D in both models are separated by 2.7 nautical miles. It is not negligibly small in comparison with the 5 nautical mile conflict threshold. When we consider the conflict prediction and resolution problems during surveillance by air route surveillance radar, a piecewise linear model assuming instantaneous heading change is not appropriate.

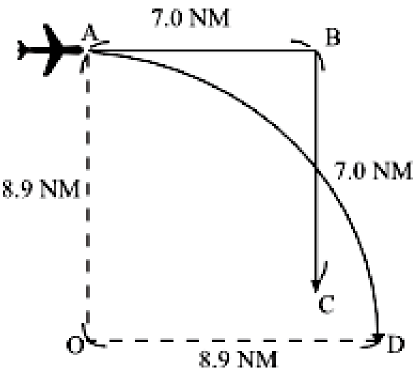

Figure 12 Turn Trajectory Models

We found that the correlation between turn duration and turn angle is weak. It suggests that aircraft control their roll angle to complete a turn in a fixed duration regardless of the turn angle in many cases. Pilots are recommended to complete turns for constant time duration regardless of the turn angle in Reference 8. However, the roll angles whose values are multiples of 5 are often selected regardless of the turn angle. In this case, turn duration and turn angle are correlated. The weak correlation between turn angle and turn duration in Section 3.2 is due to the relatively small number of the data with fixed roll angle.

We conducted a linear regression analysis of observation data of maximum roll angle of Boeing 737-800 series under the assumption that two data sets following different linear models are mixed. The residual standard deviation of the first component which could not be explained by this model was 5.1 degrees. For instance, the estimated coefficient of the first component in Table 4 is 0.59, and the roll angle is estimated to be 17.7 degrees by this model when a 30 degree turn is made. When we compare 5.1 degrees with 17.7 degrees, the deviation of roll angles of 5.1 degrees is not negligibly small for the estimation of roll angle.

4 Conclusion

In order to meet the increasing air traffic demand and realize efficient air traffic, air traffic control systems should predict aircraft trajectories accurately and automatically generate conflict-free trajectories under the trajectory-based operation concept. The turn trajectory data observed by SSR Mode S were analyzed to develop a simple turn trajectory model for the application of conflict detection and resolution. We only used the turn trajectory data whose maximum roll angle is not smaller than 5.0 degrees. We showed the followings through the analysis.

- The mean and standard deviation of turn duration are 64 seconds and 43 seconds, respectively. 80 percent of the turn finishes between 30 seconds and 110 seconds.
- The duration in which aircraft change their roll angle

is 20 seconds to 40 seconds in many cases.

- The correlation between turn angle and turn duration is extremely weak.
- The correlation between the true air speed of aircraft and maximum roll angle is weak. Here, the maximum roll angle means the observed roll angle during a single turn which is maximal in magnitude.
- The 15 degree and 25 degree roll angles are preferred than other values close to them.
- Maximum turn rate and maximum roll angle have an extremely strong correlation.
- There exist linear correlations between maximum roll angle and turn angle. However, it is not true when the value of roll angle is a multiple of 5. The maximum roll angle is constant regardless of the value of turn angle in this case.

We found that aircraft choose their roll angles in their turn so that the turn duration is fixed regardless of the turn angle except in the case where the selected roll angle is a multiple of 5. Turn duration is independent of roll angle in both fixed turn duration case and fixed roll angle case. As a result, turn duration is only weakly correlated with turn angle. The weak correlation between turn angle and turn duration is due to the relatively small number of the data with fixed roll angle.

We tried to develop linear models whose regressors are turn angles and whose regressands are maximum roll angles. This is because we can estimate the turn rate, turn duration and aircraft trajectory at high precision if the roll angle of the turn is estimated from the turn angle at high precision. We estimated the linear models from the data of Boeing 737-800 series under the assumption that two data sets following the different linear models are mixed in the given data. The residual standard deviation of one component is 5.1 degrees. Even if we succeed in developing the technique to identify which aircraft follows which model, the residual standard deviation of 5.1 degrees will severely restrict trajectory prediction in ground ATC systems.

The future work is to develop a model for estimating roll angle or turn rate at high precision in the ground ATC systems.

Acknowledgements

The author appreciates the surveillance technology team of Electronic Navigation Research Institute (ENRI) for the provision of the data collected at the Chofu SSR Mode S ground station. He also appreciates Dr. Karikawa, Dr. Koga, Dr. Nagaoka and Ms. Hirabayashi in ENRI for their useful comments.

References

1) International Civil Aviation Organization (ICAO): Global Air Navigation Capacity & Efficiency Plan 2013-2028, Doc 9750, 2014-2016 Triennium edition, 2014
2) International Civil Aviation Organization (ICAO): Working Documents for Aviation System Upgrades, 2012.
3) Erzberger, H.; The Automated Airspace Concept, 4th USA/Europe Air Traffic Management R&D Seminar, Santa Fe, USA, 2001.
4) Erzberger, H.; Automated Conflict Resolution for Air Traffic Control, 25th International Congress of Aeronautical Sciences, 2006
5) Erzberger, H., Lauderdale, T. A. and Chu Y. -C. ; Automated Conflict Resolution, Arrival Management and Weather Avoidance for ATM, 27th International Congress of Aeronautical Sciences, 2010
6) Matsunaga, K, Senoguchi, A. and Koga, T.: Validation of Downlink Aircraft Parameters (DAPs) via SSR Mode S Experimental System, Technical Report of IEICE, **112**(2012), no.229, pp.211-216.
7) Bulfer, B.: FMC User's Guide – Advanced Guide to the 737 Flight Management Computer, Leading Edge Publishing, 1991.
8) Noguchi A.: 747-no-soujyuu (in Japanese) Ikaros Publications ltd., 2000.
9) Bishop, C. M.: Pattern Recognition and Machine Learning, Springer-Verlag, New York, 2006.

Appendix

Reference 9 introduces the Expectation-Maximization (EM) algorithm used to estimate the coefficients of mixed linear regression models. A mixed linear regression model is used when the data set is the mixture of different data sets from different linear regression models. In the original work, the deviation components of all the mixed regression models are assumed to follow the same Gaussian distribution. This work can be extended to the case where the error components follow the different Gaussian distributions. We summarize this algorithm in this appendix.

We first introduce the notations. Let X and Y be the regressor and regressands of the linear regression model, respectively. Let N be the total number of samples. The n-th sample is described as (x_n, y_n). Here, x_n and y_n are realizations of X and Y, respectively. The number of mixed components are denoted by K. The notations π_k and w_k are the mixing coefficient and the coefficient of the regressor in the mixed linear regression model. We assumed that the intercepts of the linear regression models are zero. The notation σ_k denotes the standard deviation of the k-th component. We denote the following probability density function of a Gaussian distribution by $N(x,\sigma)$. Here, σ is the standard deviation.

$$N(x,\sigma) = \frac{\exp(-x^2/2\sigma^2)}{\sqrt{2\pi}\sigma} \tag{1}$$

The following is the EM algorithm used in this paper.

1. Initialize all the parameters w_k, π_k and σ_k.
2. Compute the following number $\gamma_{n,k}$ of all n and k with $1 \le n \le N$ and $1 \le k \le K$.

$$\gamma_{n,k} = \frac{\pi_k N(y_n - w_k x_k, \sigma_k)}{\sum_{j=1}^{K} \pi_j N(y_n - w_j x_k, \sigma_j)} \tag{2}$$

3. Update the parameters w_k, π_k and σ_k by the

following equations in this order.

$$N_k = \sum_{n=1}^{N} \gamma_{n,k} \tag{3}$$

$$\pi_k = N_k / N \tag{4}$$

$$w_k = \frac{\sum_{n=1}^{N} \gamma_{n,k} x_n y_n}{\sum_{n=1}^{N} \gamma_{n,k} x_n^2} \tag{5}$$

$$\sigma_k = \frac{\sum_{n=1}^{N} \gamma_{n,k} (y_n - w_k x_n)^2}{N_k} \tag{6}$$

4. Repeat Steps 2 and 3 until the following log-likelihood function converges.

$$\sum_{n=1}^{N} \log\left(\sum_{k=1}^{K} \pi_k N(y_n - w_k x_n, \sigma_k)\right) \tag{7}$$