STUDYING THE MEO & GEO SPACE DEBRIS ENVIRONMENTS WITH THE INTEGRATED DEBRIS EVOLUTION SUITE (IDES) MODEL

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ABSTRACT

The Integrated Debris Evolution Suite (IDES) has been upgraded to facilitate the modelling of the current and future space debris environments throughout Earth orbit. This paper will highlight the principal features of the model that were upgraded to allow the simulation of the environment from low Earth orbit altitudes up to the geosynchronous region. It will then give a summary of the full capabilities of IDES 3.0. Having described the upgrade, some initial results for an historical evolution of the space debris environment in Earth orbit will be presented.

1. INTRODUCTION

The Integrated Debris Evolution Suite (IDES) — developed at the Defence Evaluation and Research Agency (DERA), UK — has been established over the past few years as an excellent model for examining the long-term evolution of the space debris environment in low Earth orbit (LEO). It is able to study the historical, current and future space debris populations, in addition to providing directional collision risk assessments for satellites in LEO. However it is clear that space operations over the past four decades have not been confined to LEO but have extended to high Earth orbit and beyond. This raises the issue of how the space debris populations in medium Earth orbit (MEO) and geosynchronous Earth orbit (GEO) have evolved and will possibly evolve over the coming decades and centuries.

At GEO altitudes the United States Space Command (USSPACECOM) Space Surveillance Network can only detect and catalogue objects that are larger than ~ 1 m in size. However, recent observational campaigns by the NASA CCD Debris Telescope (CDT) [1] and the ESA 1m telescope in Tenerife [2] have revealed a substantial population of uncatalogued objects in the geosynchronous orbital region. These observations show that the number of uncorrelated (uncatalogued) targets increases towards the observational limits of the telescopes. Results from the ESA 1m telescope, which has an observational limit of 20 magnitudes (corresponding to an object diameter of ~ 10–20 cm), found that almost three-quarters (73%) of the observations could not be correlated with a known target in the catalogue.

These recent observations further emphasise the need to model both the present and possible future debris population in high Earth orbit and in the geostationary orbital region in particular. With this motivation the IDES model has been upgraded to IDES 3.0. This version of the Integrated Debris Evolution Suite is able to model the historical, current and future space debris environments throughout LEO, MEO and GEO.

2. UPGRADING THE IDES MODEL

Simulating the debris environment in high Earth orbit introduces a number of unique considerations that have to be incorporated within the model. This section highlights the key areas considered during the upgrade, including the specific challenges of GEO modelling and the approaches used within IDES to meet them.

Launch/Explosion Traffic

The launch and explosion traffic plays a pivotal role in determining the population growth and collision rate within the Earth orbital environment. For historical evolutions of the environment every known debris source and sink since the launch of Sputnik 1 in 1957 is included within the model. The databases from which the future launch and explosion traffic are derived, have been determined from recent historical activity. The current population epoch within IDES is 31 March 1998, although this is currently being updated to 2001.

Population Representation

Within IDES 3.0 all objects are represented using particles with associated weighting factors. The debris generated by a fragmentation event (explosion or collision) is added to the population as a user-defined number of representative objects.

Flux Determination

The flux environment is determined using a technique similar to the Klinkrad method. To facilitate this the Earth orbital environment is divided into three inertial control volumes: one for low Earth orbit, one covering

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MEO and one for the geosynchronous region. The precise extent of these volumes is dependent on the resolution chosen for the radius, declination and right ascension in each of the three regions.

Breakup Models

Typical relative velocities within the geostationary ring are of the order of only a few hundred metres per second. This increases to 3–5 kms^{-1} for objects in geostationary transfer orbits intersecting the ring. Comparing these values to a typical relative velocity in LEO of about 10 kms^{-1}, it is apparent that a low-collision-velocity breakup model is needed in conjunction with the existing hyper-velocity models within IDES. The low-velocity model implemented in IDES 3.0 is taken from the work of Hanada et al. [3].

The threshold velocity, below which the low-velocity breakup model is used, is taken as the lower limit of the hyper-velocity impact tests used to derive the hyper-velocity breakup models, that is 3 kms^{-1}.

Orbit Propagation

Two aspects of the orbit propagation within IDES have been considered: the orbital perturbations, and the manner in which the different types of orbit are treated within the propagator. As orbital altitude increases through to the medium and geosynchronous regions, the dominant orbital perturbations become lunar and solar gravity, solar radiation pressure and geopotential. In addition to the zonal harmonics of the Earth's gravitational field, the tessoral harmonics play an influential role for geosynchronous orbits. To accurately model the evolution of the population in the geostationary ring it is essential that the J_{22} tessoral harmonic, otherwise known as longitudinal drift, be included within the orbit propagator. The principal effect of this perturbation is to produce an oscillation in the semi-major axis of an orbit.

In the geosynchronous region there are *three* distinct types of orbit to be taken into account:

a. Geostationary orbits: these operational satellites are subject to both east-west and north-south station keeping manoeuvres, maintaining them within a given latitude-longitude box. To model this active orbit control such orbits are not subjected to any perturbations within the propagator.
b. Geosynchronous or "free-drift" orbits: these operational satellites are subject to east-west station keeping manoeuvres only, maintaining them within a given longitude slot. Hence these orbits are not perturbed by the J_{22} tessoral harmonic.
c. Uncontrolled orbits: these objects are not subject to any station-keeping manoeuvres and are thus influenced by all orbit perturbations. All non-operational satellites and debris are in this category.

Mitigation Measure Modelling

When assessing the long-term evolution of the debris environment, it is important to consider the effectiveness of implementing mitigation measures for controlling future debris growth. In high Earth orbit regions, these measures include mission related object limitation, explosion prevention, and re-orbiting of objects at their end-of-life. To accurately model these measures within IDES 3.0 it is possible to define multiple storage orbits, one for each of the orbital regions being considered.

2.1 Summary of IDES 3.0 Model Capabilities

IDES 3.0 is a semi-deterministic model, employing a Monte Carlo method, to simulate the historical, current and future space debris environments in Earth orbit. A full summary of the capabilities of the model is given in Table 1.

3. RESULTS

Following the upgrade to IDES 3.0 a first historical evolution has been performed, simulating the growth of the man-made space debris population in Earth orbit. The principal purpose of these results was to test the operation of the upgraded software and as such the resolution used to produce the results (given in Table 1) is not the highest available.

Table 1. Resolution of the control volumes for this historical evolution

	Δr (km)	**$\Delta\delta$ (°)**	**$\Delta\alpha$ (°)**
LEO (6,498 – 8,378 km)	25	5	360
MEO (8,378 – 41,378 km)	1000	20	360
GEO (41,378 – 43,178 km)	50	5 (-20° – 20°)	10

Fig. 1 shows the spatial density distribution over altitude at the current population epoch of 31 March 1998. For object sizes greater than 10 cm the peaks representing the most popular orbits can be observed: the 800–1000 km and 1400 km peaks in LEO, the 12-hour orbits in MEO and the geostationary ring. The collection of graphs in Figs 2–4 shows the growth in debris greater than size thresholds of 1 mm, 1 cm and 10 cm. Each of these graphs is broken down into the average number of objects in each of the LEO, MEO and GEO orbital regions. The increase in the low Earth orbit population during the 1980s, due to a combination of a high explosion rate and the release of NaK droplets into the environment from the Russian RORSAT

Table 2. A summary of IDES 3.0 model capabilities

	Details
Orbital Regions Modelled	LEO, MEO & GEO
Sources	▫ Launches (including all launch related objects) ▫ Fragmentation events (see below) ▫ NaK droplets
Launch/Explosion Traffic	Historical: ▫ Every launch and fragmentation event from Sputnik 1 in 1957 up to 31 March 1998 (being updated to 2001) Future: ▫ Launch/Explosion traffic databases derived from 8 years of historical data: 31 March 1990 – 31 March 1998 (being updated in 2001) ▫ Traffic events statistically determined, from the databases, using a Poisson distribution ▫ Includes satellite constellation mission model ▫ Yearly launch/explosion rate scaling factors
Population Representation	Representative particles with weighting factors. User-defined number of representative particles used to model each fragmentation event.
Flux Determination	Klinkrad method with 3 control volumes representing LEO, MEO & GEO: ▫ Three-dimensional (radius r, declination δ, right ascension α) ▫ 8 mean flux vectors defined per cell of the control volume ▫ User-defined resolution
Collision Prediction	Walker Target-centred approach. Target is taken as any object in population with mass > 50kg.
Fragmentation Events	▫ High intensity explosions – 50:50 split of breakup mass between exponential and power-law distributions ▫ Low intensity explosions ▫ Catastrophic collisions ▫ Low-velocity collisions – A collision is 'low-velocity' if the impact velocity is $\leq 3\ \text{kms}^{-1}$ ▫ Damaging impacts – Defined as impacts with an energy-to-mass ratio (EMR) < lethality ratio of the target
Orbit Propagation	Fast analytical method determining the variations in orbital elements over a user-defined timestep. All major orbit perturbations for debris larger than 10μm: ▫ Geopotential – J_2 & J_3 zonal harmonics + J_{22} tessoral harmonic – J_3 & J_{22} are switched off for operational satellites ▫ Atmospheric drag – Stationary, spherically symmetric, exponential atmosphere with a constant scale-height – Switched off for operational satellites ▫ Luni-solar gravity – Switched off for objects with apogee altitude < 2000km ▫ Solar radiation pressure (SRP) – Including Earth shadow effects – Switched off for objects > 1mm in size
Mitigation Measure Modelling	The following mitigation measures can be switched on/off as required: ▫ Mission-related object limitation ▫ Passivation (explosion prevention) ▫ De-orbiting at end-of-life for rocket bodies and payloads below a certain threshold altitude within a given lifetime limitation ▫ Re-orbiting at end-of-life for rocket bodies and payloads above a certain threshold altitude – Multiple storage orbits (one for each control volume being modelled) Note: different implementation dates can be entered for each mitigation measure (payloads and rocket bodies are handled separately).

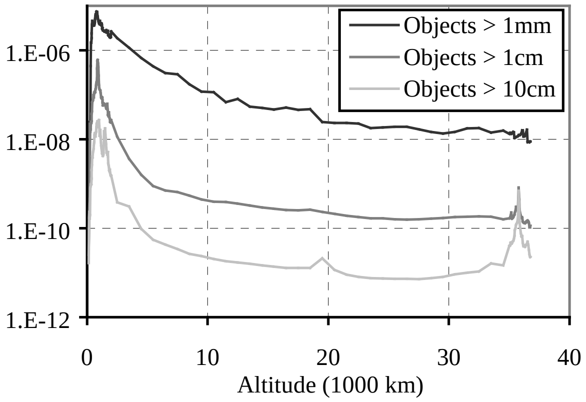

Fig. 1. Spatial density distribution of all man-made objects in Earth orbit as of 31 March 1998

satellites, can be clearly seen. This increase is also reflected in the growth of the small size (> 1 mm) population in medium Earth orbit. Indeed the nature of these fragmentation events has resulted in there being a greater average number of objects in the vast MEO region than there is in LEO. In comparison the debris population at geosynchronous altitudes is small, although the results show that there is a steady increase in the number of large (> 10 cm) objects. However, given the usage of the GEO environment this small absolute number does result in a sharp peak in the spatial density (see Fig. 1).

4. CONCLUSION

The successful upgrade of the IDES model to IDES 3.0 has provided an excellent tool for studying the space debris environment throughout Earth orbit. It is able to examine both the historical and future evolution of the debris population, and will provide an insight into the effectiveness and implications of mitigation measures in LEO, MEO and GEO.

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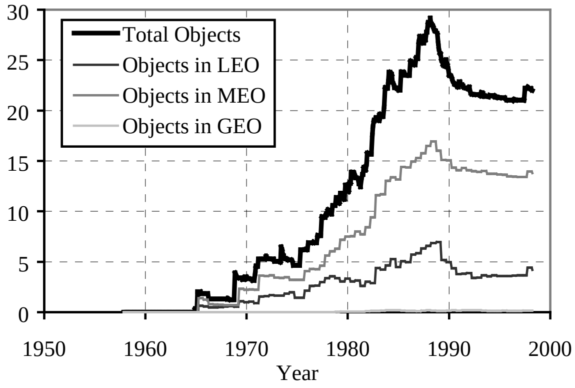

Fig. 2. Historical evolution of the number of man-made objects in Earth orbit > 1 mm in size

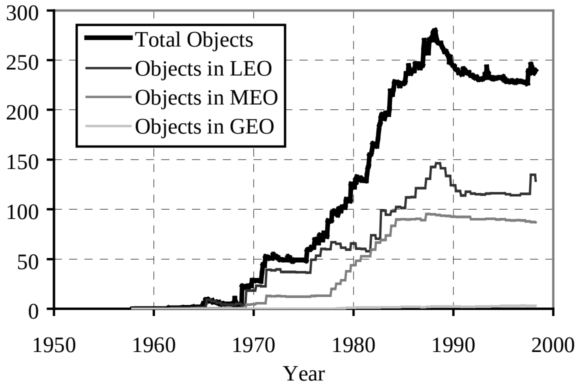

Fig. 3. Historical evolution of the number of man-made objects in Earth orbit > 1 cm in size

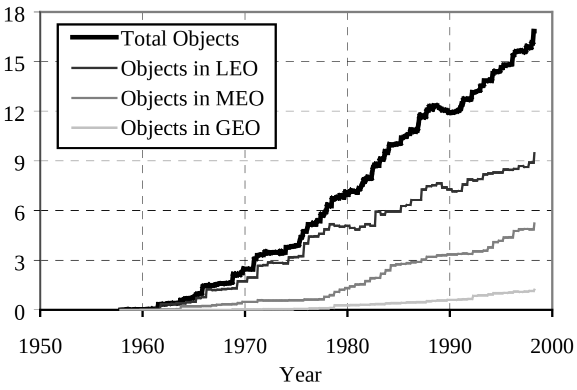

Fig. 4. Historical evolution of the number of man-made objects in Earth orbit > 10 cm in size