Alan B. Jenkin⁽¹⁾, Marlon E. Sorge⁽²⁾, John P. McVey⁽³⁾, Glenn E. Peterson⁽⁴⁾, Bernard Y. Yoo⁽⁵⁾

⁽¹⁾ The Aerospace Corporation, P.O. Box 92957, Los Angeles, CA 90009-2957, USA, Email: <u>Alan.B.Jenkin@aero.org</u>
⁽²⁾ The Aerospace Corporation, 2155 Louisiana Blvd., NE, Suite 5000, Albuquerque, NM 87110-5425, USA, Email: Marlon.E.Sorge@aero.org

⁽³⁾ The Aerospace Corporation, P.O. Box 92957, Los Angeles, CA 90009-2957, USA, Email: <u>John.P.McVey@aero.org</u> ⁽⁴⁾ The Aerospace Corporation, P.O. Box 92957, Los Angeles, CA 90009-2957, USA, Email: <u>Glenn.E.Peterson@aero.org</u>

⁽⁵⁾ The Aerospace Corporation, P.O. Box 92957, Los Angeles, CA 90009-2957, USA, Email: <u>Bernard.B.Yoo@aero.org</u>

ABSTRACT

The recently developed Aerospace Debris Environment Projection Tool was used to project the future debris environment in medium Earth orbit (MEO) over the next 200 years. The entire Earth orbital population was modeled to account for the possibility of cross-coupling between the MEO population and the low Earth orbit (LEO) and geosynchronous populations via objects on highly eccentric orbits that transit through MEO. It was found that a large fraction of the MEO debris originated from collisions in LEO involving satellites and rocket bodies that transit through LEO and MEO. Results showed that world-wide compliance with orbit lifetime reduction will significantly reduce the amount of debris in MEO.

1 INTRODUCTION

Over the last few years, various changes to the United States (U.S.) Government Orbital Debris Mitigation Standard Practices (ODMSP) [1] have been proposed. To address the impact of some of these changes on future debris risk posed to the Global Positioning System (GPS), it became evident that there was a need for a medium Earth orbit (MEO) debris environment projection model. At the request of the U.S. Air Force Space and Missile Systems Center Engineering Directorate. Enterprise Engineering Division (SMC/ENC), The Aerospace Corporation (Aerospace) performed a MEO debris environment projection study. One goal of this work was to determine the overall effect of world-wide compliance with key recommended disposal practices on the future MEO debris environment. This paper presents the model that was developed and the results of the study. Funding for this work was provided jointly by the SMC/ENC and GPS program offices.

2 STUDY METHODOLOGY

The ADEPT (Aerospace Debris Environment Projection Tool) simulation process was used to generate a model of the future orbital population over 200 years. The initial version of ADEPT that only modeled the future low Earth orbit (LEO) debris population is described in [2]. For this study, ADEPT was modified to model the entire future Earth orbital population. This was considered necessary to account for the possibility of cross-coupling between the MEO population and the LEO and geosynchronous (GEO) populations via collisions involving objects on highly eccentric orbits that transit through MEO.

Two environmental scenarios were considered, one in which there is world-wide compliance with recommended disposal practices, and one in which there is no world-wide compliance. Once the future debris population was generated for a given scenario, plots of spatial density of objects down to 1 cm vs. altitude at various future time points were created. Statistical distributions of collisions and collisional debris as a function of altitude and eccentricity were generated to determine the source of the collisional debris in MEO. Finally, the collision risk posed to satellites in the GPS operational constellation over 200 years was quantified.

A related study that modeled the entire future Earth orbital population and considered the effectiveness of various MEO constellation disposal strategies is presented in [3].

3 ADEPT

The ADEPT debris model generation process consists of the following steps:

Step 1. The initial population of objects is generated. This population includes unclassified catalog objects and statistical representations of unknown tracked objects and small (untrackable) debris down to 1 cm.

Step 2. The population of future launched objects is generated (see Section 4).

Step 3. Initial and future launched objects are propagated using the Aerospace mean element propagator MEANPROP (which uses the Draper Semi-

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Analytic Orbit Propagator [4]) to determine mean element trajectories up to 200 years after the start epoch.

Step 4. Explosion events of future launched objects are randomly generated based on object type (e.g., satellite or rocket body) and explosion debris down to 1 cm in size is generated using the Aerospace breakup modeling code IMPACT [5].

Step 5. Monte Carlo ensembles of statistical collisions are generated. An orbit trace crossing method is used to compute probability of collision between each object pair. A random variate is then drawn and compared to the collision probability to determine whether a collision between a pair occurs. In this study, this step assumed that operational satellites in constellations perform station-keeping and collision avoidance, and therefore do not collide with each other or any other object. Also in this study, 100 Monte Carlo ensembles were generated.

Step 6. Collision debris down to 1 cm in size is generated using IMPACT.

Step 7. The debris fragment set is down-sampled, weighted, and propagated.

Steps 5-7 are repeated as needed to feed the new generation of debris back into the previous population.

Details of the various steps are presented in [2]. One important change since the study in [2] was performed is that an independent database of sizes and masses has been developed at Aerospace for the intact objects and some of the debris population. The object sizes have a strong influence on the number of collisions, and the object masses have a strong influence on the amount of debris generated by collisions. As a result, ADEPT is now component-wise fully independent of any other debris environment projection model in the debris community, including those described in [6-10].

Another change since the study in [2] was performed is that collisions are now generated (Step 5) between all objects down to 1 cm in size in both the initial and future populations. As a result, the number of collisions generated is much larger than would be created if only objects down to 10 cm in size were included. This reflects the fact that there are many collisions in which one object is large and the other is small.

Additionally, an updated version of the IMPACT fragmentation model [5] was used in this study. The IMPACT collision model was modified to better represent several recent collision events. This modification affected the numbers of fragments and spread velocity distributions. The resulting collisional debris distributions are somewhat different than those generated in [2].

4 GENERATION OF FUTURE LAUNCHED

POPULATIONS

The future launch population is composed of four sets of satellite and rocket body objects: GEO objects, LEO constellations, MEO constellations, and all other objects.

GEO objects consist of satellites at or near GEO altitude and their associated rocket bodies. These objects are selected from the Joint Space Operations Center (JSpOC) unclassified space object catalog ("Satcat") from 1997 through 2011. This 15 year GEO launch history is repeated into the future. GEO objects are assigned 15 year lifetimes.

LEO constellations are modeled with nominal reference constellations representing the IRIDIUM, GLOBALSTAR, and ORBCOMM satellite systems (i.e., not directly based on Satcat entries). The reference constellations are assigned 10 year lifetimes and are constantly replenished to maintain the full constellation.

MEO constellations are modeled with nominal reference constellations representing the GPS, COMPASS, GALILEO, and GLONASS satellite systems (i.e., not directly based on Satcat entries). GPS satellites are assumed to be replaced at a rate of 2.2 per year (estimated from recent launch schedule of GPS IIF and GPS III satellites). This study assumed one satellite and upper stage per launch and did not model the possibility of dual launches. COMPASS satellites are assumed to be replaced at an average rate of 3.75 per year based on a 30 satellite constellation with design life of eight years. One satellite and upper stage per launch was assumed. GALILEO satellites are assumed to be replaced at an average rate of 2.5 per year based on a 30 satellite constellation with design life of 12 years. It was assumed that two satellites and one upper stage are launched at a time. GLONASS satellites are assumed to be replaced at an average rate of 3.4 per year based on a 24 satellite constellation with design life of 7 years. It was assumed that each plane is populated at first by three satellites (and one upper stage) per launch and then by two satellites (and one upper stage) per launch to achieve the correct number in the plane.

"All other objects" represent the remaining satellite and rocket bodies not included in the first three sets. LEO satellites that are not part of the IRIDIUM, GLOBALSTAR, and ORBCOMM constellations are included in this set. These satellites are selected from the Satcat from 2002 through 2011 and are assigned a five year mission life.

Fig. 1 shows the historical record and future projection of launches per year for the various object categories, excluding those for the MEO constellations. The historical pattern that is cyclically repeated is also shown. Fig. 2 shows the resulting cumulative count of launched objects (satellites and rocket bodies) vs. time over the next 200 years, also excluding MEO constellation satellites and rocket bodies.



Figure 1. History and projection of future launches per year (excluding launches for MEO constellations).



Figure 2. Cumulative future launched satellites and rocket bodies vs. time (excluding MEO constellation satellites and rocket bodies).

5 DISPOSAL RULES

5.1 Non-MEO Constellation Objects

Two scenarios were considered in this study. These scenarios only affect satellites and rocket bodies that are not a part of the MEO constellations. In the first scenario, all world-wide future launched objects (excluding MEO constellation objects) comply with specific disposal options. In this study, this is referred to as the Compliance scenario. In the second scenario, no future world-wide future launched objects comply with any recommended disposal options. This is referred to as the Non-Compliance scenario. These two scenarios bracket the range of future real-world compliance levels. In the Compliance scenario, the following disposal options were available. These options are permitted in the Inter-Agency Debris Coordination Committee (IADC) debris mitigation guidelines [11].

Disposal Option 1: Placement on a disposal orbit with lifetime less than 25 years.

Disposal Option 2: Placement in a storage orbit in the disposal region above GEO as defined by the IADC formula [11].

Disposal Option 3: Placement in a storage orbit between LEO and GEO. This is referred to as the MEO disposal region. In this case the altitude boundaries were taken from the ODMSP [1].

The disposal option that involves the minimum change in orbit energy is selected.

In the Non-Compliance scenario, the only change to the satellite or rocket body mission orbit at end of life was to increase or decrease mean altitude by 50 km to clear the operational altitude.

5.2 MEO Constellation Objects

MEO constellation satellites and rocket bodies followed an independent set of disposal rules depending upon the specific constellation. The reason for this is that all of the satellites and many of the rocket bodies are already in the MEO disposal region (Disposal Option 3). It was assumed nevertheless that most satellites and rocket bodies would not remain in operational orbits.

In this study, all GPS, COMPASS, and GALILEO satellites were moved above the operational satellite orbits to near circular orbits. GPS satellites were raised to orbits with perigee 780 km above the GPS operational reference altitude (following the system specifications for both). COMPASS and GALILEO satellites were raised to orbits with perigee 300 km above the respective operational reference altitudes of those constellations.

Disposal of upper stages varied with constellation. GPS IIF 1-10 upper stages were left on disposal orbits with perigee 278 km above the GPS operational reference altitude (hence inside the GPS operational altitude range of +/-500 km). GPS IIF 11-12 upper stages were left on disposal orbits with perigee 692 km above the GPS operational reference altitude (hence outside the GPS operational altitude range). The upper stages for GPS III and COMPASS were moved to low perigee transfer orbits that were affected by atmospheric drag but not guaranteed to re-enter within 25 years. The GPS III upper stage orbit parameters were taken from data available at the beginning of this study. The COMPASS upper stage orbit parameters were taken from JSpOC catalog information on the first COMPASS satellite in MEO. GALILEO upper stages were moved to near

circular with perigee 300 km above the GALILEO operational reference altitude.

GLONASS satellites and upper stages were left in their mission orbits. It should be noted that in a change from the historical pattern, recent actual GLONASS launch missions have left the upper stage on disposal orbits away from the satellite mission orbits.

6 STUDY RESULTS

Figs. 3-4 show scatter plots of the collisions between objects in the initial population and the future launched population that were generated by the ADEPT process. Each symbol (diamond) represents a collision and shows the epoch (x-axis) and altitude (y-axis) of occurrence. Collisions between all objects down to 1cm in size are included. Collisions from all 100 Monte Carlo ensembles are plotted together to show the coverage of the altitude-time space. Fig. 3 shows the collisions for the Non-Compliance scenario, and Fig. 4 shows the collisions for the Compliance scenario. It is seen that the concentration of collisions is highest in LEO and GEO.



Figure 3. Collision altitude vs. time for all collisions from all 100 Monte Carlo ensembles: Non-Compliance Scenario.



Figure 4. Collision altitude vs. time for all collisions from all 100 Monte Carlo ensembles: Compliance Scenario.

Fig. 5 shows the cumulative distribution of the collisions over altitude for both the Non-Compliance and Compliance scenarios. The count includes collisions between all objects down to 1 cm in size. The average count per Monte Carlo ensemble is shown. It is seen that the vast majority of collisions occur in LEO. The number of collisions in the Compliance scenario is approximately 30% lower than in the Non-Compliance scenario. Most of the reduction is in LEO collisions.



Figure 5. Cumulative distribution of collisions over altitude.

Fig. 6 shows the cumulative distribution of collisions over altitude in the region above LEO. Only collisions above 2200 km altitude are included. A lower bound altitude of 2200 km was selected instead of 2000 km to avoid including collisions involving LEO disposed objects that accumulate at 2000 km. Also for this group of collisions, the number of collisions in the Compliance scenario is approximately 30% lower than in the Non-Compliance scenario. This result is due to reduction in orbital lifetime of MEO-transiting objects (Disposal Option 1), which would reduce the rate of accumulation of objects in MEO. If MEO-transiting objects were placed fully in the MEO disposal region (Disposal Option 3), the rate of accumulation of objects in MEO would increase. This would, in general, result in an increase of MEO collisions.

Figs. 7-8 show the number of collisional debris objects down to 1 cm in size on orbit vs. time. A curve is shown for each of the 100 Monte Carlo ensembles. The count includes debris in LEO, MEO and GEO. The spread of the count over the Monte Carlo cases is due to the random draws in the collision generation process. The amount and growth rate of debris on orbit is lower for the Compliance scenario mainly because fewer collisions produce less debris. In addition, debris originating from objects on low lifetime orbits (as would occur if Disposal Option 1 were used) also have low orbital lifetime.



Figure 6. Cumulative distribution of collisions over altitude: collisions above LEO.



Figure 7. Number of collisional debris objects down to 1 cm in size on orbit vs. time: Non-Compliance Scenario. Curves for all 100 Monte Carlo cases are shown.



Figure 8. Number of collisional debris objects down to

I cm in size on orbit vs. time: Compliance Scenario Curves for all 100 Monte Carlo cases are shown.

Figs. 9-10 show the spatial density of objects down to 1 cm in size vs. altitude. The curves are averages over all 100 Monte Carlo ensembles. Fig. 9 shows the curve at 100 years, and Fig. 10 shows the curve at 200 years. It is seen that overall cumulative object spatial density in the Compliance scenario is lower than that in the Non-Compliance scenario by approximately 50% at the 100-year point and about 67% at 200 years. Most of this reduction is seen in the LEO regime.



Figure 9. Spatial density of objects down to 1 cm in size vs. altitude: 100 years.



Figure 10. Spatial density of objects down to 1 cm in size vs. altitude: 200 years.

Figs. 11-12 show close-ups of the object spatial density in Figs 9-10, respectively, over the altitude range 15000 km to 25000 km, which contains all four MEO constellations (note the y-axis scale is linear whereas in Figs. 9-10 it is logarithmic). Overall object spatial density in this MEO region is lower in the Compliance scenario at 200 years by approximately 32%. At 100 years, the overall reduction of object spatial density in the Compliance scenario is less than 10%. Spatial densities in MEO are not largely affected by the Compliance vs. Non-Compliance issue until after 100 years.



Figure 11. Close-up of spatial density of objects down to 1 cm in size vs. altitude in the altitude range 15000 km to 25000 km within MEO: 100 years.



Figure 12. Close-up of spatial density of objects down to 1 cm in size vs. altitude in the altitude range 15000

km to 25000 km within MEO: 200 years.

Fig. 13 shows the cumulative distribution of collisional debris (from all 100 Monte Carlo ensembles, down to 1 cm in size) over altitude of the collision that created the debris. The count shown is per Monte Carlo ensemble and includes all debris created over 200 years. Only debris objects whose initial orbits are contained inside or cross the MEO region between 15000 km and 25000 km altitude are counted. It is seen that, in the Non-Compliance scenario, LEO collisions over 200 years generate 50% of debris passing through this MEO region. In the Compliance scenario, LEO collisions over 200 years generate 33% of this debris. Although few collisions occur in MEO (see Figs. 5-6), those collisions individually contribute more debris to MEO than LEO collisions do. The total amount of debris generated over 200 years is approximately 45% lower in the Compliance scenario than in the Non-Compliance scenario. From the figure, it can be seen that most of this debris reduction is due to reduction of LEO collisions.



Figure 13. Cumulative distribution of collisional debris contained inside or passing through MEO between 15000 km and 25000 km over altitude of the collision that created the debris.

Fig. 14 is the same as Fig. 13 except that only debris from collisions that occur above 2200 km are included in the count. A lower bound altitude of 2200 km was selected instead of 2000 km to minimize including debris from LEO disposed objects that accumulate at 2000 km. It is seen that a large fraction of this debris is generated by collisions in the MEO constellation graveyards. The total amount of debris generated over 200 years by MEO collisions is ~30% lower in the Compliance scenario than in the Non-Compliance scenario. This is due to reduction of lifetime (Disposal Option 1) of satellites and rocket bodies that transit through MEO, thereby reducing collisions with MEOresident objects. The lifetime of those objects would only be reduced if they were also crossing LEO in the Non-Compliance scenario. The reduction in debris is not due to placing satellites and rocket bodies fully in the MEO disposal region (Disposal Option 3), since this would in general increase the probability of collision with MEO-resident objects.

In order to achieve greater than 30% reduction in debris generated over 200 years, collisions between MEO resident objects must be reduced. This can only be achieved via MEO constellation disposal practices [3, 12, 13].



Figure 14. Cumulative distribution of collisional debris contained inside or passing through MEO between 15000 km and 25000 km over altitude of the collision that created the debris. Only collisions above 2200 km are counted.

Fig. 15 shows the cumulative distribution of collisional debris (from all 100 Monte Carlo ensembles, down to 1 cm in size) over eccentricity of the initial orbit of the debris. As in Fig. 12, the count shown is per Monte Carlo ensemble and includes all debris created over 200 years. Only debris objects whose initial orbits are contained inside or cross the MEO region between 15000 km and 25000 km altitude are counted. Most of the debris reduction in the Compliance scenario is for debris on highly eccentric orbits (e > 0.5). This debris is mostly from satellites and rocket bodies transiting through MEO. There is some reduction in debris on orbits with eccentricity between 0.02 and 0.2. This debris is from MEO resident objects. The reduction of this debris is due to reduction in collisions between MEO-resident objects and satellites and rocket bodies transiting through MEO. This reduction in collisions can only be achieved through orbit lifetime reduction (Disposal Option 1) of those objects since fully placing them in the MEO disposal region (Disposal Option 3) would in general increase those collisions.

Fig. 16 shows the cumulative collision probability posed to the operational GPS constellation over time. The total future population, including collisional debris down to 1 cm in size, was used to compute the risk. The orbit trace-crossing method used in the ADEPT process for collision generation was used here to compute the collision probability [2]. The probability shown is averaged over 100 Monte Carlo runs. The curves for the Non-Compliance and Compliance scenarios begin to diverge after ~120 years. This divergence continues to increase. By 200 years, the risk reduction in the Compliance scenario relative to the Non-Compliance scenario has grown to ~33%. Risk reduction is expected to continue increasing after 200 years.



Figure 15. Cumulative distribution of collisional debris contained inside or passing through MEO between 15000 km and 25000 km over eccentricity of the initial orbit of the debris.



Figure 16. Cumulative collision probability posed to the operational GPS constellation by objects down to 1 cm in size over time.

7 CONCLUSIONS

A model of the future MEO debris environment over 200 years was developed using the ADEPT process. Debris down to 1 cm in size was modeled. The entire Earth orbital population was modeled to account for the possibility of cross-coupling between the MEO

population and the LEO and GEO populations via objects on highly eccentric orbits that transit through MEO. Two scenarios were considered: world-wide compliance with recommended disposal practices and world-wide non-compliance with those practices. In the Non-Compliance scenario, results showed that approximately 50% of collisional debris in MEO down to 1 cm in size generated over 200 years comes from collisions in LEO. In the Compliance scenario, approximately 33% of that debris comes from LEO collisions. The amount of debris in MEO over 200 years is reduced by approximately 45% in the Compliance scenario. It was determined that this reduction is due to reduction of orbit lifetime and not due to movement of objects into the MEO disposal region. Reduction in orbit lifetime of LEO resident objects and LEO-MEO transiting satellites and rocket bodies reduces LEO collisions. Reduction of lifetime of LEO-MEO transiting satellites and rocket bodies also reduces some collisions in MEO. The corresponding reduction in collision risk posed to GPS begins to take effect after ~120 years, continues to increase, and reaches 33% by 200 years. GPS collision risk reduction is expected to continue increasing after 200 years.

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9 REFERENCES

- 1. U.S. Government Orbital Debris Mitigation Standard Practices, February 2001, accessible at <u>http://orbitaldebris.jsc.nasa.gov/mitigate/mitigation.ht</u> <u>ml</u>.
- Jenkin, A.B., Sorge, M.E., Peterson, G.E., McVey, J.P., Yoo, B.Y., "100-Year Low Earth Orbit Debris Population Model," Paper No. AAS 11-410, AAS/AIAA Astrodynamics Specialists Conference, Girdwood, AK, July 31- August 4, 2011.
- 3. Rossi, A., Anselmo, L., Pardini, C., Jehn, R.,

"Effectiveness of the De-Orbiting Practices in the MEO Region," *Proceedings of the Fifth European Conference on Space Debris*, SP-672, ESA, July 2009.

- 4. Sorge, M.E., "Satellite Fragmentation Modeling with IMPACT," AIAA/AAS Astrodynamics Specialist Conference, Honolulu, HI, August 18-21, 2008.
- McClain, W.D., "A Recursively Formulated First-Order Semianalytic Artificial Satellite Theory Based on the Generalized Method of Averaging," Computer Sciences Corporation, CSC/TR-77/6010, Greenbelt, MD, November 1977.
- Liou, J.C., "LEGEND A Three-Dimensional LEOto-GEO Debris Evolutionary Model," Advances in Space Research 34 (2004) 981-986.
- Walker, R., Hauptmann, S., Crowther, R., Stokes, H., Cant, A., "Introducing IDES: Characterizing the Orbital Debris Environment in the Past, Present, and Future," American Astronautical Society, AAS Paper 96-113, Feb. 1996.
- 8. S. Flegel et al., "The MASTER-2009 Space Debris Environment Model," Proceedings of the Fifth European Conference on Space Debris, Darmstadt, Germany, March 30 – April 2 2009 (ESA SP-672, July 2009).
- A. Rossi, L. Anselmo, C. Pardini, R. Jehn, "The New Space Debris Mitigation (SDM 4.0) Long Term Evolution Code," Proceedings of the Fifth European Conference on Space Debris, Darmstadt, Germany, 30 March - 2 April 2009, (ESA SP-672, 2009).
- H.G. Lewis, G.G. Swinerd, R.J. Newland, A. Saunders, "Active Removal Study for On-Orbit Debris Using DAMAGE," Proceedings of the Fifth European Conference on Space Debris, Darmstadt, Germany, March 30 April 2 2009 (ESA SP-672, July 2009).
- 11. IADC Space Debris Mitigation Guidelines, IADC-02-01, Revision 1, September 2007, accessible at <u>http://www.iadc-online.org</u>.
- 12. Jenkin, A.B., McVey, J.P., 'Constellation and "Graveyard" Collision Risk for Several MEO Disposal Strategies,' *Proceedings of the Fifth European Conference on Space Debris*, SP-672, ESA, July 2009.
- Jenkin, A.B., Gick, R.A., "Dilution of Disposal Orbit Collision Risk for the Medium Earth Orbit Constellations," *Proceedings of the Fourth European Conference on Space Debris*, SP-587, ESA, edited by D. Danesy, ESA Publications Division, Noordwijk, The Netherlands, August 2005, pp. 309-314.