Effect of Latitude Bias in Entry Angle on Ground Casualty Risk from Naturally Decaying Space Objects

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ABSTRACT

An improvement to the long-term estimation of ground casualties from naturally decaying space objects is the refinement to the distribution of entry angle at the entry interface as a function of latitude. Previous analyses were based on an assumed "small angle," typically -0.1°, and entry interface at the equator. This study expands on work by Bacon and Matney [1, 2] that indicated there is significant latitude bias in the location of reentries, compared to prior assumptions of equal temporal probability.

A new model has been developed, which describes the distribution of entry angle as a function of orbital inclination and argument of latitude. This model has been used to generate inputs for ODPO's certified reentry survivability software, Object Reentry Survival Analysis Tool (ORSAT). These new results are compared with the prior standard model to assess the magnitude of the effects on reentry casualty risk.

1. INTRODUCTION

Historically, Object Reentry Survival Analysis Tool (ORSAT) simulations have relied on the assumption that the final stage of reentry (i.e., final crossing of 122 km altitude) is equally likely to occur at any point in time along an object's orbit. For moderate orbital inclinations, most time is spent near the boreapsis and notoapsis (northern and southern latitudinal extremes, respectively). This idea is used to generate "bathtub charts" like those seen in [3], and cause populations near the maximum latitude extent of an object's ground tracks to be weighted higher when computing the latitude-averaged population density for risk assessments.

Previous publications by Bacon, Matney, and Lips [1, 2, 8] have challenged the assertion that there is equal temporal likelihood in reentries; indeed, there appears to be a higher likelihood of reentry near the equator than near the poles—exactly the opposite of the prior model's predictions. This concentration of reentries as a function of argument of latitude (and indeed, latitude) is largely due to the "wall of air" seen by objects heading towards the equator; this "wall of air" is an artifact of the ellipticity of the Earth. [1]

A subtle difference between the results presented in [1, 2] and those presented here is the altitude of interest: Bacon and Matney were interested in the ground impact location of reentering objects, and presented data at 80 km altitude (propagating to-ground impact using an orbit integrator is prohibitively expensive, computationally, and does not model the terminal aerodynamics as well as ORSAT). The data presented here are at 122 km, the typical definition of entry interface for ORSAT simulations.

An implication of the variation of reentry locations, especially around an aspherical Earth, is that the conditions at entry will also differ: speed relative to the atmosphere and flight path angle (FPA), measured relative to the local horizontal both change as a function of argument of latitude; see Fig. 1 for a geometric depiction of FPA.

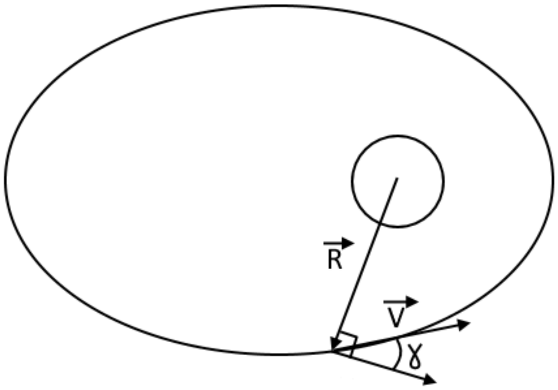

Figure 1. Flight path angle geometric depiction

2. SIMULATING DECAY TRAJECTORIES

NASA's General Mission Analysis Tool (GMAT) is a freely-available, open-source software package with a variety of orbit propagators, force models, and other features that allow users to design and analyze space missions with high fidelity. It was used previously in [1] and [2] to analyze the latitude bias in reentry locations by simulating large numbers of terminal reentry trajectories.

A similar methodology is used here, with GMAT serving as an orbit integrator for tens of thousands of reentry trajectories. A sample spacecraft having mass of 3000 kg and drag area of 14.5 m^2 was initialized at an altitude of ~200 km in a nearly-circular orbit (eccentricity values of 0 and 0.0011 were analyzed with little difference in final results) and propagated forward in time until it reached an altitude of 90 km.

The entry interface conditions (flight path angle, speed, latitude, and longitude) were recorded for each simulated trajectory at an altitude of 122 km (consistent with typical ORSAT inputs). Sample plots of the variation of FPA with geodetic latitude over several inclinations are seen in Figs. 2-7 (all trajectory data presented were simulated around the June solstice). For further information on time-of-year and sun-angle effects on the latitude bias of reentries, see [7].

Upon first glance, we see that at inclinations above about 36°, a latitude gap appears around the equator, between which no reentries occur. This fact is in sharp contrast to the previous standard assumption, present in many reentry codes, which is the terminal reentry trajectory can begin at any location. A second interesting aspect of these charts is that the magnitude of the FPA increases with orbit inclination, but does not exceed 0.1° until approximately 60° (and nearer to polar). Retrograde trajectories show a similar trend to their supplementary orbit inclinations, with a slight shift towards a steeper FPA (compare Figs. 4 and 7).

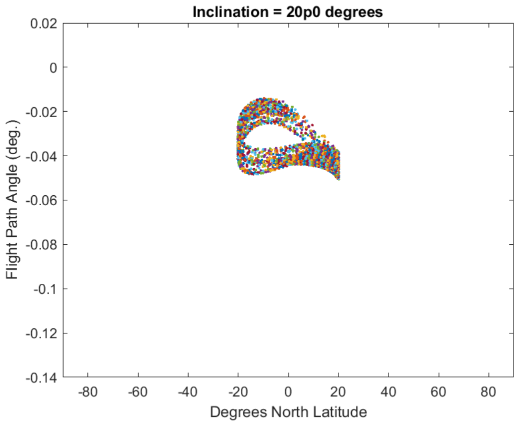

Figure 2. FPA variation with Latitude, Inclination = 20°.

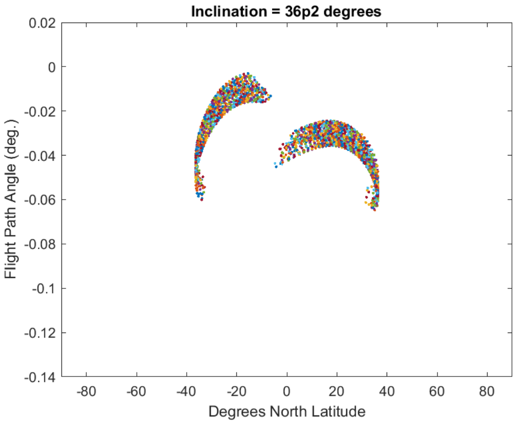

Figure 3. FPA variation with Latitude, Inclination = 36.2°.

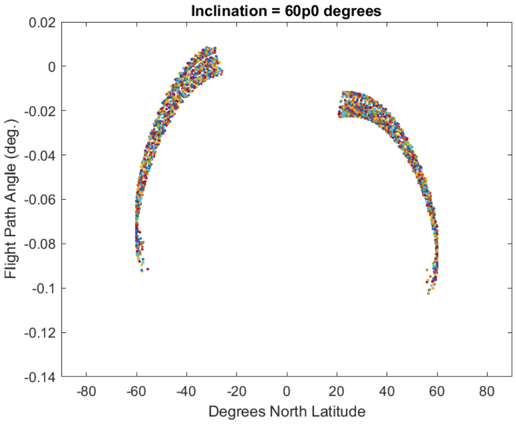

Figure 4. FPA variation with Latitude, Inclination = 60°.

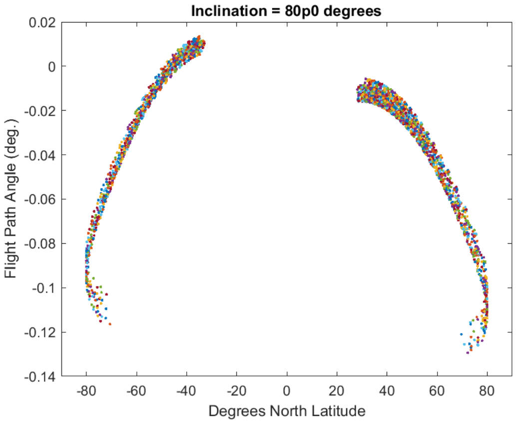

Figure 5. FPA variation with Latitude, Inclination = 80°.

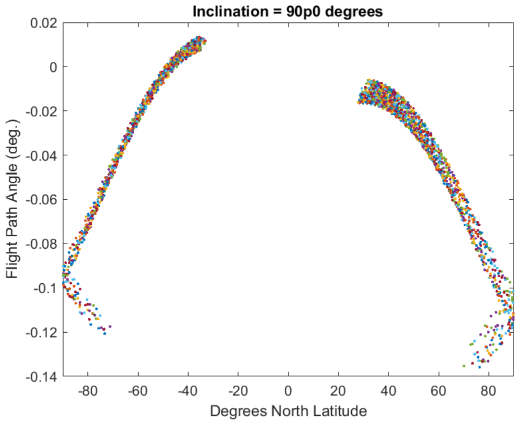

Figure 6. FPA variation with Latitude, Inclination = 90°.

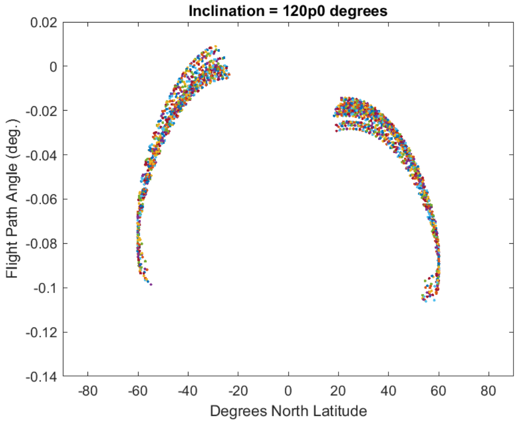

Figure 7. FPA variation with Latitude, Inclination = 120°.

3. SATELLITE TEST CASE

The effect of the FPA on spacecraft-level reentry casualty risk is examined here through the *Fermi* spacecraft (formerly *Gamma-ray Large Area Space Telescope*, or *GLAST*). This satellite was originally analyzed by members of the NASA Orbital Debris Program Office in 2003-2004 using ORSAT 5.8 [5]; the current analysis uses ORSAT 6.2 and the recently developed AutoORSAT Python wrapper [6]. A total of 105 unique components were modeled for this analysis, comprising several levels of nesting, various materials, and all shape models that ORSAT has available.

Three quantities of interest are chosen for comparison between the two methods: debris casualty area (DCA), footprint length, and expectation of casualty (E_c). For the purposes of this study, we will compare the "standard" ORSAT analysis— -0.1° FPA at entry interface, beginning at the equator, and using the inclination-based, latitude-averaged population density to compute the expectation of casualty—with the new model, incorporating the variation in FPA with latitude, and the risk calculation scheme presented in the next section. Note that any numerical results presented here are representative, and do not constitute an official estimate of risk from the NASA Orbital Debris Program Office.

The *Fermi* spacecraft is currently in a 25.6°-inclination orbit, so GMAT was exercised to generate the initial FPA distribution with latitude (see Fig. 8). A subset of these results was used as inputs to ORSAT, namely samples at the boreapsis, notoapsis, equator, and mid-latitude points (corresponding to approximately every 45° of argument of latitude). A total of 17 ORSAT scenarios were run for the current study (out of ~2400 trajectories analyzed in GMAT), in addition to the base case using standard ORSAT inputs. The input FPA values and latitudes for all 18 cases is seen in Fig. 9. Values for standard ORSAT inputs are marked with crosses.

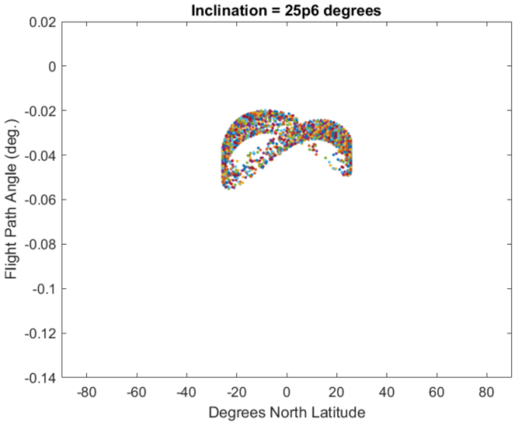

Figure 8. FPA variation with Latitude, Inclination = 25.6°.

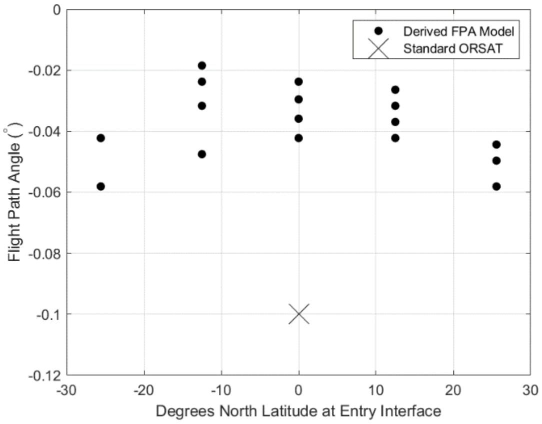

Figure 9. Input Latitudes and Corresponding FPA Values

Initial analyses conducted in 2003-2004 of the *Fermi* spacecraft indicated a total DCA of 57.6m^2; for an expected reentry in 2020, this implied an E_c of 1:900. The mission has planned for a controlled reentry to mitigate this risk. Updates to the ground population, as detailed in [3], have changed the current best estimate to approximately 1:800. The DCA for the 17 new ORSAT runs is consistent, predicting 20.4 m^2 in each case; the standard ORSAT analysis also predicts a DCA of 20.4 m^2. Footprint length is plotted as a function of initial latitude in Fig. 10 (again, standard ORSAT analysis is indicated by a cross).

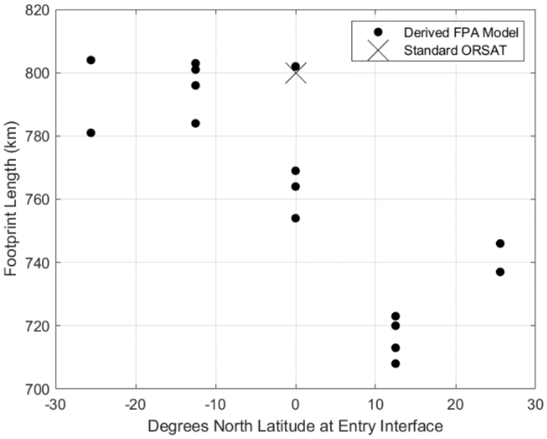

Figure 10. Footprint Length Variation with Initial Latitude

4. REENTRY CASUALTY RISK CALCULATION

To accommodate the latitude bias in reentry location, a new scheme must be developed to compute reentry casualty risk (after the DCA is determined). The simplest way to do this is to compute the E_c for each individual surviving component; the DCA for each component is multiplied by the population density of the latitude band in which it landed. These component E_c values are then summed to compute the total E_c for a given reentry trajectory.

Population density is computed as in [3] for years up to 2100 and all latitudes (though only the latitudes between 85°N and 60°S are assumed to have any human population). The data are computed using the full resolution of the Gridded Population of the World, version 4 (GPW4) database (i.e., at 30 arc-second intervals), but for reentry casualty risk, the data are binned into one-degree intervals (seen in Fig. 11). This binning allows for some uncertainty in the initial conditions, which simply are generated using a sampling scheme already described in Section 2.

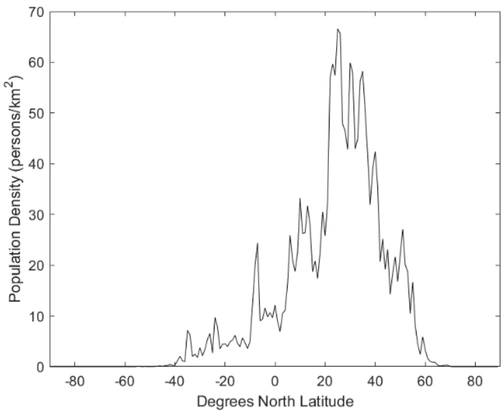

Figure 11. 2020 Population Density in 1° Latitude Bands

Four of the 17 sample ORSAT test cases (plus the base case of standard ORSAT assumptions) were chosen to show the spread of E_c with initial latitude (see Fig. 12). All these cases have the same associated DCA (of 20.4 m^2). The only differentiating factor between these E_c values is the location of the impacting fragments. The base ORSAT case, assuming initial FPA of -0.1°, has an E_c very close to the value predicted using the inclination-based, latitude-averaged population density for the 25.6-degree inclination orbit (both 1:2200, to two significant figures).

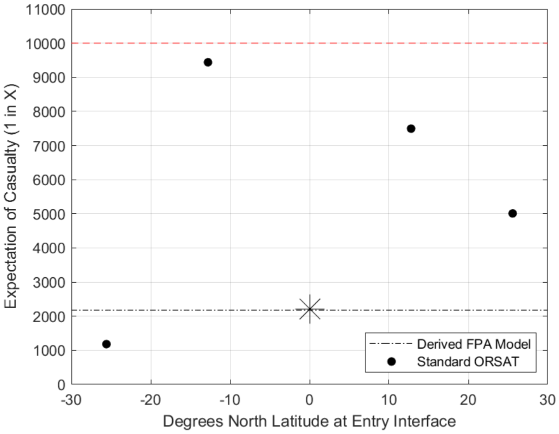

Figure 12. Variation of E_c with Initial Latitude.

5. CONCLUSIONS

The flight path angle at entry interface, originally estimated as a constant -0.1°, varies as a function of inclination and latitude. For objects with orbit inclinations less than approximately 60° (or greater than approximately 120°), no initially circular orbit resulted in a trajectory with FPA as steep as the previously assumed value (see Figs. 4-7).

Debris casualty area varies with initial FPA and latitude, but does not have an obvious relationship with these variables and is the subject of ongoing research. Footprint length also varies with the initial conditions, but a shallower FPA (i.e., closer to zero) does not necessarily imply a longer footprint, which also bears further research. The effect of latitude bias on expectation of casualty has already been demonstrated by Bacon and Matney [1, 2] to differ strongly from the previous models that use inclination-based, latitude-averaged population density; this study further shows the variation of E_c with initial reentry location (even with a constant DCA) of as much as ± 80%. As a large majority of the ground population of the Earth is in the northern hemisphere, reentry trajectories that start south of the equator and are northbound have greater expectation of casualty, even if the number of objects surviving reentry does not change.

6. REFERENCES

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