UNCERTAINTY ASSESSMENT FOR THE BREAKUP OF SATELLITES DUE TO HYPERVELOCITY IMPACTS

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Abstract

The breakup of a spacecraft or its components due to hypervelocity impact is a very chaotic event. Given the best of conditions, no two breakups will be exactly the same. This uncertainty in the physical processes spills over into attempts to develop computer models to do breakup analysis and future debris environment forecasting. Because of this uncertainty, even the "best" breakup models for hypervelocity impacts of spacecraft components have a large level of uncertainty. Exactly what that uncertainty is remains an unknown. This paper analyzes how statistical information (if available) can be incorporated into debris environment projections.

1 INTRODUCTION

Space agencies and governments throughout the world are making decisions about future space operations and how to deal with the issue of space debris. Computer models that predict the growth of the space debris environment use very limited breakup data to predict how a spacecraft will break up. Due to that shortfall, there have been no error bars associated with the growth of this debris population. In computer programs such as EVOLVE [1], IDES [2] and MASTER [3], among others, the future debris environment is predicted using empirical models based on very limited test data. If a modeler were to be able to know with some uncertainty how a spacecraft will break up, they would be better able to model the uncertainty in the growth of the debris environment due to orbital breakups.

This paper presents the methodology one may take to build statistical information into future debris environmental projections. It also introduces an error propagation approach that can be used in conjunction with any orbital debris environmental projection model to accommodate uncertainty associated with the number of pieces produced in a hypervelocity impact.

2 BACKGROUND

Many natural and man-made events in every day life are subject to forecast errors. Statistical forecasting has long been a preferred method for analysis of data sets activity, number of people living in a city in 20 years, or the number of fragments produced by a breakup in space are all subject to errors due to variations in the assumptions, model validity, or unpredicted random events. This section discusses how forecast errors can influence the results of complex predictions, and draws parallels between results from financial data and census forecasting, and orbital debris population predictions.

2.1 Fragmentation Event Variation

What we know about the behavior of complex bodies (like satellites) when they are fragmented due to hypervelocity is very sparse. Limited ground hypervelocity tests have been conducted but not in a methodical way to glean information about the variation of the behavior of objects as they breakup. Similarly, explosion tests have been conducted. The emphasis of these tests has tended to be focused on the lethality issues rather than a study of the breakup characteristics.

Bess [4] is the foundation of many of the spacecraft breakup models used today. He developed empirical formulas for both low- and high-intensity explosions, as well as hypervelocity collisions. Su and Kessler [5] used Bess' empirical model for estimating the number of fragments produced by explosions of space objects. The formula used to determine the number of pieces from an explosion is presented in Eq. (1) as:

$$N = \begin{cases} 1.71\text{x}10^{-4}\, M_t \exp\left(-0.02056 M^{1/2}\right), \text{for } M > 1936\text{g} \\ 8.69\text{x}10^{-4}\, M_t \exp\left(-0.05756 M^{1/2}\right), \text{for } M < 1936\text{g} \end{cases} \tag{1}$$

Here, N is the cumulative number of fragments with mass greater than M measured in grams (M_t is the total mass of the pre-explosion object in grams). Likewise, Su and Kessler derived an empirical formula for the cumulative number of pieces versus size, as:

$$N = 0.4478\left(\frac{M}{M_e}\right)^{-0.7496} \tag{2}$$

Although these equations are based on analysis of experimental data, there is no information about the statistical uncertainty of the results.

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Brechin and McKnight [6] analyzed data from eight different hypervelocity tests. Each test had different combinations of structure type, target and projectile mass, and projectile speed. Here, there is no statistical data between tests is presented, only the chi-square goodness-of-fit between the results of these tests and previously published work by Bess and Su and Kessler.

2.2 Error Modeling in Financial Data Forecasting

Another relatively new use for statistical modeling and forecasting methods is financial data prediction. From day to day, financial analysts examine forecasts for such economic factors as interest rates, exchange rates and stock value. They then use these forecasts to make decisions regarding substantial sums of money. Other uses for econometric forecasting are applicable to more of a long-term set of predictions, namely trading volume and overall market value. These more extended applications often include a historical dataset with a more robust collection of information.

Predictions in the financial world are driven by many outside influences and are thusly functions of another indicator or indicators. Financial forecasters and anyone else who is interested in developing a forecasting model that is “better than the rest” have created an extensive set of models that are essentially the same, but for which the differences play a key role. This often leads to numerous projections with a wide range of solutions from data that is essentially the same.

Econometric forecasting is different from natural forecasting, such as census and meteorological forecasting, in that many more numerous yet varying factors influence an economic model at any particular time. Natural occurrences such as weather can play a large role in the fluctuations of an economic projection model. There are also interdependent correlations between economic factors of one interest and economic factors of a completely different aspect. Furthermore, the forecasting of economic models often fluctuates at a high frequency. All of these factors present problems more specific to econometric modeling, but have some correlation to environmental projections.

2.3 Error Modeling in Census Data Forecasting

One particular data set that is analyzed often using statistical forecasting is the periodic census data. Generally, the government and other organizations interested in the demographics of a particular set of the population most often collect this data.

Census data collection and archival has been a long-standing practice around the world. The collection has evolved greatly over the years to allow for collection of information on a wide range of data from employment and housing data to social, economic, race and ancestral information. This data is then analyzed using existing forecasting models to predict population figures for segments of the whole population set well into the future. These predictions are major governmental decision-making factors that help to plan everything from the economy to legislative representation to funding for schools, housing and education.

One particular use for census data that helps the government plan for the future is population data as it applies to the “labor market” or available workforce. This data is used to predict unemployment needs or economic growth potential for a region. Simply put, this model, Labor Market Projections Model (LMPM) developed by the Lawrence Berkeley Laboratory [7], takes as input census data and produces a prediction for population, labor force and unemployment, broken down by age group, for some point in the future. The combination and analysis of this data then becomes an influential part of many decision made about a region. Similar statistical tools and methodologies used for human population census projections can be applied to the space debris “census” projections.

3 STATISTICAL THEORY

There are many statistical theories for determining the error in a set of historical data. There are also a certain number of theories that allow a known or estimated quantity of error to be applied into the future. While these theories are beneficial to the analysis of space debris population, it is the compounding effect of fragmentation events that presents a certain difficulty when attempting to predict into the future.

So many of the factors involved with the prediction of future satellite population have the opportunity to have error associated with them. Everything from the growth and decay factors to the frequency of the events has a certain amount of error involved. Of these errors, the one that has the greatest effect on estimating the future of the earth-orbiting satellite population is the errors that exist when calculating the extents of a fragmentation event. This error is the focus of the research at hand.

Another important focus of this research is flexibility and adaptability. It is critical to the nature of the research that the assumptions are minimized to allow the greatest applicability to all cases. For example, the ability to select any environment model allows the opportunity to select whichever best suits the specific scenario at hand. Another key element that requires flexibility is the rates at which growth and decay are applied to the predictions. Simple assuming a linear or exponential growth rate nullifies the possibility that growth is periodic or logarithmic.

A good example of this is growth and decay rates. Trend analysis is currently the most popular for the ongoing effects of growth and decay. By examining the history of the growth and decay in the number of objects in the orbital elements catalog maintained by U.S. Space Command, these trends can be applied to estimate future growth and decay patterns. Fig. 1 shows the growth, decay and cumulative counts of cataloged objects from 1957 to 2000. By analyzing this data, the historical trends in growth and decay rates can be determined.

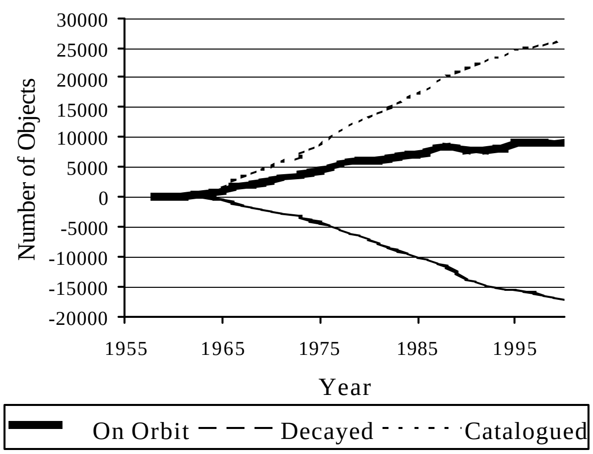

Fig. 1: Orbital Elements Catalog Historical Trends (as of 31 July 2000)

A simple 3rd degree polynomial fit of each of the growth (cataloged) and decay rates from Fig. 1 results in the polynomials for prediction of growth rate, *G(t)*, and decay rate, *D(t)*, respectively (Eqs. (3) and (4)).

$$G(t) = 0.0156t^3 - 2.7168t^2 + 96.412t - 98.263 \qquad (3)$$

$$D(t) = 0.0304t^3 - 0.8166t^2 - 23.758t + 12.812 \qquad (4)$$

In these equations, time, *t*, is in years from 1956. This data is valid for the next few years – any longer and the growth rate turns negative and produces erroneous results. It is meant only to show a point that error growth can be incorporated into any statistical fit desired. As can be seen, it is difficult to generalize the particular effects of growth and decay into specific functions. Each model of growth and decay is its own unique solution to representing a particular function. For this reason, growth and decay must be represented by equations customized to the desired rates.

Events themselves also prove to be difficult to model. The frequency of events, or the time period between events, is nearly random and is a function of so many differing and changing factors. This is also a point of flexibility. In most cases, an average period between events can be assumed. This assumption, however, has the potential to introduce great errors. Allowances must be made to provide for varying time discretization of events. While each event is its own period of time, its beginnings are always the results of some previous time period or event.

The result of all of these considerations is the following set of equations. The set as a whole allow the modeling of the space debris environment from any starting point in time to an ending point at any time in the future. The events need not cover identical spans of time. The rates of growth, decay and events need not be of any particular form.

The number of objects in the space debris and orbital material environment, *N(t)*, can be represented as seen in Eq. (5). Also, t_0 represents the time of the preceding event, or, in absence of any preceding event, the initial object count. *E(t)* is the modeling compensation for the actual fragmentation events (which are subject to various errors).

$$N(t) = N(t_0) + \int_{t_0}^{t} \left(G(t) - D(t)\right) dt + E(t) \qquad (5)$$

It is at this point that the flexibility complicates the theory. Because growth is not assumed to have any predetermined form, the growth function can be a function of any form. The following are examples of growth equations representing different possibilities for actually growth.

If growth rate is constant for all values of time, then the *G(t)* function would be that seen in Eq. (6).

$$G(t) = c \qquad (6)$$

If growth rate is linear and the rate of growth is *A*, then the *G(t)* function would be similar to Eq. (7).

$$G(t) = A(t - t_0) \qquad (7)$$

What is more likely the case is a complex growth rate involving polynomial or sinusoidal factors. In this case, a custom growth rate would have to be designed.

Now, the adaptive design of this modeling set allows for error to be introduced at any point. This research examines the varying effects of error when introduced at the event consequence level. That is, if *E(t)* as it pertains to Eq. (5) were to also be a factor of some 3σ error, what is the effect at some point in the future.

4 MODELING

The only feasible way to examine the build-up effects of these prediction errors for any relevant period of time is to model the system. This modeling can provide for not only propagation of the initial state and any expected on the system to be analyzed at any point in the future. Modeling can be a crucial tool in the prediction of the error build-ups. Visualization of this modeling can also permit easier interpretation of the system output.

The modeling of the uncertainty of breakup events and their effects is best done using computer based modeling methods. Fundamentally, the model for this system is a static catalog count with adjustments for both standard growth and decay as well as adjustments for event effects. The proposed addition would allow an error rating to be associated with any particular breakup event. This error would then also be adjusted for growth and decay and then carried out until either the next event or the end of the desired span of analysis.

4.1 Space Environment Models

There are several programs that exist to calculate the effects of a fragmentation event, and are discussed further in [1-3]. Each of these models is designed to generally focus on the portion of the space environment that is not observable due to the size of the object. Normal means of tracking space objects, including laser, radar and optical tracking, often are not able to identify objects less than 10 cm. Objects below this limitation still pose significant threats to an operation mission spacecraft. Collisions with objects of any size can be damaging to various subsystems of a spacecraft depending on their sensitivity to collisions. Objects as small as 1 mm can potentially by fatal to a spacecraft if they strike a critical component such as electronics, fuel lines, or mechanical joints. Shielding can be added to guard critical components, but can only prevent damage from objects up to 1 cm. It is nearly impossible to guard against a collision with an object large then 1 cm.

Several of these models are empirically based, namely ORDEM96 [1]. Space damage from on orbit experiments and spacecraft pieces that have been returned to Earth has been analyzed to determine the effects of a collision. These effects were then fit into the empirically based models. Growth rates and other factors included in the model are also based on trends observed throughout the space age.

The MASTER model exemplifies another type of space environment model. MASTER is a fundamental model because the basis for its prediction comes from the frequency and extent of known events such as historical spacecraft collisions and solid rocket firings. Each of these types of event contribute significantly to the space debris environment and produce debris which is rarely detectable or able to be cataloged.

While each of these models is highly developed, none of them presently are capable of modeling that incorporates error in its predictions. For this reason, just such a program, DEBRIStat, was developed for the research being presented here.

4.2 DEBRIStat

DEBRIStat is a space environment modeling enhancement. It is not a model itself. It simply takes the output from a space environment model, applies an error factor to the output and propagates the output over a desired span. DEBRIStat is extremely adaptive to allow interface with any space environment model.

The fundamental premise of DEBRIStat is that no model can accurately predict the effects of an event every time. Therefore, each model inherently has errors that are often ignored. While these errors are undoubtedly small in size, a problem occurs when the period of interest includes several years or, worse yet, several events. In this case, the error in any one event will experience the same growth effects as the accepted output from the model for that particular event. The compounding of these errors occurs when the period of interest involves two or more events, each of which has its own error and has the opportunity to be based on the error of the previous prediction.

DEBRIStat is designed to handle multiple events that can occur at any time while still applying standard growth and decay as ongoing effects that constantly skew the results of each of the predictions before it. As it runs, it applies the predicted effects of growth and decay that occur while checking for the possibility of an event at even, user-selected intervals. When an event occurs, in determines the extent of the event using the environment model and begins to propagate the results of the model's output. Its strongest point, however, is that it also applies an error factor to the model's results and predicts that as well. This leads to the need to handle multiple possibilities for the magnitude of the catalog at any one time. In the end, the output includes not only the standard results generated by the models, but also provides an overall set error bars to validate the entire spectrum of possibilities in the predicted events.

DEBRIStat in its most fundamental form is designed to propagate a given set of input parameters governing space environment population to a specific period of interest while determine the effects of satellite fragmentation events on the population. The calculations are based on a set of given initial conditions, such as catalog count, growth and decay rates and time interval, and event parameters, including frequency and extent of the events. This program takes the assigned error rating on the given extents for each event and propagates them. In the case of multiple events, this error is also compounded as needed.

The main product of DEBRIStat is the catalog count of space object population and its associated error at any point in time. DEBRIStat systematically applies the appropriate factors such as growth and decay to the catalog count at evenly spaced time intervals. The program determines if the current time step contains an event. If so, the results of that event are calculated and applied to the input or, if an event has already occurred, the previous results. The output gives the mean, max and min values for the catalog count at that time. These steps are then iterated over the entire time span.

A fundamental example of the basic event and event error modeling of DEBRIStat is shown in Fig. 2. This example was based on an initial count of approximately 8400 objects. This example also shows one event occurring mid-way through the time span. For this example, the event's mean effect is 4% of the object count at the event date. The maximum and minimum effects are 7% and 2%, respectively.

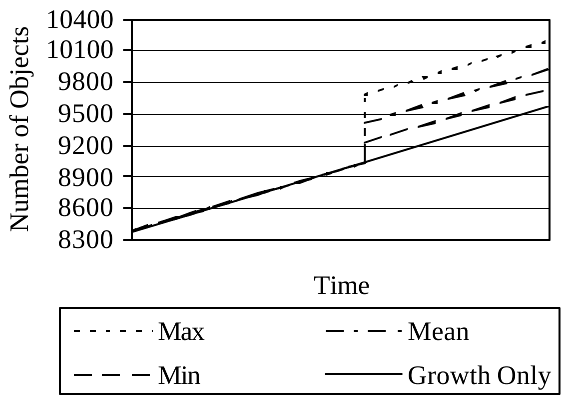

Fig. 2: DEBRIStat Prediction Example with One Event

In its current form, DEBRIStat is designed to allow for two modes of modeling when handling the effects of growth, decay and events – percentage effects and flat-rate effects. The flat-rate effect method simply applies a certain number of objects to the existing count. If the flat-rate method is used for growth or decay, these effects are taken as a number objects over a certain time period. In the preceding example, the growth rate was modeled using the flat-rate method (linear growth rate). The percentage method is similar, however, the number of objects to be applied is determined at the actual time of interest. The event effect in the preceding example was modeled using the percentage method. The minimum, mean and maximum value for the extents of the event were modeled as 2%, 4% and 7% respectively. Even though these are the two primary methods that currently exist in DEBRIStat, the highly open design of the program allows for limitless possibilities for

Another example of the compounding effects that may occur if error is present in the estimation of the effects of a fragmentation event is shown in Fig. 3. This example uses the same inputs as the previous example. This example was constructed, however, to show the effects that small errors might have when compounded over multiple events – in this case three.

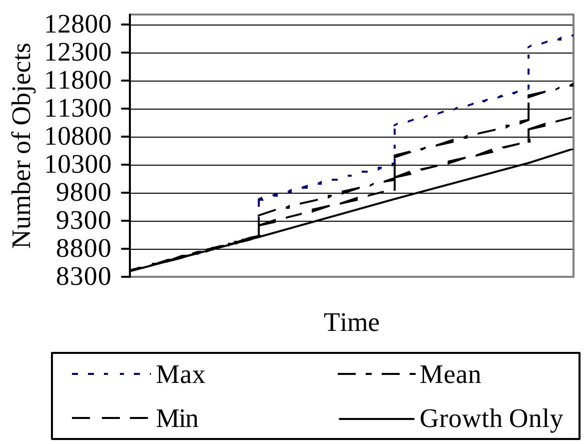

Fig. 3: DEBRIStat Prediction Example w/ Three Events

An example of the long-term prediction capabilities of DEBRIStat can be seen in the simple example diagramed in Fig. 4. This figure shows the accumulation present when multiple events occur within the span of interest. In this example, a total of 11 events were found over the time span chosen. In this case, the minimum, mean, and maximum are 2.0%, 3.0% and 6.0%, respectively. As seen in the example shown here, the initial mean of 3.0% with errors of +3.0% and -1.0% has grown substantially by the end of the period of interest. The final values of error from the mean event effects are +18.4% and -7.9%, respectively.

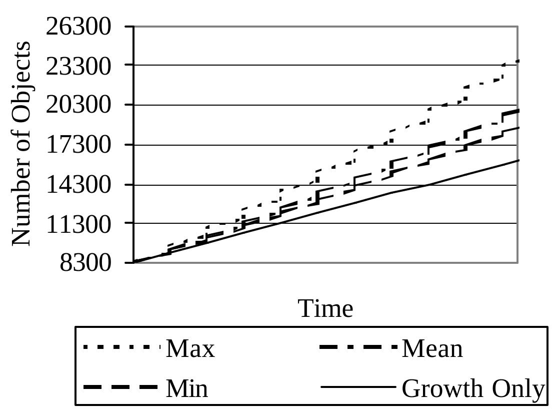

Fig. 4: DEBRIStat Long-term Prediction Example w/

The functionality of DEBRIStat is currently limited by the lack of actually data for error values. However, when this data becomes available, DEBRIStat will become a powerful tool for evaluating the long-term effects of small errors in estimated fragmentation event extent and how these small errors can cause large problems in the future. With the addition of whichever environment model best fits the situation, the method presented in DEBRIStat will become a powerful tool for analyzing the population of the space environment well into the future.

5 SUMMARY AND CONCLUSIONS

This paper has outlined a process for including errors in the number of pieces created from a hypervelocity breakup in space. We have shown how simple statistical information can be fed into space debris environmental projections, and how that information can be used for future debris environmental projections. We also introduced a simple computer model, DEBRIStat, which demonstrates how statistical information can be incorporated into other environmental projection models. Once information from a future experimental program can be gathered, that information can be used to validate the assumptions that were made in DEBRIStat, and could then be used to bound the future debris environment forecast models.

6 FUTURE WORK

Errors in the number of pieces produced following a hypervelocity breakup can be estimated in a variety of ways. A very feasible way to gain a gross understanding of what these error values could be would be to conduct a series of hypervelocity experiments. A proposed series of a minimum of 12 tests using identical complex targets to simulate a complex structure on a satellite bus (obsolete personal computers will work well – they are inexpensive, readily available, and from a gross standpoint, mimic many of the internal components of a spacecraft) should be undertaken. Each computer will be the target for one shot, and will be mounted in the test chamber in identical configurations. The gun will be aimed at the same location on each target. The goal here is to duplicate as many of the test conditions as possible by reducing the variability from one test to another, and to separate out the effects of one variable on the breakup characteristics (namely projectile size or projectile velocity). After each test, the debris from the hypervelocity impact will be collected and analyzed. Before the next test, the chamber will be swept out thoroughly. The characteristics of the breakups that will be examined include the size, mass, and number of objects created from each breakup, and other information such as spread velocities.

With this sufficiently large number of tests, information about the statistical distribution of the number, size, velocity, and area of the pieces collected from the tests can be determined. From this, some of the results obtained from hypervelocity breakup models can be bounded, and realistic statistical information can be incorporated into environmental projection models.

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