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KEY ASPECTS OF SATELLITE BREAKUP MODELING

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ABSTRACT

The fragmentation, or breakup, of satellites while in orbit is the greatest contributor (by number) to the present orbital debris population. Therefore, the modeling of such events is crucial to determining both current and future levels of orbital debris and its resulting hazard. This paper examines the key aspects of satellite breakup modeling as they relate to the evaluation of the present and future environments. The current environment is largely the result of explosive events. The difficulty in the analysis of these events centers on uncertainties in phenomenology, exact causes for breakups, and correlation between laboratory and on-orbit data. On the other hand, the state of the future on-orbit population may be largely a function of collision-induced fragmentations. Uncertainties in the modeling of collisions are in phenomenology and determination of conjunction information. In all instances, more testing dedicated to the collection of data to refine debris distributions is required. Seven key aspects of breakup modeling detailed are: be physics-based, supported by test data, accurate, flexible, easy to use, have usable output, and clearly stated limitations.

1. INTRODUCTION

Breakup modeling techniques for application to orbital debris analyses have matured greatly over the last twenty years. In the early 1970s, the models used to depict the debris resulting from collisions were merely simple equations based on crater excavation theory extrapolated to spacecraft, since no data was available for such structures [Refs. 1, 2]. Explosion modeling was based upon more applicable physics algorithms and a larger empirical database which was still, however, sparse for test articles resembling spacecraft [Refs. 2, 3]. During the 1980s, hypervelocity collisions in space became a well-studied topic due to the emerging Strategic Defense Initiative (SDI) of the United States and its emphasis on kinetic kill mechanisms. Anti-satellite (ASAT) initiatives by both the U.S. and the former Soviet Union also provided an impetus for realistic hypervelocity impact testing [Refs. 3, 4]. As the data from SDI and ASAT test programs became available to debris modelers, the potential for improved breakup models increased. However, the development of improved breakup models is a multidisciplinary and multidimensional activity requiring more than just data; several key aspects must be considered to ensure a useful product.

2. KEY ASPECTS OF BREAKUP MODELING

Examination of the subtleties of breakup modeling need not be constrained to either explosion or collision events; the rules are equally applicable to both. There are seven primary areas which must be scrutinized when developing breakup models:

1. be physics-based
2. supported by test data
3. accurate
4. flexible
5. easy to use
6. usable output
7. clearly stated limitations

Each of these will be individually described, but the underlying theme for all topics is to balance three complementary needs: empiricism, analytics, and user needs. Use of well-conceived analytic model without empirical results to compare against is nothing more than an academic exercise. Data from tests can be used to help refine the coefficients or exponents of an analytic model. Conversely, a purely empirical model is very limited in its application: extrapolation outside of the range of available data is almost always in error, while interpolation between data points is suspect unless the physics of the problem are well understood. Last, the need of the user must be considered in all cases. While this may appear to be merely a stating of the obvious, it has been found to be the most critical pitfall for debris model application in general. The "user's needs" include not only to what scenario the model will be applied, but also by whom, for whom, when, how often, why, where, and to what level of accuracy. Table 1 lists the types of available breakup models and some characteristics.

Model Type	Characteristics		Example
	Advantages:	Limitations:	
Empirical	- Simple to use - Broad empirical base	- May not accurately reflect physics across range of initial conditions	NASA model and IMPACT
Semi-empirical/Semi-analytic	- Simple to use - Broad empirical base - Sensitive to changes in initial conditions	- Questionable extrapolation beyond initial data sets	FAST, BUMP
First Principles	- Reflects physics at the lowest practical level	- Difficult to implement and interpret	Hydrocodes

Table 1. Available breakup model types.

A. Physics-based: Foremost, a model must be based on first principles of physics. This does not mean that a breakup model must start as an analytical model, but it does mean that in its operational mode variations in input conditions must be consistent with basic physics laws. Hydrodynamic (hydro) codes, output examples of which are shown in Figures 1a-b, are the epitome of this type of model, with their operation based on first principles of physics and supporting empirical data being integrated at the lowest possible level (i.e., equations of state). Unfortunately, being based on physics does not mean that the results are always accurate since most are usually applicable for a limited target set and velocity regime.

Empirical models should reflect physics considerations by conserving mass, momentum, and energy, either through small analytical additions to the code or constants which force these conditions to be met. These models should also be sensitive to changes in initial impact conditions and at least qualitatively show this in their results. Higher impact velocities, for example, should be reflected in higher debris velocities and possibly more target fragmentation.

B. Supported by Test Data: A model must be verified, or at least corroborated, as much as possible against APPLICABLE data. A distinction is made between verification and corroboration. Verification is considered the quantitative positive correlation of the model to test data across a wide parameter space, while corroboration is the positive qualitative correlation of a limited data set to the model. Depending on the fidelity of the model, it may be very difficult to determine what data set is applicable "enough." There are significant difficulties in determining how many parameters of a test condition must be replicated to allow a useful comparison: mass, velocity, material, impact location, target structure, energy to mass ratio, etc. Scaling relationships may assist in this area, but their application to debris distributions is very suspect.

C. Accurate: A model must be accurate enough to satisfy user requirements. Accuracy, however, should not be confused with precision. This is a common pitfall in the application of purely analytical models, since physical constants and physics equations may be very precise, but this does not equate to accuracy in their application. A model should be sensitive to changes in input conditions such that more accurate input conditions result in predictions closer to the actual results.

D. Flexible: A model should be applicable to as wide a range of scenarios as possible without degrading the model's accuracy below user requirements. This is always a tenuous balance between covering a broader parameter space while maintaining a specificity, and thus, accuracy level for certain scenarios. An analytical model is inherently more flexible because it is better suited, at least if well-developed, to extrapolation beyond existing data. Flexibility, however, does not only apply to the variety of physical situations in which a model may be used but also to how easily it is used by a variety of users in different contexts (i.e., operational situations) without any application beyond the initially prescribed parameter space. In this situation, simpler algorithms may prove to be more transportable and more easily incorporated into larger models.

E. Easy to Use: Implicit in determining a model's ease of use is the user's experience in breakup modeling and simulation models in general. For this reason, we can only qualitatively propose the appropriate attributes to make a model easy to use. The objective of the model must be clearly understood so that the reason for requiring specific input parameters needs no detailed explanation. A clear logic flow in the model will aid in this process by identifying to the user how each of the input variables will be used and how variations in them will affect the resulting output. At an operational level, it is imperative that the model requests the required information in a clear way. Input conditions may be passed to the main program via some standard data file

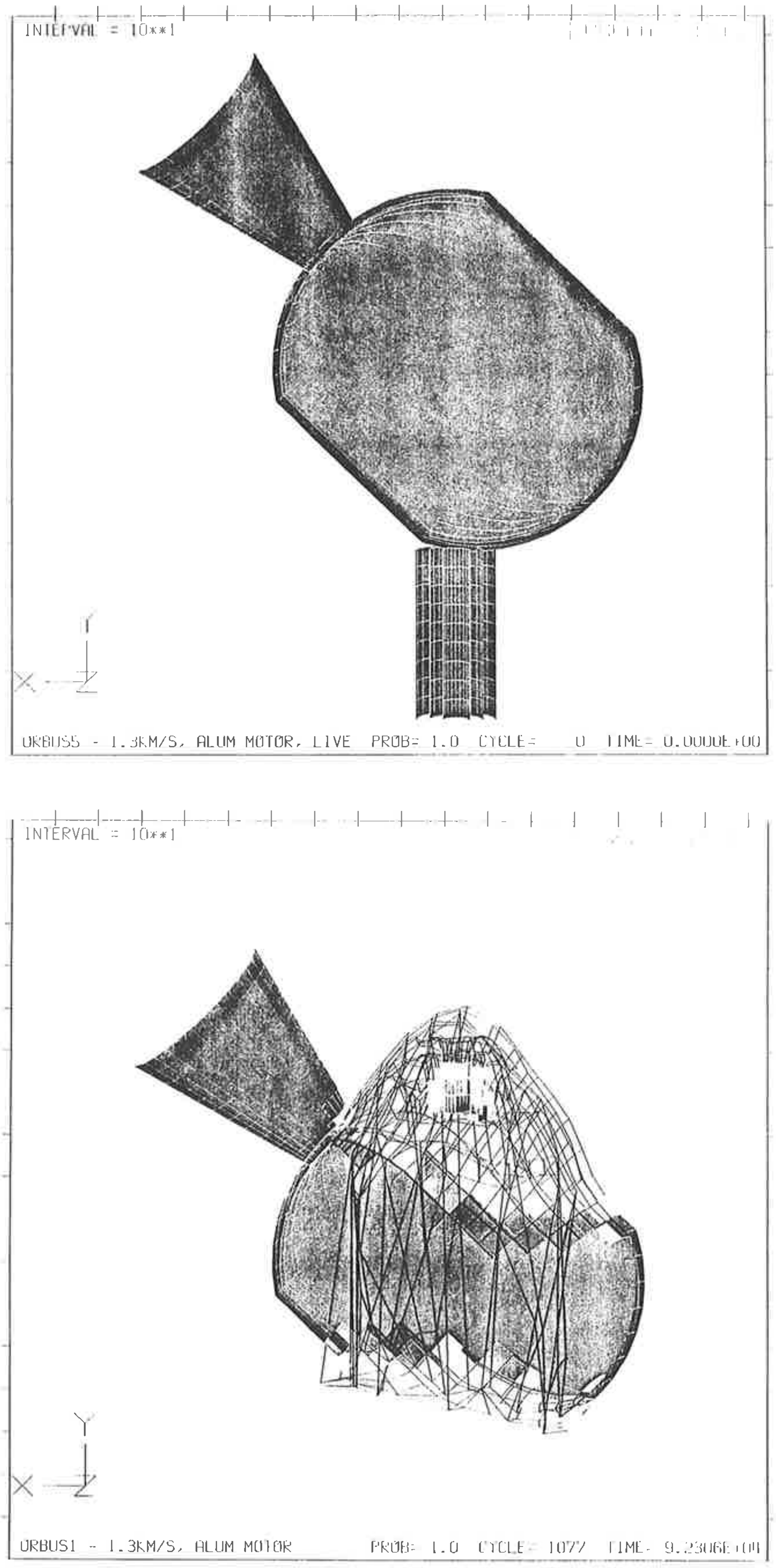

Figure 1a, b. Hydrocodes can characterize a breakup over a period of time: Upper figure is at impact and lower figure is about 1 ms later.

incorporated as part of a batch processing sequence. Alternatively, the model may be interactive by prompting the user for input along the way. Batch processing may be easier to use for the experienced programmer performing many runs, while the interactive approach may be more appropriate for defining the limits of model applicability by users who are less comfortable with performing computer tasks.

F. Usable Output: A model is only as good as the ability of the user to assimilate its results. It is a common misconception that more output information is better. Extensive output may be valuable for the very experienced observer who is well-versed in the phenomenology being simulated. But for most users, it is more important to present the results in a fashion that facilitates the formulation of valid and useful observations. This aspect of good breakup modeling is closely linked to model flexibility, already discussed. The best way to insure that the output from a model is usable is to provide a variety of output formats. For example, when depicting the results of a hydro code run, plots may be generated showing the stress, strain, or strain rate throughout the target over time; each provides a different perspective on the physical destruction being simulated.

G. Clearly Stated Limitations: The constraints on the use of the model's results must be clearly stated to preclude misapplication by users. Most breakup models are limited in their accuracy and range of applicability (e.g., impact velocity, material, time, fragment size, etc.). The best way for the breakup modeler to handle this concern is to clearly state what the limitations are and provide supporting proof such as comparisons to data.

3. FAST MODEL DEVELOPMENT: A CASE STUDY

The Fragmentation Algorithms for Satellites Targets (FAST) Model was developed for the Defense Nuclear Agency (DNA) in support of the U.S. Department of Defense Orbital Debris Program [Ref. 4]. FAST is a semi-empirical breakup model which simulates the debris field characteristics (mass, velocity, and ballistic coefficient distributions) of a satellite fragmentation. The genesis of FAST was work performed by NASA in the 1970s and 1980s [Refs. 2, 3]. FAST advanced breakup models through several methods: by accessing and integrating new breakup data, applying analysis of variance (ANOVA) techniques to the existing database, developing predictive relationships using event-specific information, and incorporating a target structure descriptor. However, while past efforts have emphasized breakup due to collisional encounters, current work for the Defense Nuclear Agency is concentrating on improvements to the explosion portion of the model.

As developers of the FAST model, the authors can specifically detail how FAST has incorporated the key aspects of breakup modeling being discussed in this paper:

A. Physics-based: FAST started as a purely empirical model but has had modifications to incorporate trends based purely on analytical expressions. The number/mass distribution conserves mass, then the velocity distribution conserves energy and momentum. Additionally, material strength and gas expansion physics are also accounted for in the mass and velocity algorithms, respectively.

B. Supported by Test Data: The strong point of FAST is its development and validation against a large database. Over twenty sets of data from experiments with widely varying target mass/geometry, projectile mass/geometry, and impact velocity have been used. The data used is well-documented in the appendix of Reference 4.

C. Accurate: FAST not only has been validated by test data via high positive correlations between data and FAST simulations, but has actually proven to be accurate to within 10 percent when complete target fragmentation occurs. Figure 2 shows the percent error in the mass distribution exponent as a function of encounter energy to target mass ratio. This figure shows that the accuracy decreases if FAST is used below the 35-45 J/gm collision threshold. This high accuracy is especially noteworthy considering the wide range of impact scenarios represented: from a simple 27 gm target being destroyed by a 2 gm projectile to an 850 kg satellite being broken up by a 15 kg impactor.

D. Flexible: FAST has been used by managers, scientists, engineers, and programmers in support of range safety, on-orbit hazard assessment, and theater missile engagement scenarios. Its simple form and well-documented manual allows its use as either a module to a larger program or as a stand-alone tool.

E. Easy to Use: FAST can be nearly totally represented by five equations. Accompanying the FAST manual [Ref. 4] is a Quattro Pro personal computer file which interactively guides a user through the application of FAST and plotting of the results, an example of which is in Figure 3. The manual also includes an example problem worked out in the appendix.

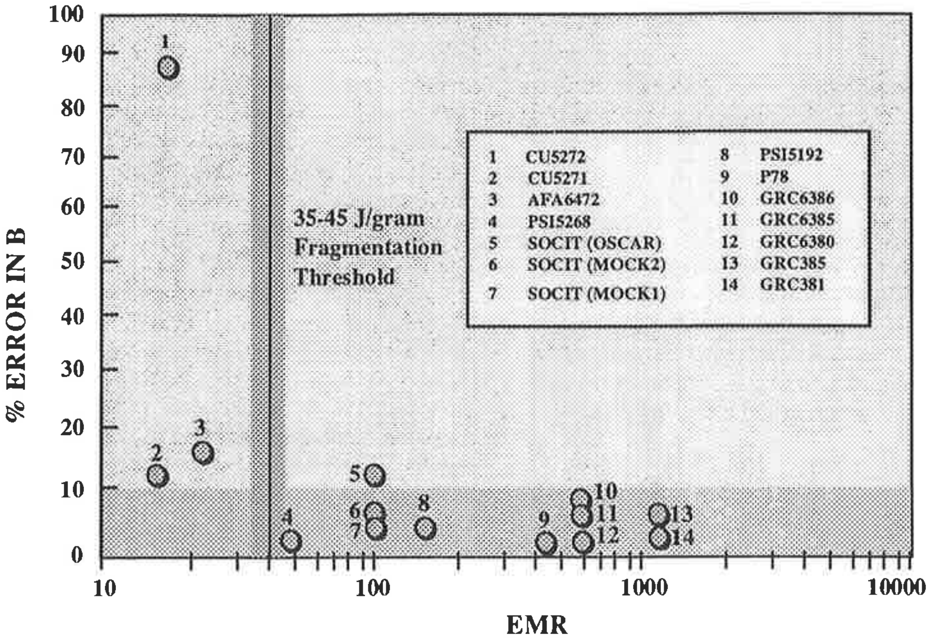

Figure 2. The FAST model is accurate within 10% when the fragmentation threshold is exceeded.

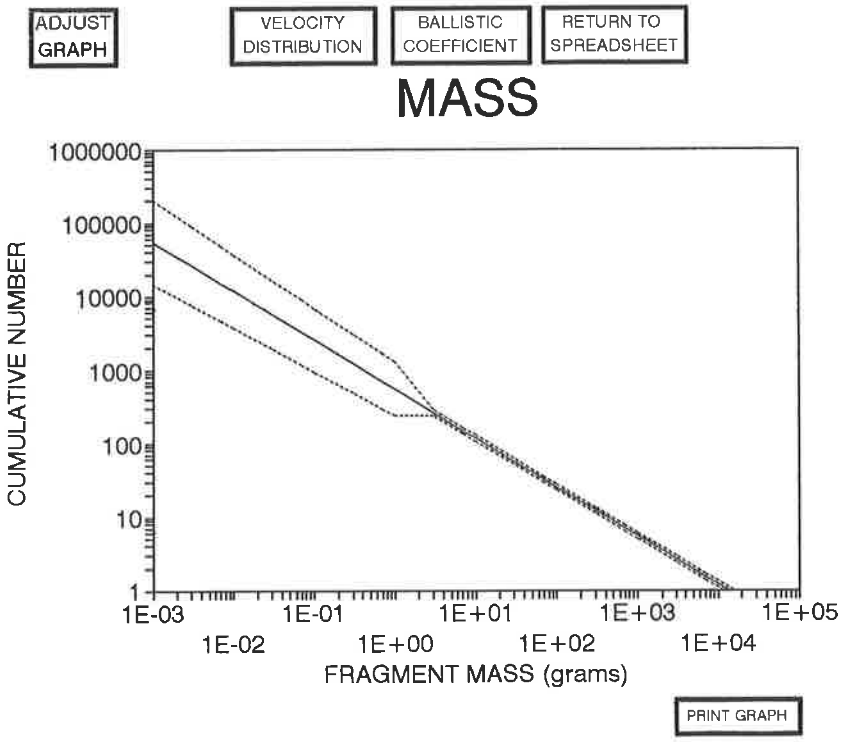

Figure 3. Interactive features are incorporated into the FAST personal computer program.

F. Usable Output: The key to making FAST's output usable is to understand the user's needs. Generally, a plot of physical parameters (e.g., a scatter-plot of BC values vs mass) is sufficient, but FAST also provides a listing of all fragments simulated, describing each in detail as shown in Figure 4.

G. Clearly Stated Limitations: Since FAST is a semi-empirical model, it is vitally important for its range of applicability to be clearly defined. At the beginning of the FAST manual [Ref. 4], the appropriate target material/geometry and impact velocity ranges are clearly identified. The data sets in the appendices will also help to determine a user's confidence in applying

4. SUMMARY

Clearly, a breakup model is good if it satisfies a user's requirements, but this paper attempts to address specific ways in which model developers may work to enhance the utility of a model which they are creating for an identified need. Many of the guidelines described above may be considered common sense by many, but they are often neglected in the haste to provide a product or to address a preconceived output. There are many good breakup models and related models being used worldwide. Three loosely grouped categories are: empirical, semi-empirical/semi-analytic, and first principles. There is even debate at times as to which models fit into which categories. This apparent lack of orchestration between models and model development often times leads to inconsistencies during specific model applications. For instance, the characterization of range safety issues from a suborbital impact test may produce a wide range of answers by using different breakup models. This situation could be remedied early in a program by deciding which breakup model to use and then subsequently deciding on the related propagation and dispersion models. However, while standardization may produce apparent reduced uncertainty levels in the final result, it also may preclude productive discussions which will aid in the more complete assessment of the test results. Eventually, the user must decide which model is the "best" for the specific application at hand, but the dialog between independent model developments serves a lot of useful purposes as long as it does not put an undue financial burden on program managers.

5. ACKNOWLEDGMENTS

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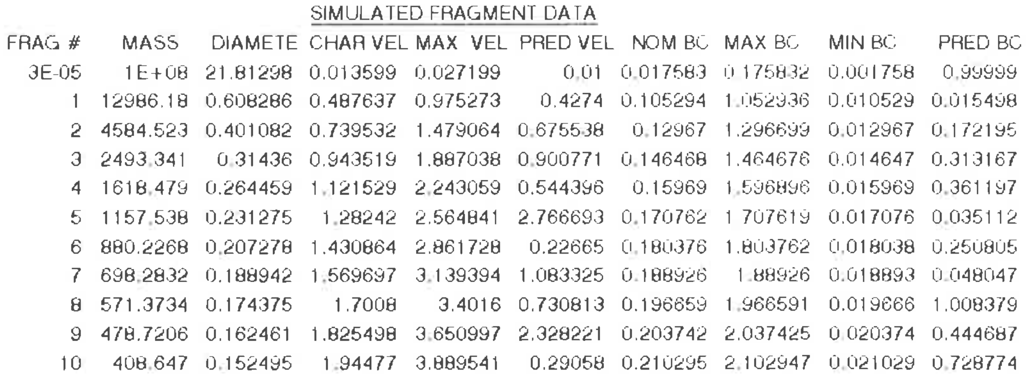

SIMULATED FRAGMENT DATA

FRAG #	MASS	DIAMETE	CHAR VEL	MAX VEL	PRED VEL	NOM BC	MAX BC	MIN BC	PRED BC
3E-05	1E+08	21.81298	0.013599	0.027199	0.01	0.017583	0.175832	0.001758	0.99999
1	12986.18	0.608286	0.487637	0.975273	0.4274	0.105294	1.052936	0.010529	0.015498
2	4584.523	0.401082	0.739532	1.479064	0.675538	0.12967	1.296699	0.012967	0.172195
3	2493.341	0.31436	0.943519	1.887038	0.900771	0.146468	1.464676	0.014647	0.313167
4	1618.479	0.264459	1.121529	2.243059	0.544396	0.15969	1.596896	0.015969	0.361197
5	1157.538	0.231275	1.28242	2.564841	2.766693	0.170762	1.707619	0.017076	0.035112
6	880.2268	0.207278	1.430864	2.861728	0.22665	0.180376	1.803762	0.018038	0.250805
7	698.2832	0.188942	1.569697	3.139394	1.083325	0.188926	1.88926	0.018893	0.048047
8	571.3734	0.174375	1.7008	3.4016	0.730813	0.196659	1.966591	0.019666	1.008379
9	478.7206	0.162461	1.825498	3.650997	2.328221	0.203742	2.037425	0.020374	0.444687
10	408.647	0.152495	1.94477	3.889541	0.29058	0.210295	2.102947	0.021029	0.728774

Figure 4. Complete characteristics of simulated fragments are available for sensitivity studies.