NASA/TP–2005–213159

# Fluctuations in Conjunction Miss Distance Projections as Time Approaches Time of Closest Approach

*John A. Christian, III*
*Lyndon B. Johnson Space Center*
*Houston, Texas*

July 2005

# THE NASA STI PROGRAM OFFICE . . . IN PROFILE

Since its founding, NASA has been dedicated to the advancement of aeronautics and space science. The NASA Scientific and Technical Information (STI) Program Office plays a key part in helping NASA maintain this important role.

The NASA STI Program Office is operated by Langley Research Center, the lead center for NASA's scientific and technical information. The NASA STI Program Office provides access to the NASA STI Database, the largest collection of aeronautical and space science STI in the world. The Program Office is also NASA's institutional mechanism for disseminating the results of its research and development activities. These results are published by NASA in the NASA STI Report Series, which includes the following report types:

- TECHNICAL PUBLICATION. Reports of completed research or a major significant phase of research that present the results of NASA programs and include extensive data or theoretical analysis. Includes compilations of significant scientific and technical data and information deemed to be of continuing reference value. NASA's counterpart of peer-reviewed formal professional papers but has less stringent limitations on manuscript length and extent of graphic presentations.

- TECHNICAL MEMORANDUM. Scientific and technical findings that are preliminary or of specialized interest, e.g., quick release reports, working papers, and bibliographies that contain minimal annotation. Does not contain extensive analysis.

- CONTRACTOR REPORT. Scientific and technical findings by NASA-sponsored contractors and grantees.

- CONFERENCE PUBLICATION. Collected papers from scientific and technical conferences, symposia, seminars, or other meetings sponsored or cosponsored by NASA.

- SPECIAL PUBLICATION. Scientific, technical, or historical information from NASA programs, projects, and mission, often concerned with subjects having substantial public interest.

- TECHNICAL TRANSLATION. English-language translations of foreign scientific and technical material pertinent to NASA's mission.

Specialized services that complement the STI Program Office's diverse offerings include creating custom thesauri, building customized databases, organizing and publishing research results . . . even providing videos.

For more information about the NASA STI Program Office, see the following:

- Access the NASA STI Program Home Page at http://www.sti.nasa.gov

- E-mail your question via the Internet to help@sti.nasa.gov

- Fax your question to the NASA Access Help Desk at (301) 621-0134

- Telephone the NASA Access Help Desk at (301) 621-0390

- Write to:
  NASA Access Help Desk
  NASA Center for AeroSpace Information
  7121 Standard
  Hanover, MD 21076-1320

NASA/TP–2005–213159

# Fluctuations in Conjunction Miss Distance Projections as Time Approaches Time of Closest Approach

*John A. Christian, III*
*Lyndon B. Johnson Space Center*
*Houston, Texas*

July 2005

Available from:

NASA Center for AeroSpace Information
7121 Standard Drive
Hanover, MD 21076-1320

National Technical Information Service
5285 Port Royal Road
Springfield, VA 22161

This report is also available in electronic form at http://ston.jsc.nasa.gov/collections/TRS

## Contents

## Tables



## Figures

## Acronyms

| | |
|---|---|
| EDR | energy dissipation rate |
| Ha | apogee |
| Hp | perigee |
| ISS | International Space Station |
| OCM | orbital conjunction message |
| RCS | radar cross section |
| TCA | time of closest approach |
| TOPO | Trajectory Operations Officer |
| USSPACECOM | United States Space Command |

# 1 Introduction

In the event that a piece of orbital debris is expected to come close to the International Space Station (ISS), a debris avoidance maneuver may be necessary. This provides an overview of how United States Space Command (USSPACECOM) projections of debris miss distance fluctuate over time and tend to converge to the final, true miss distance. In this report, historical data was compiled and analyzed to provide a basis for predicting the behavior of miss distance data during real-time operations. It was determined that the driving components, in order of impact on miss distance fluctuation, are energy dissipation rate (EDR), radar cross section (RCS), and inclination.

## 1.1 Background

One of the many responsibilities of the Trajectory Operations Officer (TOPO) is to ensure that the ISS avoids collision with debris. Although USSPACECOM tracks and catalogs a portion of the debris in Earth orbit, it only tracks objects with a perigee less than 600 km and an RCS greater than 10 cm. Since these objects represent only a small fraction of the objects currently in Earth orbit, the ISS uses shielding to protect itself against collisions with smaller objects. When a piece of debris comes close to the ISS (i.e., in conjunction), the TOPO office is notified to assess the likelihood of a collision. USSPACECOM provides the TOPOs with the information necessary to make appropriate calculations and draw associated conclusions, and also continues to update these predictions approximately every 4 hours by providing the TOPO on console with an orbital conjunction message (OCM).

The data used in this analysis, calculations made, and conclusions drawn are stored in Microsoft Excel log sheets. A separate log sheet created for each conjunction contains information such as predicted miss distances, apogee and perigee of debris orbit, EDR, RCS, inclination, tracks and observations, statistical data, and other evaluation/orbital parameters. Although some operational details are not included in the conjunction log sheets, this information can often be found in the daily logs.

## 1.2 Purpose and Scope

By Flight Rule criteria, the TOPO is responsible for recommending whether a debris avoidance maneuver is required. It is therefore necessary that all TOPOs understand the nature of the data upon which these recommendations are based. The purpose of this study is to assess and determine trends in the fluctuation of predicted miss distances in conjunctions of debris with the ISS. These data, provided by USSPACECOM, tend to converge as time approaches time of closest approach (TCA). This study is intended to provide a better understanding of how quickly, and to what degree, these projections tend to converge to the final, true miss distance. The information is formulated for the purpose of better forecasting the behavior of miss distance data during real-time operations.

To begin the analysis, the conjunctions were broken into three categories—circular orbit, mid-eccentricity orbit, and high-eccentricity orbit—each of which is based on the type of orbit the debris exhibited. These three categories will be addressed here, beginning with the circular orbit category.

# 2 Circular Orbit Analysis

The information presented and discussed in this section pertains only to objects that fall within the circular orbit category. A number of analyses were conducted to determine what drives the behavior of the data provided by USSPACECOM. Those analyses are summarized below.

## 2.1 The Data Set

The first step in understanding an analysis of any kind is to become familiar with the set of data used and the extent to which that set represents the entire population. Conjunctions were selected for the circular orbit category if they demonstrated a similar apogee (Ha) and perigee (Hp), defined as a difference in apogee and perigee altitude of less than 250 km (Ha-Hp < 250 km; average Ha-Hp: 70.3 km; Ha-Hp standard deviation: 75.2 km). The debris with a "circular orbit" showed an average apogee of 442 km and an average perigee of 371 km. Typically, the apogee was about 20% larger than the perigee. Since August 1999, 59 conjunctions have exhibited "circular orbits;" 24 (41%) of these were applicable for this analysis. The remaining 35 conjunctions were not used because of missing data or a lack of data points. Data used in this analysis were collected from each event's conjunction log sheet. For a conjunction to be included, it had to have a minimum of four updates prior to TCA. A summery of all of the conjunctions used is given in Appendix A.

The value of EDR for the ISS and debris changes with each OCM update. For the purposes of the following studies, a single EDR value was needed for each conjunction. To ensure consistency, the EDR value of the last OCM was taken as truth and used in the analyses.

The majority of the conjunctions used for this analysis have their first notification about 60 hours prior to TCA. However, six conjunctions (25%) have their first notification within 48 hours to TCA.

## 2.2 Deviation from Actual Miss Distance

It was observed that the conjunctions with circular orbits can be broken into two groups: ΔEDR values that are less than 0.02 W/kg, and ΔEDR values that are greater than 0.03 W/kg. There are insufficient conjunctions with ΔEDR values between 0.02 and 0.03 W/kg to derive trends for this range. Until further data can be accumulated, it will be necessary to make a judgment call based on the EDR, the RCS, the behavior of the data thus far, and other relevant factors.

The following sections contain figures illustrating the deviation of the projected miss distance from the actual miss distance (in kilometers) compared to time to TCA. As a standard, time is represented on the x-axis, beginning at 80 hours prior to TCA; deviation is shown on the y-axis, ranging from –30 to +30 km. Some sections may include additional figures with different scales as necessary. Each individual directional component (radial (U), downtrack (V), and out of plane (W)) is inspected separately in its own section.

### 2.2.1 Radial

The radial (U) component is by far the most stable of the three components. This is clearly demonstrated in Figure 2-1 by how little fluctuation is seen in the projected radial miss distance for all 24 of the conjunctions. These fluctuations stayed within ±1 km for all conjunctions.

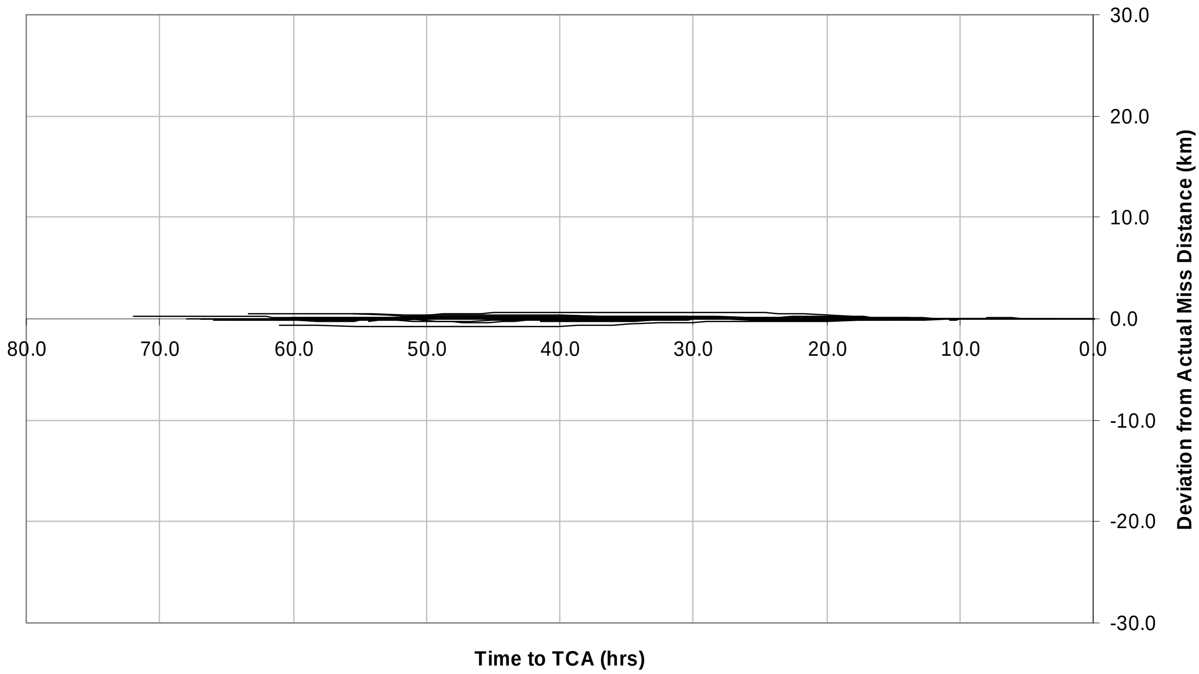


**Figure 2-1. Circular orbit: all conjunctions, radial (U).**

The scale of ±30 km is used for ease of comparison with downtrack and out of plane data. However, because the scale is somewhat inappropriate for the radial component, a second figure, Figure 2-2, was generated to better show the behavior of the data.

From Figure 2-2, we can determine that a combination of high EDR and low RCS can cause even the predicted radial miss distance to exhibit discrepancies as high as 800 m from the final miss distance. It is relevant to note that the most severe cases are those with an EDR greater than 0.1 W/kg.

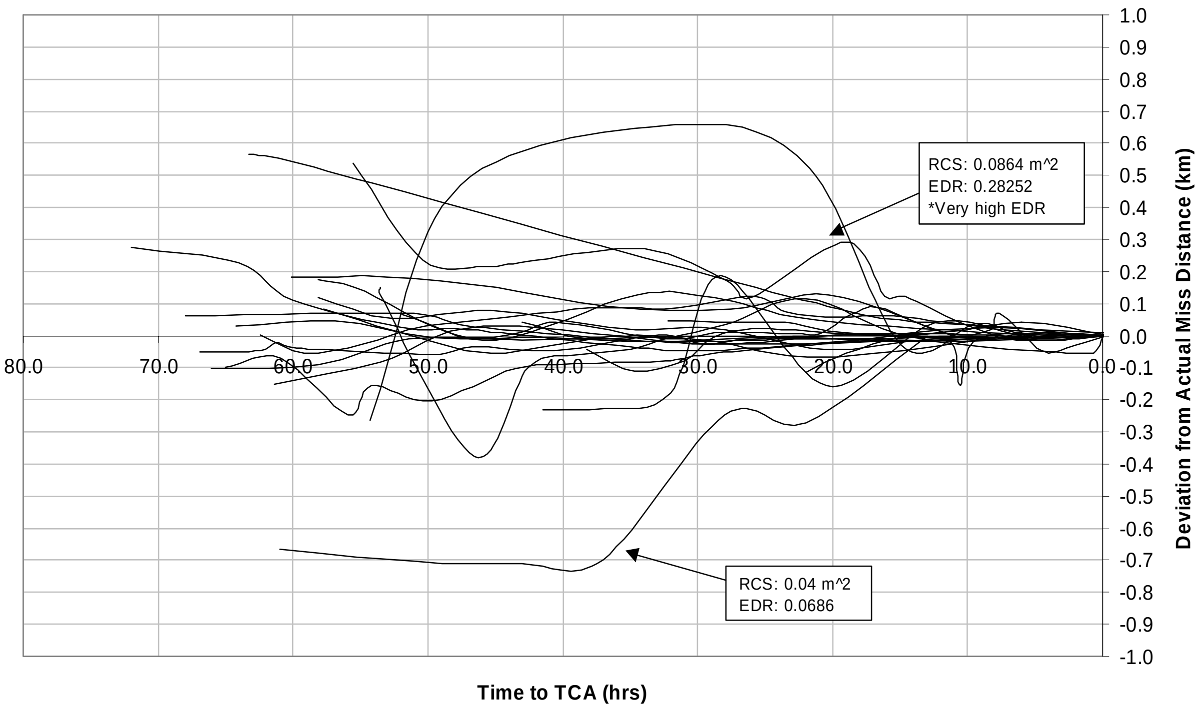


**Figure 2-2. Circular orbit: all conjunctions, radial (U); ±1 km.**

Table 2-1 outlines the time to TCA at which we should expect the projected radial miss distances to remain within a given parameter of the actual miss distance. (i.e., the radial component should not fluctuate more than 50 m when it is within approximately 12 hours to TCA).

**Table 2-1. Projected Radial Miss Distances**

| Deviation | Time to TCA |
|---|---|
| < 25 m | ~ 8 hours |
| < 50 m | ~ 12 hours |
| < 75 m | ~ 15 hours |
| < 100 m | ~ 35 hours |
| < 150 m | ~ 45 hours |
| < 200 m | ~ 55 hours |
| < 300 m | ~ 60 hours |

### 2.2.2 Downtrack

The downtrack (V) component is perhaps the most volatile of the components. The majority of the trends and conclusions drawn in the pages to come are based on an in-depth analysis of the behavior of this component. It was also observed that the behavior of the out-of-plane (W) component is directly proportional to the behavior of the downtrack component. Figure 2-3 clearly illustrates the vast fluctuation that should be expected in the predicted downtrack miss distance.

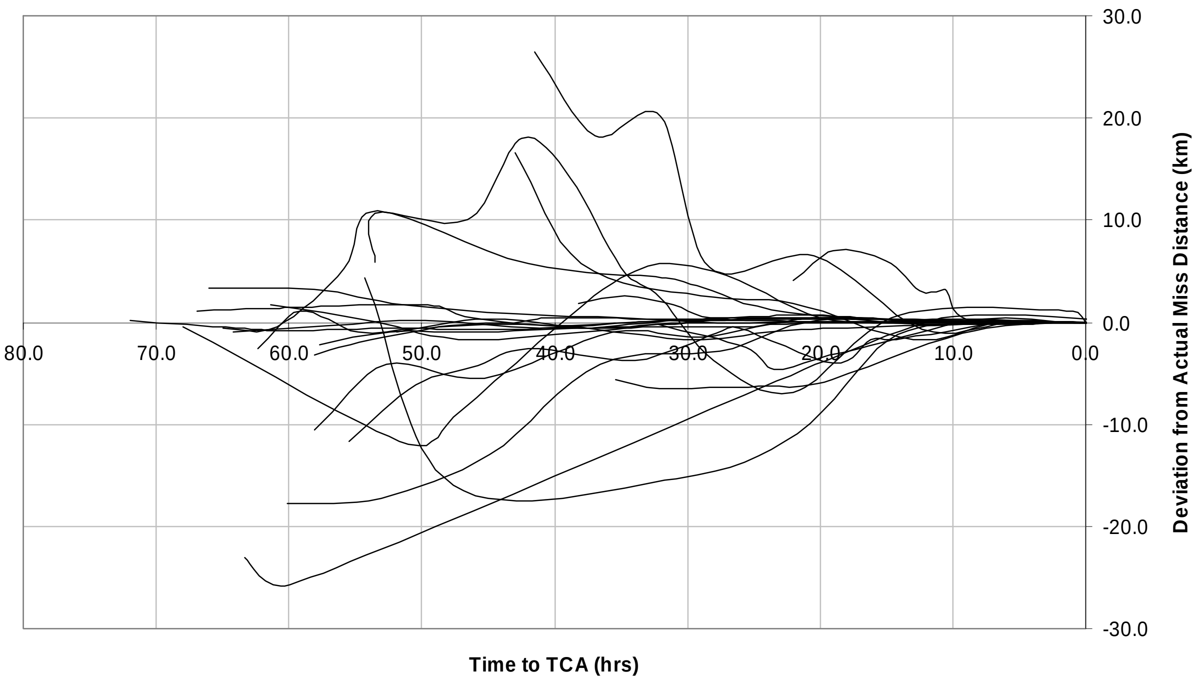


**Figure 2-3. Circular orbit: all conjunctions, downtrack (V).**

#### *2.2.2.1 Group 1 (ΔEDR < 0.02 W/kg)*

For the downtrack component, group 1 represents objects with a ΔEDR < 0.02 W/kg. Figure 2-4 shows the deviation from the actual miss distance for group 1 conjunctions. A number of conclusions can be drawn from this figure. For objects with a ΔEDR < 0.02 W/kg, the downtrack miss distance should remain within 3 km beginning approximately 50 hours prior to TCA. Certain factors, however, can cause objects with a low EDR to diverge from this trend. Most notable among these is the quality of tracking and observations. Poor tracking and inadequate observations are responsible for all four of the objects that are shown to diverge in Figure 2-4.

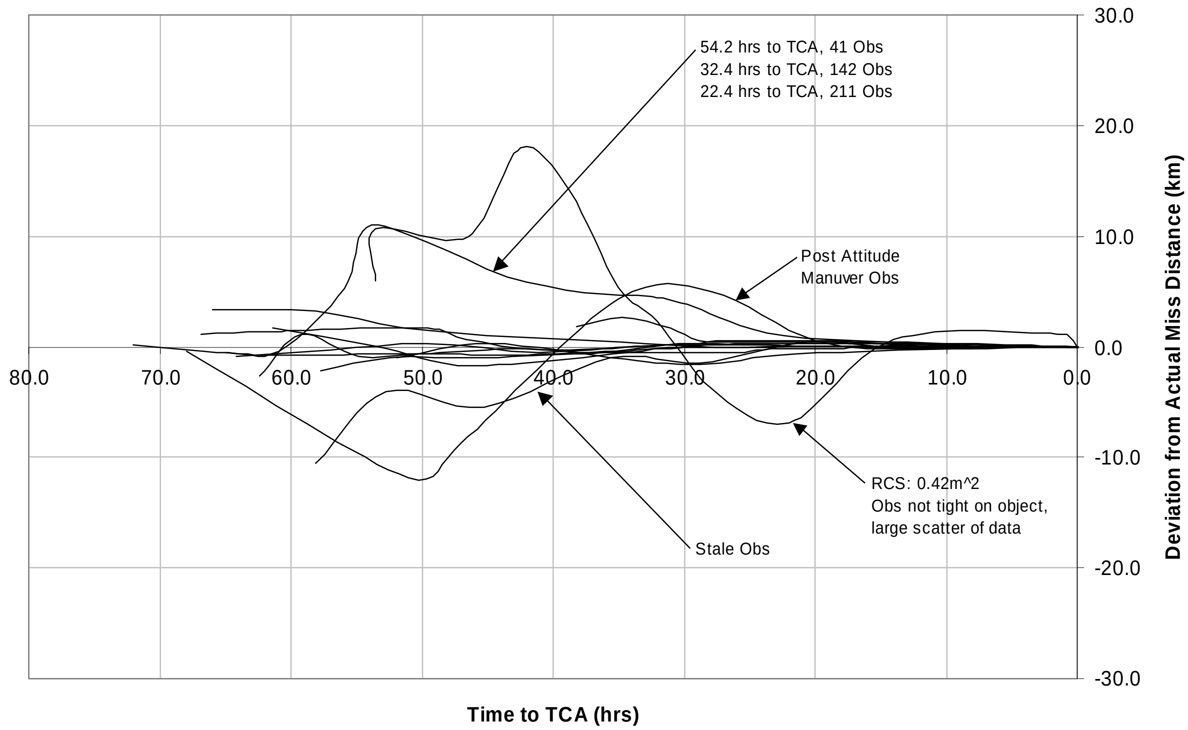


**Figure 2-4. Circular orbit: group 1, downtrack (V).**

Table 2-2 outlines the time to TCA at which the projected downtrack miss distances should remain within a given parameter of the actual miss distance for objects with a ΔEDR < 0.02 W/kg (i.e., the downtrack component should not fluctuate more than 1 km when it is within approximately 37 hours to TCA).

**Table 2-2. Projected Downtrack Miss Distances (ΔEDR < 0.02 W/kg)**

| Deviation | Time to TCA |
|---|---|
| < 500 m | ~ 30 hours |
| < 1 km | ~ 37 hours |
| < 2 km | ~ 48 hours |
| < 3 km | ~ 52 hours |

### *2.2.2.2 Group 2 (ΔEDR > 0.03 W/kg)*

For the downtrack component, group 2 represents those objects with a ΔEDR > 0.03 W/kg. Figure 2-5 shows the deviation from the actual miss distance for group 2 conjunctions and also demonstrates that the behavior of group 2 objects is simply an extension of the conclusions drawn for group 1 objects. The first, and most obvious, conclusion is that objects with a ΔEDR > 0.03 W/kg do not exhibit reliable miss distance projections for the downtrack component until approximately 10 hours prior to TCA. It is shown, however, that, regardless of the high EDR, a large RCS and good tracking can result in accurate predictions. It is important to note that while the two objects singled out in Figure 2-5 have good observations, the quality of these observations is only marginally better than the rest of the group 2 objects. For this reason, objects with high EDRs should be treated with great care—even in situations where good tracking is available.

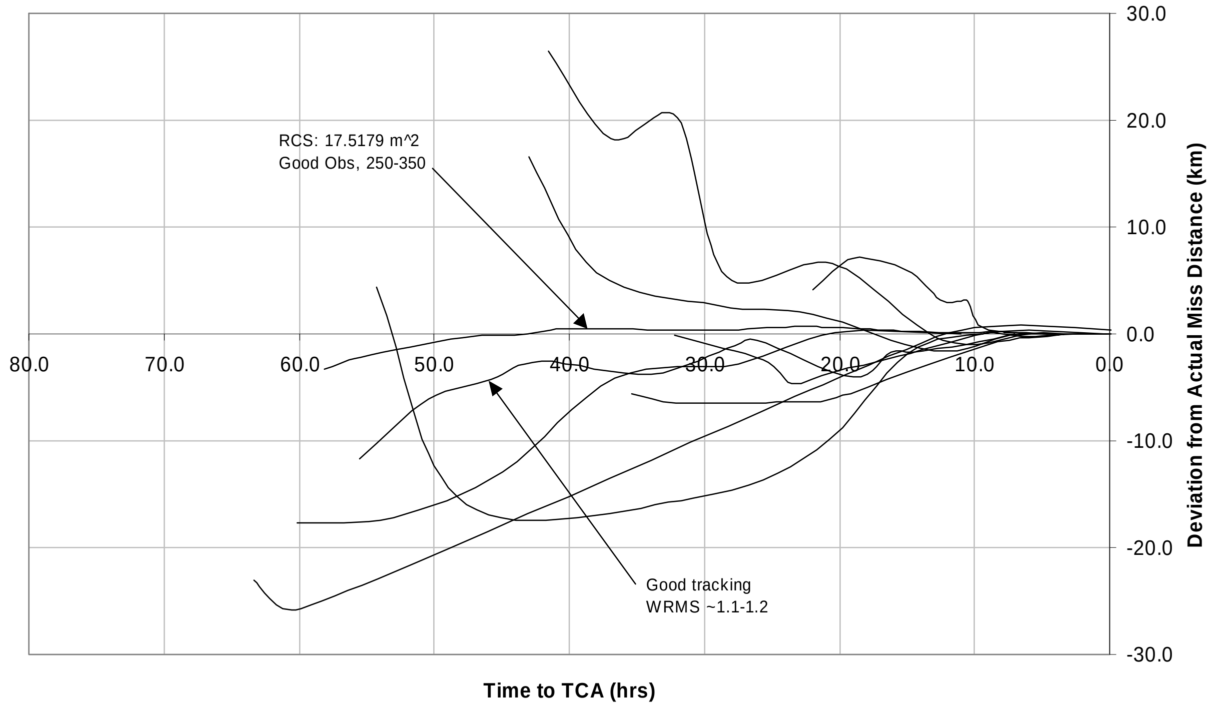


**Figure 2-5. Circular orbit: group 2, downtrack (V).**

Table 2-3 outlines the time to TCA at which the projected downtrack miss distances should remain within a given parameter of the actual miss distance for objects with a ΔEDR > 0.03 W/kg (i.e., the out-of-plane component should not fluctuate more than 1 km when it is within approximately 11 hours to TCA).

**Table 2-3. Projected Downtrack Miss Distances (ΔEDR > 0.03 W/kg)**

| Deviation | Time to TCA |
|---|---|
| < 500 m | ~ 8 hours |
| < 1 km | ~ 11 hours |
| < 5 km | ~ 20 hours |
| < 10 km | ~ 30 hours |
| < 20 km | ~ 50 hours |

### 2.2.3 Out-of-plane

Because the out-of-plane (W) component is directly proportional to the downtrack (V) component, the out-of-plane component tends to follow the same trends outlined for the downtrack component. Figure 2-6 shows the behavior of the out-of-plane component.

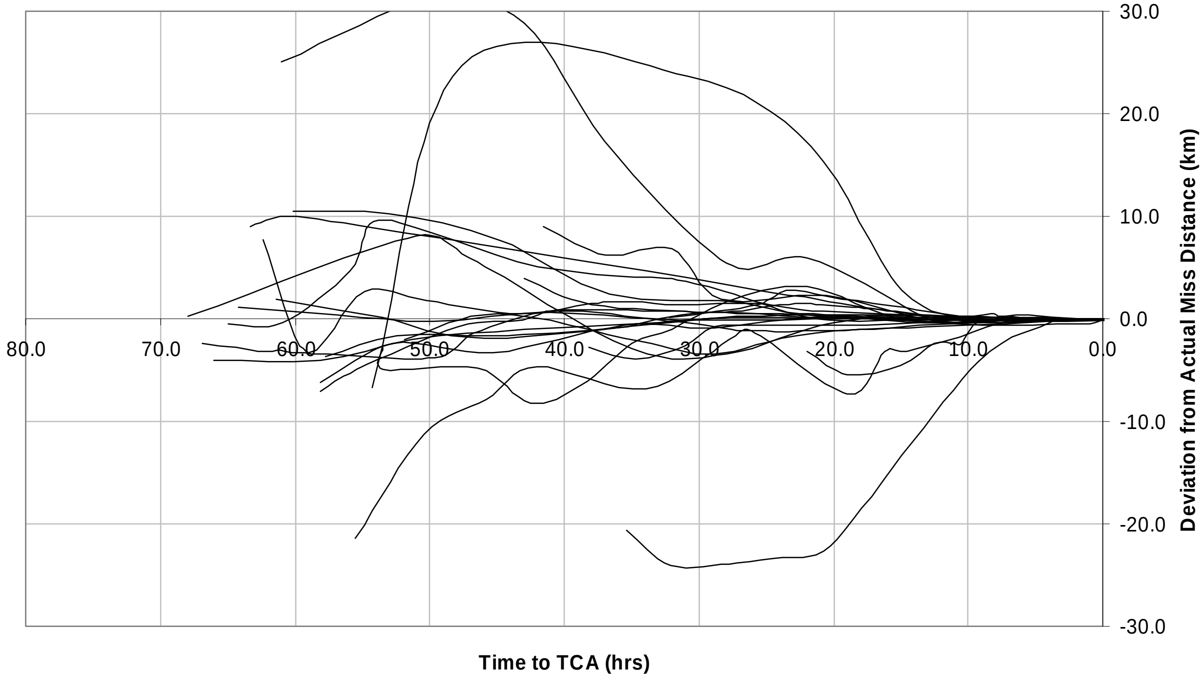


**Figure 2-6. Circular orbit: all conjunctions, out-of-plane (W).**

#### *2.2.3.1 Group 1 (ΔEDR < 0.02 W/kg)*

For the out-of-plane component, group 1 represents objects with an ΔEDR < 0.02 W/kg. Figure 2-7 shows the deviation from the actual miss distance for group 1 conjunctions. This figure clearly shows that the behavior of the out-of-plane component for objects with a ΔEDR < 0.02 W/kg remains quite stable with few outliers.

Comparison with Figure 2-4 (downtrack for the same group of objects) highlights the fact that, while it is the same objects that deviate from the norm, deviation is much less pronounced for the out-of-plane component.

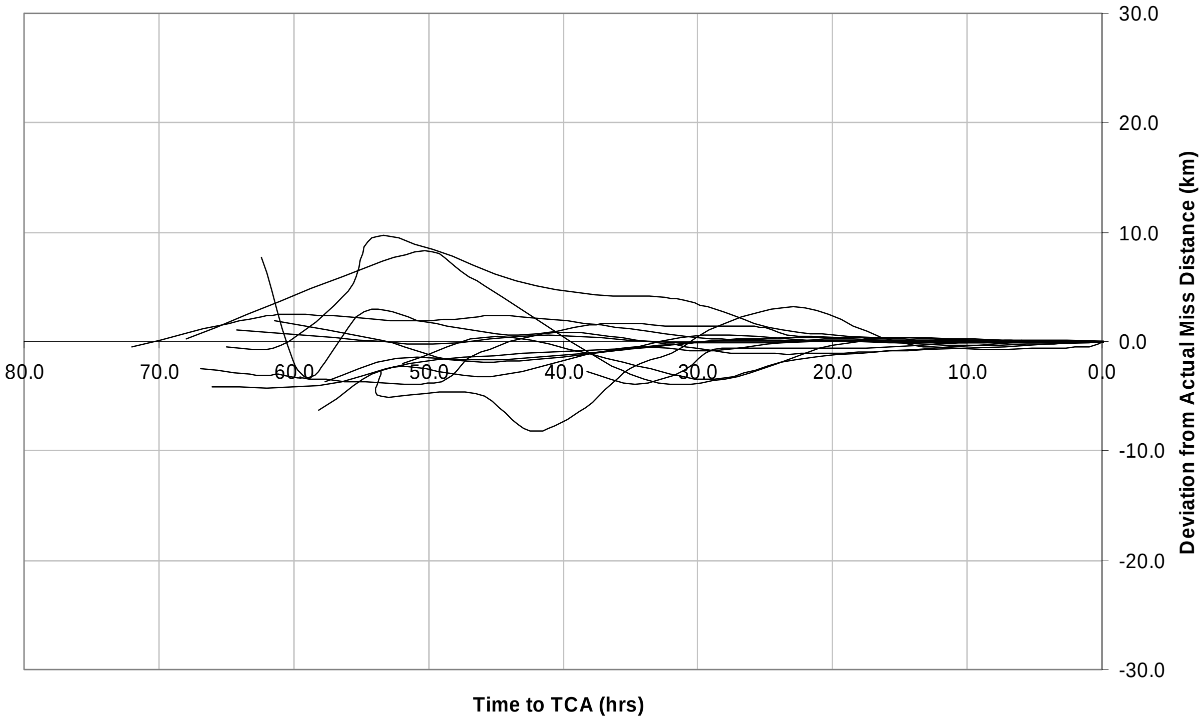


**Figure 2-7. Circular orbit: group 1, out-of-plane (W).**

Table 2-4 outlines the time to TCA at which the projected out-of-plane miss distance should remain within a given parameter of the actual miss distance for objects with a ΔEDR > 0.03 W/kg (i.e., the out-of-plane component should not fluctuate more than 2 km when it is within approximately 30 hours to TCA).

**Table 2-4. Projected Out-of-Plane Miss Distances (ΔEDR > 0.03 W/kg)**

| Deviation | Time to TCA |
|---|---|
| < 500 m | ~ 15 hours |
| < 1 km | ~ 22 hours |
| < 2 km | ~ 30 hours |
| < 3 km | ~ 48 hours |

### *2.2.3.2 Group 2 (ΔEDR > 0.03 W/kg)*

For the out-of-plane component, group 2 represents objects with a ΔEDR > 0.03 W/kg. Figure 2-8 shows the deviation from the actual miss distance for group 2 conjunctions, completing the picture of how miss distance projections behave. Generally, objects with a ΔEDR > 0.03 W/kg tend to display somewhat erratic behavior. It is especially clear that objects with *very* high EDR values (i.e., those that exceed 0.1 W/kg) do not converge to the true value until they are *very* close to TCA.

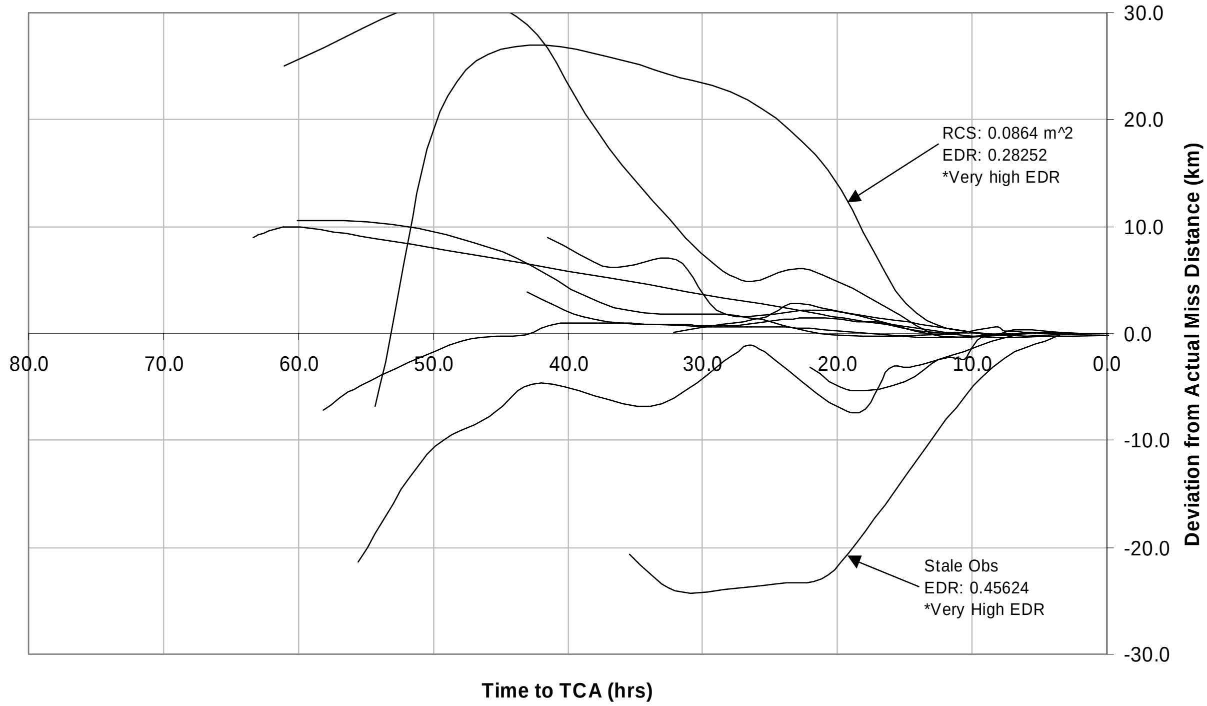


**Figure 2-8. Circular orbit: group 2, out-of-plane (W).**

Table 2-5 outlines the time to TCA at which the projected downtrack miss distances should remain within a given parameter of the actual miss distance for objects with a ΔEDR > 0.03 W/kg. (i.e., the out-of-plane component should not fluctuate more than 5 km when it is within approximately 25 hours to TCA).

**Table 2-5. Projected Downtrack Miss Distances**

| Deviation | Time to TCA |
|---|---|
| < 500 m | ~ 8 hours |
| < 1 km | ~ 11 hours |
| < 5 km | ~ 25 hours |
| < 10 km | ~ 35 hours |
| < 20 km | ~ 50 hours |

## 2.3 Driving Factors and General Trends

The following sections discuss the time to TCA at which miss distance projections tend to stabilize. For purposes of this report, *stabilization* is defined as remaining within 200 m of the finial miss distance for the radial (U) component, and within 1 km of the finial miss distance for the downtrack (V) and out-of-plane (W) components.

### 2.3.1 The driving factors

From what was discovered during the first part of this study, three potential driving factors were chosen for further analysis. These factors were plotted against the time to TCA and the correlation coefficient (r) was determined for body of data. (r = 1 indicated a perfect line, r = 0 indicated no correlation in the data set) The driving factors considered were

1. ΔEDR; r: 0.7123
2. RCS; r: 0.5101
3. Inclination; r: 0.1152

From this analysis, it was determined that EDR was the primary driver while RCS simply pulls the time of data stabilization one way or another. EDR, RCS, and inclination are discussed in detail in Sections 2.3.2, 2.3.3, and 2.3.4, respectively.

### 2.3.2 Energy dissipation rate

#### *2.3.2.1 General trends*

EDR is a value used to determine the rate at which kinetic energy is removed from an object. EDR is the heaviest driver of fluctuation in miss distance. This is primarily because the rapid loss of energy tends to compound errors in propagation. Usually, very high EDR values result in late stabilization of miss distance projections. It is often useful, to look at ΔEDR, or the difference in EDR between the debris and ISS, instead of EDR for just the debris. Figures 2-9 and 2-10 are provided to demonstrate the difference in EDR and ΔEDR. As is clear here, the ΔEDR provides a noticeably “tighter” plot than simply the EDR of the debris alone.

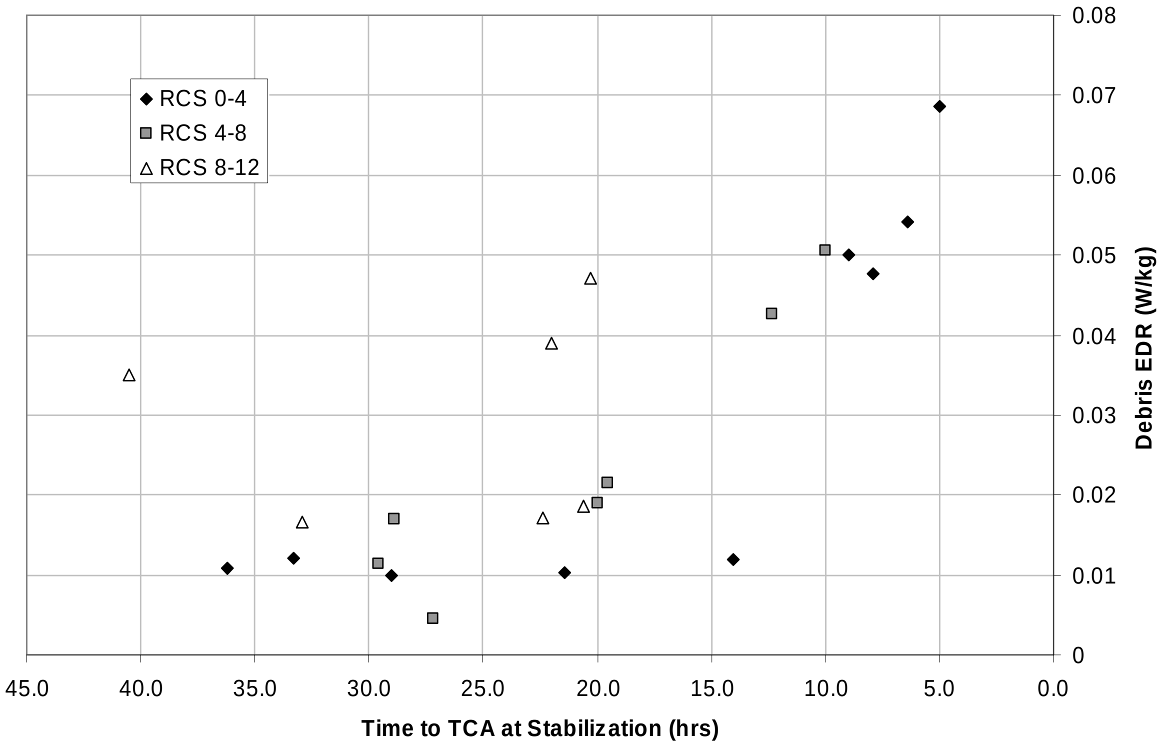


**Figure 2-9. Circular orbit: time to TCA at stabilization vs. debris EDR, downtrack (V).**

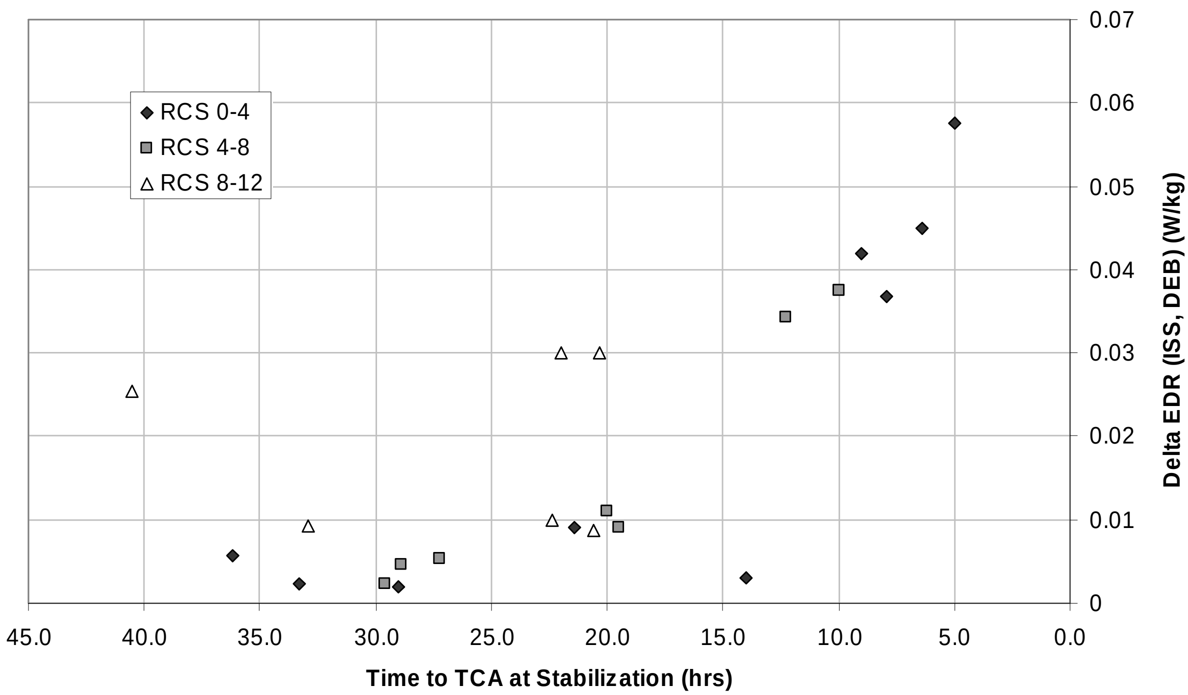


**Figure 2-10. Circular orbit: time to TCA at stabilization vs. ΔEDR, downtrack (V).**

The radial component should remain stable in most cases, staying well within 300 m from the first observation. However, this rule of thumb *cannot* be applied for cases of very high EDR or bad tracking. There are other factors that are not listed that can cause fluctuation out of the 300-m box. Table 2-6 is thus provided as a summery of *general* conclusions that can be drawn from the EDR and ΔEDR scatter plots.

**Table 2-6. Summary of General Conclusions**

| ΔEDR (true debris EDR) W/kg | Comments |
|---|---|
| < ~0.02 (0.03) | Downtrack miss distance should stabilize prior to ~20 hours to TCA |
| < ~0.03 (0.04) | Sizable fluctuations in downtrack miss distance should be expected until within ~10 hours to TCA |

### *2.3.2.2 Regression analysis*

A regression analysis was performed on the ΔEDR scatter plot to assess the type of relationship generally seen between EDR and projection stabilization. Linear, logarithmic, power, and 3rd-order polynomial regressions were tested. The plot appears to be best approximated by the power regression. See Figure 2-11 for a visual representation of the fit.

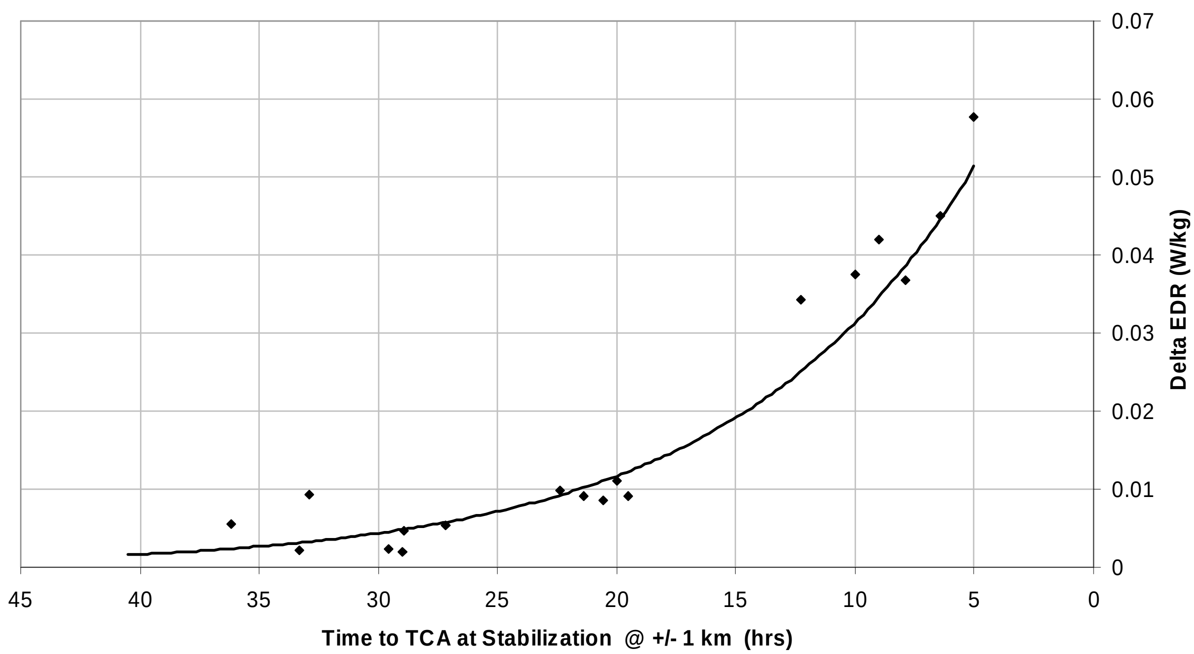


**Figure 2-11. Circular orbit: time to TCA at stabilization vs. ΔEDR, downtrack (V); power regression curve fit with stabilization = ±1 km.**

It should be noted that four outlying data points were removed from the regression calculations to allow for a better fit. Based on the behavior of the data thus far, it appears that the simple equation derived from the regression analysis may be used to provide an *estimate* to the *approximate* time at which the data of the downtrack and out-of-plane components should stabilize. Unfortunately, this equation is not in a form that lends itself to practical application. It is therefore necessary to solve this equation for time as a function of ΔEDR. The simple calculations below lead to a more usable form of the equation, where time, $t$, is in hours and ΔEDR is in W/kg.

$$\Delta EDR = 0.0842e^{-0.0987t}$$

$$\frac{\Delta EDR}{0.0842} = e^{-0.0987t}$$

$$-\ln\left(\frac{0.0842}{\Delta EDR}\right) = 0.0987t$$

$$t = 10.132 \cdot \ln\left(\frac{0.0842}{\Delta EDR}\right)$$

The scatter plot of ΔEDR, with stabilization defined as a deviation of ±1 km, provided such a clean plot that it was decided to observe how this plot changes as the stabilization criteria is moved to 2 km and 3 km. These changes are shown in Figures 2-12 and 2-13, respectively. As the bounds of *stabilization* are increased to 2 km and then to 3 km, the data tend to spread away from the trend line and become uniformly distributed over the time line. For an analysis of this type, it is necessary to have sufficiently small bounds to control the deviation and error in the data points. The distribution in the 2- and 3-km figures show that a ±1-km bound for downtrack was the appropriate choice.

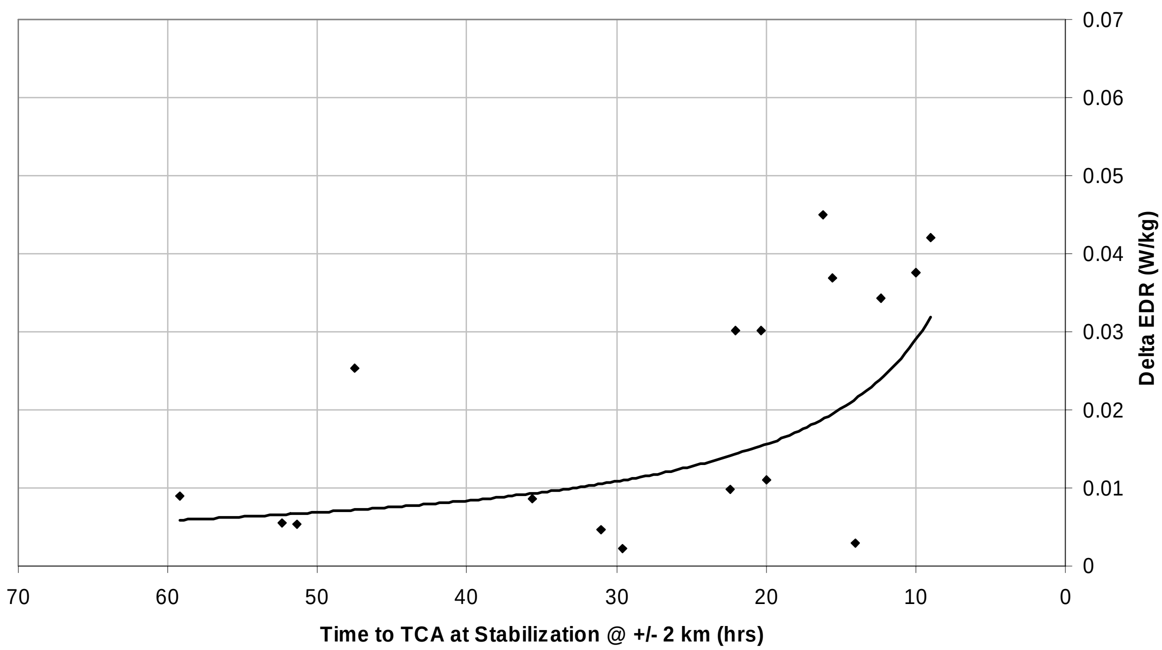


**Figure 2-12. Circular orbit: time to TCA at stabilization vs. ΔEDR, downtrack (V); power regression curve fit with stabilization = ±2 km.**

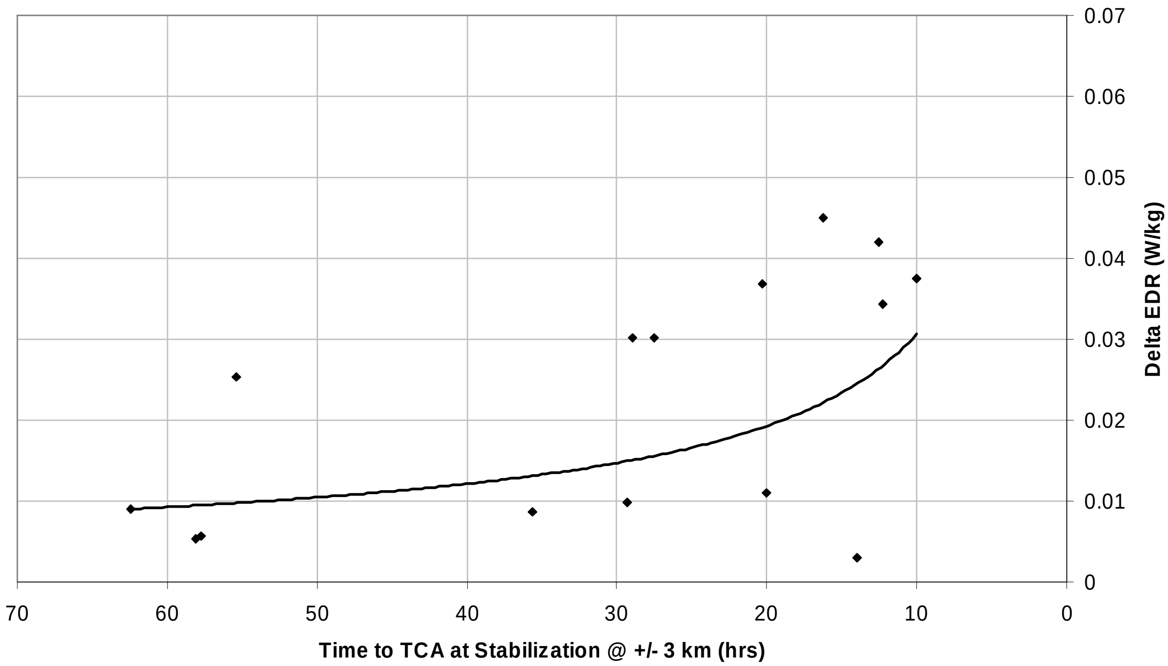


**Figure 2-13. Circular orbit: time to TCA at stabilization vs. ΔEDR, downtrack (V); power regression curve fit with stabilization = ±3 km.**

### 2.3.3 Radar cross section

Despite having units of area ($m^2$), RCS is not the geometric cross section of an object. It is, however, a measure of how much energy is returned by the object to the sensor. While it is true that larger objects generally return a larger RCS than smaller objects, the RCS term also represents the reflectivity and directivity of the object. The RCS influences fluctuation in miss distance projections primarily because it affects USSPACECOM's ability to acquire good observations on the object. Figure 2-14 highlights the fact that RCS simply "pulls" the time to TCA at stabilization one way or the other.

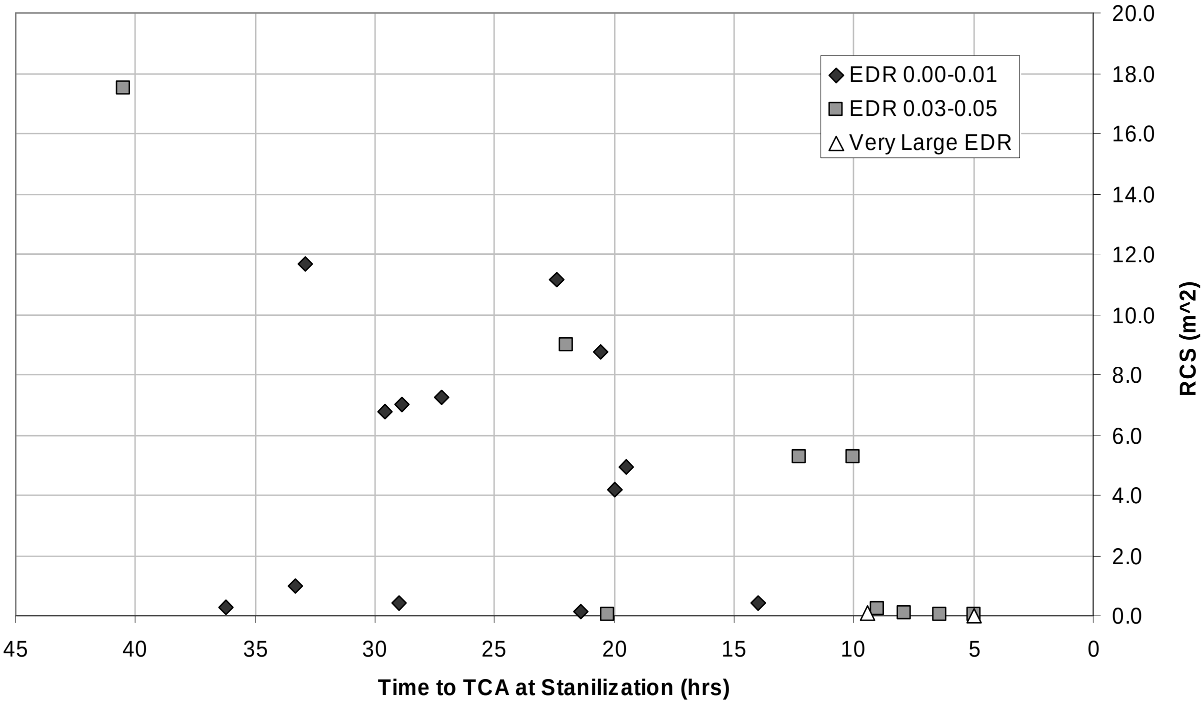


**Figure 2-14. Circular orbit: time to TCA at stabilization vs. RCS, downtrack (V).**

Objects with a small RCS are seen to exhibit data stabilization ranging from approximately 5 hours to TCA to approximately 38 hours to TCA. While a vague trend can be seen in this figure, it is clear that objects with a large EDR tend to form the top half of the line while objects with a small EDR tend to form the bottom half of the line. Simply stated, the effects of EDR are seen to outweigh the effects of RCS. These conclusions are summarized in Table 2-7.

**Table 2-7. Effects of Radar Cross Section**

| RCS $m^2$ | Comments |
|---|---|
| < 1.0 $m^2$ | Tend to stabilize within ~15 hours of TCA; however, EDR remains the primary drive. A number of objects with a low RCS stabilize prior to 20 hours to TCA; this is due to very low ΔEDR |
| > 10 $m^2$ | Tend to stabilize early, usually prior to 20 hours to TCA. |

### 2.3.4 Inclination

Little correlation between inclination and projected miss distance fluctuation can be seen from the available data. However, it is believed that certain inclinations (specifically very high inclinations) may cause difficulty in acquiring good observations on an object. Poor observations, as mentioned earlier, will likely result in miss distance projections stabilizing close to TCA (Figure 2-15).

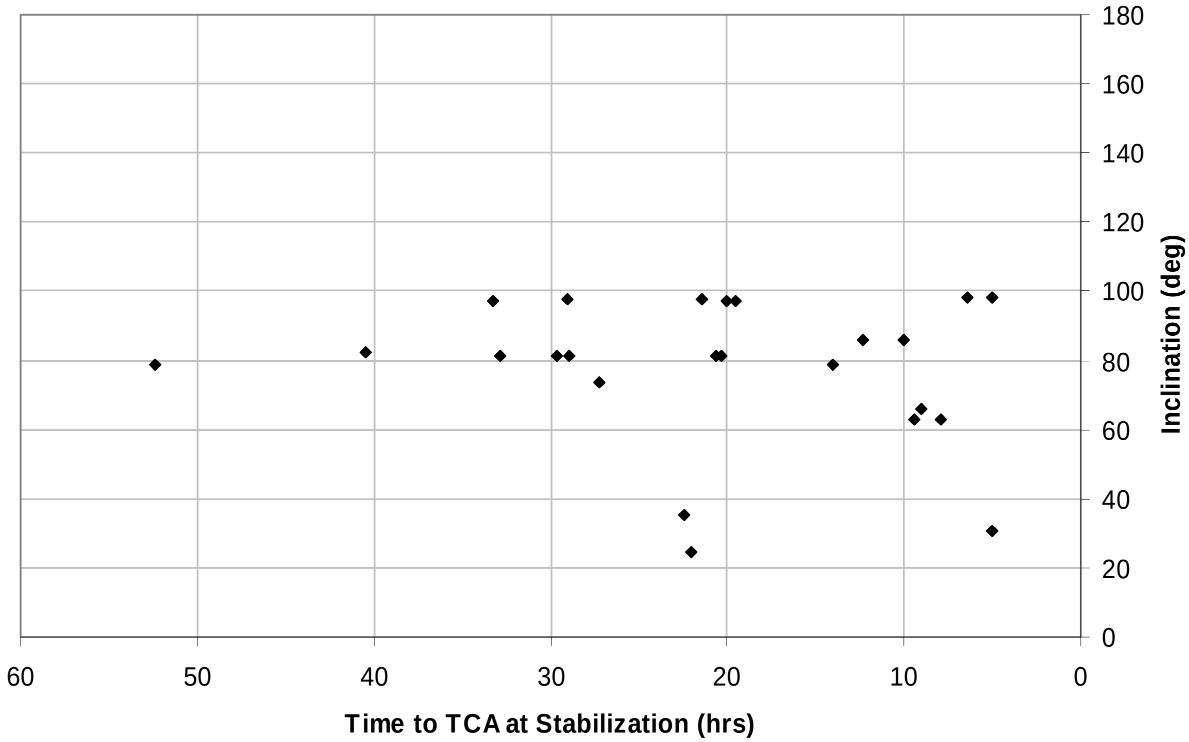


**Figure 2-15. Circular orbit: time to TCA at stabilization vs. inclination; downtrack (V).**

# 3 Mid- and High-Eccentricity Orbit Analysis

The information presented and discussed in this section pertains only to objects that fall within the mid- and high-eccentricity orbit category. A number of analyses were conducted to determine what drives the behavior of the data provided by USSPACECOM for these particular orbit classifications. The following is a summery of those analyses.

## 3.1 The Data Set

A total of 21 conjunctions that exhibit "mid-eccentricity orbits" were identified. Of these, 13 (62%) were applicable for this analysis. The remaining eight conjunctions were not used because of missing data or a lack of data points. About half (54%) of the conjunctions have their first notification between 48 and 72 hours prior to TCA, with an average of 62.8 hours prior to TCA. The remaining conjunctions had their first notification within 48 hours to TCA, with an average first notification at 37.8 hours to TCA. Conjunctions were selected for the mid-eccentricity orbit category if they demonstrated a difference in apogee and perigee between 250 and 7500 km (250 km < Ha-Hp < 7500 km; average Ha-Hp: 1547.3 km; Ha-Hp standard deviation: 885.7 km). The debris with a "mid-eccentricity orbit" showed an average apogee of 1919.2 km and an average perigee of 371.9 km.

A total of seven conjunctions that exhibit "high-eccentricity orbits" were also found. Of these, four (57%) were applicable for this analysis. The remaining three conjunctions were not used because of missing data or a lack of data points. Conjunctions were selected for the high-eccentricity orbit category if they demonstrated a difference in apogee and perigee greater than 7500 km (Ha-Hp > 7500 km; average

Ha-Hp: 18397.8 km; Ha-Hp standard deviation: 11571.9 km). The debris with a high-eccentricity orbit showed an average apogee of 18682.3 km and an average perigee of 284.5 km.

It is important to note the small size of the data pool used for these analyses. The lack of data (especially for the high-eccentricity orbit) prohibits the analyses from yielding substantial results. Nonetheless, the findings are presented in a clear and concise format to outline the known behavior of conjunctions with debris in mid- and high-eccentricity orbits.

## 3.2 Deviation from Actual Miss Distance

Unlike circular orbit analysis, the mid- and high-eccentricity orbit conjunctions were not separated into two groups based on EDR. This is primarily because there were not enough conjunctions to justify a split.

As in the circular orbit analysis, the corresponding sections contain figures illustrating the deviation of the projected miss distance from the actual miss distance compared to time to TCA. For easy comparison, the standards used in Section 2.2 remain unchanged below. Data in this section are provided solely for purposes of comparison with debris that exhibit circular orbits. There is not enough data for the mid- or high-eccentricity orbit categories to draw any conclusions.

### 3.2.1 Mid-eccentricity orbit

A mid-eccentricity orbit can cause important changes in the projected miss distances, especially for the radial component. Figure 3-1 shows the fluctuation in miss distance projections for the radial component. It is clear that the radial component has the potential to be much less stable for mid-eccentricity orbits than for circular orbits.

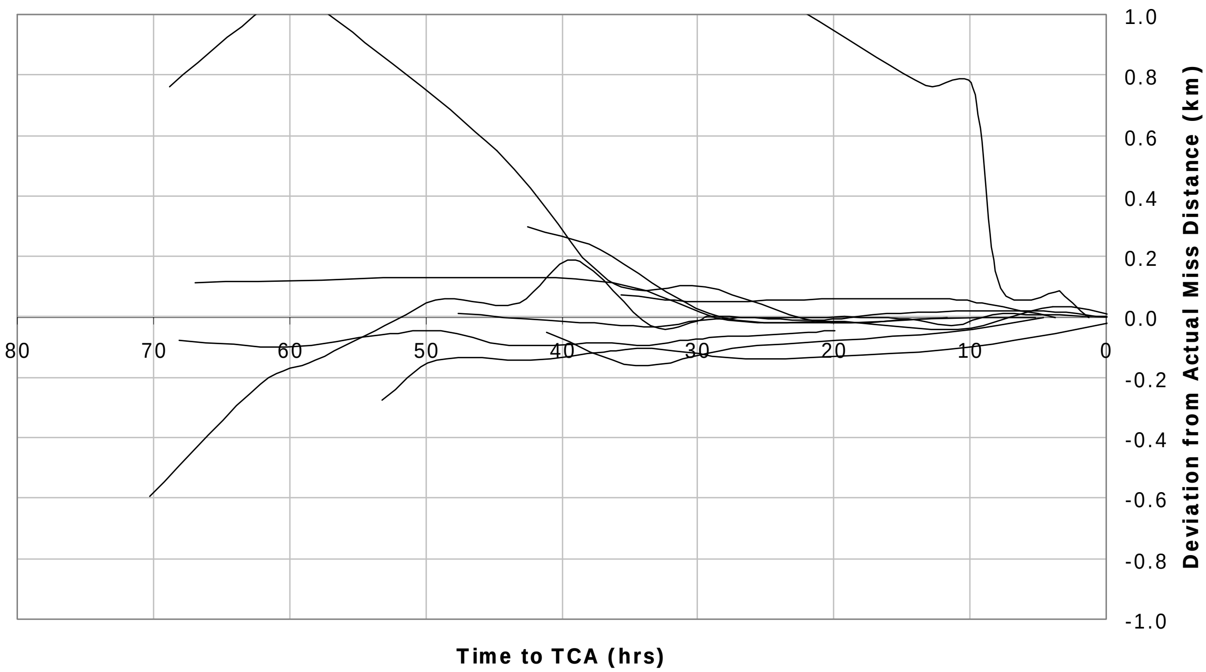


**Figure 3-1. Mid-eccentricity orbit: all conjunctions, radial (U).**

Figures 3-2 and 3-3 shows the data gathered for the downtrack and out-of-plane components. From these data it appears that the same general trends observed in the circular orbit category apply to mid-eccentricity orbits but simply on a different time scale. When viewing the figures below, it is important to remember that with only 13 conjunctions few conclusions can be drawn. It is recommended that this category of orbits be reevaluated when more data become available.

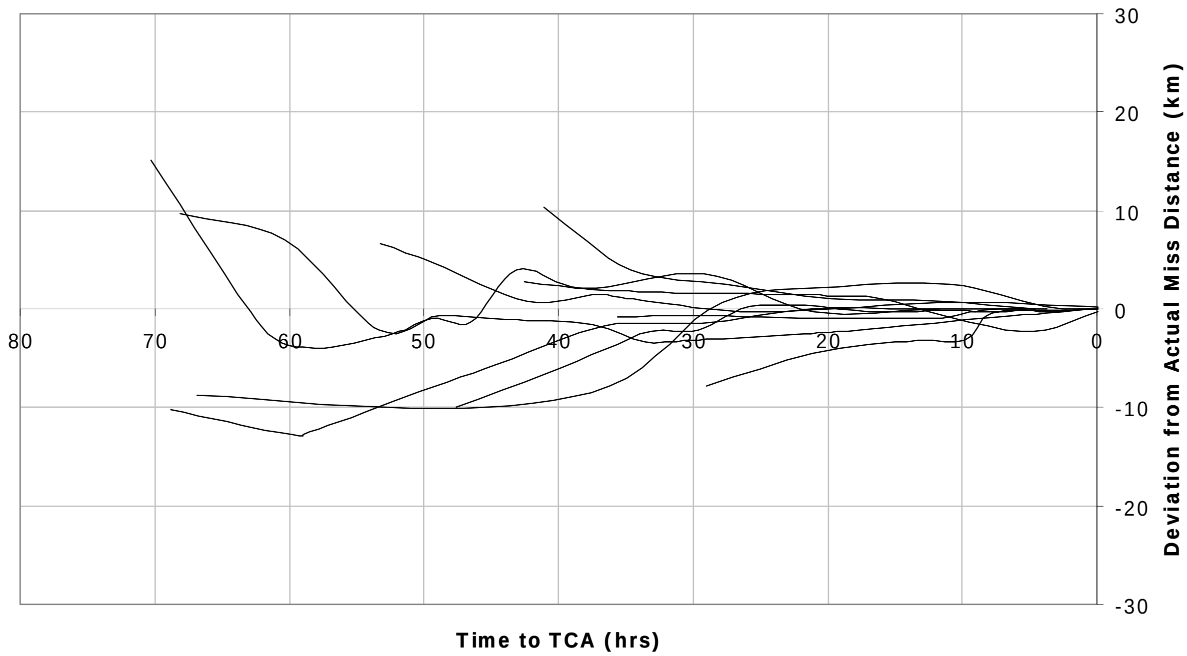


**Figure 3-2. Mid-eccentricity orbit: all conjunctions, downtrack (V).**

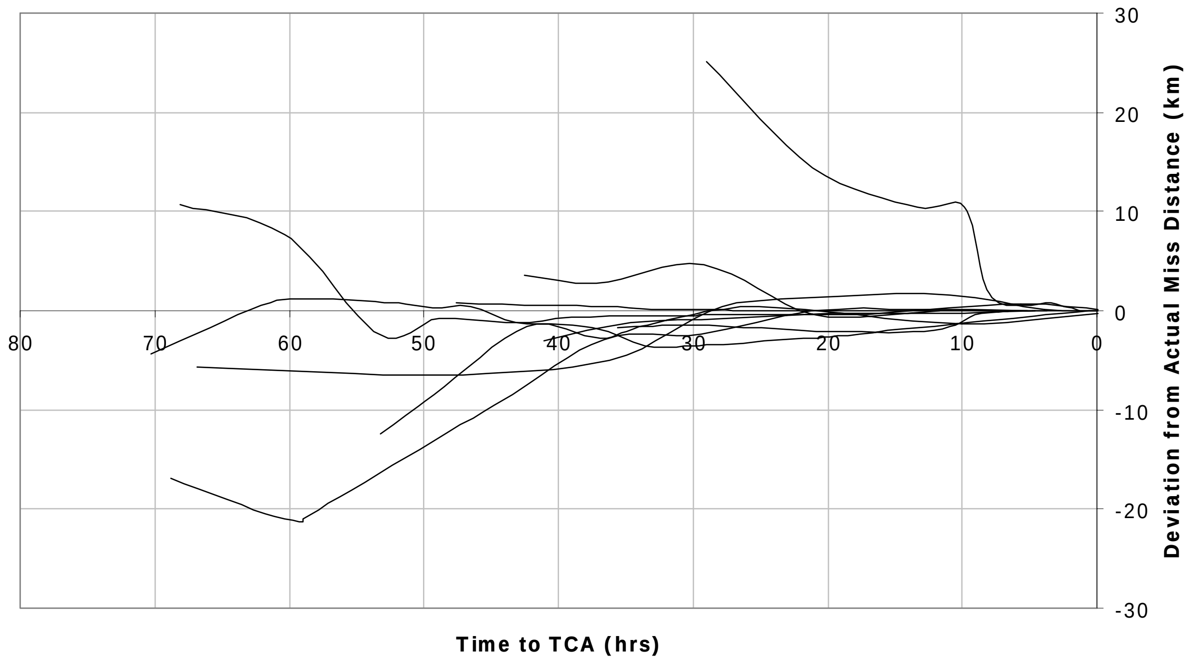


**Figure 3-3. Mid-eccentricity orbit: all conjunctions, out-of-plane (W).**

### 3.2.2 High-eccentricity orbit

With only five usable conjunctions, few conclusions can be drawn from the high-eccentricity orbit category. Figures 3-4, 3-5, and 3-6 show the miss distance deviation for the radial, downtrack, and out-of-plane components, respectively. Once again, the radial component is much more stable than downtrack and out-of-plane components. One surprising observation is the extreme stability of the out-of-plane component, as seen in Figure 3-6. It is recommended that this category of orbits be reevaluated when more data become available.

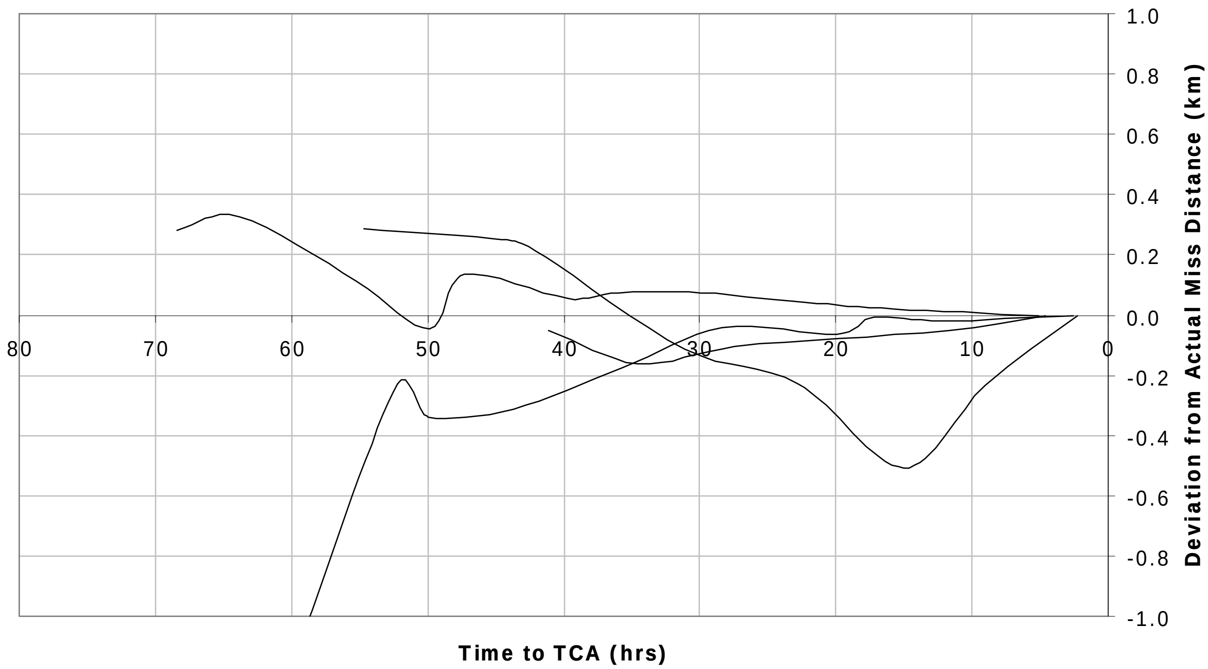


**Figure 3-4. High-eccentricity orbit: all conjunctions, radial (U).**

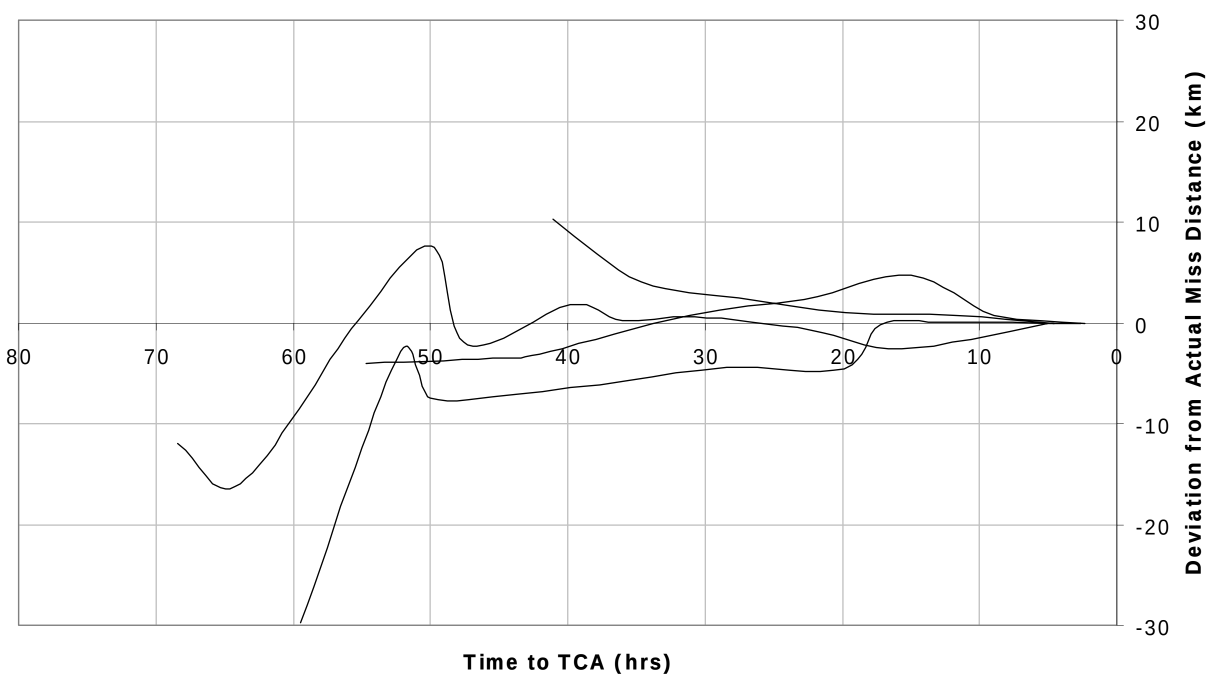


**Figure 3-5. High-eccentricity orbit: all conjunctions, downtrack (V).**

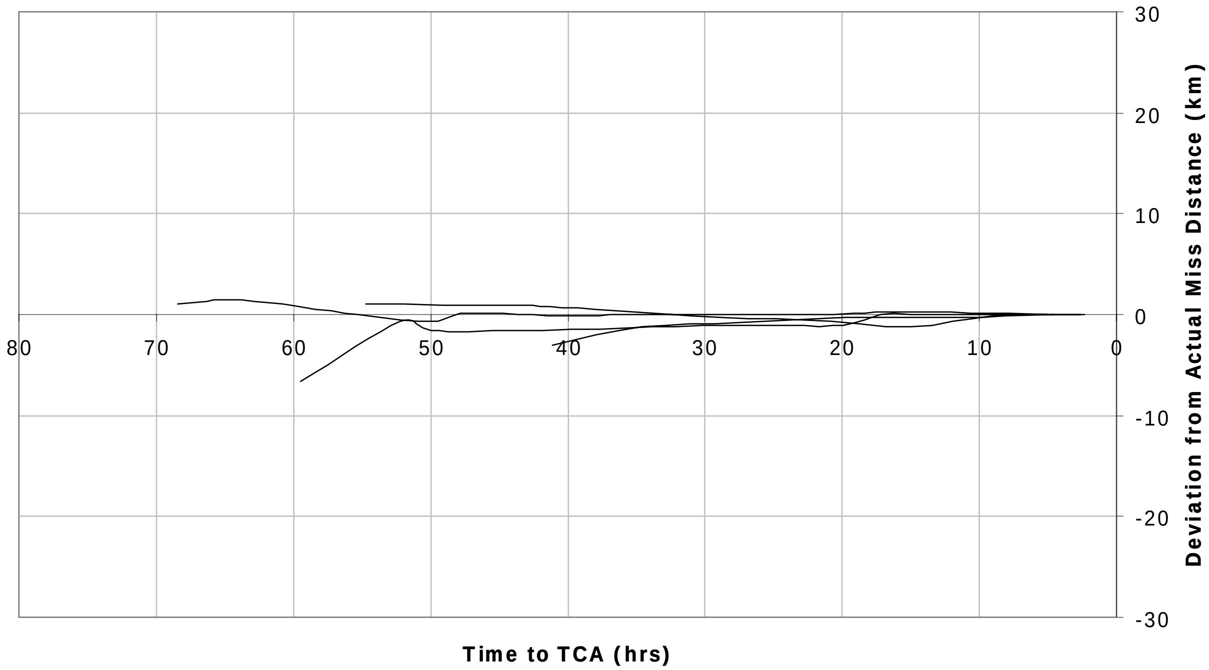


**Figure 3-6. High-eccentricity orbit: all conjunctions, out-of-plane (W).**

# 4 Conclusions and Recommendations

In conclusion, it was determined that although the primary driver of projected miss distance data behavior is EDR, RCS is also a key driver—especially RCS values that cause difficulty in obtaining quality observations on an object. In Section 2.2, deviations from the actual miss distance were broken into incremental steps and their associated time frames were established. These values are duplicated below in Tables 4-1, 4-2, and 4-3 in a more concise format for ease of use.

**Table 4-1. Radial**

| Deviation | Radial |
|---|---|
| 25 m | ~8 hours |
| 50 m | ~12 hours |
| 75 m | ~15 hours |
| 100 m | ~35 hours |
| 150 m | ~45 hours |
| 200 m | ~55 hours |
| 300 m | ~60 hours |

**Table 4-2. Group 1 ($\Delta$EDR < 0.02)**

| Deviation | Downtrack | Out of Plane |
|---|---|---|
| 500 m | ~30 hours | ~15 hours |
| 1 km | ~37 hours | ~22 hours |
| 2 km | ~48 hours | ~30 hours |
| 3 km | ~52 hours | ~48 hours |

**Table 4-3. Group 2 ($\Delta$EDR > 0.03)**

| Deviation | Downtrack | Out of Plane |
|---|---|---|
| 500 m | ~8 hours | ~8 hours |
| 1 km | ~11 hours | ~11 hours |
| 5 km | ~20 hours | ~25 hours |
| 10 km | ~30 hours | ~35 hours |
| 20 km | ~50 hours | ~50 hours |

It was also determined that the primary driver of data stabilization is ΔEDR. This value is so heavily weighted that the time to TCA at which the data should stabilize can often be approximated using solely the ΔEDR. This relationship is shown in the equation below:

$$t = 10.132 \cdot \ln\left(\frac{0.0842}{\Delta EDR}\right)$$

It is recommended that the findings of this report be used as a supplement to already existing means to determine the level of threat a piece of debris exhibits to the ISS.

While this study indicates certain distinctive trends, the data sets for all three orbit categories remain relatively small. It is therefore recommended, for a more complete picture, to maintain an easily accessible database of the required data and reassess the findings of this study with a larger data set. It is important to continue to refine and enhance our understanding of these data.

# 5 References and Acknowledgments

## 5.1 Acknowledgments

The author greatly appreciates the contributions of Keith W. Carley, Lark Howorth, Xuan-Trang Le, and Scott D. Paul in the development of this report.

## 5.2 References

"Orbital Debris Overview." Orbital Debris 21108. NASA Johnson Space Center. Houston, TX. August 1997.

Carley, Keith W, Cooney, James S, Howorth, William L. "USSPACECOM Trip Report." NASA Johnson Space Center. Houston, TX. September 1999.

# Appendix A

**Circular**

| Object # | Log Sheet File Name |
|---|---|
| 4625 | LOG_001113_s1_jsc_Obj_4625_0537 |
| 4726 | LOG_010514_s1_jsc_Obj_4726_0443 |
| 5143 | LOG_000927_s1_bmc_Obj5143 |
| 5328 | LOG_010526_s1_fma_Obj_5328 |
| 5761 | Conj_990831_obj05671 |
| 8577 | LOG_001019_s3_was_Obj_8577 |
| 11056 | LOG_010906_s1_sdp_Obj_11056 |
| 11252 | LOG_001227_s1_nk_Obj_11252 |
| 11268 | LOG_000509_s1_kwc_Obj_11268 |
| 11269 | LOG_010903_s1_fma_Obj_11269 |
| 16084 | Conj_990922_obj16084 |
| 16085 | LOG_011030_s2_fma_Obj_16085 |
| 19764 | LOG_010527_s1_fma_Obj_19764_0813 |
| 20919 | Conj_000127_0513_obj20919 |
| 22822 | Conj_991214_obj22822 |
| 23019 | LOG_001102_s2_was_23019 |
| 24657 | LOG_010615_s1_kwc_Obj_24657 |
| 24745 | LOG_000903_s1_sdp_obj_24745 |
| 25031 | LOG_000603_s1_jsc_Obj_25031 |
| 25387 | LOG_010117_s1_kwc_Obj_25387_1533 |
| 25389 | LOG_010306_s1_was_Object_25389 |
| 25390 | Conj_000113_obj25390 |
| 25470A | LOG_000925_s1_was_Obj_25470A |
| 25470B | LOG_001003_s1_bmc_Obj_25470B |

**Mid-eccentricity**

| Object # | Log Sheet File Name |
|---|---|
| 2208 | LOG_000606_s1_kwc_Obj_2208 |
| 4221 | LOG_001208_s1_bmc_Obj_4221_0444 |
| 5729 | LOG_010509_s0_jsc_Obj_5729_0546 |
| 7337 | LOG_011030_s1_was_Obj_7337_1737 |
| 10269 | Conj_991021_Obj10269 |
| 12138 | LOG_010819_s1_bmc_Obj_12138_0210 |
| 12388 | LOG_011021_s1_bmc_Obj_12388 |
| 14484 | LOG_001130_s2_kwc_Obj_14484_1027 |
| 20101 | LOG_010906_s1_sdp_Obj_20101 |
| 20775 | LOG_011116_s1_kwc_revA_Obj_20775 |
| 23198 | Conj_991213_obj23198 |
| 23281 | LOG_000218_s1_sdp_Obj_23281 |
| 23853 | LOG_010825_s1_wlh_Obj_23853_1753 |

**High-eccentricity**

| Object # | Log Sheet File Name |
|---|---|
| 14484 | Conj_991009_obj14484 |
| 15996 | Conj_991009_obj15996 |
| 20411 | LOG_010626_s1_wlh_Obj_20411_0407 |
| 22448 | LOG_000503_s1_wlh_Obj_22448 |
| 88231 | LOG_000927_s1_bmc_Obj_88231 |

| **REPORT DOCUMENTATION PAGE** | Form Approved<br>OMB No. 0704-0188 |
|---|---|



| 1. AGENCY USE ONLY *(Leave Blank)* | 2. REPORT DATE<br>July 2005 | 3. REPORT TYPE AND DATES COVERED<br>NASA Technical Paper |
|---|---|---|

| 4. TITLE AND SUBTITLE<br>Fluctuations in Conjunction Miss Distance Projections as Time Approaches Time of Closest Approach | 5. FUNDING NUMBERS |
|---|---|
| 6. AUTHOR(S)<br>John A. Christian III | |
| 7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)<br>NASA-Lyndon B. Johnson Space Center | 8. PERFORMING ORGANIZATION REPORT NUMBERS<br>S-953 |
| 9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)<br>National Aeronautics and Space Administration<br>Washington, DC 20546-0001 | 10. SPONSORING/MONITORING AGENCY REPORT NUMBER<br>TP-2005-213159 |
| 11. SUPPLEMENTARY NOTES | |
| 12a. DISTRIBUTION/AVAILABILITY STATEMENT<br>Unclassified/Unlimited<br>Available from the NASA Center for AeroSpace Information (CASI)<br>7121 Standard<br>Hanover, MD 21076-1320 Category: 88 | 12b. DISTRIBUTION CODE |

13. ABSTRACT *(Maximum 200 words)*

A responsibility of the Trajectory Operations Officer is to ensure that the International Space Station (ISS) avoids colliding with debris. United States Space Command (USSPACECOM) tracks and catalogs a portion of the debris in Earth orbit, but only objects with a perigee less than 600 km and a radar cross section (RCS) greater than 10 cm—objects that, in fact, represent only a small fraction of the objects in Earth orbit. To accommodate for this, the ISS uses shielding to protect against collisions with smaller objects. This study provides a better understanding of how quickly, and to what degree, USSPACECOM projections tend to converge to the final, true miss distance. The information included is formulated to better predict the behavior of miss distance data during real-time operations. It was determined that the driving components, in order of impact on miss distance fluctuations, are energy dissipation rate (EDR), RCS, and inclination. Data used in this analysis, calculations made, and conclusions drawn are stored in Microsoft Excel log sheets. A separate log sheet, created for each conjunction, contains information such as predicted miss distances, apogee and perigee of debris orbit, EDR, RCS, inclination, tracks and observations, statistical data, and other evaluation/orbital parameters.

| 14. SUBJECT TERMS<br>space debris; miss distance; predictions; forecasting; energy dissipation; shielding; collision avoidance; radar cross sections; inclination, orbits; circular orbits | 15. NUMBER OF PAGES<br>36 | 16. PRICE CODE |
|---|---|---|

| 17. SECURITY CLASSIFICATION OF REPORT | 18. SECURITY CLASSIFICATION OF THIS PAGE | 19. SECURITY CLASSIFICATION OF ABSTRACT | 20. LIMITATION OF ABSTRACT |
|---|---|---|---|
| Unclassified | Unclassified | Unlimited | Unlimited |