[EN-110] Safety Analysis for Reduction of Longitudinal Time Separation Minima on Oceanic Routes

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Abstract: Currently, the minimum allowed longitudinal time separation between two aircraft on oceanic routes is set to 15 minutes. However, to deal with heavy traffic, a decrease to 10 minutes has been under consideration. So far, a major disadvantage of the conventional loss distribution method applied to calculate the risk of collision has been that it cannot guarantee safety in the case of reduced separation minima. In this paper, the loss distribution method is refined to avoid over-estimation by considering the relative speed of two aircraft and appropriate data sampling.

1. INTRODUCTION

As the air traffic has been increasing with the growth of the global economy, more efficient use of air space is expected. A possible solution can be the reduction of aircraft separation. Actually, the reduced vertical separation minimum (RVSM) was firstly introduced over the North Atlantic in 1997, where the vertical aircraft separation minima were changed to 1000 ft from 2000 ft. Currently, RVSM is worldwide accepted. As for the longitudinal separation, on oceanic routes which are the current target of my study, although the longitudinal separation was conventionally defined by time-based separation only, a distance-based separation to shorten the longitudinal separation can also be applied with a certification of RNAV 10 or RNP 4. At present, the minimum longitudinal separation is 30 NM when a pair of aircraft has both a certification of RNP 4 and an ADS system [1] installed. The RNAV or RNP certification assures the aircraft navigation performance[2]. As long as the aircraft has an ADS system installed, it automatically sends information about current position at a specific rate (usually about 27 minutes), which is referred to by air traffic controllers (ATC). However, there are still aircraft without an ADS system installed. Moreover, since it is required that both aircraft have the ADS system installed for distance-based separation to be applied, the percentage of aircraft with an ADS system exceeds the percentage of distance-based separation application. Therefore, the time-based separation is still widely used with the longitudinal time separation minima being 15 minutes. Actually, even at present the time separation can be reduced to 10 min as long as a pair of aircraft applies the so-called mach number technique, but this is rarely used.

The 15 minutes time separation was established long time ago, but improved aircraft navigation performance has enabled 10 minutes time separation. 10-minute time separation has already been introduced in the United States. However, even though 10-minute time separation minima is proved to be safe for a certain airspace, it does not necessarily indicate the 10 minutes time separation minima is accepted worldwide. There are many independent factors related to safety, e.g., the amount of traffic, the navigation performance, the size or type of the aircraft flying in the airspace under consideration. The safety analysis should be conducted in each airspace to introduce the new system. In order to evaluate the safety of the system, International Civil Aviation Organization (ICAO) has established the target levels of safety (TLS) during an en-route phase. The TLS is defined to be a generic term representing the level of risk acceptable under particular circumstances. The TLS is set to 5.0×10^{-9} accidents per flight hour in each dimension (lateral, longitudinal, and vertical collision). Therefore, the 10 minutes time separation can be acceptable, when the estimated risk of collision is less than the TLS.

Several factors should be considered when calculating the risk of collision. First of all, to take into account even the worst case scenario, the expected risk of collision should be greater than the actual risk of collision. Secondly, to avoid conservativeness, the expected risk of collision should be as close to the actual risk of collision as possible. The existing loss distribution method [3] calculates the expected risk of collision, but it fails to meet the second requirement stated above, because it guarantees unnecessarily over-secure separation. Therefore, in this paper, the method is refined to obtain a more realistic risk of collision.

2. CONVENTIONAL LOSS DISTRIBUTION AND THE EXPECTED RISK OF COLLISION

2.1 Loss distribution

First, the loss distribution is explained. When time-based separation is applied, the aircraft has to report to the ATC when it passes a waypoint as shown in Fig. 1. However, during the flight between the waypoints, no report is obtained from the aircraft, so a collision is likely to happen while a pair of aircraft flies on the same segment. In order to calculate how often such a collision happens, the loss distribution has been applied. Consider a pair of aircraft entering the same segment at the same flight level with a certain interval which is defined to be an initial time separation (Fig. 2). The two aircraft exit with a certain separation, defined as the final time separation. Here, the loss time is defined as the final time separation minus the initial time separation. The relative frequency of loss time is obtained based on numerous data and finally the empirical probabilistic distribution of loss time $l(t)$ can be acquired. However, even if a certain loss time is not observed during the period, there is no guarantee that this never happens. Therefore, based on $l(t)$, probability density function of the loss time $l_m(t)$ is estimated. The double exponential distribution function $D(t; \mu, \lambda)$ is often used for fitting the empirical distribution. The bigger λ indicates the wider distribution. Using this function, a big loss time is assumed to be observed with very low probability.

$$D(t; \mu, \lambda) = \frac{1}{2\lambda} \exp\left(\frac{-|t - \mu|}{\lambda} \right) \qquad (1)$$

When the loss time is greater than the initial time separation, the longitudinal separation is totally infringed. Therefore, the probability that the longitudinal separation is infringed when the initial time separation is equal to t (defined $P_x(t)$) is calculated based on the following expression:

$$P_x(t) = \int_t^\infty l_m(\tau) d\tau \qquad (2)$$
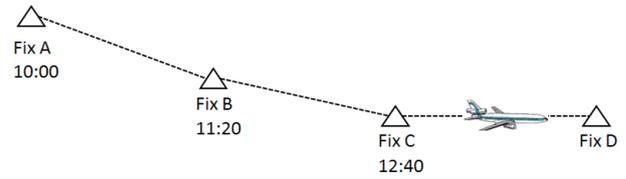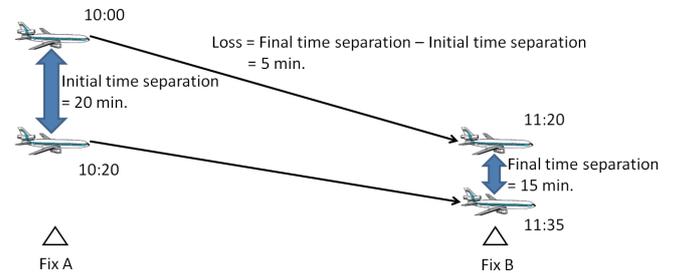

Figure 1 The time report when passing the waypoints.

Figure 2 The loss time calculation.

2.2 Expected risk of collision

A collision between two aircraft happens when all of the longitudinal, lateral, and vertical separations are simultaneously infringed. Even when the longitudinal separation is infringed, as long as the aircraft sometimes deviate laterally and vertically, a collision is avoided.

Table 1 The parameters in the calculation of the risk of collision.

	Explanation	Value used	Source of the values
$P_y(0)$	The overlap probability in the lateral sense.	0.2	EMA handbook [4]
$P_z(0)$	The overlap probability in the vertical sense.	0.5380	ICAO SASP safety assessment [5]
λ_x	The length of a typical aircraft.	0.040 NM	B777-300ER
λ_y	The wingspan of a typical aircraft	0.035 NM	B777-300ER
λ_z	The height of a typical aircraft.	0.010 NM	B777-300ER
$\overline{|\dot{x}|}$	The average relative velocity between two aircraft necessary to erode the planned longitudinal spacing.	100 kt	EMA handbook [4]
$\overline{|\dot{y}(0)|}$	The average relative velocity between two aircraft, across track.	1 kt	EMA handbook [4]
$\overline{|\dot{z}(0)|}$	The average relative velocity between two aircraft, vertically.	1.5 kt	ICAO SASP safety assessment [5]
T	The average time to fly the segment.		
$E_x(t)$	The proportion of aircraft initial separation.		
$P_x(t)$	The probability of the loss of longitudinal separation. (explained earlier)		

Considering a three dimensional collision, the expected risk of collision N_{ax}, which is defined as the expected number of accidents per flight hour due to loss of assigned longitudinal separation, is calculated by the following expression.[3][4]

$$N_{ax} = P_y(0)P_z(0)\frac{2\lambda_x}{|\dot{x}|T}\left[\frac{|\dot{x}|}{2\lambda_x} + \frac{|\dot{y}(0)|}{2\lambda_y} + \frac{|\dot{z}(0)|}{2\lambda_z}\right]\sum E_x(t)P_x(t) \quad (3)$$

The parameters are summarized in Table 1. The values of most parameters are used according to other documents. The values correspond to the worst case scenario, so the expected risk of collision is higher than the actual risk of collision.

3. CALCULATION OF THE EXPECTED RISK OF COLLISION ON OCEANIC ROUTES

3.1 Data acquisition and airspace considered

This time, the oceanic routes bound south in Fukuoka FIR (shown in Fig. 3) are chosen as a target airspace and a total of eight segments are considered (as shown in Table 2). Since the loss distribution depends highly on the distance between the segments, the segment No. 1 to No. 4 are defined as Airspace A, and the segment No. 5 to No. 8 are defined as Airspace B. There is no characteristic wind in this area, so the distribution of the loss time is assumed to be the same in each airspace. No distinction based on the flight direction is made.
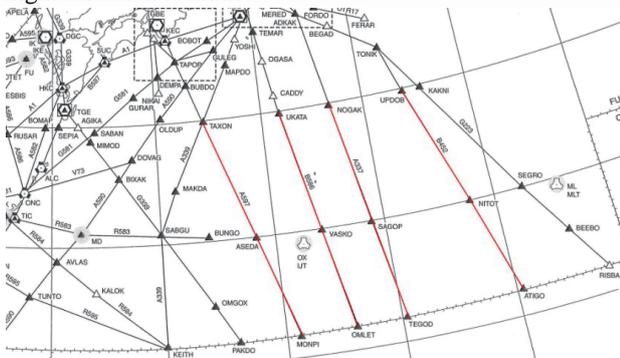

Figure 3　The target routes of this study.

The time when the aircraft passes the fix is recorded in the FDP (Flight Data Processing) data. Data obtained between May 2008 and May 2010 is used. A pair of aircraft is extracted based on the following conditions. All of the required data is recorded in the FDP data. The obtained number of the data sets is 27,695 for Airspace A, and 28,971 for Airspace B.

- A pair of the aircraft flies on the same flight level and the same route segment, and does not change the flight level during the segment.

- Either of the aircraft does not have an ADS system installed and does not apply mach number technique.

- The initial time separation is 15 minutes or larger.

Table 2　The target route segments of this study.

No.	Segments	Distance	Remarks
1	TAXON-ASEDA (A597)	317 NM	Airspace A
2	UKATA-VASKO (B586)	305 NM	Airspace A
3	NOGAK-SAGOP (A337)	306 NM	Airspace A
4	UPDOB-NITOT (B452)	318 NM	Airspace A
5	ASEDA-MONPI (A597)	252 NM	Airspace B
6	VASKO-OMLET (B586)	246 NM	Airspace B
7	SAGOP-TEGOD (A337)	245 NM	Airspace B
8	NITOT-ATIGO (B452)	253 NM	Airspace B

3.2 Obtained data and estimation of the probability density function

First of all, the probability density distribution of the initial time separation is obtained. Herein $E_x(t)$ is considered up to 60 minutes, which assumes a zero risk of collision when the initial time separation exceeds 60 minutes. $E_x(t)$ in the Airspace A is shown in Fig. 4. The recorded time in the FDP data is discretized by 1 minute, so the probability density is also discretized by 1 minute. In this airspace, there is not so much traffic, so 83.6 % of the pair of the aircraft has more than 60 minutes of initial time separation, which has no risk of collision.
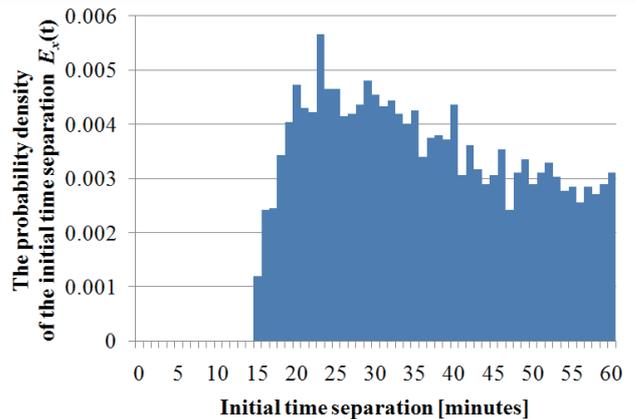

Figure 4.　The empirical distribution of The empirical distribution of $E_x(t)$.

Next, the average flying time is obtained: 0.6848 hours for Airspace A and 0.5439 hours for Airspace B.

Finally, the loss distribution is estimated. The loss time depends on the initial time separation, because in the case of big initial time separation, the wind condition is likely to

change resulting in the big loss time. Therefore, the loss time should be calculated within the limited range of initial time separation, otherwise causing an over-estimation. Here, the restriction of the initial time separation is set to 60 minutes according to the other examples [3], i.e. only aircraft with initial time separation of more than 60 minutes are considered when constructing the loss distribution.

Next, the probability density function should be constructed based on the actual loss distribution. When fitting the probability density function, the maximum likelihood estimation (MLE) is often used. According to this method, the parameters are optimized to maximize the following likelihood:

$$lik = \prod_{i=1}^{n} D(t_i; \mu, \lambda) \qquad (4)$$

where n is the number of the sampling data sets, and indicates the loss time of each data. Fig. 5 shows the distribution based on actual data and the estimated function by MLE. According to the figure, the actual data and the estimated function fit well between –6 and 1 minutes. However, for the rest time, especially when the loss time is less than –6 or bigger than 6 minutes, the estimated function causes an under-estimation, which might be critical in the calculation of the risk of collision. MLE gives the same importance to all the data, which indicates the smaller loss time highly affects the distribution, because there are more data sets of the small loss time. In order to avoid under-estimation, the least square method (LSM) is introduced. The probability density of each actual data in each minute is defined to be $p_{act}(t)$, and the probability density of the estimated function is defined to be $p_{est}(t)$. In such a case, the parameters are optimized to minimize the following function.

$$F = \sum_{t}^{p_{act}(t) \neq 0} \left[\log(p_{act}(t)) - \log(p_{est}(t)) \right]^2 \qquad (5)$$

Table 3 The optimized parameters in each airspace by MLE and LSM.

Airspace	MLE		LSM	
	λ	μ	λ	μ
Airspace A	0.7974	0	1.0599	0.2676
Airspace B	0.6507	0	1.0038	0.2888

The obtained parameters are summarized in Table 3. According to the figure, the function based on the LSM fits better especially in the low probability part. However, it should be confirmed which method is preferred to fit the probability density function. Here, a binomial test [6] is conducted. As shown in Fig. 5, the data which are less than –6 or greater than 6 minutes of loss time are far from the

fitted probability density function. These data are called abnormal values here, and it is investigated that the chances of abnormal values appearing are statistically appropriate. For Airspace A, the number of the abnormal values is 8 out of 4553 samples. The probability of the appearance of abnormal values is calculated as follows:

$$\int_{-\infty}^{-6.5} \frac{\exp(-|t-\mu|/\lambda)}{2\lambda} dt + \int_{6.5}^{\infty} \frac{\exp(-|t-\mu|/\lambda)}{2\lambda} dt$$
$$= \frac{1}{2} \left(\exp\left(-\frac{6.5+\mu}{\lambda} \right) + \exp\left(-\frac{6.5-\mu}{\lambda} \right) \right) \qquad (6)$$

The time is discretized by a minute, so the calculation is conducted from 7–0.5. Now, using the parameters optimized by MLE,

$$p_A = \frac{1}{2} \left(\exp\left(-\frac{6.5+0}{0.797403} \right) + \exp\left(-\frac{6.5-0}{0.797403} \right) \right) \quad \text{is}$$

0.000288314, so the probability of the 8 times or greater appearance of the abnormal values is calculated as follows based on binomial test method:

$$\sum_{i=8}^{4553} \frac{4553!}{i!(4553-i)!} p_A^i (1-p_A)^{4553-i} = 6.84 \times 10^{-5} \ll 0.01 \ (7)$$

Therefore, it is concluded that the chances of abnormal values appearing are significantly high with 1 percent level. On the other hand, using LSM, the abnormal values are observed when the loss time is 10 minutes, 2 out of 4553 samples. The probability is calculated in the same manner:

$$p_B = \frac{1}{2} \left(\exp\left(-\frac{9.5+0.2676}{1.0599} \right) + \exp\left(-\frac{9.5-0.2676}{1.0599} \right) \right)$$
$$\sum_{i=2}^{4553} \frac{4553!}{i!(4553-i)!} p_B^i (1-p_B)^{4553-i} = 0.1225 > 0.01 \qquad (8)$$

This result indicates that the appearance of the abnormal values in LSM is not significantly high. Therefore, it is concluded that the estimated function by LSM is more appropriate, and the LSM is used from here.
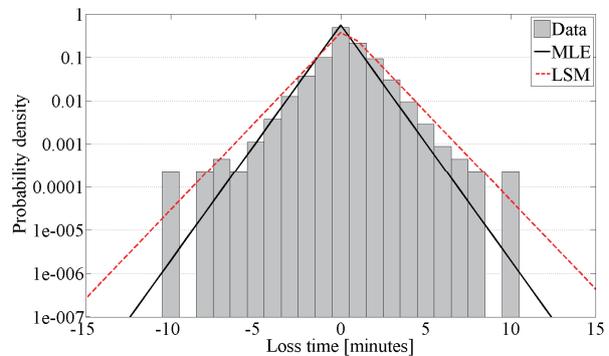

Figure 5. The actual loss distribution and the fitted probability density function.

3.3 Calculation result of the expected risk of collision

Based on the data obtained in the last section, the risk of collision is calculated under 10 minutes time separation. However, the current probability density of the initial time separation $E_x(t)$ is obtained under 15 minutes time separation, so $E_x(t)$ under 10 minutes time separation must be estimated. This time, the estimated probability density of the initial time separation $E_{x\_est}(t)$ is calculated based on the following expression as it appears in [3].

$$E_{x\_est}(t) = E_x(t+5) \quad t \geq 10 \qquad (9)$$

Finally, the risk of collision is calculated in each airspace: 4.977×10^{-8} for Airspace A, and 2.688×10^{-8} for Airspace B. Unfortunately, for both airspaces, the expected risk of collision is greater than the TLS. Does that mean that 10 minutes time separation is too risky? The author thinks that the current calculation method is likely to cause an over-estimation, since there are many assumptions leading to an over-estimation. In the next section, more reasonable assumptions are provided, and a more accurate risk of collision is calculated.

4. REFINEMENT OF ESTIMATING THE RISK OF COLLISION

4.1 A. Which assumption leads to an over-estimation?

Following the current calculation method, 10 minutes time separation does not guarantee safety. However, there are many assumptions in these calculations, and some of them may cause an over-estimation. In terms of the calculation, only $E_x(t)$ and $P_x(t)$ are estimated, and other parameters are fixed, which limits the refinement to these two parameters only. However, $E_x(t)$ is an uncertain parameter so it should also be considered to avoid an under-estimation. Therefore, the loss distribution $P_x(t)$ is the only parameter which can be adjusted to avoid an over-estimation.

In general, the distribution model is used to model the uncertainty of the system. However, it is arguable that the loss time is entirely uncertain. Assuming that the following aircraft flies faster than the preceding aircraft, a positive loss time is to be expected. The current loss distribution does not consider such a notion, though.

In addition, the loss distribution consists of a pair of aircraft which has 60 minutes or less of the initial time separation. However, the reason why the threshold is 60 minutes is not discussed enough. As mentioned before, the bigger the threshold, the wider the distribution is likely to become, which is also reported on the other document[7]. On the other hand, the smaller the threshold, the fewer data

sets are obtained, which is sometimes statistically insufficient. An appropriate threshold should be chosen.

4.2 Loss distribution considering the relative speed

First, the aircraft speed problem is discussed. As mentioned before, the conventional loss distribution includes a certain predictable loss time originating from the relative speed. If the relative speed of a pair of aircraft is obtained, the effect of the relative speed can be eliminated from the loss distribution. Although the FDP data contains the true air speed (TAS) at each waypoint, the TAS recorded in the FDP data is the one written in the flight plan and not updated. However, as most aircraft follow the flight plan, the recorded TAS is used to eliminate the predictable loss time. It is expected that the loss time increases linearly with the increase of the relative TAS and the length of the segment. Therefore, in each airspace, the relationship between the loss time and the relative TAS can be calculated. A positive relative TAS is defined in the case when the following aircraft flies faster than the preceding aircraft.

The loss time t_i and the relative TAS ΔV_i are assumed to have the following relationship.

$$t_i = a\Delta V_i + b \qquad (10)$$

The parameters a and b are optimized by the LSM, namely to minimize the following expression:

$$\sum_{i=1}^{n}(t_i - (a\Delta V_i + b))^2 \qquad (11)$$

When the parameters are optimized, the refined loss time t_i^{new} is calculated based on the following expression:

$$t_i^{new} = t_i - (a\Delta V_i + b) \qquad (12)$$

Based on t_i^{new}, the refined loss distribution $l^{new}(t)$ and its refined estimated probability density function $l_m^{new}(t)$ are obtained. Finally, the refined probability where the longitudinal separation is infringed $P_x^{new}(t)$ is calculated based on the following function:

$$P_x^{new}(t) = \sum_{\Delta V} e(\Delta V) \int_t^{\infty} l_m^{new}(\tau - (a\Delta V + b))d\tau$$

$$\sum_{\Delta V} e(\Delta V) = 1 \qquad (13)$$

where $e(\Delta V)$ is the obtained probability density in each relative speed. In this calculation, it is assumed that the distribution of the relative speed is the same according to the initial time separation. However, when the relative speed is greater, the risk of collision increases. Under the limited time separation (e.g. less than 20 minutes), how likely is it to have a pair of aircraft with a big relative

speed? Fig. 6 shows the cumulative probability distribution of the relative speed for Airspace A. The blue line indicates the data where the initial time separation is 20 minutes or less (case a), and the red line indicates the data where the initial time separation is 60 minutes or less (case b). This figure clearly shows that the probability for the positive relative speed is smaller in case a, i.e., the positive relative speed is unlikely when the initial time separation is relatively small. Therefore, if the average probability where the initial time separation is less than 20 minutes is used for $e(\Delta V)$, no under-estimation will occur. Headings, or heads, are organizational devices that guide the reader through your paper. There are two types: component heads and text heads.
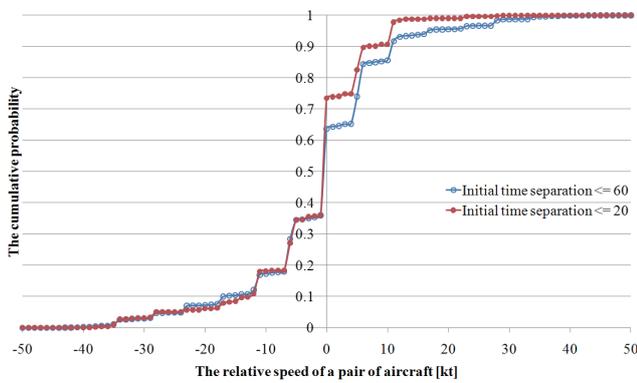
Figure 6 The cumulative probability distribution according to the relative speed of a pair of aircraft.

Using the proposed method, the expected risk of collision is recalculated. The calculation results are summarized in Table 4.

Table 4 The parameters and the risk of collision by refined loss distribution.

	Airspace A	Airspace B
New risk of collision	1.949×10^{-8}	5.462×10^{-9}
Old risk of collision	4.977×10^{-8}	2.688×10^{-8}
λ	0.9280	0.8603
μ	0.1121	0.1629
a	0.0605	0.0454
b	0.3616	0.3325

Although the expected risk of collision is decreased by more than 60 %, it is still greater than the TLS. Therefore, the consideration of the relative speed is not enough.

4.3 Loss distribution considering appropriate data sampling

The next question is what initial time separation should be considered when making a loss distribution. The current threshold of 60 minutes has no solid foundation. This time, abnormal values are concentrated on. Fig. 7 shows the refined loss time distribution for Airspace A. The solid line is fitted by the data with loss time between –6 and 6 only, and the dotted line by all data. Naturally, the dotted line fits well for the low probability parts, but the solid line fits better between –6 and 6 minutes of the loss time. The distribution function of solid line gets wider because of the abnormal values surrounded by blue rectangles. The author supposes that the abnormal values can actually be neglected as they come from inappropriate data sampling. Next, the relationship between the appearance of abnormal values and the initial time separation is investigated. Table 5 shows the number of the abnormal values observed and the number of the sampling data in each initial time separation range. For Airspace B, the data which have more than 5 or less than –5 minutes of the loss time is extracted as the abnormal values.
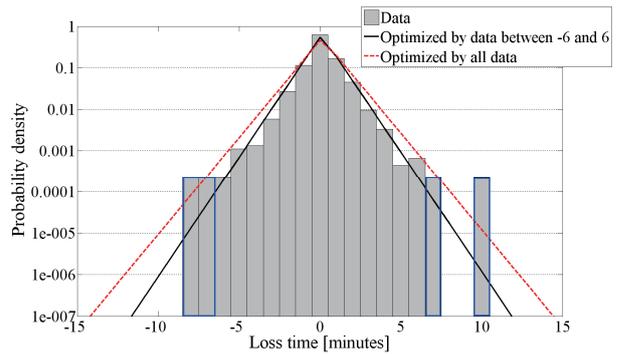
Figure 7 he refined loss distribution (Airspace A)

Table 5 The relationship between abnormal values and initial time separation.

(the number of abnormal values/the number of the data)

Initial time separation x	Airspace A	Airspace B
$0 < x \le 20$	0/526	0/506
$20 < x \le 30$	0/1358	0/1262
$30 < x \le 40$	1/1187	4/1115
$40 < x \le 50$	1/972	2/862
$50 < x \le 60$	2/761	2/722

This table clearly shows that the abnormal values are observed only when the initial time separation is greater than 30 minutes, which indicates that the number of abnormal values and the initial time separation are related. However, it should also be verified whether this difference is statistically significant or not. Within 30 minutes of the initial time separation, no abnormal value is observed in the case of 3652 samples. On the other hand, if the

appearance of the abnormal values is independent of the initial time separation, the expected value of the appearance of the abnormal values (p_{exp}) will be 12/9271 = 0.0129436. Now, a binomial test is conducted. In order to prove that the number of the abnormal values within 30 minutes of the initial time separation is significantly small, the sum of the probability of 0 or less times appearance of the abnormal values must be calculated.

$$\sum_{i=0}^{0} \frac{3652!}{i!(3652-i)!}\left(1-\frac{12}{9271}\right)^{3652-i}\left(\frac{12}{9271}\right)^{i} \quad (14)$$
$$= 0.001952 < 0.01$$

This result indicates that the hypothesis of the lack of relationship between the initial time separation and the appearance of the abnormal values is entirely rejected with the 1 percent level. Therefore, it is concluded that the initial time separation is related to the number of abnormal values, so the distribution of the loss time should include only the data which have 30 minutes or less of the initial time separation in order not to cause an over-estimation.

Using the data within 30 minutes of the initial time separation, the risk of collision is recalculated. Fig. 8 shows the refined loss distribution within 30 minutes of the initial time separation only, and Table 6 summarizes the calculation result.
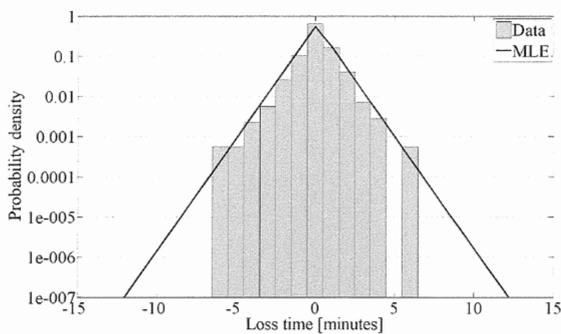

Figure 8 The refined loss distribution within 30 minutes of the initial time separation only.

Table 6 The parameters and the risk of collision by refined loss distribution within 30 minutes of the initial time separation only.

	Airspace A	Airspace B
New risk of collision	2.394×10^{-9}	1.425×10^{-10}
Old risk of collision	4.977×10^{-8}	2.688×10^{-8}
λ	0.7770	0.6521
μ	0.0603	0.0122
a	0.0614	0.0481
b	0.3379	0.3295
Old risk of collision	4.977×10^{-8}	2.688×10^{-8}

The estimated refined loss distribution fits well for all data, because the abnormal values are not observed. For both airspaces, the expected risk of collision is smaller than the TLS, which proves that the 10 minutes initial time separation can be introduced safely. However, this result is valid under the assumptions considered above. For example, if the traffic is drastically increased or the traffic pattern is changed, the risk of collision should be calculated again. In addition, the loss distribution may be changed due to various reasons, such as altered navigation performance. In such a case, the loss distribution should be estimated continuously, and the risk of collision should be calculated again, even after the 10 minutes initial time separation is introduced.

5. CONCLUSIONS

In times of increasing aviation demand, it is critical that the airspace be used as efficiently yet safely as possible. In this paper, the longitudinal time separation on oceanic flights was considered, where the time separation minima was reduced to 10 minutes from 15 minutes. In order to evaluate the safety of the airspace, the conventional distribution model of the loss time was applied, but it did not meet the safety criterion. Therefore, some unclear assumptions were identified and refined, and finally, the safety criterion was met by considering the relative speed of a pair of aircraft and the appropriate data sampling. The proposed method can also be applied other airspaces, and thus can help the efficient use of airspace without sacrificing the safety.

6. ACKNOWLEDGEMENT

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