THINKING PROBLEMS OF THE PRESENT COLLISION WARNING WORK BY ANALYZING THE INTERSECTION BETWEEN COSMOS 2251 AND IRIDIUM 33

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ABSTRACT

After Cosmos 2251 and Iridium 33 collision breakup event, the institutions at home and abroad began the collision warning analysis for the event. This paper compared the results from the different research units and discussed the problems of the current collision warning work, then gave the suggestions of further study.

Key words：Cosmos 2251 and Iridium 33 collision, collision warning, collision threshold, engineering application

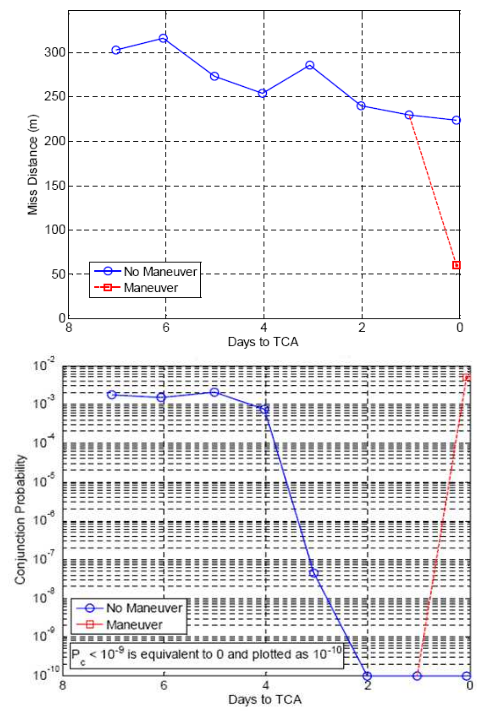
1 Introduction

American Iridium 33 satellite and Russian dead Cosmos 2251 satellite collided on 2009 Feb 10 at 16:56 UTC which is the first collision of the two catalog satellites. By 2012 Aug 31,2199 debris had been cataloged, in which the number of Cosmos 2251 debris was 1602,the number of Iridium 33 was 597.They affected the satellite launch and in-orbit running near the breakup altitude in LEO. After the collision, many research organizations had made the collision analysis for this event. This paper compared the different warning results in different organizations and found that the results were different for the intersection time and distance, collision probability. The deep analysis was made for the differences. The results indicated that the differences were caused by three factors: the data source, orbit determination and prediction model, the error cope method. On the basis of this, combined the collision warning experience for many years, the current warning problems were pointed, the further study of the collision warning work was suggested. There is a long way to make the collision warning into the actual project.

2 The results of American-Russian satellite collision warning in different units

2.1 NASA results[1]

Before the American-Russian satellite collision, about 50 satellites were included in the collision warning project in NASA, in which Iridium 33 was not included, so the dangerous intersection was not predicted. After that, Iridium corporation put forward the need of surveillance and then confirmed the collision. But the Iridium 33 made two minor orbit maneuver. Fig.1 gave the intersection distance and collision probability change trend considering maneuver and no maneuver two situations with the data before the collision. In the figure the blue line represent the situation with no maneuver, the red line represent the situation with maneuver.



Figer 1. intersection distance and collision probability change with time

From Fig.1, 8 predictions were given 7 days before the intersection, the last was given with considering maneuver and no maneuver, the warning results were as follows:

(1)Not considering the maneuver, the intersection distance change was small, about from 220 to 320 meters, the magnitude was about hundred meters. Although the intersection distance had the decrease trend, the errors decreased with the approaching intersection time, the collision probability decreased

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gradually. Before the intersection, the probability decreased rapidly from 10^{-3} to 10^{-10}.So not considering the maneuver before the intersection, the risk of this intersection was very low.

(2)Compared with the last intersection results with maneuver and no maneuver, the intersection distance was respectively 223 meters and 60 meters when considering the maneuver; the collision probability was from 10^{-10} to 4.98×10^{-3}.NASA thought that the collision breakup was caused by the Iridium 33 orbit maneuver.

2.2 Russian warning results[2]

Russia has its own independent space surveillance network. After the American-Russian satellite collision breakup, Russia fetched out the surveillance data to analyze. With the newest orbital data, one was 2009 Feb 10 16:46:56UTC， the other was 16:46:45,the time of data was very near the collision epoch. The prediction duration was 10 minutes, the collision time of satellites was 16:56:00.

Russia gave the intersection distance 10 days before the collision with the different orbit prediction methods. The results were as following:

Table 1. The intersection distance of different time before the collision

Time before the collision	The intersection distance(meters)			
	analytic	Numerical（8×8）	Numerical（16×16）	Numerical（32×32）
<10 days	2100	1100	900	650
<7 days	1100	650	300	300
<3 days	1000	350	250	250
<2 days	1000	350	250	250
<1 day	300	200	180	200

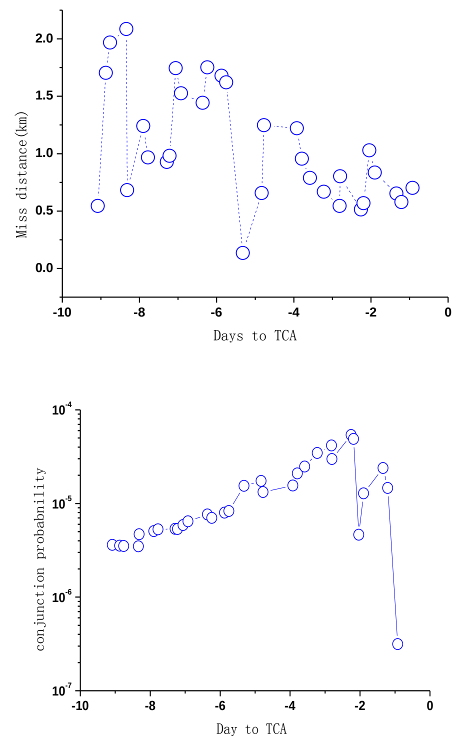
From the above table, the precision was the highest for the high degree numerical method. The intersection distance was 650 meters, the probability was 3×10^{-5}, 10 days before the collision. The intersection distance was 200 meters, the probability was 2×10^{-4}, 1 day before the collision.

2.3 CSSI warning results[3]

CSSI made routine collision warning analysis for about 3000 in-orbit satellites with TLE data and STK software, every day its website published the top 10 dangerous intersections, in which the American-Russian satellite intersection was not. The newest report was on Feb 10 15:02UTC）,the intersection distance was 584 meters, the intersection time was 2009 Feb 10 16:56（UTC）which was the calculation results with data on 12h Feb 9 for Cosmos 2251 and 8h Feb 9 for Iridium 33.The data of Iridium 33 was not the nearest intersection epoch.

2.4 Our warning results

After the event, we made the collision warning analysis with TLE data 7 days before the collision, Fig.2 gave the change trend of the intersection distance and collision probability. From Fig.2, the intersection distance decreased with the intersection time, but some results of intersection distance was unstable. The collision probability was first increased then decreased, the last result was less than 10^{-7}.

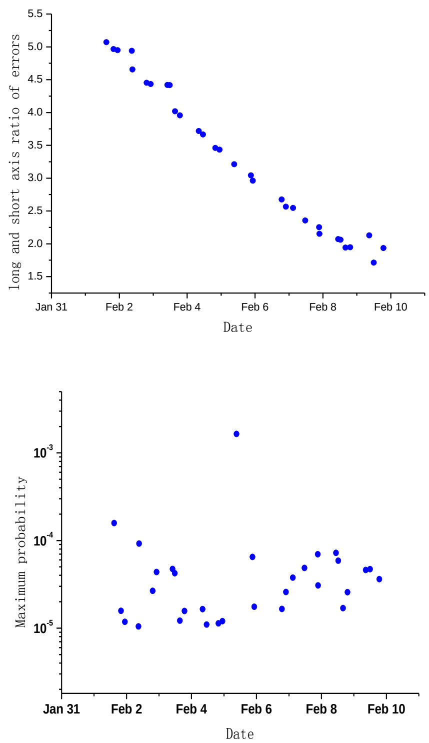


Figer 2. the intersection distance and collision probability change with time

Error cope methods were different for the research units for the TLE errors were not published publicly. Many units adopted the maximum collision probability conservatively. The formula of the maximum probability was:

$$P_{\max} = 9.2\times10^{-8}\frac{k\cdot d^2}{dist^2} \qquad (1)$$

In the above equation, P_{max} was the maximum probability, *dist* was the intersection distance, d was the combined size, k was the ratio of error long and short axis and was greater than 1.From the above equation, the maximum probability was relevant with the ratio of the long and short error axis, the intersection distance, the combined size. Fig.3 gave the error long-short axis ratio and the maximum probability with time. From Fig.3, the maximum probability and the intersection distance were correlative closely. The corresponding maximum probability was mostly 10^{-5} for the closest distance.



Figer 3. Error long-short axis ratio(left) and the maximum probability with time(right)

3 Warning results comparison analysis

The calculation results of collision warning are correlated with the data, model and error. Their difference can make the results different. The last section gave the calculation results in different units. In this section the comparison and analysis were made from the data source, the orbit determination and prediction model, the error cope method. Some units such as CSSI used TLE, data and model was matched. The errors can be gotten in the orbit determination process, also can be gotten from the comparison analysis for the historical data.

3.1 NASA and Russian results comparison and analysis

For this collision intersection, NASA and Russian used their own surveillance data with their own high precision orbit determination and prediction model. Tab.3 gave their last calculation results comparison.

Table 3. Russian and NASA last calculation results comparison

unit	Intersection distance （meters）	Estimated errors （meters）	Collision probability
Russian	200	200	2×10^{-4}
NASA（no maneuver）	223	60	0
NASA（maneuver）	60	60	4.98×10^{-3}

From table 3, the intersection distance difference was small between two units which manifested the data and prediction model precision was near, while the collision probability had large difference. The collision probability is the function of the relative position, error and size under the certain intersection geometry between the objects. For this intersection, the intersection geometry and size were almost same, so the error made the probability different.

Usually when the error and intersection distance were near, the probability could reach to the maximum. When the intersection distance was fixed, the collision probability became smaller, however the errors increased or decreased. If the orbit maneuver of Iridium 33 was not considered, the calculated intersection distance was both about 200 meters for NASA and Russian. The collision probability was about 10^{-4}, which was in coincidence with Russia, So Russian thought calculated and actual errors were coincident. While the probability of NASA was near zero which indicated that the errors NASA adopted were much smaller than the intersection distance.

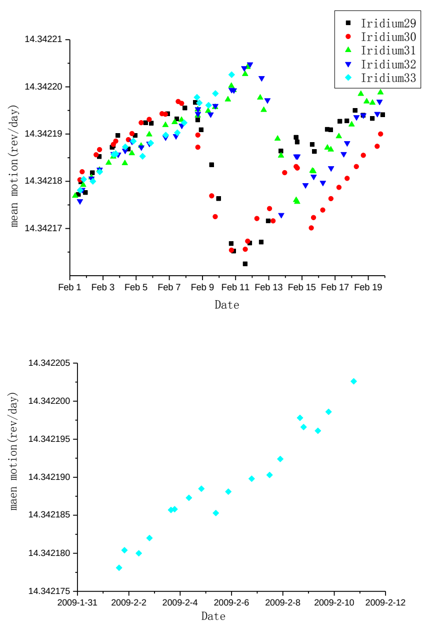
The intersection distance was only 60 meters after Iridium 33 orbit maneuver which was matched with 10^{-3} of the maximum probability which indicated that the last calculation error was about 60 meters. So the cause of the results difference between Russian and NASA was that Russian adopted about 200 meters error, NASA adopted about 60 meters error.

3.2 CSSI and other results comparison with TLE data

CSSI and some units made the collision warning for the event with TLE data. Although the data source was same, the results were different for the units. Because some units had not given the data epoch, it was difficult to compare the results. For the intersection epoch and distance, the difference cause should be the intersection calculation method, which meaned that the choice of the step length near the intersection time could make the difference of the intersection time. However the collision probability difference was large mostly for the adopted errors and effective size difference.

3.3 Did Iridium 33 maneuver before the collision?

TLE data were fetched out from Feb 1 to Feb 20 in 2009 for Iridium 29,30,31,32,33, Fig.4 gave the changes of the mean motion. From fig.4,the orbits of iridium 29 and 30 changed abnormally during these period, the mean motion decreased, that was the orbit altitude increased, in detail see table 3.Although orbits of many iridium series satellites changed abnormally on Feb 10, Iridium 33 orbit abnormal change before the collision had not been seen.



Figer 4. Orbit abnormal change of Iridium series satellites and Iridium 33 on Feb 10

3.4 Warning results analysis summary

Based the above the analysis and comparison of different units for the American-Russian satellite collision warning results, the followings were summarized:

(1)NASA and Russian collision warning results were compared with high-accuracy data. If the orbit maneuver was not considered, their calculated intersection distance was same, but their adopted different errors made the probability very different, the errors NASA adopted were smaller than Russian.

(2)CSSI and other units adopted TLEs to make the warning analysis for the American-Russian collision, the data source was same, so the intersection time and intersection was almost same, the collision probability differed largely for the error cope method.

(3)The calculation results between TLEs and high accuracy data was largely different, the intersection distance calculated with high accuracy data was about 400 meters, which was more than the results calculated by TLEs. The difference of the intersection time was about 0.2 seconds.

(4)The position errors were small for the relative high collision altitude with small atmosphere drag, the prediction error for 1 day duration was about hundred meters. It was be noted that the accuracy of TLEs was limit for collision warning.

4 Considering the current collision warning work

Collision breakup of American-Russian satellite made the space debris environment in LEO be changed abruptly, which affected the safety of launch and in-orbit for the satellites near the breakup altitude. How to avoid the similar events was the problem, which we had to consider deeply. By comparing the warning results of different units, the breakup cause was summarized, there were two main reasons, one was that both Iridium 33 and Cosmos 2251 had not been considered by the project, the other was that no connector was founded with satellite department. However some technique problem can affect the precision and avoidance strategy implement, including how to get actual errors, how to determine the threshold, and so on.

4.1 Warning project object determination

With the development of the aerospace activity, the number of space debris was increasing, so was the collision risk for in-orbit satellites. The debris collision warning work of many nations was adopted into the project with deeper and deeper cognition of debris collision warning work by people. But because of the complexity of the collision warning, the scope of the collision warning into the project was different, such as America and Russia. America made the collision warning into project especially for the space shuttle in 1988,after the challenger event. When the ISS came out, it was adopted into the project. Then in 2007 Aug, the collision warning work was extended to the unmanned spacecrafts, initially mainly for the earth science constellation satellites, then some spacecrafts which could not maneuver were be included as the hypervelocity impact breakup events in 2007 and America-Russia satellite collision breakup events. By 2009 Oct 1 ,there were 70 spacecrafts into the warning project in all[1].

From the America-Russia collision event, before the event, America did not adopt the Iridium 33 into the

Table 3. Orbit change of Iridium series satellites

Name	No	First orbit change time （UTC）	Mean motion	Time of the lowest motion（UTC）	Mean motion
Iridium 29	24944	2009-02-08 13:45	decrease	2009-02-11 13:45	increase
Iridium 30	24949	2009-02-08 17:24	decrease	2009-02-10 17:57	Increase- decrease-increase
Iridium 31	24950	2009-02-11 17:15	decrease	2009-02-14 17:15	Increase
Iridium 32	24945	2009-02-11 20:54	decrease	2009-02-13 18:07	Increase
Iridium 33	24946	2009-02-10 18:16	Increase		

project, the department of the collision warning did not get two maneuver information, so the collision event could not be predicted. The work on Russian collision warning project was not reported in public. The abandoned Cosmos 2251 should not been into the project by the collision event.

Studied indicated that the threat of the objects lager than 1cm to the spacecrafts could be ignored, the collision between the objects larger than 10cm and spacecrafts might affect largely to the space debris environment. In order to avoid the hazardous collision events, the collision warning work should be done for all the cataloged objects. But for the current surveillance and cataloged ability, only a part of spacecrafts were into the project, and founded the connection with the satellite department to get the orbit change information in time.

4.2 Data, model and error cope method

The last aim of collision warning into the project is to alleviate or avoid the risk, so the high accuracy data, orbit determination and prediction model, error careful cope method are critical of collision warning.

Data, model and error were coincident. Data and error were the product of the orbit determination. The model of orbit determination and predict model need be matched. If any one of three was not coincident, the precision of collision warning results could be decreased even incredible. The calculation and actual errors also need be coincident which need be modified for the coincidence. The error in the orbit determination and prediction is not coincident, usually the errors in the orbit determination were less than that the actual errors.

Data often used included two classes: one is TLE data, the other is high accuracy data. TLEs is the public data, also the corresponding model. But TLE errors are not given. Further the data precision is limit, it can not be used in the avoidance decision, but it is very useful in the early filter. It can filter out many objects which can not collide the object, so much surveillance resource were saved. The error cope method for TLEs mainly used data comparison. High accuracy data was mainly the product of high precision orbit determination model which was matched by the high precision prediction model, the errors were modified based on the experience in order to warning analysis and support the decision of risk mitigation.

4.3 Collision threshold determination

Collision thresholds include the distance threshold and probability threshold. Distance threshold was mainly for early filter, probability threshold was for supporting the avoidance decision. The determination of the intersection distance threshold was mainly correlated with the intersection distance errors. With the surveillance frequency increase and model precision improve, the distance threshold will smaller and smaller so which can ensure the dangerous objects to monitor enhancing.

The determination of probability threshold was correlated with many factors, including the space debris environment near the orbit of the spacecraft, the errors, the task demand of the spacecraft and so on. Foster put forward the avoidance threshold determination means based on the collision probability. Supposed an avoidance threshold, based on the error covariance and space debris flux, the correlation between the residual risk percent and yearly avoidance number. At last the ISS debris avoidance system was founded which can estimate the percent of risk decrease and the minimal avoidance number.

Russia put forward the problem of the false alarm rate. The threshold could be adjusted by analyzing the false alarm rate. It was not that all predicted high risk intersection could happen the collision, for the errors, the collision itself was a probabilistic event. If all the predicted high risk intersection sent the alarm, the false alarm rate problem came out. The determination of the false alarm rate can adopt a simple method to determine, see the following: (1)determine the threshold of the dangerous intersection;(2)analyze the historical intersection events to get the intersection information in the different ahead time;(3)sum the frequency of the dangerous intersection.(4)interpolate or propagate to get the frequency of the dangerous intersection for the certain intersection, that is the false alarm rate. In the analysis the number change and altitude distribution need to be considered, the altitude region of the intersection is coincident with the analyzed event. For the America-Russia satellite collision event, the false alarm rate was once two month[2].If the value was receivable, it was confirmed, or it need to be adjusted.

However for the current collision warning work, the determination of the threshold need consider both the debris environment update and the surveillance ability, the orbit model accuracy, the ability of orbit control and operation and so on.

4.4 Other problems

(1)error mean and normality analysis

Now the calculation of the probability is based on the zero mean and the normality of errors. But the actual errors were not so especially for the long duration prediction. So it is necessary to analyze the mean and normality of the errors and modify the formula of the collision probability.

(2)atmosphere model precision

One of the main perturbation factors is the atmosphere drag. For the complexity of the atmosphere model, it is the most important problem in the warning work. Solar and the geomagnetic activity are the main factor affecting the atmosphere density whose exact prediction is very complex. So to improve the accuracy of the atmosphere model and the collision warning, more data and study work were demanded.

5 Conclusion

This paper first gave the collision warning results of different units for the America-Russia satellite collision events, then compared and analyzed them combined with our own results. It concluded that the data, model and errors are the difference cause of the warning results, and then deeply analyzed the every factor. On the basis of this, the current problems in the collision warning work were summed and analyzed. The project of warning in different nation need consider the national conditions. In the propel of the warning technique, different departments make the endeavor together and progress little by little.

6 References

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