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ORBITAL DEBRIS STUDIES AT THE UNIVERSITY OF COLORADO

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ABSTRACT

The University of Colorado was the first University to begin extensive studies on man-made orbital debris, and as far as is known, has the only American graduate program in orbital debris. Work has been conducted on many facets of the orbital debris environment. This paper gives a brief description of the work that has been performed by the University of Colorado in cooperation with several government and private enterprise entities. The main areas of research have been: fragmentation modeling, background environment modeling, evolution modeling, SMART catalog, ground based hypervelocity testing, shielding design, mass-diameter-RCS-BC studies, and most recently optical calibration for the ODERACS objects. This brief history of the research and graduate program in orbital debris is followed by projections of the future course of research at the University of Colorado. The University of Colorado is committed to continuing research in space debris and welcomes collaborative research with other institutions.

1. INTRODUCTION

The University of Colorado (CU) has been studying aspects of the space debris problem since the early 1980's. This paper presents some of the work that has been done and outlines the continuing work. The University of Colorado was the first University to begin extensive studies of man-made orbital debris, and as far as is known, has the only American graduate program in orbital debris. Darren McKnight earned the first Ph.D. in debris work in 1986 (Ref. 1), and is extremely active in the field. Presently there are three doctoral candidates, two masters students and several undergraduates working on various space debris projects.

The University of Colorado is interested in basic research to help understand the fundamental processes driving the debris environment and its impact on spacecraft and operations. The research of this program is becoming more applied in an evolutionary manner, yet still addresses all aspects of the debris threat. The University maintains its commitment to provide basic research and training for the debris community.

2. RESEARCH AREAS

The following sections briefly highlight the major topics of research carried out at the University of Colorado. The main thrust of this research is to understand the debris environment and its impact on spacecraft design and operations.

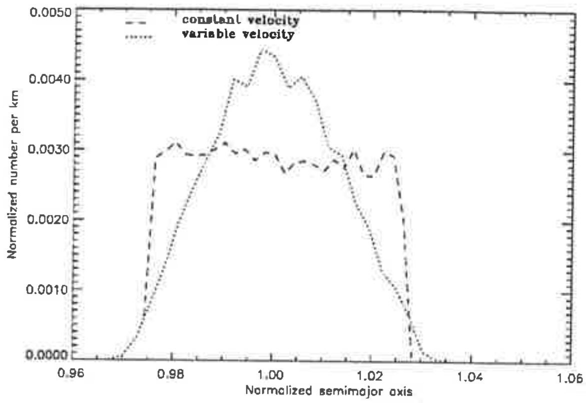

Figure 1: Simulated fragmentation with different velocity distributions

2.1. Breakup models

Early work developed computer models to simulate breakups caused by collisions, high-intensity explosions, and low-intensity explosions (Ref. 2). Techniques were developed which were moderately successful in using debris characteristics to differentiate between collision-caused and explosion-caused fragmentations (Ref. 3). Research refining fragmentation models continues with an emphasis on examining the effects of varying breakup parameters.

An example of the effect of different velocity distributions on the distribution of the semimajor axis is presented in Fig. 1. In this example the normalized number of objects with a certain semimajor axis are compared for two simulated fragmentations. The flat distribution is for a fragmentation with a constant ΔV, and the peaked distribution uses a triangular distribution with a peak at the same ΔV as the other distribution (Ref. 4). This Figure highlights that differences in breakup parameters can affect greatly the dynamics of a debris cloud.

2.2. Environment modeling

Environment modeling is an important aspect of space debris research because only certain portions of the debris spectrum are detectable from the Earth or returned spacecraft surfaces. Both the present background environment and future evolution scenarios are being studied at the University.

From its inception this group has been involved in the effort to model the space debris environment. The primary goal has been to provide a usable, realistic model of the untrackable debris. The characteristic dimension (size) of the debris of most concern is from one millimeter to ten centimeters. This untrackable debris population that presents a wide range of hazard to resident space objects (Refs. 5, 6).

One model, entitled FRAG, is a computer model which predicts the debris population via simulation of documented on-orbit breakup events and propagation of the resulting environment (Refs. 7, 8). Each breakup event is assumed to be spherically symmetric, and the number of generated fragments is determined by calibrating the model predictions with recently published LDEF data. Debris apogees and perigees are propagated at six month intervals using an analytic drag algorithm. Possible encounters with a given satellite of interest are accumulated throughout its time of flight. The program outputs the following: an estimate of the expected number of impacts with various sizes of debris, the probability of not being struck by a fragment in a given size range, probability distributions for impact velocity and impact angle, and the present debris population expressed as a spatial density. Missions extending into the future are analyzed by assuming a scenario of future breakups.

2.3. Debris cloud evolution

Debris cloud evolution work was based upon the earlier work representing fragmentation clouds. The short term evolution of the cloud under the influence of atmospheric drag and gravitational oblateness has been analyzed. The short-term collision hazards of the evolving debris clouds to resident space objects is being investigated from safety and lethality standpoints.

An important aspect of debris cloud evolution is how long it takes the cloud to approach a steady state. This so-called "time to background" can be used as a measure of how long passage through the cloud is significantly more dangerous than the background state (Ref. 9).

2.4. Advanced computer visualization

The output from debris models is often difficult to interpret without some form of data visualization. Computer imaging techniques are being developed to improve the visualization of complex data. When applied to space debris data, these techniques greatly enhance the ability of a researcher to grasp the consequences of various debris models and scenarios. This offers the potential for significantly advancing the rate of understanding of complex data, and the synthesizing of new trends apparent only when the entire structure is viewed (Ref. 10).

Two imaging techniques have been implemented on color workstations at CU to interpret complex debris data sets. The first method visualizes the cube faces of a volumetric image. The second method uses a ray-tracing technique to display surfaces within a volume. These have been applied to short term debris cloud structures and other four-dimensional data sets to investigate various data trends.

2.5. Ground based hypervelocity impact tests

A large number of hypervelocity impact tests have been conducted in various test facilities around the country. Most of these tests were conducted for other reasons, and not analyzed with a goal of providing information about space debris generated by collision. The CU group is analyzing as many of these experiments as possible to improve the data from which fragmentation models are developed. Thus far, this work has helped to improve the empirical mass distribution equations used in analyzing space fragmentations, and has contributed to the characterization of debris size-mass relations.

Mass distribution equations describe the cumulative number of fragments larger than a given mass that result from a catastrophic hypervelocity impact. By recording the sizes and masses of debris from these ground tests, mass distributions can be validated and modified to fit experimental results. The most often used distribution is the power law. A parabolic distribution was later proposed which allowed greater flexibility in fitting the data, primarily at very small masses (Ref. 11). CU has proposed a third distribution which captures the additional data traits observed at the high mass end of the data as well (Ref. 12). This equation is shown as Eq. 1, where A, B, C, and N_t are constants, and N_{cum} is the cumulative number of fragments with mass greater than M_f.

$$N_{cum} = N_t \left(1 - \frac{AM_f}{M_f + C}\right)^B \qquad (1)$$

Characterization of the relationship between size and mass for satellite fragmentation debris is another product of CU's impact test analysis. This work is important for determining ballistic coefficients which are needed to predict orbit lifetimes, and for characterizing the threat that these fragments pose as projectiles for other satellites. Ground test data for pieces larger than a few millimeters has been combined with NASA data on larger debris to determine an equation relating mass and characteristic diameter. For smaller pieces, the commonly used assumption that fragments are spherical has been analyzed and modified (Ref. 13). When combined with NASA's mean density for small debris of 4.7 $\frac{g}{cm^3}$ (Ref. 14) (aluminum at 2.7 $\frac{g}{cm^3}$ is often assumed), this analysis leads to a new expression for small debris. These new relationships for smaller and larger debris are merged by using a simple exponential term to create a smooth transition (Ref. 15). This equation is shown as Eq. 2, where the mass (M) is presented in grams and the diameter (d) is in cm. α is a constant with a value of 1200 $\frac{1}{m}$. A fit of this equation with available data is shown in Fig. 2.

$$M = 10^6 \cdot \frac{\pi d^3}{2}(e^{-\alpha d}) + 22,000 d^{2.44}(1 - e^{-\alpha d}) \qquad (2)$$

2.6. Advanced shielding techniques and design

Spacecraft shielding is typically based on the Whipple concept of placing a thin metal plate some distance in front of the structural wall needing protection. At orbital impact velocities, this plate induces a shock wave in the projectile sufficient to cause complete pulverization, and will likely melt, or even vaporize it. In order to improve the shield's efficiency, CU has been investigating the effect of modifying the plate's front (and rear) surface topography (Ref. 16). The aim is to increase the shock amplitude in the projectile by superposition of shock waves generated at each contact point. The situation is pictured schematically in Fig. 3 for a Topographically Modified Bumper (TMB) with ribs on the front only, and a spherical projectile. By increasing the shock, the final temperature is increased, leading to a greater chance of melting or vaporization and a decreased impulse for the structural wall. Studies carried

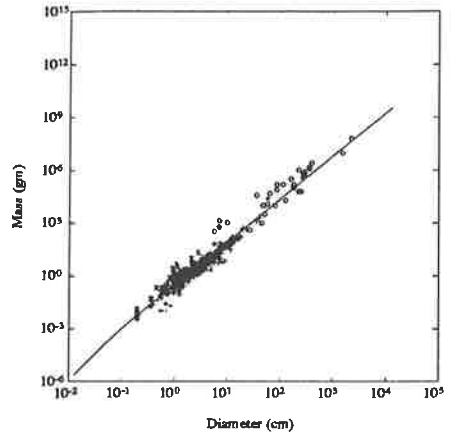

Figure 2: Unifying mass versus diameter

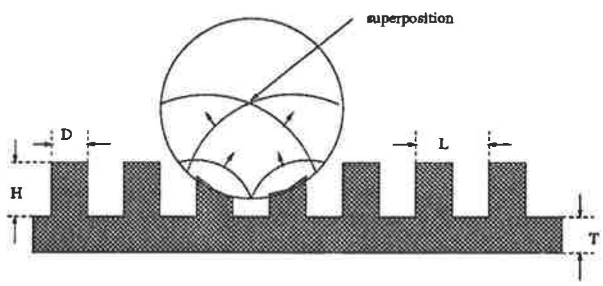

Figure 3: Shielding design

out numerically using the CTH hydrocode have been performed to investigate the influence of various rib height (H), width (D), spacing (L), and backing thickness (T) on debris cloud characteristics. These results have been verified experimentally in cooperation with the University of Dayton Research Institute, NASA Johnson Space Center, and Martin Marietta Space Systems.

2.7. Size and radar cross section studies

The relation between physical size, mass and radar cross section (RCS) was studied at CU (Refs. 17, 18, 19). This investigation answered several fundamental questions concerning the assumptions relating ballistic coefficients of debris particles and their radar cross sections. Fig. 4 shows an example of the estimated cross section area versus the RCS for a set of small fragments. The estimated cross section is found from the orbit decay, and is then divided by the RCS to create an area ratio, which is the y-axis.

Current work involving fragments from ground-based hypervelocity impact tests will provide further information on radar signatures of space debris and the correlation of these signatures with physical characteristics. This work is being extended to investigate the similar relation between optical signatures, mass and size. A comprehensive study of size, mass, and radar and optical signatures is the goal.

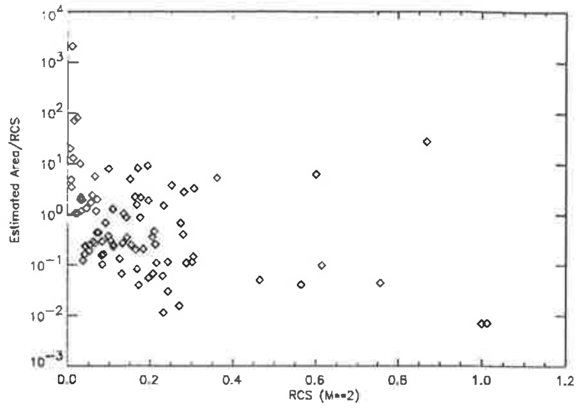

Figure 4: Area ratio versus Radar Cross Section

2.8. SMART catalog

CU was involved in early workshops to determine the feasibility of creating a catalog for small objects. This concept was intended to improve satellite tracking efficiency and expand the current catalog to include smaller debris (Ref. 20). Though the SMART catalog database was never implemented, it offers the possibility to reduce the load on the space surveillance network while providing more data for debris researchers.

2.9. Radar and optical sensor calibration

Detection and measurement of small space debris objects are vital to verify the validity of debris models for the low Earth orbit (LEO) environment. Calibration of optical instruments is necessary so that reliable estimates of the size and albedo of man-made orbiting objects can be found. The Orbital Debris Radar Calibration Spheres (ODERACS) project is being conducted to calibrate both radar and optical tracking facilities for small objects.

The University of Colorado has conducted the preflight optical calibration for the ODERACS objects (Ref. 21). The purpose of this study is to determine the spectral reflectivity, scattering characteristics and albedo for the visible wavelength region. The measurements are performed by illuminating the flight spheres with a collimated beam of light, and measuring the reflected visible light over possible phase angles. This allows the estimation of reflective characteristics as well as the albedo. Fig. 5 shows the basic setup for the ODERACS pre-flight optical calibration.

Tests were conducted on several flight and test metal spheres with varying diameters and surface characteristics. The polished metal spheres were shown to be very good specular reflectors, while the diffuse and blackened surfaces exhibit both specular and scattering reflection characteristics. The ODERACS are scheduled to be deployed later in 1993 from the space shuttle.

Future missions for this project are planned with darkened spheres and possibly dipoles. These objects have already been calibrated at the University of Colorado. This research has shown that the albedo of the metal spheres greatly depends upon the surface characteristics of the spheres. Therefore a wide range of albedos could be expected for on-orbit objects.

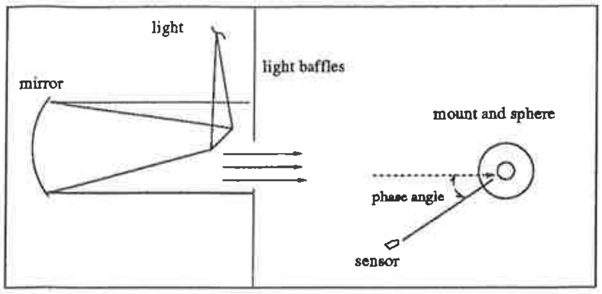

Figure 5: ODERACS experimental setup

2.10. Lethality and space-based defensive systems

The hypervelocity impact between a particle and a resident space object is being investigated in regard to the lethality of the impact to the target. This research is in support of the Strategic Defense Initiative kinetic energy weapon program, and the anti-satellite program. This involves studies of hypervelocity impact, energy transfer during collisions, primary and secondary damage due to space debris impact, and the connection of such impacts to remote damage in a large space structure through stress waves and dynamic response (Ref. 22). Hazards to satellite defensive systems, design of satellite constellations, and encounter scenarios for space-based systems are also being studied.

2.11. High-altitude debris hazards

Some work has begun on specific and potential hazards in geosynchronous orbits and in geosynchronous transfer orbits. Other long-term questions regarding eventual development of debris bands at altitudes above 2,000 kilometers will be included in this research. Effectiveness of storage orbits above geosynchronous altitudes are being studied.

3. CONCLUSIONS

This paper has outlined the main areas of past and present research in space debris at the University of Colorado. The university has contributed basic research and provided training for the debris community. The University of Colorado is committed to continuing research in space debris and welcomes collaborative research with other institutions.

4. ACKNOWLEDGEMENTS

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