DAMAGE: A DEDICATED GEO DEBRIS MODEL FRAMEWORK

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ABSTRACT

A project is underway at Southampton University to create a software analysis tool, DAMAGE, dedicated to modelling debris in High Earth orbits over the long-term. The DAMAGE project aims to account for the unique characteristics involved in modelling the GEO environment. Applications of the model include investigation of mitigation methods for GEO. This work will inevitably require novel solutions if the precision and speed of the software are not to be compromised. This paper presents a preliminary framework for the dedicated GEO debris model DAMAGE and discusses the challenges of GEO modelling in this context.

1. INTRODUCTION

The uniqueness and value of the Geostationary Earth orbit (GEO) has led to a rapid increase in the number of spacecraft in this region and, subsequently, to the concern of overcrowding [1]. A substantial amount of debris with sizes greater than 10 cm has been placed in GEO along with operational satellites. This debris includes spent upper stages, apogee kick motors and deployment hardware. In addition, small-sized debris resulting from explosions and surface degradation, and clouds of orbiting aluminium oxide particles with sizes between 1µm and 1mm produced by the firing of solid rocket motors (SRM) have been detected [2].

Whilst it is accepted that the spatial densities of debris objects in GEO are lower than those in Low Earth Orbit (LEO), the detection of objects in GEO by optical survey is limited to objects larger than about 1m. Consequently, the true spatial density of smaller debris objects remains unknown (see Fig. 1). Furthermore, observational results have shown that a large percentage of the detected objects are not correlated with catalogued objects [3]. Thus the growing threat to spacecraft from damaging or catastrophic collisions remains to be accurately quantified.

The probabilities of individual collision events between catalogued objects can be predicted over the short and long-terms by means of deterministic methods, and these are produced routinely for missions in LEO. However, the probabilities of collision events involving more abundant, non-trackable objects are typically assessed using models that incorporate statistical methods.

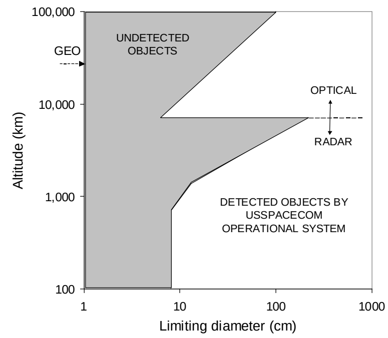

Figure 1. Capability to detect space objects

Evolutionary space debris models are typically developed for short-term or long-term analysis of space debris. Short-term analyses, of the order of days after a fragmentation event, generally focus on the collision hazard to single spacecraft or constellations. These models can contain high precision support models of the fragmentation process, orbit propagators containing short period perturbative expressions, and collision risk assessment tools that provide detailed information about the hazards to on-orbit systems. One example of such a model is the Space Debris Software (SDS) suite developed at the University of Southampton, under contract to DERA [4]. In contrast, long-term space debris models involve the evolution of the fragment clouds to a 'steady-state' environment due to the breakup. These evolutionary models require orbit propagators that incorporate long-term and secular perturbations. Further, rather than focusing on the collision risk to single spacecraft, long-term models assess the collision risk (and explosion risk) to the current and future population in order to provide predictions about the future environment. Russia's Space Debris Prediction and Analysis (SPDA) model [5], the ESA Meteoroid and Space Debris Terrestrial Environment Reference (MASTER) model [6][7], DERA's Integrated Debris Evolution Suite (IDES) model [8][9], Italy's Semi-Deterministic Model (SDM) [10], and NASA's EVOLVE model [11] use

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statistical and semi-deterministic methods to predict debris collision risk over periods ranging from tens to thousands of years. These models account for Earth orbits from LEO and, in some cases, to GEO altitudes.

The development of a new model at the University of Southampton began in 1999. Funded by the UK's EPSRC (Engineering and Physical Sciences Research Council), the work at Southampton is aimed at the investigation of the long-term evolution of space debris in High Earth Orbit (HEO) using both deterministic and statistical methods. The new model, entitled DAMAGE (Debris Analysis and Monitoring Architecture for the Geosynchronous Environment), focuses on debris populations in Geosynchronous Earth orbit. The model also includes objects in Earth orbits that intersect the GEO region such as Geostationary Transfer Orbits (GTOs).

The following paper explains the development of the DAMAGE model, including its structure, operation and evolution, and discusses the challenges of GEO modelling in this context.

2. THE DAMAGE MODEL

University of Southampton's DAMAGE model is a long-term space debris and meteoroid environment model valid for Earth orbits between 2,000 km and super-GEO (GEO + 2,000 km) altitudes. Rather than being an extension of an existing LEO model, DAMAGE is a new analysis tool dedicated to overcoming the challenges of modelling the GEO environment. One of the key features of this new model is the incorporation of a set of collision risk assessment tools that can be used separately or in combination depending on the application. The main applications of the DAMAGE model are:

- Assessment of risk to spacecraft operating in HEO
- Evaluation of the long-term stability of the HEO environment
- Assessment of a variety of proposed mitigation measures
- Evaluation of proposed and new spacecraft disposal strategies

In order to fully explore these applications and to ascertain which collision risk method is appropriate, the new model must provide a framework on which existing and new methodologies can be developed and validated. This requirement ensures that optimal algorithms can be identified, whereby the best compromise between precision and computational expense guarantees quality of results in the minimum of computational time. To meet this requirement, DAMAGE is being designed and developed using object-oriented techniques.

In a departure from the development of other models, the DAMAGE model operates on PC-based computer systems running Microsoft Windows, rather than on Unix-based operating systems. The code development is done in C++, under Microsoft's Visual C++ Developer Studio and takes full advantage of the Microsoft Foundation Classes (MFC) to allow user interaction. In addition, the graphical user interface (GUI) is enhanced by the use of OpenGL, which removes the computational difficulties of generating high-performance graphical output.

DAMAGE utilises a similar flow of data to existing debris models such as IDES (see Fig. 2) [9]. Upon initialisation, the orbiting objects at the reference epoch are analysed to determine if a breakup has occurred as a result of an explosion or a collision. Any new debris objects created as a result of a breakup are added to the population and all are propagated to the next epoch. Mitigation measures are then imposed upon the population and new launch objects are added. The processing steps are repeated until the final epoch is reached. At each time-step, a record of the full information scope of the model is made.

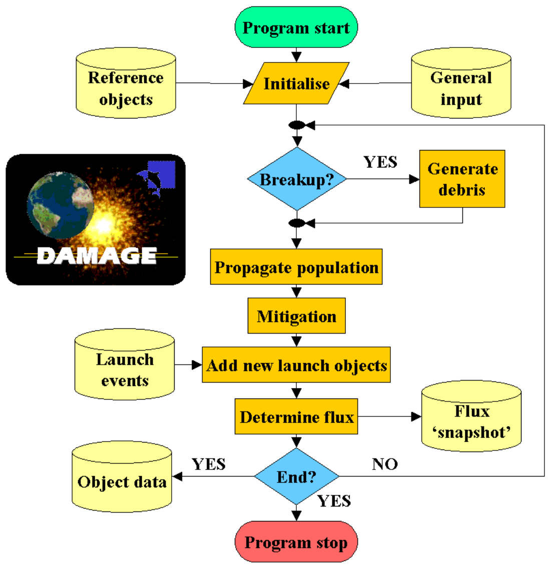

Figure 2. DAMAGE flowchart

DAMAGE follows an object-oriented design, which allows the key components of the model to be developed independently and then easily integrated. In addition, different versions of common components can be developed and selected at run-time, either automatically or manually depending on the application. Fig. 3 illustrates the basic architecture of the DAMAGE model.

The key components, represented by C++ classes within the software, include a computational model of the environment (Environment), and support models to evolve the environment. The support models include a model of orbiting objects (Satellite), an orbit propagator (Propagator), an event model (Event), a breakup model (Breakup), an inertial control volume (Volume) and a set of mitigation processes (Mitigation). The graphical user interface (GUI) communicates with the Environment component via the standard Microsoft Windows Document-View class structure. This latter design strategy allows the key components to remain entirely portable across different operating systems. The key components of DAMAGE are described in detail in the following sections.

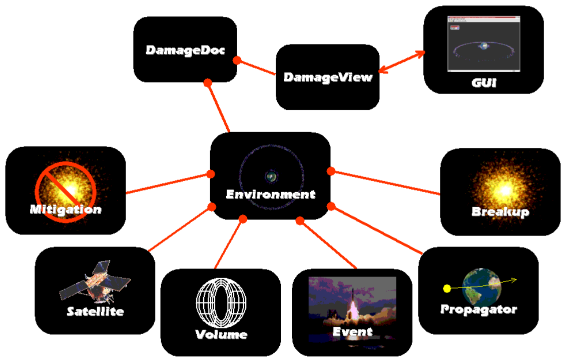

Figure 3. DAMAGE architecture

2.1 Environment

The Environment component of DAMAGE will maintain initially a record of the population of objects with sizes larger than 0.1 mm orbiting at altitudes from 2,000 km to GEO disposal orbits at super-GEO altitudes. Later developments will also concentrate on smaller particles, such as those resulting from SRM burns.

As part of the validation of DAMAGE, it is intended to use historical launch data to evolve the environment from 1957 to the reference epoch of 1 August 1999 using the support models in the form of Propagator, Event, Breakup, and Mitigation C++ classes. The population at the reference epoch can then be evolved over a period of years using the support models to predict the state of the future environment.

2.2 Volume

As well as storing a record of orbiting objects, the Environment component will also use a series of inertial control volumes to store information, such as object numbers, spatial densities and particle fluxes for use in statistical and semi-deterministic collision risk assessment routines and for producing snapshots of the space debris environment. At each epoch the information content of the control volumes is updated by the Environment component.

Inertial control volumes are found in many evolutionary models, such as IDES 2.0, MASTER99 and EVOLVE 4.0. Typically, the environment is separated into a number of bins in right ascension, declination and altitude as shown in Fig. 4. Spatial densities for each bin can be computed simply as the number of objects resident in the bin divided by the volume of the bin. Particle fluxes and collision probabilities can then be estimated from relative velocities and residential probabilities [12].

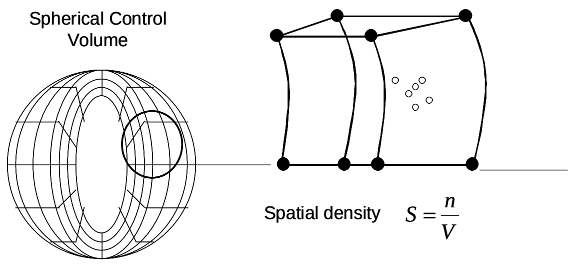

Figure 4. Inertial control volume for DAMAGE.

Statistical models of the LEO space debris environment, such as SPDA [5], store the orbiting population in a limited set of altitude bins. Fast projections of the future long-term evolution of debris can then be made using analytical expressions for the spread of objects due to launches, explosions and collisions.

One of the key characteristics of GEO spacecraft operations is found in the use of deadband slots that delimit the longitude assigned to spacecraft. As the Geostationary arc is a limited resource spacecraft operators often have to share slots with other operators leading to satellite bunching in certain longitude zones, and an increase in the probability of collision [13]. In addition to the standard volumes described above, DAMAGE will also incorporate a deadband-based Volume component that will enable the risks associated with bunching to be investigated.

Another volume that will be investigated within the DAMAGE framework is a novel dynamic control volume that aims to maximize the computational speed associated with spatial density and particle flux calculations. The dynamic control volume method proposed for DAMAGE utilises volume cells in the form of spheres of constant radius, dubbed 'Bubbles', which are centred on satellites and large debris to determine the spatial density within localised areas of space. As the method only creates as many bubbles as there are large objects, the number of cells in the volume remains low, thereby reducing the memory requirements and the time to calculate collision probabilities for all large objects.

Aside from the increase in speed, the dynamic volume method is able to generate wholly new representations of the space debris environment that can be visualised via the DAMAGE GUI. One example of such a representation is the dynamic spatial density map that displays density 'hot-spots' (see Fig. 5).

Figure 5. DAMAGE dynamic spatial density map.

2.3 Satellite

The Satellite component stores information about an orbiting object for use in the semi-deterministic support models. In first versions of DAMAGE, this information will include:

- Orbital elements a, e, i, ω, Ω, θ and state vectors **r** and **v**,
- Longitude λ,
- Mass, m, and size, d, and
- Description and catalog number.

Whilst the number of objects in Geosynchronous Earth orbit is much less than the number in LEO, the population still remains a source of computational burden. In order to reduce the total number of orbiting objects, representative particles may be used. Here objects of common properties are grouped and are assigned a weighting factor corresponding to the group size [6]. This approach would increase the computational speed of the semi-deterministic support models and reduce the overall memory requirement. Whilst some precision may be lost with this approach, the ability to simulate long time periods using semi-deterministic methods remains of paramount importance for mitigation studies.

2.4 Propagator

Unlike Earth orbits at LEO altitudes, objects at altitudes greater than 2,000 km do not encounter atmospheric drag, so that debris persists for much longer periods in Earth orbit. However, there are other characteristics of the HEO regime that affect the orbital evolution of orbiting debris significantly. The main orbit perturbative forces considered in DAMAGE's propagator are:

- Earth gravitational harmonics including zonal (for example, J_2 secular terms cause a slow precession in nodal position) and tesseral (for example, $J_{2,2}$ causes objects on the GEO ring to undergo a longitudinal drift).
- Solar Radiation Pressure (SRP), which induces an eccentricity oscillation in the orbits of objects having high area-to-mass ratios.
- Luni-solar gravitational attraction which causes the inclination of objects in GEO orbits to change up to 15 degrees.

Of primary importance is the gravitational perturbation associated with the Earth tesseral harmonic $J_{2,2}$. This causes the longitude of objects at, or near, GEO altitudes to drift in an Easterly or Westerly direction, such that the rate of change of longitude is,

$$\ddot{\lambda} = \frac{1}{2} k^2 \sin 2\left(\lambda - \lambda_{2,2}\right), \qquad (1)$$

where

$$k^2 = 36 n^2 J_{2,2} \left(\frac{R}{a}\right)^2 \cos^4(i), \qquad (2)$$

λ is the longitude of the spacecraft, $\lambda_{2,2}$ is the closest stable longitude, n is the spacecraft's mean motion, $J_{2,2}$ is the constant associated with the 2,2 tesseral harmonic, R is the mean equatorial radius of the Earth, a is the semi-major axis length of the spacecraft, and i is its inclination [14]. The impact of this orbital perturbation is that operational spacecraft require many station-keeping manoeuvres to maintain their position within an assigned longitude slot. Dead spacecraft and debris will oscillate about the stable longitude positions.

2.5 Event

The Event component combines several support models under one event manager. The support models utilised by Event include a future launch traffic database, a future explosion database and a collision risk assessment tool.

The use of an object-oriented approach in DAMAGE's design, and a variety of control volume representations, will allow a number of different collision risk assessment tools to be investigated. These will include statistical particle-in-a-box methods, as in [5], incremental collision flux methods using control volume cell passage events [12] and dynamic control volume cell residency, as described above, and near-deterministic methods using closest approach information to define uncertainty ellipsoids, as in [15]. The closest approach methods are suited to the collision risk assessment of relatively few objects and have been used operationally to address the collision avoidance requirements of the Space Shuttle and the International Space Station [16]. However, closest approach methods have been successfully implemented in Air Traffic Management systems to assess the collision risks to multiple aircraft [17].

In order to achieve the contradictory aims of high precision and low processing time, one phase of the DAMAGE model's development will investigate the combined use of some of these collision risk assessment methods. For example, where catalog and debris measurement data exist, closest approach methods may provide detailed information about collision events. Where little or no information is known about the small-size debris population, statistical methods such as the particle-in-a-box approach may be more appropriate and computationally faster.

2.6 Breakup

If the Event component determines that a breakup has occurred as a result of an explosion or a collision, the Breakup component of DAMAGE is used to determine the number, mass, size, relative velocities and ballistic coefficients of the fragments. In contrast to the LEO debris environment with relative velocities up to 16 km/s and averages around 10 km/s, the GEO environment features relative velocities that are typically less than the speed of sound in the spacecraft material (i.e. less than 3 km/s). Geosynchronous spacecraft in inclined orbits and those intersecting Geostationary Transfer Orbits (GTOs) will see the highest collision velocities in the range of 800 m/s to 1.5 km/s. As such, a collisional breakup model will be developed for DAMAGE to account for breakups caused by collisions occurring at these low relative velocities. Initially, this breakup model will be based upon existing models, as in [18], but later versions of DAMAGE will incorporate new models following a detailed review of current methods.

2.7 Mitigation

One of the main applications of the DAMAGE model is the investigation of debris mitigation strategies for the Geostationary environment. The Mitigation component of DAMAGE will be developed to incorporate a variety of mitigation strategies, but principally, explosion suppression, and the use of disposal orbits at super-GEO altitudes [19] and in stable, inclined Geosynchronous orbits [20]. In addition, research into the use of resonance effects in Geosynchronous orbits to reduce orbit lifetimes, as in [21], may also be conducted.

As SRP tends to modify the orbital eccentricity of small debris, disposal orbits at super-GEO altitudes proposed by the Inter-Agency Space Debris Coordination Committee are determined from the area-to-mass ratio of the spacecraft to be disposed,

$$\Delta H = 235 + 1000 C_r \left(\frac{A}{M} \right) \tag{3}$$

where ΔH is the new perigee altitude above GEO, A is the satellite average cross-sectional area, M is the satellite mass and C_r is the radiation pressure coefficient. Mitigation studies using this approach have shown that the long-term average density of fragments in the GEO ring remains at least two orders of magnitude below the current background [19].

3. MODEL VALIDATION

The validation of the DAMAGE model will be undertaken, first, by evolving the space debris environment from 1957 to the reference epoch and comparing the modelled results with historical data. Following this work, the DAMAGE model will be validated using existing evolutionary models, such as IDES and MASTER, and by comparing modelled outputs with measurement data.

4. MODEL STATUS

The first version of the DAMAGE model is currently undergoing development. The object-oriented framework has been implemented using the tools described, and several key components have been incorporated. These include the Environment component, standard and dynamic control volumes, the Satellite component, an orbit propagator, which accounts for secular terms in J_2 and oscillatory terms in $J_{2,2}$, an Event component that includes several collision risk assessment methods, and a basic GUI component. The next phase of development will address the future traffic database, the future explosion database and a low-velocity collisional breakup model. In addition, work to extend the set of orbital perturbations considered by the orbit propagator will continue. Following this work, development effort will focus on developing appropriate mitigation strategies.

5. SUMMARY

University of Southampton's new DAMAGE model is based on statistical and near-deterministic methods to generate and evolve the space debris population in high Earth orbit over long time periods. The object-oriented design allows both existing and novel methods to be applied to the challenges of modelling this orbital environment. The first version of the DAMAGE model is being developed for a limited 2001 release. In future releases the model will be extended to smaller size ranges and meteoroids.

6. ACKNOWLEDGEMENTS

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