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THE GEOSYNCHROUS ENVIRONMENT FOR ORDEM2010

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The new version of the NASA Orbital Debris Engineering Model (ORDEM2010) requires accurate populations as input files to be used in the calculation of orbital debris fluxes on chosen spacecraft or within telescope/radar fields-of-view. Populations in ORDEM2010 are derived from an amalgam of data and modeling. Geosynchronous orbit (GEO) satellites and debris form a distinct ORDEM2010 population that is applied to the distinct analysis of GEO fluxes. Low Earth orbit (LEO) populations are derived by combining modeling results with ground-based data, primarily from radar systems, and in-situ data. In contrast, the GEO region has not been as well observed. The distance between orbiting objects and ground-based instruments precludes the wide usage of radar as a means of observation. Instead, optical instruments dominate in the study of GEO. Of these, the NASA sponsored Michigan Orbital Debris Survey Telescope (MODEST) has provided 3 years of surveys of the region detecting cataloged objects (correlated targets) and non-cataloged objects (uncorrelated targets) to an estimated minimum size of 30 cm.

This paper describes the methods of combining NASA launch database and satellite breakup and orbital propagation modeling with MODEST 2004-to-2006 uncorrelated target data to attain a GEO environment to 10 cm. Assuming that MODEST uncorrelated targets are breakup debris allows for the extension of the debris survey data to smaller sizes using the NASA Standard Breakup Model. Each orbit within the total resulting GEO population is marked by a random argument of perigee and nearly constant mean motion, eccentricity, inclination, and right ascension of ascending node (RAAN) over the nearly 3 years of observation. Lack of published references of past breakups in GEO is mitigated by the orbital propagation of MODEST extended data to 1995 (the beginning epoch of ORDEM2010).

Introduction

The GEO region forms a comparatively narrow circular band centered at about 36000 km altitude and extending about ±6000km altitude in nearly equatorial orbit. For the purposes of this paper, "GEO" will refer to any satellite in the general GEO region, not only true geosynchronous satellites specifically placed in orbits so that their periods match the sidereal rotation rate of the Earth (mean motions of one revolution/day). Most of the objects defined as "GEO objects" in this paper were either launched in association with a true GEO satellite, or their parent body was such an object.

The GEO region is distinguished by its use and its orbital dynamics. The active spacecraft population consists of mainly communications and Earth-observing satellites restricted to the equatorial belt with orbits strictly maintained by regular station-keeping maneuvers. The dominant perturbative forces of the region result in orbit evolution of GEO satellites different from those in LEO. One

distinct feature is the 53-year cycle in inclination and RAAN followed by uncontrolled satellites. This behavior, noted in previous work, is a function of the interaction of luni-solar gravity with perturbations due to the Earth's oblateness.[1,2] Mean motion and eccentricity are also coupled. Argument of perigee is generally random.

The distance from Earth limits the routine use of radar systems in observing small objects in GEO due to the high power and narrow field-of-view required. Much of the GEO survey work by U.S. Space Surveillance Network (SSN) is done using optical instruments, with a minimum estimated size of about 70 cm, compared to the radar-limited minimum size in LEO of about 5 cm. Explosions are a dominant debris source in LEO. At present, 139 accidental explosive breakups have been known to occur. This suggests that the confirmed explosive breakup count in GEO, standing at two, is an underestimate due to the lack of small object observations. For these reasons more powerful optical instruments have been used to probe the small satellite population in GEO. Presently, ESA's 1-meter Tenerife Telescope and NASA's 0.6-meter Michigan Orbital Debris Survey Telescope (MODEST) are the major systems dedicated to GEO debris research.

These systems have revealed a near-GEO environment that includes a large population of dim non-cataloged objects, termed uncorrelated targets (UCTs). The ESA system, in particular, which can detect objects in GEO down to about 10 cm, noted significant 'clouds' of dim objects in orbits associated with uncontrolled cataloged intact satellites.[3] ESA subsequently surmised the existence of 10 specific fragmentation events in the GEO region to account for the observed clumping. The ESA debris environment engineering model MASTER[2005] includes these breakups in its debris flux calculations.[4]

NASA's MODEST is sensitive to objects down to about 30 cm. However, there is a mandate to include GEO objects down to 10 cm in the updated ORDEM2010. Fortunately, statistics of the UCT population in GEO seemed to indicate that the size distribution is consistent with the NASA Standard Breakup Model based on LEO breakups. This allowed for a reasonable extrapolation of the population down to 10 cm.

In the following sections the technique of extrapolating MODEST 2004-to-2006 survey data to 10 cm is described. The use of LEGEND 2006 modeling to assign orbital elements to the extrapolated debris, and finally the derivation of the final population for 1995 through 2035 is justified. The resulting yearly GEO populations serve as input to the ORDEM2010 model.

Data Analysis and Model Support

MODEST 2004-to-2006 survey data consists of individual observations of objects moving through the telescope field-of-view at rates characteristic of GEO orbits.[5] These include correlated targets (CTs) that have been identified as SSN cataloged objects and UCTs. Because the data is limited to short arcs, the calculated orbits of UCTs are generally limited to circular orbit approximations. The calculated circular orbit mean motions are not necessarily very accurate, but in general the inclination and RAAN calculations are much better. Eccentricity and mean motion of CTs are taken directly from the SSN catalog. MODEST UCT object sizes are estimated from absolute magnitudes (the measured magnitude corrected for range and solar phase angle).

The basis for extrapolating the MODEST UCT 2004-to-2006 survey data to 10 cm is based on a detailed analysis of the data. Consideration of the dimmest MODEST UCTs as unidentified fragmentation debris has been suggested in previous work.[6] That characteristic is displayed in the current MODEST data set in Figure 1. Here the UCTs with absolute magnitudes above 14 increase in number as brightness decreases (corresponding to a decrease in size) in a manner consistent with a power-law distribution. Translating absolute magnitude to size shows a log-log slope of cumulative UCT number vs. estimated size consistent with that of the −1.6 slope for explosive fragmentation debris seen from LEO rocket bodies (Figure 2).[7] This figure suggests that assuming GEO exploding spacecraft and rocket bodies behave in the same manner as do their LEO counterparts, it is reasonable (most effective) to consider the GEO fragments as remnants of seven to nine rocket body propulsion-related explosions. The MODEST data extrapolation in number vs. size for fragments

from 10 cm to 30 cm is taken directly from this curve. The extrapolated population, of course, contains no orbital elements.
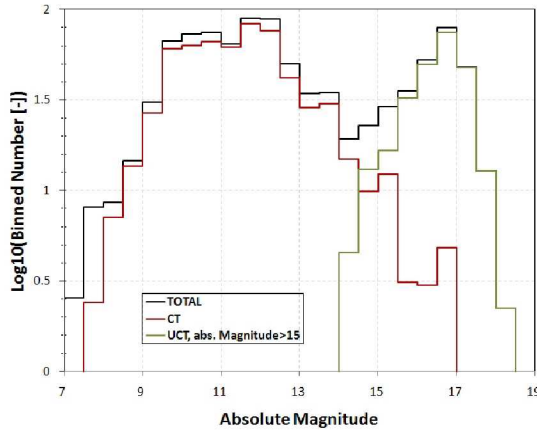

Figure 1. Absolute magnitude in bins of 0.33 from the MODEST UCT 2004-to-2006 data set. Note that the drop-off in detections dimmer than about magnitude 17 are due to the magnitude limits of the MODEST telescope system.
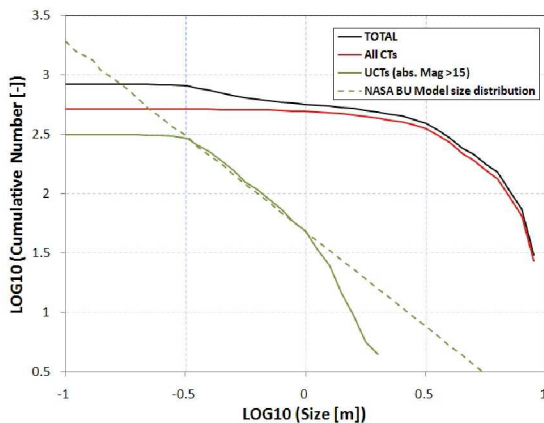

Figure 2. Cumulative size of UCTs vs. NASA Standard Breakup Model size distribution.

The judicious assignment of the unknown orbital elements (mean motion and eccentricity) to the measured MODEST UCTs and extrapolated population sets is accomplished by comparing the population from NASA's long-term environment model, LEGEND, to the MODEST sets. A standard GEO run of LEGEND to 2006 would include the two verified breakups in the region. However, the extrapolation of the MODEST UCT data in Figure 2 suggests that at least eight unrecorded explosions have occurred in the GEO region assuming the NASA Standard Breakup Model applies. To simulate these events

LEGEND is edited to run in a 'historical random breakup mode'. That is, explosions and collisions are set to occur by two means, through the historical database files (standard historical modeling), and through random happenstance, which is based on predefined event probabilities (standard projection modeling, based on historical experience in LEO). The resulting LEGEND run for the year 2006 with a total of 100 Monte Carlo simulations, gives a GEO population of 10 cm and larger objects. These include launched objects from a SSN-derived data file from 1964 through 2006, and fragmentation debris from a predicted average of eight random rocket body explosions. No collisions occur randomly during this time period, as is expected. LEGEND results for the randomly derived fragments are used as probability distribution functions (PDFs) and are applied to the MODEST and extrapolated MODEST data sets. Orbital elements consistent with those of this LEGEND environment are the result.

The assignment of eccentricity and mean motion must be done for debris from both MODEST and extrapolated MODEST data sets. The size of each object is calculated from the data absolute magnitude or the extrapolated data NASA breakup model curve, respectively. Therefore fragment size can justly be considered to be the independent variable. Explosion fragments are modeled in LEGEND with accompanying empirically derived initial velocities from the explosive force. These ΔVs are size dependent (i.e., smaller fragments have the maximum ΔVs). The initial orbit eccentricities, therefore, also should display fragment size dependence. The LEGEND sizes and eccentricities at the end of 2006 shown in the density chart of Figure 3 retain the character expected given the ΔV discussion above. As size decreases the maximum eccentricity values increase. With eccentricity selected based on a PDF derived from Figure 3, the mean motion is chosen by the same process. Figure 4 displays that 2006 LEGEND density chart.
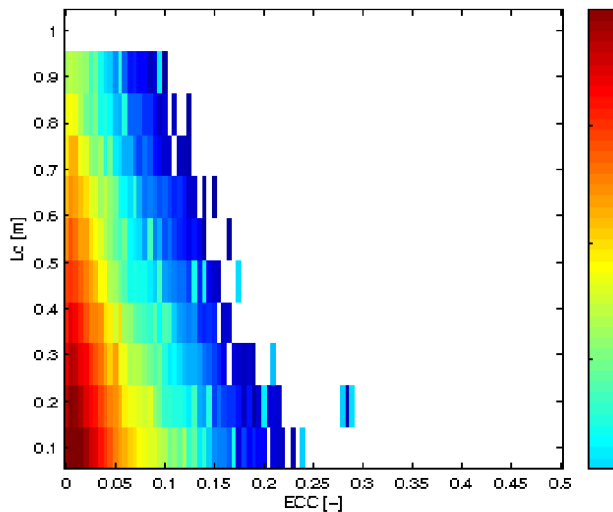
Figure 3. 2006 LEGEND GEO fragment environment population density chart for size vs. eccentricity (in log_{10} density space) in the historical random breakup mode. Bins are 0.1m by 0.005.
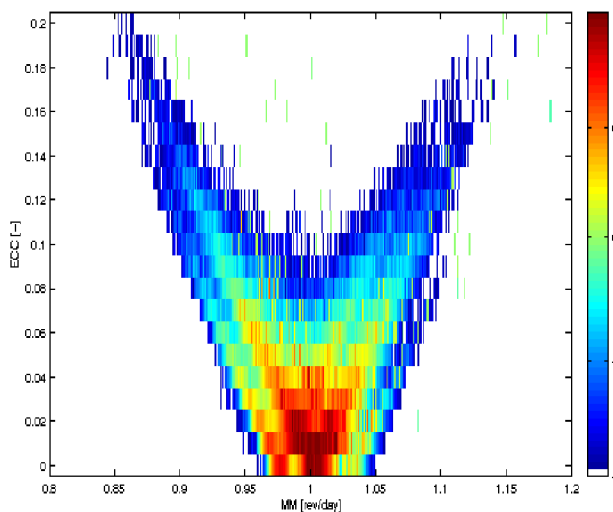

Figure 4. 2006 LEGEND GEO fragment environment population density chart for eccentricity vs. mean motion (in log_{10} density space) in the historical random breakup mode. Bins are 0.005 by 0.001.

Inclination and RAAN are used directly from the MODEST data for the larger UCTs, but need to be estimated for the extrapolated MODEST data set. Figure 5 displays the 2006 LEGEND density chart. Fragment inclination and RAAN assignments are not obviously related to fragment size. Both elements depend on age of the uncontrolled fragment (i.e., how long the parent object drifted in the 53-yr cycle before it

exploded, and how long the fragments drifted after breakup).

In this case the fragment inclination is first chosen from the normalized frequency distribution of 2006 LEGEND fragment inclination (Figure 6). This figure serves as the inclination PDF. With fragment inclination chosen, fragment RAAN is derived from Figure 5.
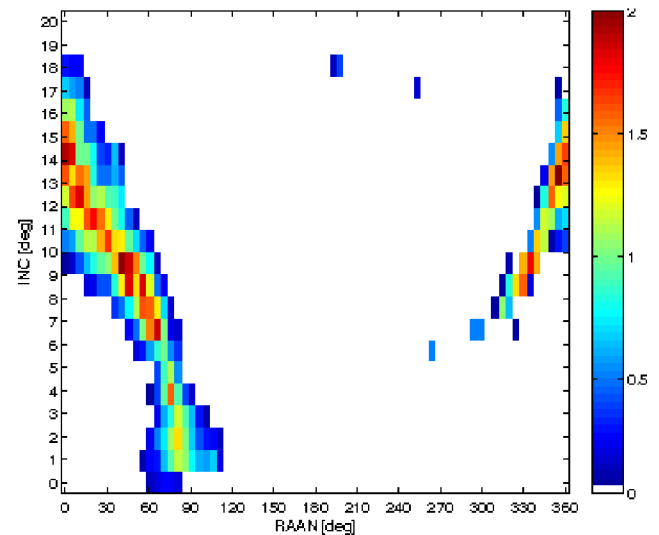

Figure 5. 2006 LEGEND GEO fragment environment population density chart for inclination vs. RAAN (in log_{10} density space) in the historical random breakup mode. Bins are 1° by 5°.
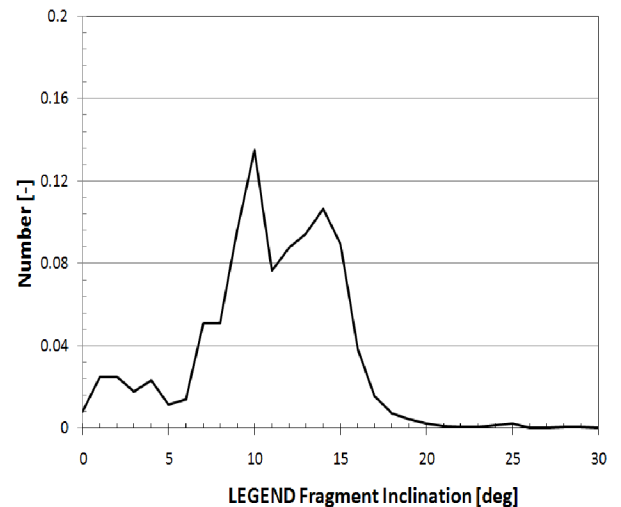

Figure 6. Normalized 2006 LEGEND model inclination PDF. Fragment inclination serves as an independent variable in the fragment RAAN assignment.

The resulting MODEST and extrapolated MODEST data include observations down to 30 cm plus the unseen, but surmised, debris population from 30 cm down to 10 cm. It includes fragment size, eccentricity, mean motion, inclination, and RAAN in terms of number of objects in orbital element bins (Figures 7a and 7b).
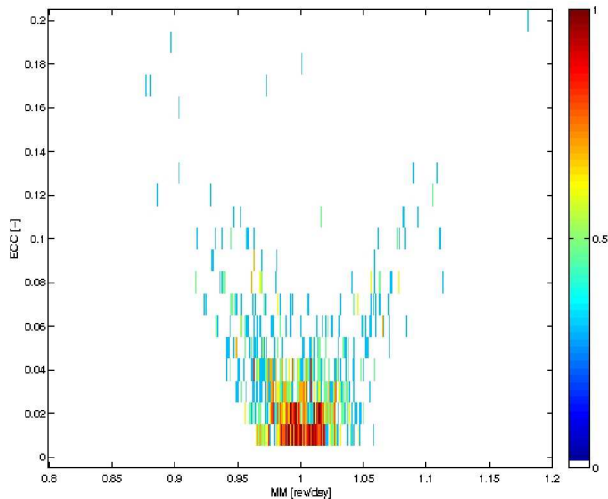

Figure 7a. Derived MODEST and extrapolated MODEST debris population eccentricity vs. mean motion for 2006.
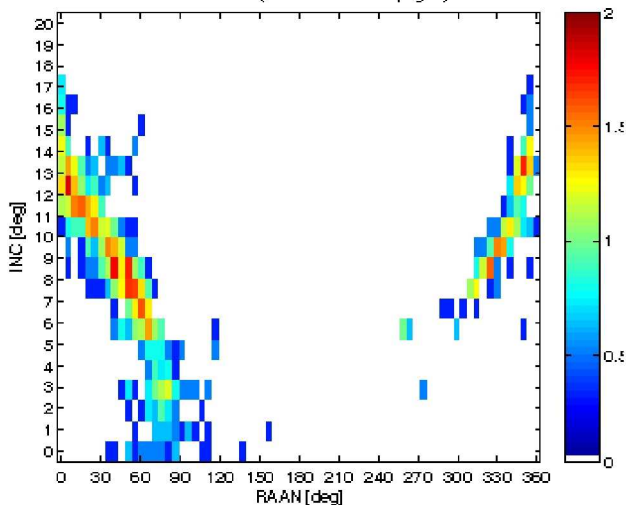

Figure 7b. Derived MODEST and extrapolated MODEST debris population inclination vs. RAAN for 2006.

ORDEM2010 GEO Input Population

The total GEO input population for the year 2006 is composed from two sources. This paper has

reported on one of them, the fragments from the MODEST and extrapolated MODEST data. In this sub-population orbital elements are derived from a LEGEND 'historical random breakup mode' population as the average of 100 Monte Carlo iterations. The second sub-population consists of known launched intacts (i.e. spacecraft and rocket bodies) and the two identified explosion event fragments. These are deposited via a standard LEGEND historical run. The resulting GEO population is the sum of the two. Figure 8 depicts the size distribution of the total derived population. LEGEND intacts and verified breakups are coupled with the MODEST derived fragments to form the ORDEM2010 GEO population for 2006, which extends in size from 10 m (large intacts) to 10 cm (fragments).
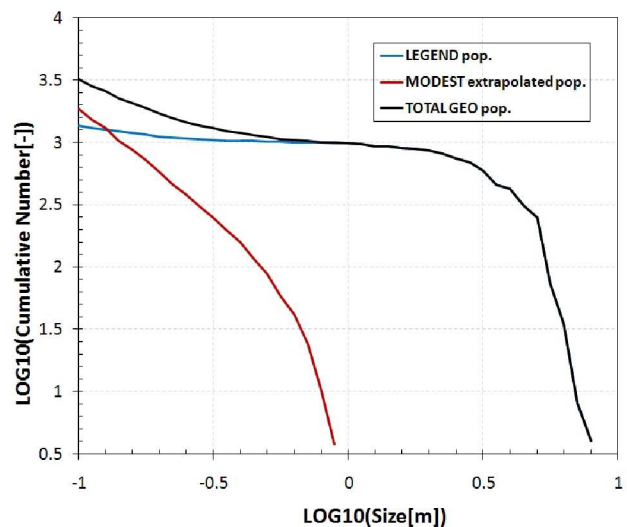

Figure 8. Total ORDEM2010 GEO population size distribution for the year 2006.

All other years within the ORDEM2010 analysis range (1995 through 2035) are derived with some reference to this 2006 population. For the historical period, 1995- 2006, the yearly LEGEND standard historical environment with known breakup events and launch traffic is supplemented with the MODEST and extrapolated MODEST small debris population that is back-propagated through those years. For the projection period, 2007 – 2035, LEGEND in projection mode deposits launched intacts on an 8-year cycle and allows random explosions and collisions to occur. The MODEST and extrapolated MODEST small debris population is forward-propagated through those years.

Summary

ORDEM2010 is the first model of the series to include a GEO population and the accompanying debris flux calculations on spacecraft through GEO or for telescope/radar detections in GEO. The detection rates and cataloging of the environment itself is far behind that of LEO. The distance to GEO precludes wide use of radar systems for statistical detection.

NASA has turned to optical instruments for that purpose, in particular the current instrument MODEST. A recent survey set for 2004-to-2006 is being used to derive a 2006 GEO population for input to ORDEM2010. The data is extrapolated from the observed 30 cm objects to 10 cm objects by the reasonable assumption that they are fragmentation debris.

Orbital elements of these fragments are chosen with reference to a LEGEND 100 Monte Carlo run in a "historical random breakup mode'. This program delivers intacts and debris into GEO regions where it would likely be seen, for random breakup events that are consistent with the MODEST data.

The 2006 population of MODEST and extrapolated MODEST fragments is propagated into the other years of the ORDEM2010 model.

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THE GEOSYNCHRONOUS ENVIRONMENT FOR ORDEM2010

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Geosynchronous (GEO) Environment

- **Region characterized by usage and dynamics**
  - Active spacecraft – communications, Earth-observing, restricted to GEO belt, orbits strictly maintained by regular station-keeping maneuvers
  - Dominant perturbative forces – interaction between luni-solar gravity and Earth-oblateness gravity terms
    - 53-year cycle of uncontrolled satellites in inclination and RAAN

- **Optical measurements in GEO**
  - Space Surveillance Network (SSN) surveys
    - Minimum size ~70 cm (subsequent radar observations)
  - ESA 1-meter Tenerife
    - Minimum size ~10 cm
  - NASA 0.6 –meter Michigan Orbital Debris Survey Telescope (MODEST)
    - Minimum size ~30 cm

- **ORDEM2010 utilizes data from MODEST 2004 – 2006 survey to build a GEO population to 10 cm.**

MODEST 2004-2006 Survey

- **Objects observed moving through MODEST field-of-view at rates characteristic of GEO orbits. Objects viewed in short arcs.**

- **Correlated targets (CTs) – objects observed by MODEST that are cataloged by the SSN.**

- **Uncorrelated targets (UCTs) – objects observed by MODEST that are not cataloged by the SSN.**

-

- **MODEST UCTs**
  - High fidelity measurements
    - object absolute magnitude, inclination, and right ascension of ascending node (RAAN)
  - Calculation of size from absolute magnitude assuming albedo=0.13
  - Circular orbit assumption necessary
    - Mean motion, eccentricity

- **MODEST UCT files include**
  - absolute magnitude, calculated size, inclination, (RAAN), mean motion, eccentricity, probability of detection

MODEST 2004-2006 Survey and Extrapolation

- **The dimmest UCT numbers appear to increase with absolute magnitude.**
- **Cumulative UCT numbers vs. calculated size appears to be consistent with the -1.6 slope for explosive fragmentation debris seen for LEO rocket bodies.**
- **The dim UCTs are assumed to be breakup fragments and the population is extrapolated to 10 cm via the NASA Standard Breakup Model.**
- **The extrapolation indicates seven to nine undetected rocket body explosions might have occurred in GEO.**
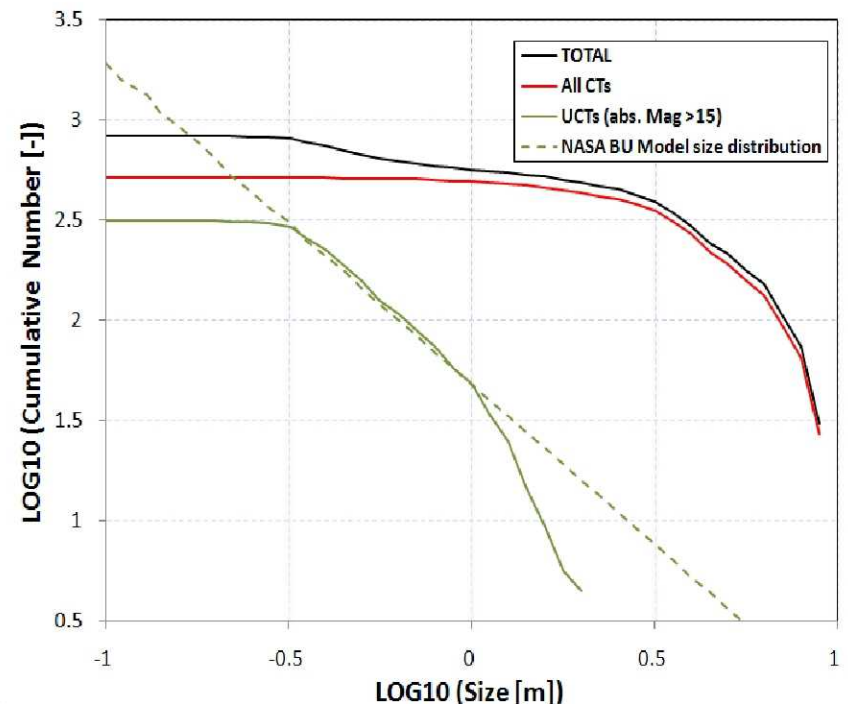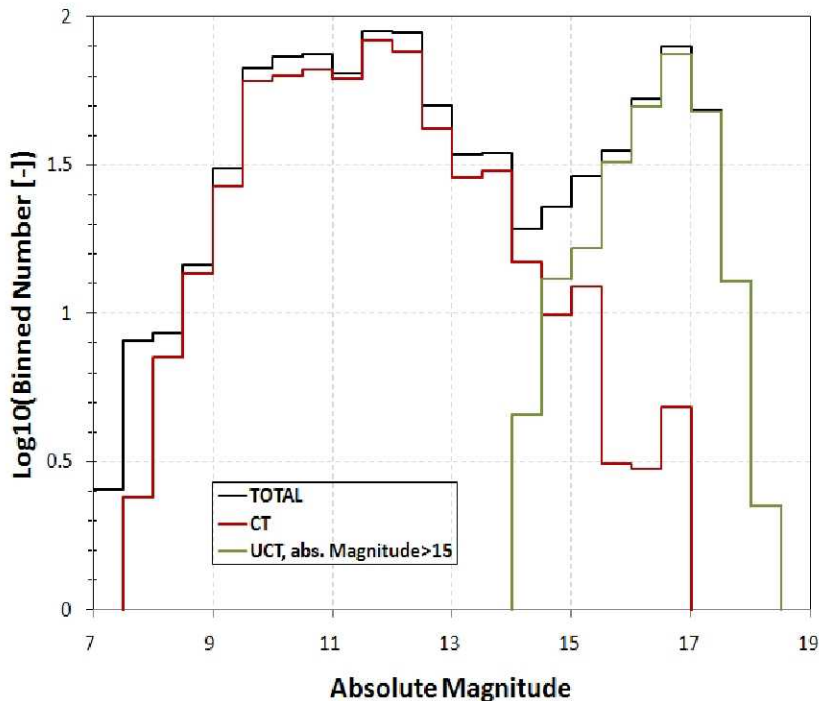
LEGEND - Assignment of Orbital Elements to MODEST data

- **MODEST data requires reasonable mean motion and eccentricity.**

- **Extrapolated MODEST data requires reasonable mean motion, eccentricity, inclination, RAAN.**

- **The NASA long-term debris environment model, LEGEND, results are used in the probability distribution functions (PDFs) for the assignment of MODEST related orbital elements.**

- **LEGEND used in an 'historical random breakup mode'**
  - Breakups (explosions and collisions) are set to occur by two means
    - From historical database (standard historical modeling)
    - Through random events (with predefined event probabilities)
  - 100 Monte Carlo iterations of the historical period (1964-2006)
  - Intacts and breakup fragments deposited every year from launches, maneuvers, historical and random events.
  - 2006 GEO environment is an average of 100 MC with an average of 8 random explosions and no collisions
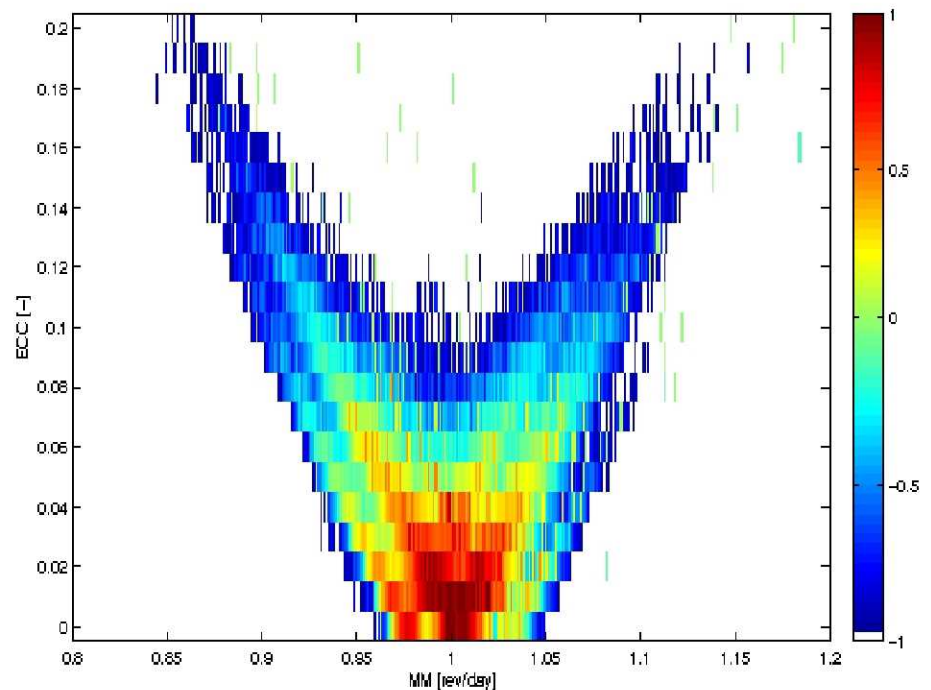 - 2006 GEO fragment environment serves as PDFs for MODEST orbital element assignments

LEGEND 2006 GEO Fragment Environment (1/2)

- **MODEST UCT derived sizes are estimated from measured absolute magnitudes (data) and the NASA Standard Breakup Model (extrapolated data), and are considered the independent variable in MM, ECC assignments.**
  - Given a fragment's size, eccentricity is derived. Given a fragment's eccentricity, mean motion is derived.

**LEGEND fragment
Size vs. Ecc density chart
(0.1m by 0.005 bins)**
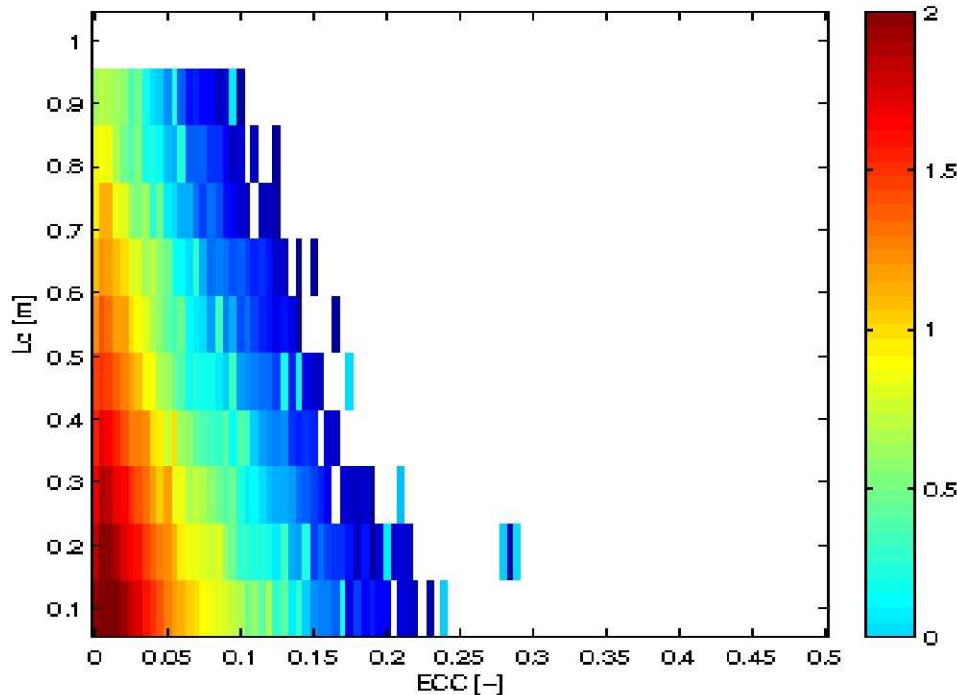
**LEGEND fragment
Ecc vs. MM density chart
(0.005 by 0.001 bins)**

LEGEND 2006 GEO Fragment Environment (2/2)

- **MODEST UCT extrapolated data also requires inclination and RAAN assignments. Neither element is directly related to object size.**

- **Inclination and RAAN depend on the age of the uncontrolled object .**
  - how long the parent objects drifted in the 53-year cycle before it exploded, and how long the fragments drifted after breakup

LEGEND fragment
Inclination frequency
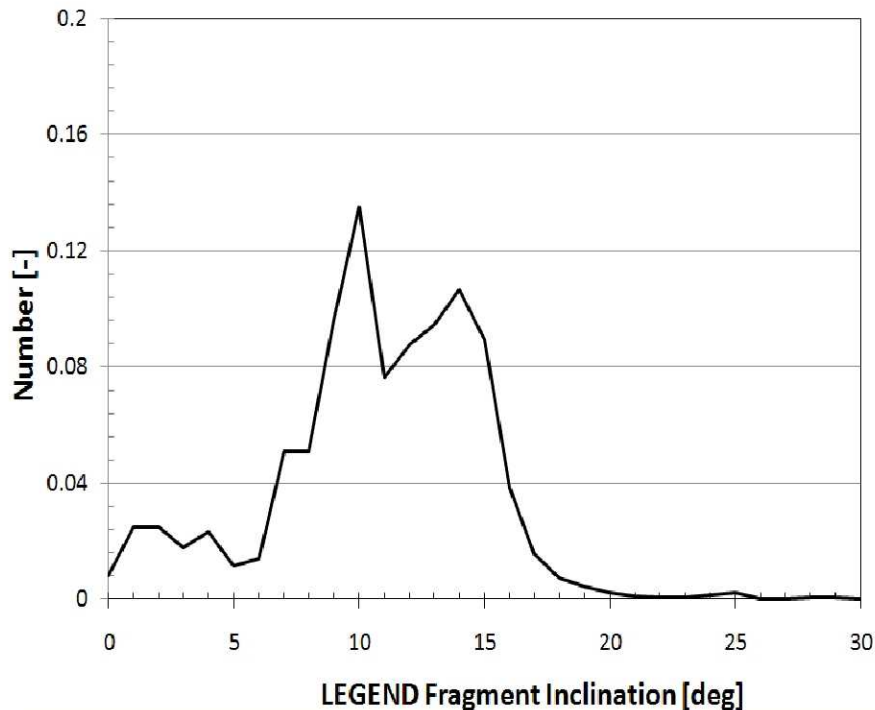
LEGEND fragment
Inc vs. RAAN density chart
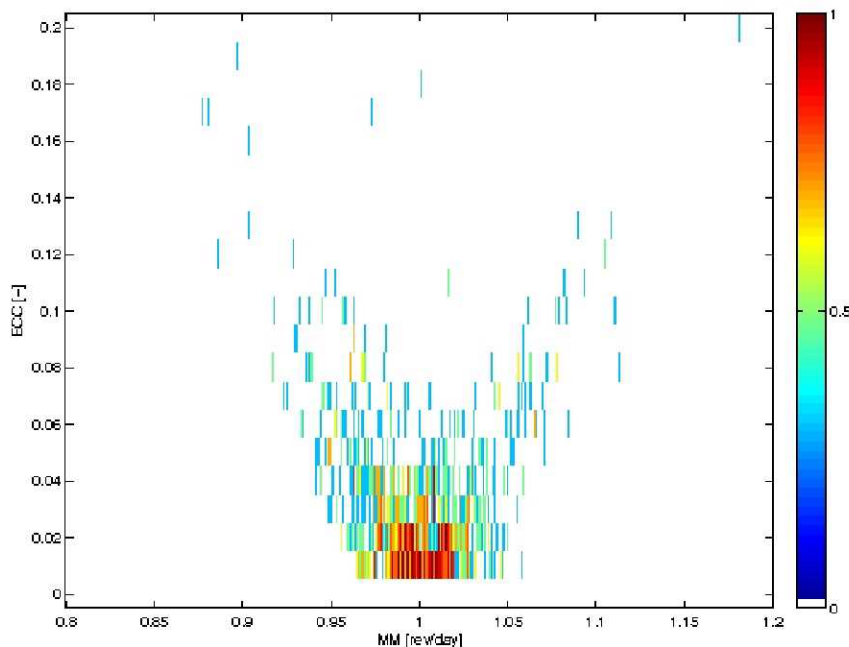**(1 deg by 5 deg bins)**
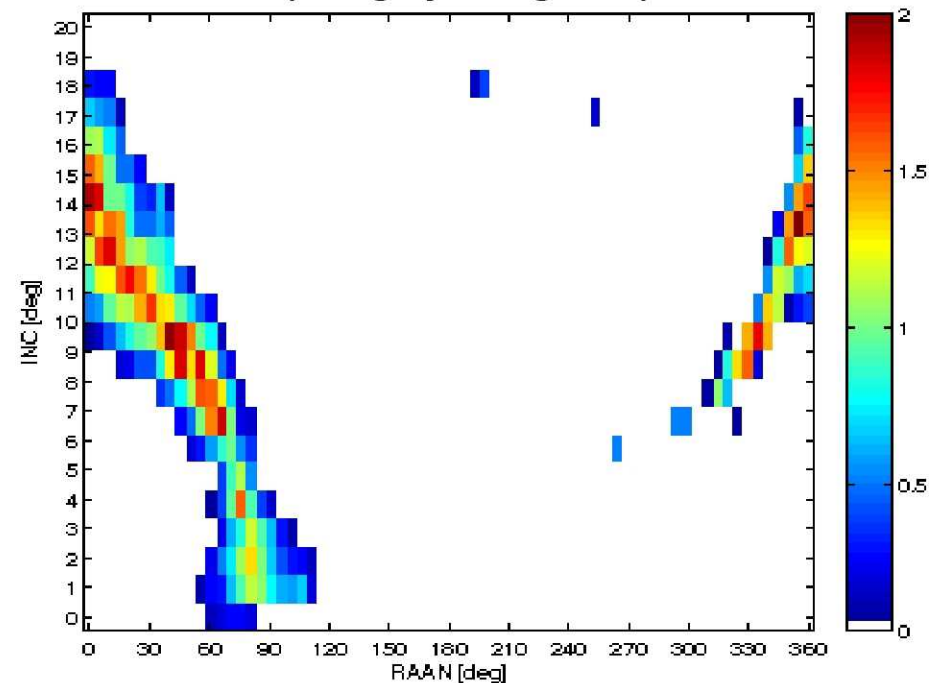
MODEST-derived 2006 GEO Fragment Environment

- **Assigned orbital elements of the MODEST-derived (data and extrapolated data) fragments are charted below.**

- **Charts represent fragments of sizes 1 m to 10 cm from seven to nine undetected explosive breakups in the GEO region.**

MODEST-derived fragment
Ecc vs. MM density chart
(0.005 by 0.001 bins)

MODEST-derived fragment
Inc vs. RAAN density chart
(1 deg by 5 deg bins)
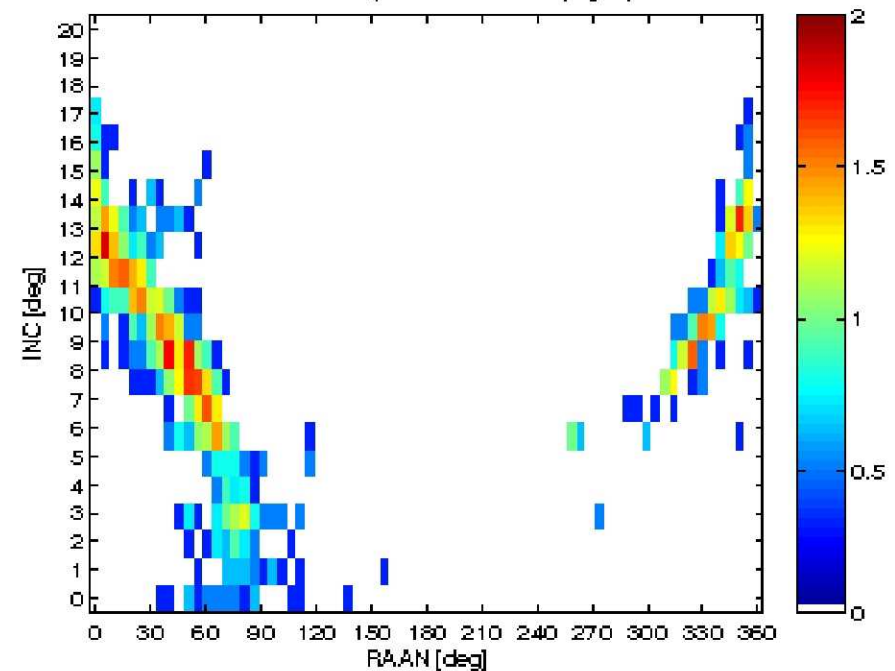
2006 GEO Environment of ORDEM2010

- **The total GEO environment for ORDEM2010 combines the MODEST-derived (data and extrapolated data) fragment population with the 2006 standard LEGEND population.**

- **The standard LEGEND historical run includes intacts deposited and propagated to 2006, and fragments from the two verified explosions in the GEO region.**
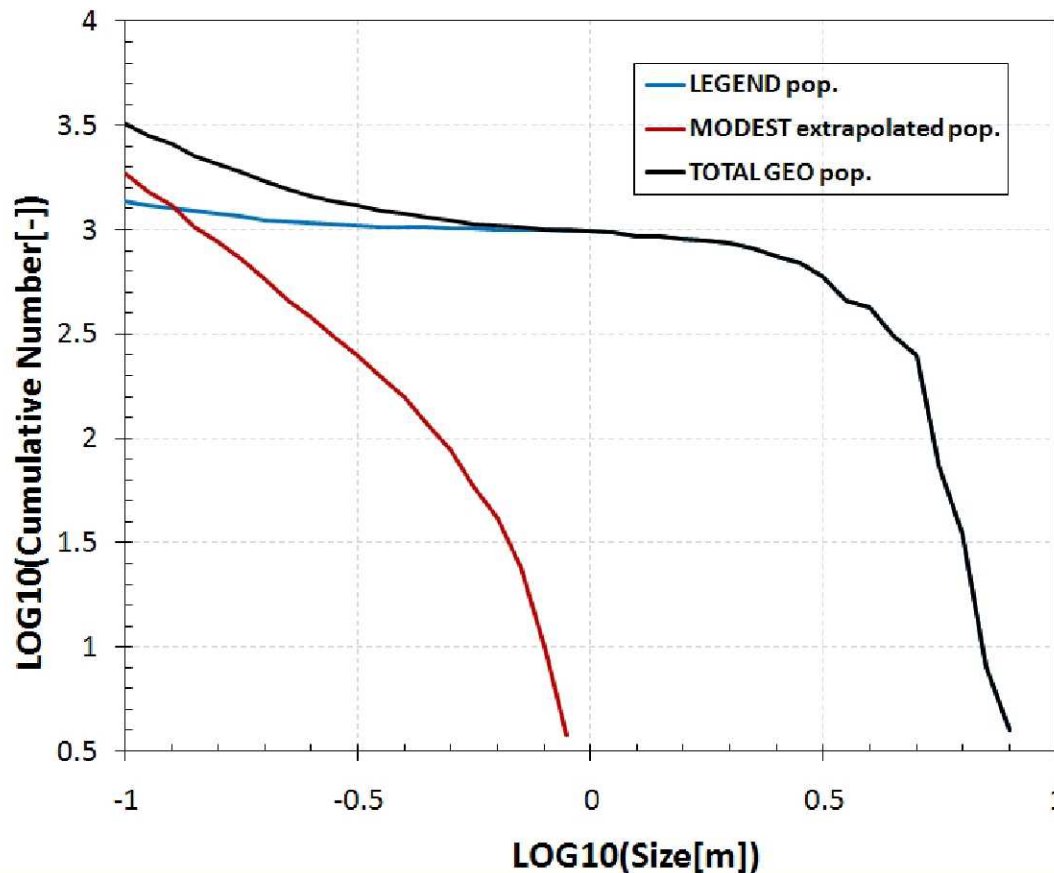
ORDEM2010 GEO Environment 1995-2035

- The derived 2006 ORDEM2010 GEO environment for 10 cm and larger objects forms the basis for all past and future environments.

- 1995 through 2005 GEO populations combine the yearly standard historical LEGEND population with the 2006 MODEST-derived population that is back-propagated to the appropriate year.

- 2007 through 2035 GEO populations begin with the yearly projection LEGEND results with random breakup events in 100 MC iterations. These are combined with the 2006 MODEST-derived population that is forward-propagated to the appropriate year.

- All years are the source of GEO fluxes on orbiting spacecraft and within telescope/radar fields-of-view in the ORDEM2010 program.