Federal Aviation Administration

Geometrical Models for Aircraft in Terminal Area Risk Analyses

Flight Systems Laboratory
DOT-FAA-AFS-450-63

April 2011

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DOT-FAA-AFS-450-63

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GEOMETRICAL MODELS FOR AIRCRAFT IN TERMINAL AREA RISK ANALYSES

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2 May 2011

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April 2011

Technical Report

Geometrical Models for Aircraft in Terminal Area Risk Analyses

Technical Report Documentation Page

1. Report No.
DOT-FAA-AFS-450-63

2. Government Accession No.

3. Recipient's Catalog No.

4. Title and Subtitle
Geometric Models for Aircraft in Terminal Area Risk Analyses

5. Report Date
April 2011

6. Author(s)
Dr. Richard Greenhaw, AFS-450

7. Performing Organization Code

8. Performing Organization Name and Address
Federal Aviation Administration
Flight Systems Laboratory, AFS-450
P.O. Box 25082, Oklahoma City, OK 73125

9. Type of Report and Period Covered
Technical report

10. Sponsoring Agency Name and Address
Federal Aviation Administration
Flight Systems Laboratory, AFS-450
P.O. Box 25082, Oklahoma City, OK 73125

11. Supplementary Notes

12. Abstract

The purpose of this study is to examine the relationship between shapes and sizes of various volume regions such as spheres, cylinders, and boxes used to model aircraft in terminal area safety studies.

Various geometrical shapes and sizes have been used to model aircraft in en route and terminal areas for collision risk analyses. And the risk analysis results can be quite sensitive to the specific shapes and sizes used. This study will describe the effects of using various of these shapes and sizes.

The study will also develop more general hazard likelihood regions about aircraft for purposes of safety management risk assessment. For example, answering such questions as "what radius sphere would correspond to a 10-7 extremely remote likelihood region?"

For parallel approach studies, we recommend using for the TCV region a cylinder based on the wing semi-spans and tail heights of the aircraft pair. The radius of this cylinder will be the sum of the wing semi-spans and its height will be the sum of the tail heights.

Since this cylinder is dependent on knowing the aircraft mix in the operations studies, we add a recommendation for situations in which this mix is unknown or cannot otherwise be used. We recommend a cylinder of radius 265 feet and height 160 feet. The dimensions of this cylinder are conservative in that they will accommodate two Airbus A380 aircraft laterally or vertically.

13. Key Words
Models
Geometry
Terminal Area
500 Foot Sphere
Cylinder

14. Distribution Statement

15. Security Classification of This Report

16. Security Classification of This Page

Executive Summary

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Since this cylinder is dependent on knowing the aircraft mix in the operations studies, we add a recommendation for situations in which this mix is unknown or cannot otherwise be used. We recommend a cylinder of radius 265 feet and height 160 feet. The dimensions of this cylinder are conservative in that they will accommodate two Airbus A380 aircraft laterally or vertically.

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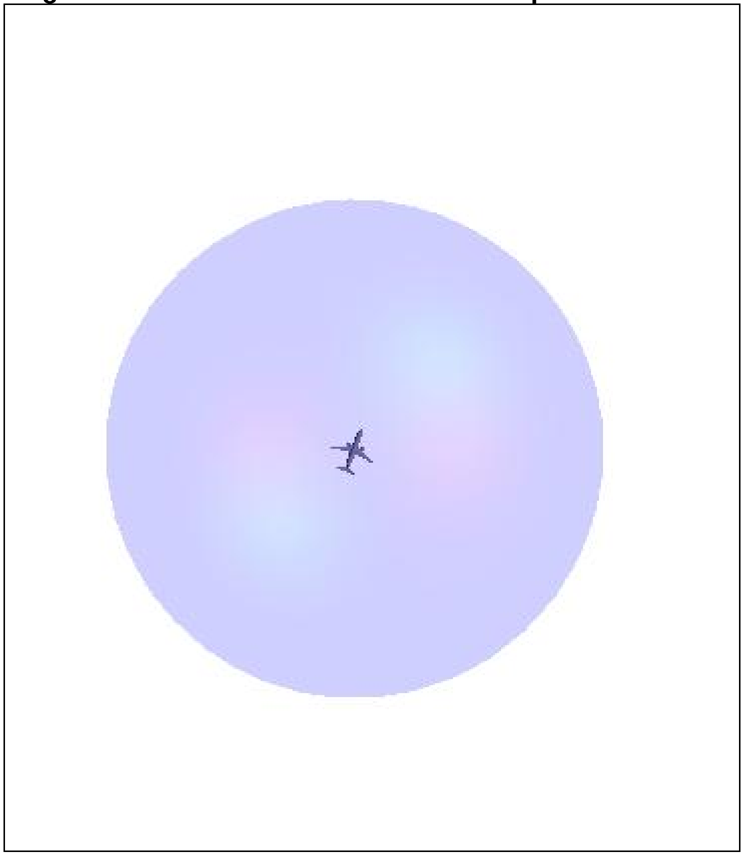
1.0 Introduction: Models for Terminal Area Collision Risk Analysis

Various geometrical shapes and sizes have been used to model aircraft in en route and terminal areas for collision risk analyses. The risk analysis results can be quite sensitive to the specific shapes and sizes used.

For example, parallel approach studies performed by the Flight Systems Laboratory (e.g., [1]) have used a 500 foot radius sphere to model a region about the target aircraft. Penetration of this region has been typically referred to as a Test Criteria Violation (TCV). In such studies the blundering aircraft is represented by a point in three space and the target (or evading) aircraft is represented by the 500 foot radius sphere. A penetration of the sphere by the point represents a TCV which models a collision.

However, the centers of gravity of two commercial aircraft might easily be found to be less 500 feet apart without a collision occurring. The 500 foot radius sphere was, in fact, chosen as a very conservative TCV model (see Figure 1). And it is possible to chose other, more precise models especially for use with smaller target levels of safety (TLS).

Figure 1 B737-400 in 500 Foot Radius Sphere to Scale



2.0 Shapes to Model Mid Air Collisions

We will examine three shapes for modeling aircraft in collision risk analyses: a sphere (small sphere), a flattened cylinder (small cylinder or hockey puck), a large cylinder, and a rectangular prism (box). For each shape we will estimate the collision risk relative to a 500 foot diameter sphere.

Small Sphere

This is a sphere of radius 140.6 feet. The radius value was calculated based on data from a Closely Spaced Parallel Operations (CSPO) study [2]. Four data sets from that study provide closest points of approach (CPAs) for pairs of blundering / evading aircraft. There are four types of aircraft used: B747-400, A330, B737-800, and an ERJ. Table 1 gives the dimensions assumed for each aircraft type.

Table 1 Four Aircraft Types Used in CSPO Data Sets

Type	Length (ft)	Wingspan (ft)	Tail Height (ft)
B747-400	231	212	64
A330	193	198	56
B737-800	120	118	41
ERJ	93	66	22

The four data sets represent a combination of two blunder angles and two approach track distances: blunders of 20 and 30 degrees and track distances of 3380 and 3600 feet. Table 2 shows the tags used to name each data set, their blunder angles. The track spacing used, and the number of runs (sample size) used to generate the TCV count in the Monte Carlo simulation used in the study.

Table 2 CSPO Data Set Tags

Tag	Blunder Angle (degrees)	Track Spacing (ft)	Number of Runs
N20	20	3380	188,078
N30	30	3380	188,078
W20	20	3600	188,149
W30	30	3600	188,149

Figure 2 shows, to scale, a B737-400 target aircraft inside this small sphere. In these models a collision is assumed to occur when the center of gravity of the blundering aircraft penetrates the sphere containing the target aircraft. Figure 3 shows the B737-400 inside the small sphere with both inside the large, 500-foot radius sphere.

Figure 2 B737-400 in 140.6 Foot Radius Sphere to Scale

Figure 3 B737-400 in Small Sphere in Large Sphere

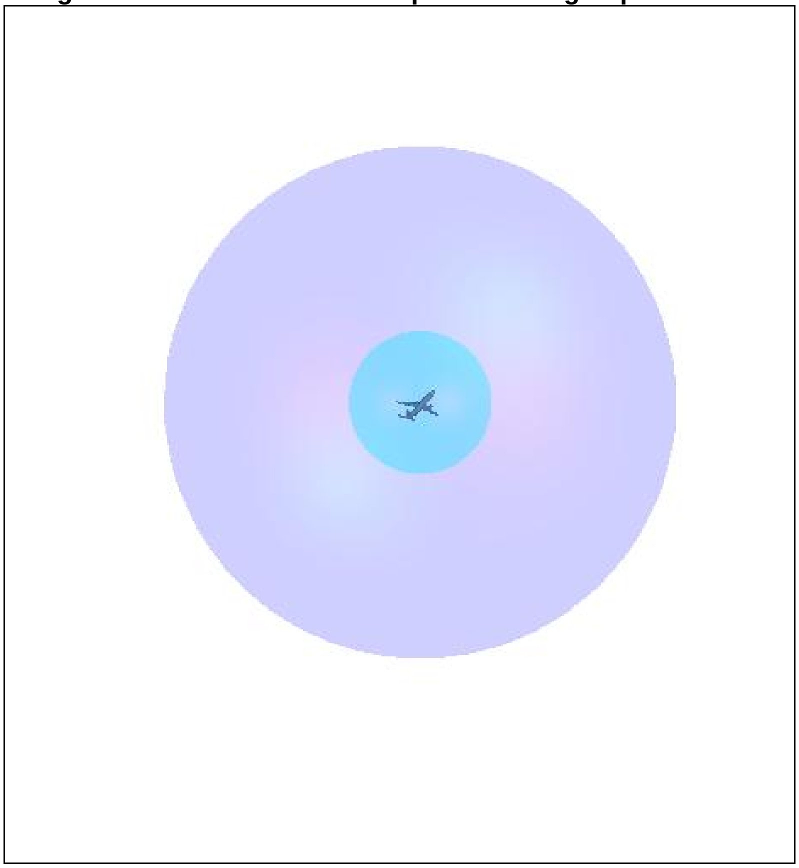


Table 3 gives the number of TCVs counted in the study for each data set. In each case a TCV occurs when the CPA for the two aircraft is less than 500 feet. Table 3 also gives the number of TCVs that would have been counted had the small sphere (of average radius 140.6 feet[1]) been used rather than one of 500 feet. And Figure 3 provides a 3-dimensional scatter graph of the 500 foot and 140.6 foot TCVs to show their geometrical relationship.

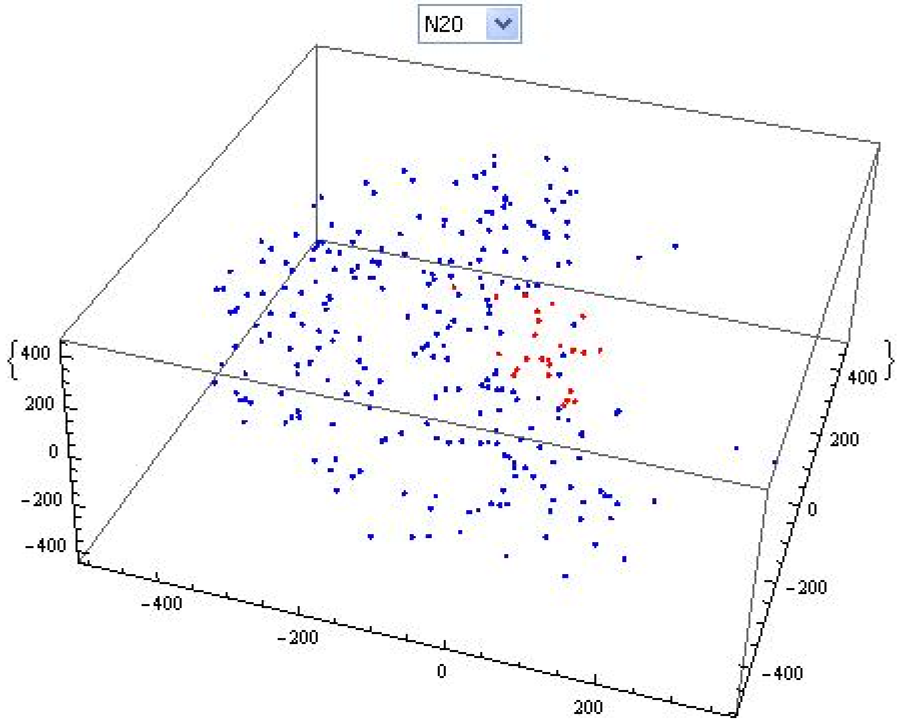
Table 3 CSPO Data Set TCVs for Large Sphere and Small Sphere

Data Set	Number of Runs	500 ft Sphere TCV Count	500 ft Sphere TCV Percent	140.6 ft Sphere TCV Count	140.6 ft Sphere TCV Percent
N20	188,078	278	0.148%	25	0.013%
N30	188,078	1342	0.714%	112	0.060%
W20	188,149	212	0.113%	14	0.007%
W30	188,149	1052	0.559%	87	0.046%
All	752,454	2,884	0.38%	238	0.03%

[1] The radius used to count TCVs varied by aircraft pair. It was calculated to be the sum of the two aircraft type wing semi-spans.

In Figure 4 the blue points represent 500 foot sphere TCVs and the red points represent 140.6 foot sphere TCVs. The number of small sphere TCVs is on the order of one-tenth those of the larger sphere.

Figure 4 Large (500 ft, blue) and Small (140.6 ft, red) Sphere TCVs



Small Cylinder (Hockey Puck)

This is a cylinder of radius 140.6 feet and height 88 feet. These values were, as with the small sphere radius, calculated based on data from the Closely Spaced Parallel Operations (CSPO) study [2].

Figure 5 shows, to scale, a B737-400 target aircraft inside the cylinder. In this model a collision is assumed to occur when the center of gravity of the blundering aircraft penetrates the cylinder containing the target aircraft. Figure 6 shows the B737-400 inside the cylinder with both inside the large, 500-foot radius sphere.

Figure 5 B737-400 in 140.6 Foot Radius (Small) Cylinder to Scale

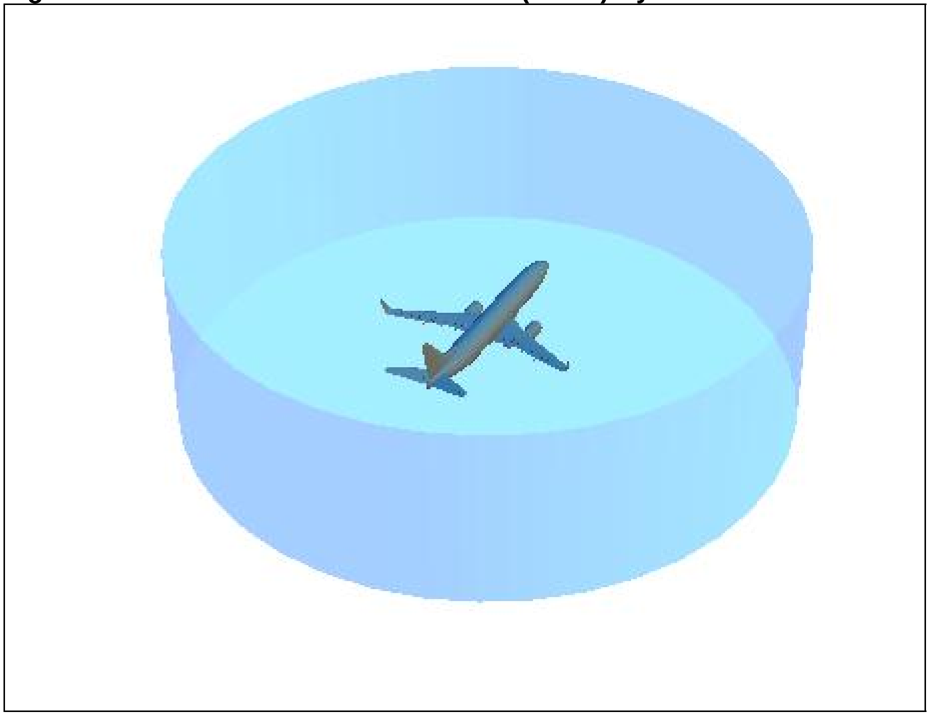


Figure 6 B737-400 in Small Cylinder in Large Sphere

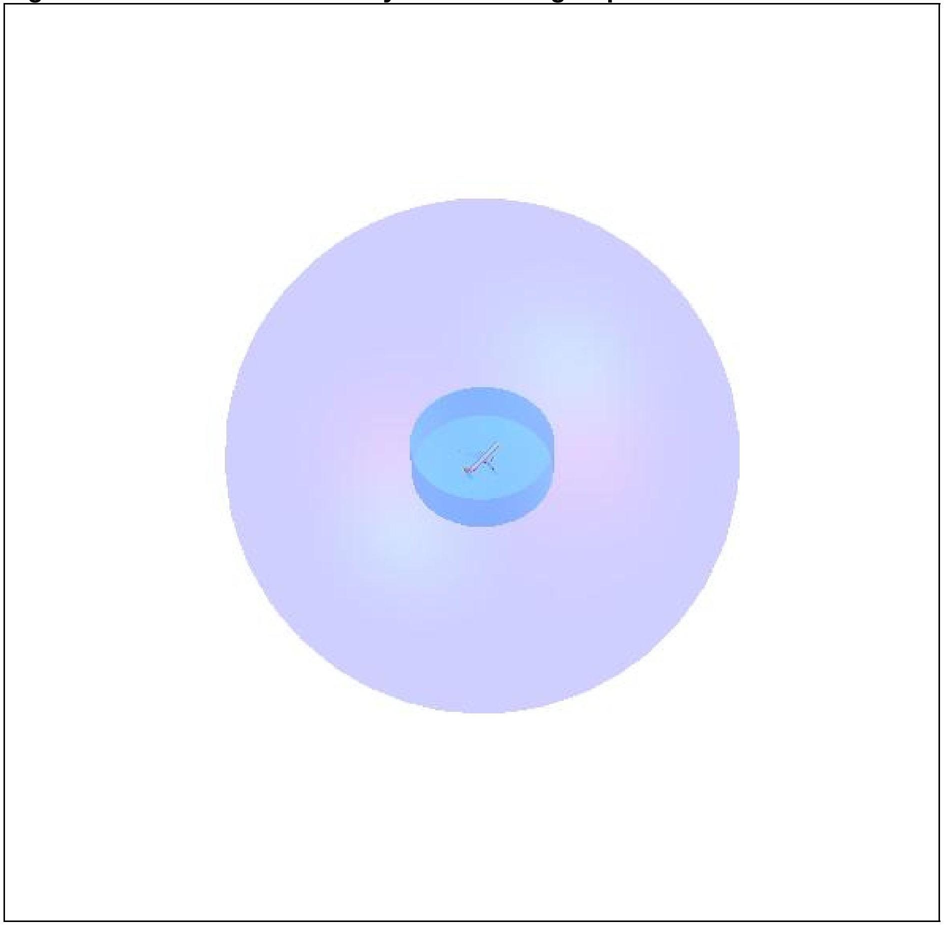


Table 4 gives the number of TCVs counted in the study for each data set. In each case a TCV occurs when the CPA for the two aircraft is less than 500 feet. Table 3 also gives the number of TCVs that would have been counted had a small cylinder (of average radius 140.6 feet and average height 88 feet[2]) been used rather than a sphere of radius 500 feet. And Figure 3 provides a 3-dimensional scatter graph of the 500 foot and 140.6 foot TCVs to show their geometrical relationship.

Table 4 CSPO Data Set TCVs for Large Sphere and Small Cylinder

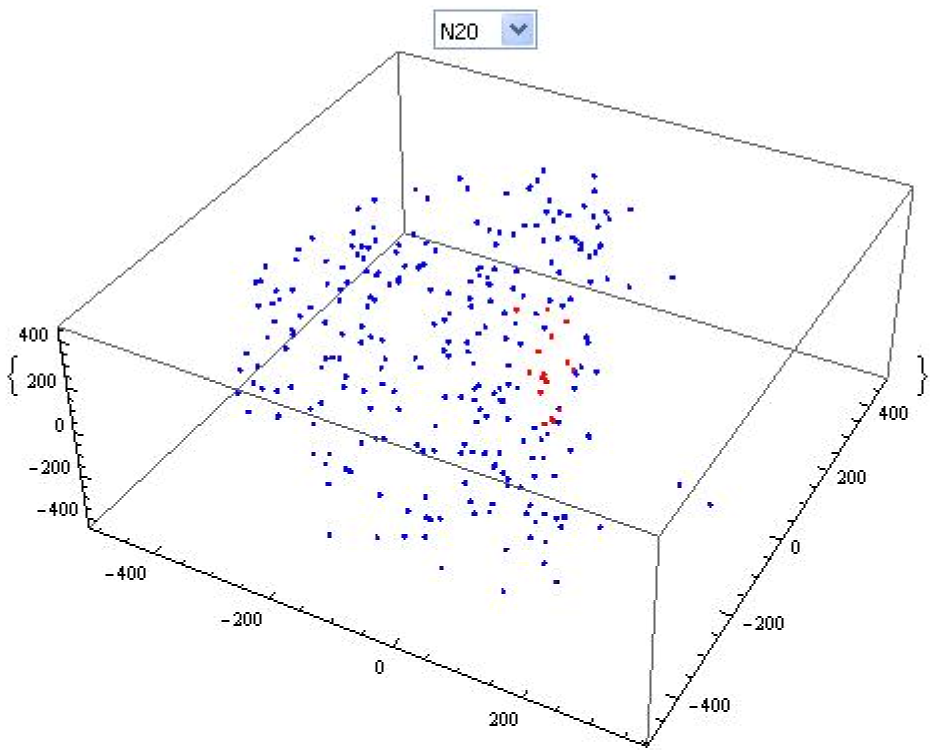
Data Set	Number of Runs	500 ft Sphere TCV Count	500 ft Sphere TCV Percent	Small Cylinder TCV Count	Small Cylinder TCV Percent
N20	188,078	278	0.148%	16	0.009%
N30	188,078	1342	0.714%	59	0.031%
W20	188,149	212	0.113%	3	0.002%
W30	188,149	1052	0.559%	45	0.024%

[2] The radius used to count TCVs varied by aircraft pair. As with the small sphere it was calculated to be the sum of the two aircraft type wing semi-spans. The small cylinder height was calculated to be the average of the two aircraft tail heights.

All	752,454	2,884	0.38%	123	0.02%

In Figure 7 the blue points represent 500 foot sphere TCVs and the red points represent the small cylinder TCVs. The number of small cylinder TCVs is on the order of one-twentieth those of the large sphere.

Figure 7 Large Sphere (blue) and Small Cylinder (red) TCVs



Large Cylinder (Large Hockey Puck)

This is a cylinder of radius 265 feet and height 160 feet. These values were calculated[3] based on a worst case scenario for an encounter between two Airbus A380 aircraft.

Figure 8 shows, to scale, a B737-400 target aircraft inside the large cylinder. In this model a collision is assumed to occur when the center of gravity of the blundering aircraft penetrates the cylinder containing the target aircraft. Figure 9 shows the B737-400 inside the large cylinder with both inside the large, 500-foot radius sphere.

[3] An A380 wingspan is 262 feet and its tail height (gear up) is 80 feet.

Figure 8 B737-400 in 265 Foot Radius (Large) Cylinder to Scale

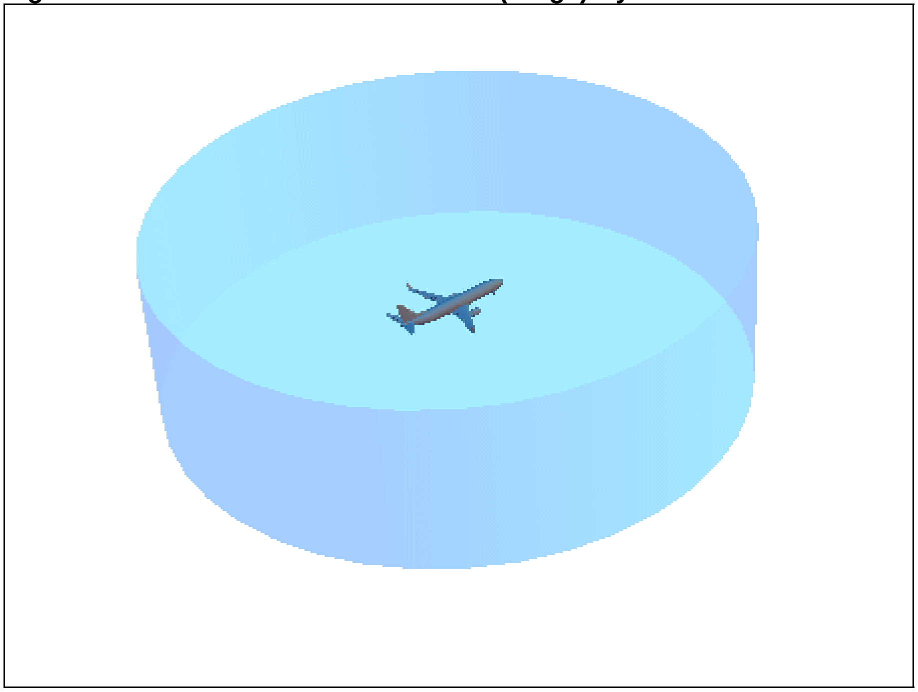


Figure 9 B737-400 in Large Cylinder in Large Sphere

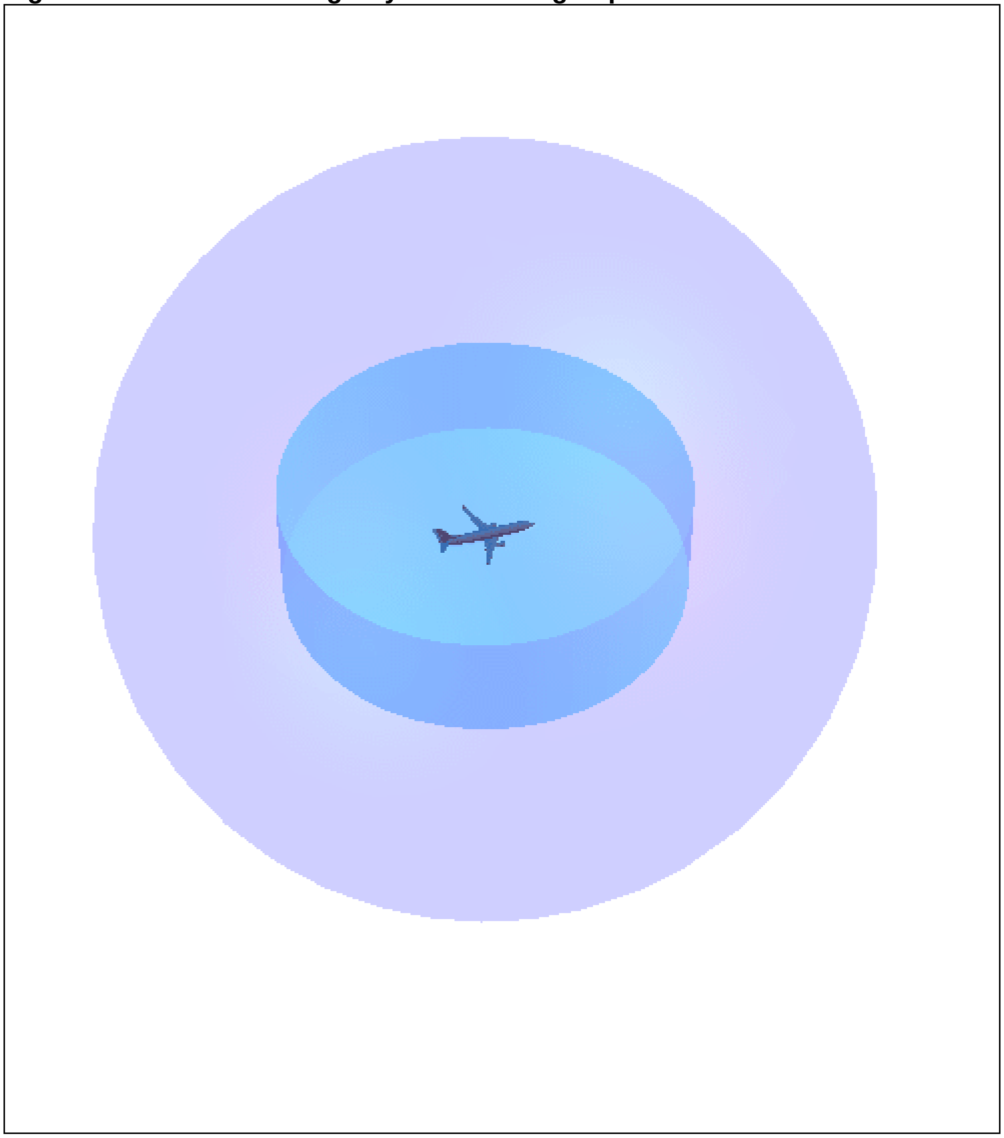


Table 5 gives the number of TCVs counted in the study for each data set. In each case a TCV occurs when the CPA for the two aircraft is less than 500 feet. Table 3 also gives the number of TCVs that would have been counted had a large cylinder (of radius 265 feet and height 160 feet) been used rather than a sphere of radius 500 feet. And Figure 3 provides a 3-dimensional scatter graph of the 500 foot sphere and 265 foot cylinder TCVs to show their geometrical relationship.

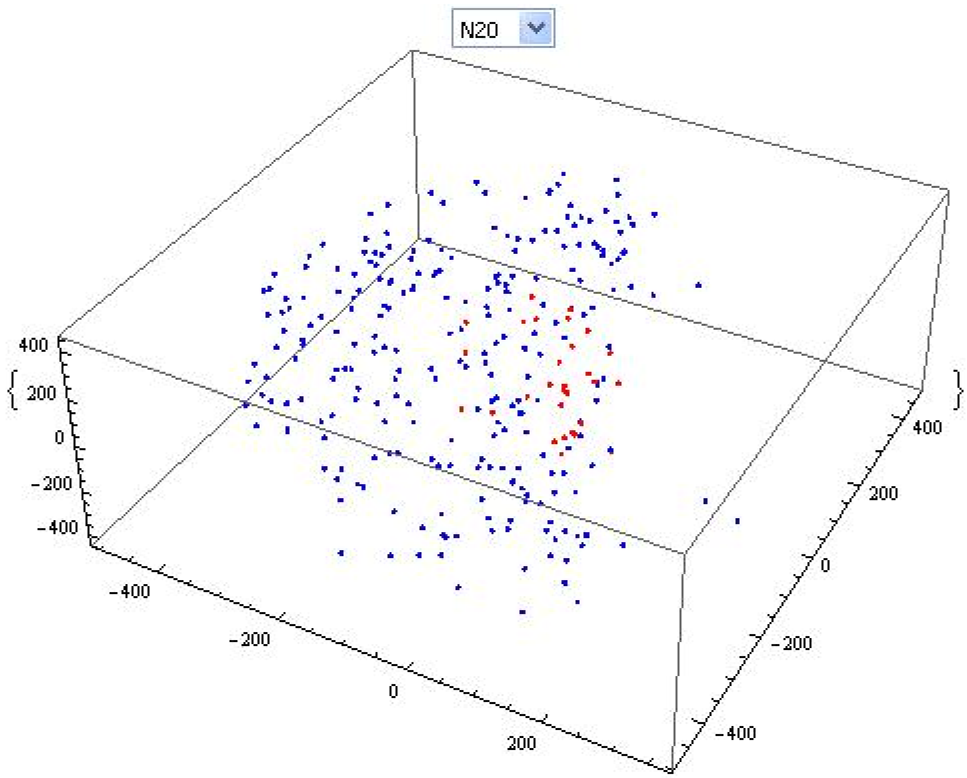
Table 5 CSPO Data Set TCVs for Large Sphere and Large Cylinder

Data Set	Number of Runs	500 ft Sphere TCV Count	500 ft Sphere TCV Percent	Large Cylinder TCV Count	Large Cylinder TCV Percent
N20	188,078	278	0.148%	29	10.432%
N30	188,078	1342	0.714%	137	10.209%
W20	188,149	212	0.113%	20	9.434%

W30	188,149	1052	0.559%	114	10.837%
All	752,454	2,884	0.38%	300	10.402%

In Figure 10 the blue points represent 500 foot sphere TCVs and the red points represent the small cylinder TCVs. The number of large cylinder TCVs is on the order of one-tenth those of the large sphere.

Figure 10 Large Sphere (blue) and Large Cylinder (red) TCVs



Box

This is a box of length 302.5 feet, width 281.2 feet, and height 88.0 feet. These values were, as with the small sphere radius and cylinder radius and height, calculated based on data from the Closely Spaced Parallel Operations (CSPO) study [2].

Figure 8 shows, to scale, a B737-400 target aircraft inside the box. In this model a collision is assumed to occur when the center of gravity of the blundering aircraft penetrates the box containing the target aircraft. Figure 9 shows the B737-400 inside the box with both inside the large, 500-foot radius sphere.

Figure 8 B737-400 in 302.5 by 281.2 by 88.0 Box to Scale

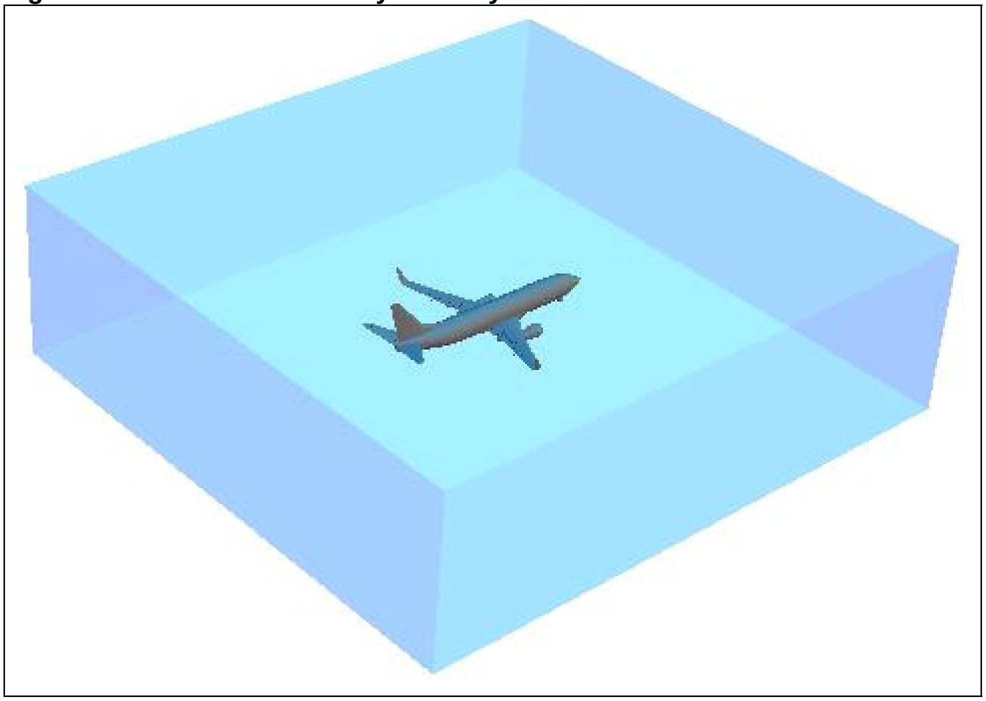


Figure 9 B737-400 in Box in Large Sphere

Table 6 gives the number of TCVs counted in the study for each data set. In each case a TCV occurs when the CPA for the two aircraft is less than 500 feet. Table 6 also gives the number of TCVs that would have been counted had a box (of average height 88.0 average width 281.2 feet, and average length 302.5 feet[4]) been used rather than one of 500 feet. And Figure 10 provides a 3-dimensional scatter graph of the 500 foot sphere and box TCVs to show their geometrical relationship.

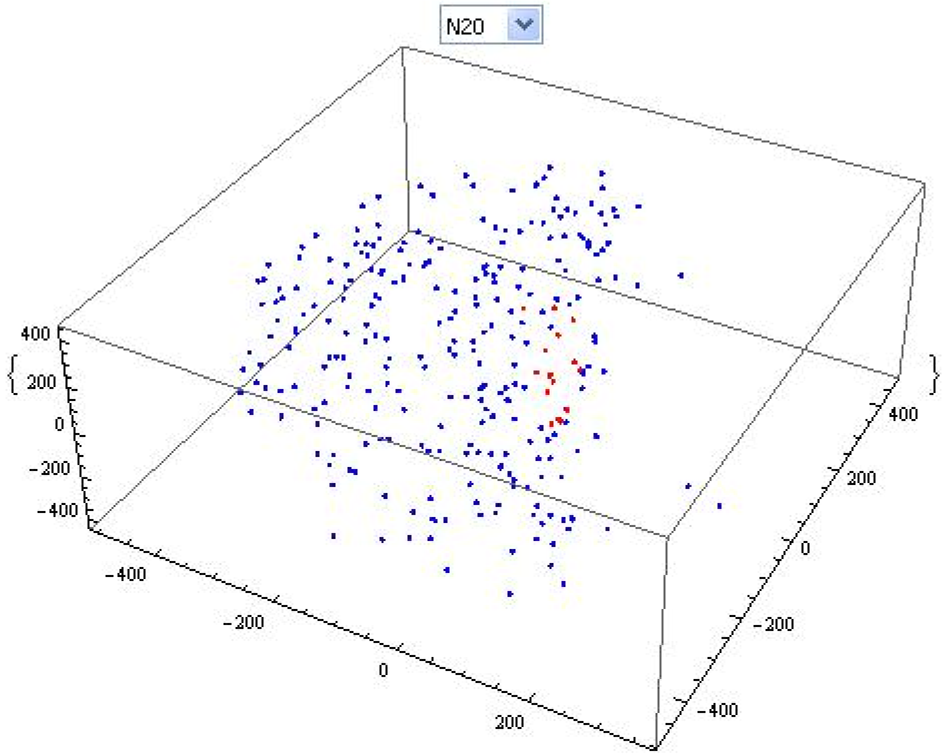
Table 6 CSPO Data Set TCVs for Large Sphere and Box

Data Set	Number of Runs	500 ft Sphere TCV Count	500 ft Sphere TCV Percent	Box TCV Count	Box TCV Percent
N20	188,078	278	0.148%	16	0.009%
N30	188,078	1342	0.714%	72	0.038%
W20	188,149	212	0.113%	4	0.002%
W30	188,149	1052	0.559%	56	0.030%
All	752,454	2,884	0.38%	148	0.02%

[4] The box dimensions used to count TCVs varied by aircraft pair. The heights, lengths, and widths were calculated as the sum of each dimension of those of the two aircraft.

In Figure 10 the blue points represent 500 foot sphere TCVs and the red points represent box TCVs. The number of box TCVs is (again) on the order of one-twentieth those of the large sphere.

Figure 10 Large Sphere (blue) and Box (red) TCVs



Shape Summary

Table 7 below gives a summary of the TCV results for the four shapes as compared with the large 500 foot sphere. The TCV ratios of the shapes to those of the large sphere are closer to the area ratios than to the volume ratios (the areas for these ratios are the cross sectional areas – height and length - rather than the plan view areas).

Also, the TCV ratios for the box and small sphere are very similar (their cross sectional areas are almost the same) and are about half those of the small sphere. The TCV metric using the small or large cylinder is likely a better measure of the metal-to-metal collision rate for parallel approaches than for either the spheres or the box.

Figure 11 shows the nested B737-400, cylinder, box, small sphere, and large sphere.

Shape	Volume (ft^3)	Volume Ratio to Large Sphere	Area Ratio to Large Sphere	Volume Ratio to Small Sphere	TCV Count	TCV Ratio to Large Sphere	TCV Ratio to Small Sphere
large sphere	5.20E+08	1.000	1.000	44.966	2884	1.000	12.118
large cylinder	2.55E+07	0.049	0.083	2.19	300	0.104	1.261
small sphere	1.20E+07	0.022	0.079	1.000	238	0.083	1.000
box	7.50E+06	0.014	0.034	0.643	148	0.051	0.622
small cylinder	5.50E+06	0.010	0.032	0.469	123	0.043	0.517

Table 7 TCV Summary by Shape

Figure 11 B737-400, Small Cylinder, Box, Small Sphere, Large Cylinder, and Large Sphere

3.0 TLS Regions

In this section we will calculate the overall TCV rates relative to the size of various volume regions centered on the target aircraft. The type of question this analysis is intended to answer is: "if a collision (a catastrophic event) has an extremely improbable likelihood of *p*, then what regions about the aircraft would overall TCV rates associated with extremely remote likelihoods?"

Extremely Improbable TLS *p* = 1.0 E-09

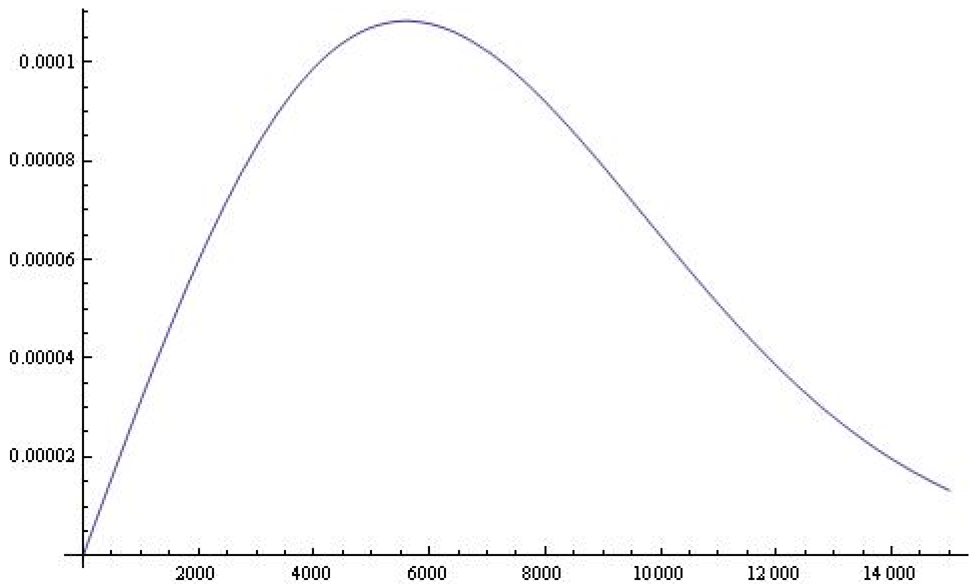
For example, if *p* is taken to be 1.0 E-09, as the extremely improbable TLS, and this is associated with a cylinder TCV rate, then what volume region would be associated with an extremely remote likelihood between 1.0 E-07 and 1.0 E-09?

Since the TCV rate is based on the CPAs within a given volume region, we will model the distribution of CPAs in order to associate a volume region with a TCV likelihood.

The distribution of CPAs for an aircraft pair, one blundering, is theoretically unbounded above and zero below: unbounded above since the blundering aircraft may blunder away from the target aircraft and zero below since the CPA is never less than zero. Also, this distribution is likely a combination of normal-like distributions for lateral, vertical, and longitudinal position differences of the two aircraft.

For these reasons, a Rayleigh distribution, $R(x; \sigma)$ is an appropriate choice. If the typical distance between approach paths is about 3500 feet, then Rayleigh distribution with parameter value $\sigma = 5600$ would be reasonable as shown below. We represent this distribution by $R(x; \sigma) = R(x; 5600)$. Figure 12 is a graph of this distribution.

Figure 12 Rayleigh Distribution, R(x; 5600)



We can verify that this distribution is reasonable by comparing the TCV rates it provides with those from the CSPO data sets. First, the likelihood of a CPA less than 500 feet can be predicted by this Rayleigh distribution. This value is calculated to be

$$\int_0^{500} R(x;5600)dx = 0.00398 .$$

The TCV rate for the large sphere (radius 500 feet) from the 4 CSPO data sets averages 0.00383. The two TCV rates are quite close.

Second, the ratio of the TCV rate of the small sphere (radius 140.6 feet) and the large sphere (radius 500 feet) can be calculated based on the Rayleigh distribution to be

$$\frac{\int_0^{140.6} R(x;5600)dx}{\int_0^{500} R(x;5600)dx} = \frac{0.000315}{0.00398} \approx 0.08$$

The TCV ratio of the small sphere to the large sphere (from Table 7) is 0.083. Again, the two values are quite close.

Now we use this Rayleigh distribution to determine what volume region corresponds to an overall TCV rate between 1.0 E-07 and 1.0 E-09. We distinguish between "TCV rate" and "overall TCV rate" because the TCV rates from the CSPO data sets represent at risk rates, and not usual rates per approach. The overall TCV rates used to compare with TLS vales should be usual rates per approach. Therefore, the CSPO TCV rates must be multiplied by a factor to accommodate the at risk nature of the data.

1. Let a collision be given a likelihood corresponding to that of an extremely improbable event: 1.0 E-09.
2. Assume that a small cylinder TCV represents a collision as recommended above.
3. The <u>overall</u> likelihood of a small cylinder TCV should then be 1.0 E-09. But the TCV rate for the small cylinder, from Table 4, is 0.0002. Therefore, this rate should be multiplied by a factor of 5.0 E-06 to give 1.0 E-09. (The TCV rate of 0.0002 from the CSPO test data is for at risk blunders, and does not include most typical parallel approach behaviors, non-blunder behavior.)
4. Next we determine the radius, r, of a sphere whose volume will give a TCV rate, T, such that T times 5.0 E-06 will equal 1.0 E-07. Thus, T must be 0.02. So that

   $$\int_0^r R(x;5600)dx = \frac{1.0E-07}{1.0E-09}(0.0002) = 0.02$$

5. From the equation above, r must equal 1125 feet. So that a spherical region of radius 1125 feet gives an overall TCV rate of 1.0 E-07.

Using this methodology, we can describe spheres about the target aircraft for various overall TCV rates. Table 8 provides these results for various overall TCV rates between 1.0 E-09 and 1.0 E-7. Rates above 1.0 E-07 do not correspond to radius distances that are reasonable for close parallel approaches.

Table 8 Overall TCV Rates and Sphere Radii (p = 1.0 E-09)

Overall TCV Rate	Sphere Radius (ft)
1.0 E-09	112
1.6 E-09	140.6
6.0 E-09	265
1.0 E-08	355
2.0 E-08	500
5.0 E-08	795

1.0 E-07	1125

As a further reasonableness check, the CSPO data provides TCV values of 133, 718, and 1441 for spheres of radius 112 feet, 265 feet, and 355 feet respectively. These empirical TCV values translate into overall TCV rates of 8.8 E-10, 4.8 E-09, and 9.6 E-09. These, in turn, compare very favorably with the overall TCV rates above (1.0 E-09 = 10.0E-10, 5.0 E-09, and 1.0E-08 = 10.0 E-09) calculated from the Rayleigh distribution. Table 9 summarizes these comparisons.

Table 9 Theoretical (Rayleigh) to Empirical (CSPO Data) Comparison

Sphere Radius (ft)	Rayleigh TCV Rate	Empirical TCV Rate
112	1.0 E-09	0.88 E-09
265	6.0 E-09	4.80 E-09
355	1.0 E-08	0.96 E-08

There are two other independent studies of parallel approach blunder rates that use variously shaped TCV regions. These studies may be used to check the reasonableness of our results. Unfortunately, these studies do not use blunder scenarios or region sizes strictly comparable to those of the CSPO data sets used here (for example, the definition of at-risk may vary considerably). However, since each of these studies compares cylinder to sphere TCV rates giving cylinder to sphere ratios, it is possible to compare those ratios with the cylinder to sphere ratios presented here.

A study by the Mitre CAASD organization [3] analyzed parallel approaches with 4000 foot spacing and PRM sensors. The at-risk TCV rate[5] it found using a 500 foot radius sphere was 0.1166 and the at-risk TCV rate for a 500 foot radius, 100 foot height cylinder was 0.0391. The cylinder to sphere TCV ratio is then 0.0391 / 0.1166 = 0.335. The TCV ratio of our 140.6 foot radius, 100 foot height cylinder to our 140.6 foot radius sphere is 0.043 to 0.083 or 0.518. Though the dimensions of our regions are somewhat smaller than those of the Mitre study, the two ratios are comparable.

A 2009 study by Air Traffic Simulation, Inc. (ATSI) [4] analyzed parallel approaches with 2500, 3000, 3500, and 4000 foot spacing and PRM sensors[6]. In the 3500 foot spacing analysis, the at-risk TCV rate it found using a 500 foot radius sphere was 0.1028 and the at-risk TCV rate for a 175 foot radius, 150 foot height cylinder was 0.0068. The cylinder to sphere TCV ratio is then 0.0068 / 0.1028 = 0.066. The TCV ratio of our 140.6 foot radius small cylinder to our 500 foot sphere is 0.043. However, the cross-sectional area of our cylinder is about one-half that of the ATSI cylinder. So, again, the results are comparable.

[5] These rates are for scenarios with level flight and climb and turn evasive maneuvers.
[6] This ATSI study analyzed TCV rates using other sensors also, but the PRM sensors are the ones comparable to our results. Also, we used the 20% heavy ATSI analysis for comparison with our values.

<u>Extremely Improbable TLS *p* = Other Values</u>

The Extremely Improbable TLS probability, *p*, may be some value other than 1.0 E-09. In that case, we can generalize the methodology presented above.

In step 4 of the methodology, the equation to calculate the sphere radius, *r*, based upon the overall TCV rate, 1.0 E-07, and the TLS probability, 1.0 E-09 is

$$\int_0^r R(x;5600)dx = \frac{1.0E-07}{1.0E-09}(0.0002) = 0.02 \ .$$

To generalize, we can replace 1.0 E-07 by a general TCV rate of *t*, and we can replace 1.0 E-09 by a general TLS probability of *p*. The equation then becomes

$$\int_0^r R(x;5600)dx = \frac{t}{p}(0.0002)\,. \qquad (1)$$

The Rayleigh cumulative distribution function given by $\int_0^r R(x;5600)dx$ can be written as $1-e^{-\frac{r^2}{2\sigma^2}}$ where σ = 5600. Equation (1) above therefore becomes

$1-e^{-\frac{r^2}{2\sigma^2}} = \frac{t}{p}(0.0002)$. This equation can be solved for the radius, *r* so that

$$r = \sigma\sqrt{\ln\left(1-\frac{0.0002t}{p}\right)^{-2}}\text{, where } \sigma = 5600. \qquad (2)$$

Table 8 can be extended to other TLS probabilities, *p*, using equation (2) above. Tables 10, 11, and 12 show these results for p = 5.0 E-09, p = 1.0 E-08, and p = 4.0 E-08 respectively. Other such tables can be calculated from this equation.

Table 10 Overall TCV Rates and Sphere Radii (*p* = 5.0 E-09)

Overall TCV Rate, *t*	Sphere Radius (ft)
5.00E-09	112
1.00E-08	158
2.00E-08	224
5.00E-08	354
1.00E-07	501
5.00E-07	1126

Table 11 Overall TCV Rates and Sphere Radii (*p* = 1.0 E-08)

Overall TCV Rate, *t*	Sphere Radius (ft)
1.00E-08	112
2.00E-08	158
5.00E-08	251
1.00E-07	354
5.00E-07	794
1.00E-06	1126

Table 12 Overall TCV Rates and Sphere Radii (*p* = 4.0 E-08)

Overall TCV Rate, *t*	Sphere Radius (ft)
4.00E-08	112
5.00E-08	125
1.00E-07	177
5.00E-07	396
1.00E-06	561
5.00E-06	1260

References

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[4] "Revision of Test Criteria (TC) for Near Mid-Air Collision (N-MAC): ASATng Runs & Analysis", Air Traffic Simulation study ATSI-2009-05-04, May 18, 2009.