IMPROVING ESTIMATION OF GROUND CASUALTY RISK FROM REENTERING SPACE OBJECTS

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ABSTRACT

A recent improvement to the long-term estimation of ground casualties from reentering space debris is the further refinement and update to the human population distribution. Previous human population distributions were based on global totals with simple scaling factors for future years, or a coarse grid of population counts in a subset of the world's countries, each cell having its own projected growth rate. The newest population model includes a 5-fold refinement in both latitude and longitude resolution. All areas along a single latitude are combined to form a global population distribution as a function of latitude, creating a more accurate population estimation based on non-uniform growth at the country and area levels.

Previous risk probability calculations used simplifying assumptions that did not account for the ellipsoidal nature of the Earth. The new method uses first, a simple analytical method to estimate the amount of time spent above each latitude band for a debris object with a given orbit inclination and second, a more complex numerical method that incorporates the effects of a non-spherical Earth. These new results are compared with the prior models to assess the magnitude of the effects on reentry casualty risk.

1. INTRODUCTION

The population database is used to estimate the casualty risk from surviving reentry debris [1]. The average population density under the satellite track is a critical factor in computing the probability of any reentering debris striking a person. Planning for uncontrolled reentries in a future year, the longitude dependency (both of the population distribution and of the reentry point) can be considered randomized, due to the precession of the orbit and the rotation of the Earth beneath the orbit. Thus, the population data presented here vary only as a function of latitude [2]. The orbital inclination of an orbiting object dictates the amount of time spent in each geographic latitude band. Each of these latitude bands has a different number of people living in it, so the density of people under a satellite's path is the average population density in each latitude band, weighted by the fraction of time the satellite travels over each band. The 'inclination-averaged' population density and casualty

risk probabilities are computed outside the population database.

This population database required an update as the data currently used are considered obsolete, being from the Gridded Population of the World, version 2 (GPWv2), released in 2001, and the U.S. Census Bureau's International Programs Center (IPC) International Data Base (IDB) projections from May 2000. The new database is based on the Gridded Population of the World, version 4 (GPWv4), released in 2015, and the updated IDB from August 2016. As with the last update to the NASA reentry casualty risk model [2], there is a significant refinement in resolution of the global population (seen in Tab. 1).

Table 1. Comparison of Population Models

	Global Model	GPWv2	GPWv4
Year(s) of Estimation	1994	1990, 1995	2000, 2005, 2010, 2015, 2020
Grid Resolution	-	2.5 arc-minute (~5 km)	30 arc-second (~1 km)
Number of Input units (subnational geographic units)	1	127,000	~12,500,000

2. POPULATION DATA UPDATE

The updated global population database is a combination of two different data sources. The GPWv4 provides the total population and its distribution within each country's borders. The population growth projections from the IDB are then applied to each country's distribution and total population.

2.1. Gridded Population of the World, Version 4

The GPWv4 is produced by the Socioeconomic Data and Applications Center (SEDAC). SEDAC is a program at Columbia University's Center for International Earth Science Information Network and is part of NASA's Earth Observing System Data and Information System.

GPWv4 data are gridded in latitude and longitude with a resolution of 30 arc-seconds [4]. The publicly available data cover 243 countries and areas on six continents

between the latitudes of 85° N and 60° S. The data are presented in a GeoTiff format, which allows georeferenced data to be included in an easy to read image file. Sample plots of the GPWv4 raw data can be seen in Figs. 1 and 2. For comparison, the same data from the previous model (GPWv2) are presented in Fig. 3 (reproduced from [5]) and Fig. 4. The population counts and densities are adjusted to the United Nations estimates for the years 2000, 2005, 2010, 2015, and 2020 [4]. All these data files, associated documents, and metadata are available for download on the internet from the SEDAC website: http://sedac.ciesin.columbia.edu/.
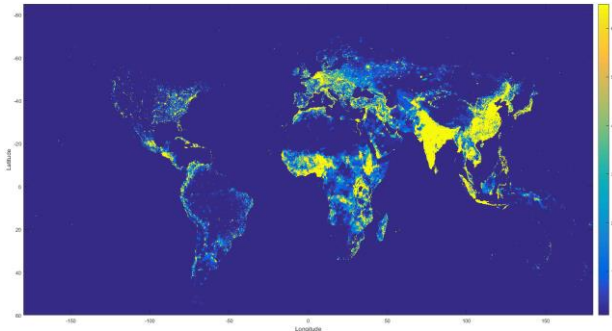

Figure 1. GPWv4 Data: U.N.-Corrected 2015 population grid of the world.
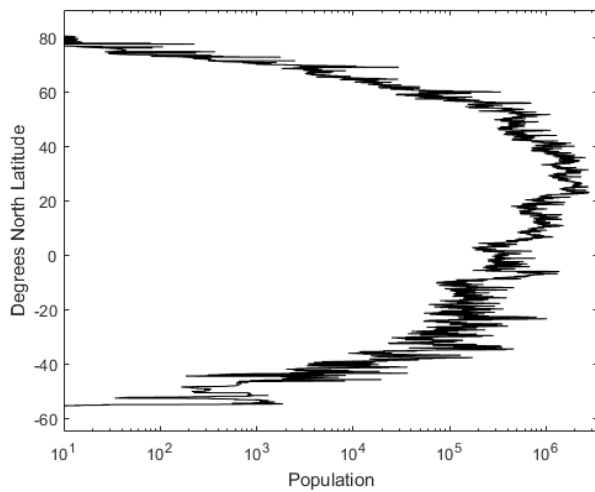

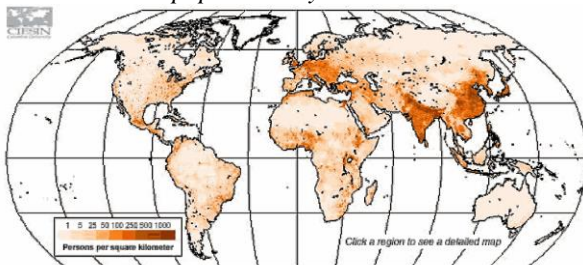*Figure 2. GPWv4 Data: U.N.-Corrected 2015 world population by latitude.*

Figure 1. Global population density, 1995 (United Nations adjusted, Robinson Projection)

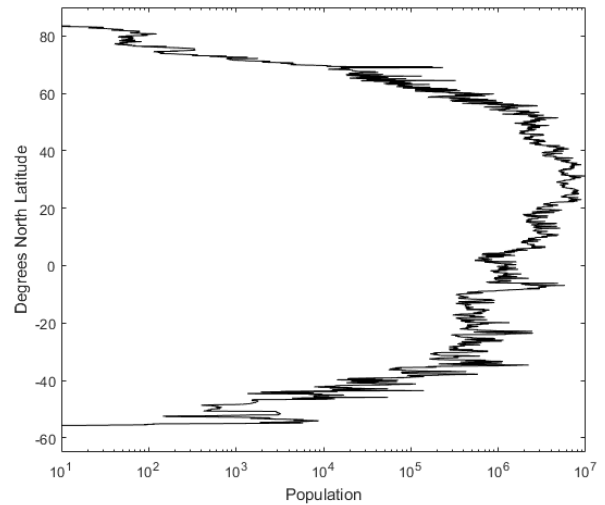*Figure 3. GPWv2 Data: U.N.-Corrected 1995 population grid of the world.*

Figure 4. GPWv2 Data: U.N.-Corrected 1995 world population by latitude.

2.2. International Data Base

The IDB is produced by the IPC of the United States Bureau of the Census. The population projection data are based on projections from national statistics offices, the United Nations, and census estimates. The IDC data used here are from the latest update of August 2016 [6].

The IDB currently lists 228 areas with 2015 midyear populations of more than 5,000 [3]. The countries and areas are listed by name, and the database provides detailed annual information on all areas for the years 1950-2050. IDB data are available via Internet at www.census.gov/population/international/data/idb.

3. PREDICTING FUTURE POPULATION

The IDB and GPWv4 datasets do not use precisely the same countries and areas, so the populations had to be reconciled. This was done by examining the documentation for each source and isolating which areas were identified individually in one source but collected in the other. For example, the GPWv4 includes populations for French Guiana, Guadeloupe, and Martinique, but IDB combines them with metropolitan France [3,4]. There are a total of 227 countries and areas that the two databases have in common, plus the global totals. This process was done using a spreadsheet, comparing each dataset line by line. Once this was complete, the gridded population data were saved for later input into the data processing code.

The grid population predictions are generated by applying the annual projected population (given by IDB) to each country or area's fixed distribution (as given by GPWv4), cell by cell. This approximation does not allow for general urbanization trends worldwide, and forces the

rural and urban populations to grow or shrink in unison within any country's borders. A future enhancement may be to apply a correction that accounts for the global urbanization trend. Such a correction is beyond the scope of the current work. Once this is complete, the cells are summed over longitude to re-create the latitude bands that are then used to compute the inclination-averaged population density. This process is summarized in Fig. 5.

This software creates tables of population and population density as a function of year and latitude, but the primary output is the annual global population distribution by 30-arcsecond latitude bin for the years 2000-2050 (with the years 1990-2000 available, but at a coarser resolution).
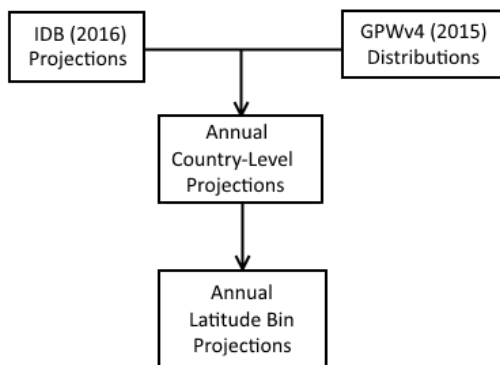

Figure 5. Data processing flow diagram.

There are two limitations to the output data produced by this scheme: the population prediction method, and the input data. The output data can only be as good as the sources of the input data (IDB and GPWv4). These are well-known and trusted data products, produced through research supported by the United Nations, the U.S. government (including NASA), and the individual countries and areas. GPW is the only source of global gridded population numbers (LandView is another gridded population dataset, produced by the U.S. Census Bureau, but does not cover non-U.S. populations), and since it does not provide a means of projecting population changes in the future, we rely on the IDB. There are many sources for population predictions; these sources (including IDB) typically rely on United Nations and individual countries and areas for data. The IDB was chosen because it uses these standard sources, and it is currently used by the previous version of this software.

The second limitation is the application of the population prediction method. The future population (by latitude bin) of each country is computed using the distribution found in GPWv4 in the year 2015. This method was previously used by Matney, *et al.*, in 2003 [2]. This method is useful, in that each country or area can have its population develop over time, but there is a potentially

serious limitation, in that the relocation of population to areas not populated in the GPWv4 2015 baseline data set is not modeled. Fig. 6 shows the estimated change in world population density from 2000 to 2050, using the 2015 GPWv4 distribution. Fig. 7 shows the differences in the latitude-binned population densities predicted using the previous method (with 1995 baseline GPWv2 distribution and 2001 IDB population projections) and the baseline data sets provided in the GPWv4 product (the years 2005, 2010, and 2015).
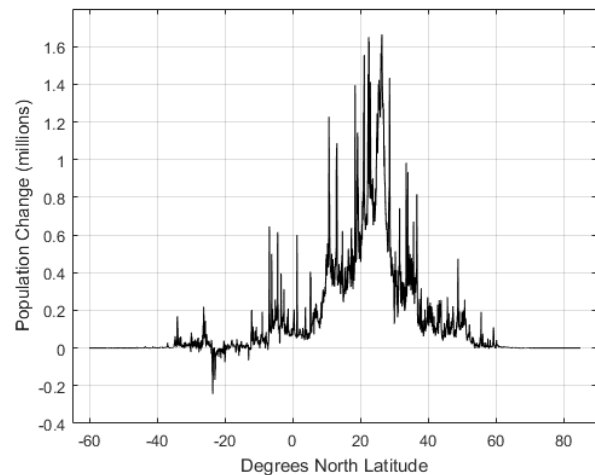

Figure 6. Predicted growth of global populations, 2000-2050 (2015 distribution)
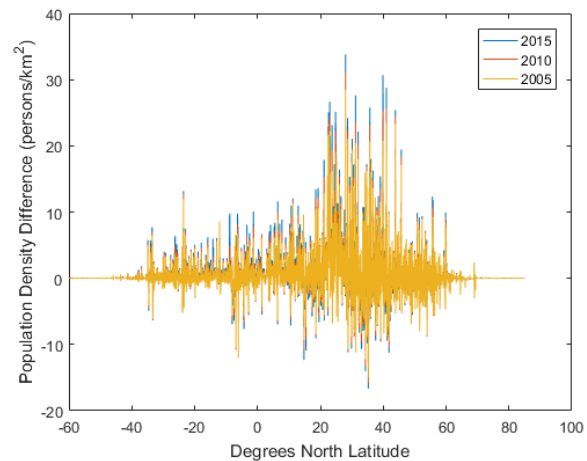

Figure 7. Population density differences between GPWv2 projections and GPWv4 baseline data.

4. INCLINATION-BASED, LATITUDE-AVERAGED POPULATION DENSITY

Objects that are decaying sufficiently far (months to years) in the future can only be predicted to reenter in a probabilistic manner. Because of the earth's rotation and the precession of the nodes, an object will not land

preferentially on any longitude (which is why we have averaged the population density along each latitude band). However, the amount of time an object spends above each latitude is not equal, as is described by the probability distribution function (PDF) Eq. 1 [2], where $-\sin(i) \leq \sin(\lambda) \leq \sin(i)$ (λ is the geocentric latitude, and i the satellite orbit inclination). The satellite does not travel over latitudes where this relation does not hold, so the PDF will be zero outside of this range. The PDF is then multiplied by the latitude-binned population density and integrated to yield the inclination-based, latitude-average population density (see Eq. 2).

Current work by Bacon and Matney [7] has further refined the probability function to include a latitude bias towards the equator in final decay. Such bias derives from the atmosphere's approximately uniform profile above the geoid, creating an effective "wall of air" at equatorial crossings in the late decay stages. Because the correction for this phenomenon is a function of both the ballistic number and of the orbit's inclination, the correction is not modeled within the scope of this geographic study. Their correction algorithm substitutes for this more generic function when solving for a particular spacecraft and a particular orbit.

$$P(\lambda)d\lambda = \frac{\cos\lambda}{\pi\sqrt{\sin^2 i - \sin^2 \lambda}}d\lambda \qquad (1)$$

$$\overline{\rho_{pop}} = \int_{-i}^{i} \rho(\lambda)P(\lambda)d\lambda \qquad (2)$$

Previous models assumed that the earth was spherical, and thus, that the geographic/geodetic latitude (as shown on maps, measured in the local horizontal on the surface of an elliptical Earth) of an object and its geocentric latitude (the angle measured at the Earth's center from the plane of the equator to the point of interest) are identical. There is however, a potentially significant difference (of up to 0.19° at 45° latitude) between these two latitudes, the geocentric (true) latitude being greater than the geographic latitude in the northern hemisphere, and the geographic latitude being greater than the geocentric latitude in the southern hemisphere. These two angles are connected through the relationship in Eq. 3, where λ_g is the geographic/geodetic latitude and λ is the geocentric latitude, and $e_\oplus = 0.08182$ is the eccentricity of the Earth's oblate ellipsoidal shape. Fig. 8 demonstrates the difference between these angles.

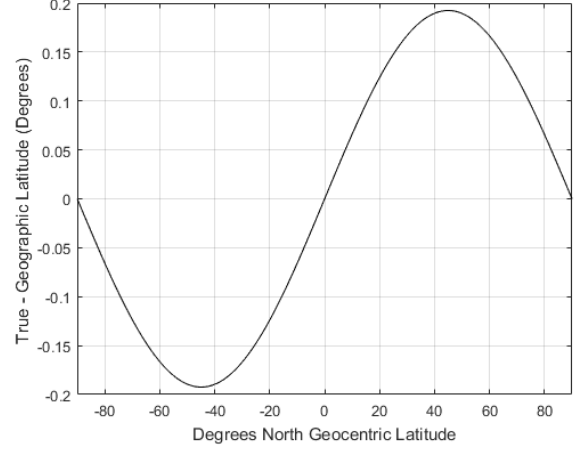$$\tan\lambda = \left(1 - e_\oplus^2\right)\tan\lambda_g \qquad (3)$$

Figure 8. Geocentric (true) latitude minus geographic latitude as a function of geocentric (true) latitude.

The oblate nature of the earth not only causes the latitude angles to shift away from the equator, but also causes the area of each grid cell to change slightly. Eq. 4 gives the area of a grid cell on a spherical earth at a given geocentric latitude and longitude. Eq. 5 gives the grid cell area as a function of geocentric latitude and longitude on an ellipsoidal earth. The difference in areas was computed using these two methods as a function of geocentric latitude, and is seen in Fig. 9. This effect is much smaller than the change in latitude (this is, at worst, less than 0.2% error).

$$dA_{sph} = r^2 \sin\lambda \, d\lambda d\varphi \qquad (4)$$

$$dA_{ell} = r(\lambda,\varphi)\cos\varphi \, [r(\lambda,\varphi) + r(\lambda,\varphi + \Delta\varphi)\cos(\varphi + \Delta\varphi)(1 - \cos\Delta\lambda)]d\lambda d\varphi \qquad (5)$$
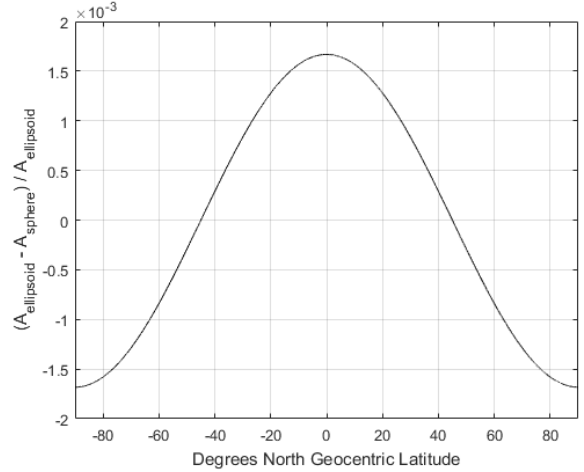

Figure 9. Relative difference in grid cell area in spherical and ellipsoidal Earth models.

Now that the population density has been corrected to geocentric latitude, and the areas have been adjusted

(already completed and included in the GPWv4 data products), the inclination-based, latitude-averaged population density can be computed for each year (2015 and 2050 seen in Fig. 10).
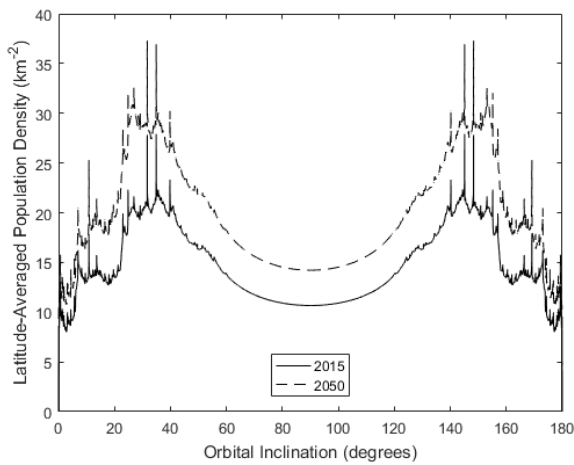

Figure 10. Latitude-averaged population density beneath a satellite, as a function of orbital inclination.

5. REENTRY CASUALTY RISK CALCULATION

The inclination-based population density can be used to compute the "acceptable" debris casualty area (DCA) for a reentry object, using Eq. 6. The factor of 10^{-4} in Eq. 6 is the level of risk specified in requirement 4.7-1 in NASA-STD 8719.14B [1]. Fig. 11 shows the difference in allowable DCA as calculated from Equation 6, applied to former population densities as calculated in Matney, *et al.* [2] and the derived densities under the new method, shown in Fig. 10.

$$DCA = \frac{0.0001}{\overline{\rho_{pop}}} \qquad (6)$$

6. CONCLUSIONS

There has been a significant increase in population density, globally, over the last 15 years, as shown in Fig. 7. This, along with finer resolution data, has contributed to a large reduction (as much as 67% in some inclination ranges) of "acceptable" DCA, seen in Fig. 11. Two effects of Earth asphericity (geocentric and geographic latitude difference, and grid cell size) have been examined, and have been incorporated into the new population-density averaging model and DCA calculation. The inclination based population density can differ by as much as 10% due to the difference in latitude, while the effect of unequal grid cells is much smaller, with a worst-case error of 0.2%.
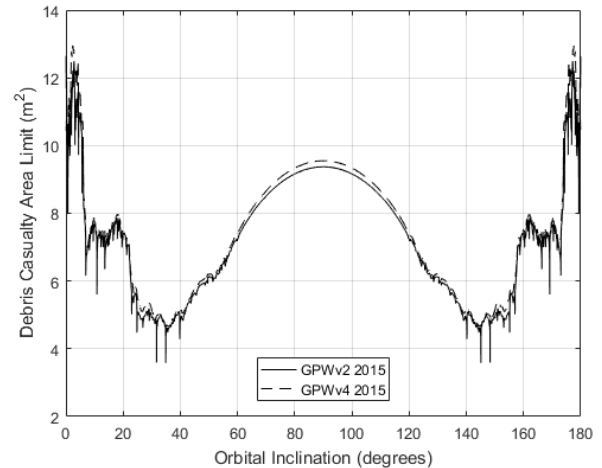

Figure 11. Maximum Debris Casualty Area to meet 1:10000 casualty risk, as a function of inclination. Comparison of GPWv2 densities on a spherical Earth, and GPWv4 densities on an ellipsoidal Earth.

7. FUTURE WORK

These estimates assume that the debris objects do not bounce off the ground, and the entire human population is assumed to be outdoors. Future augmentations to the reentry casualty risk model include accounting for global urbanization trends, the tendency for objects to reenter at latitudes nearer the equator than the poles, and any improvements to the calculation of DCA.

8. REFERENCES

1. NASA Technical Standard – Process for Limiting Orbital Debris, (May 2012). NASA-STD-8719.14A.

2. Matney, M.J., Opiela, J.N. (October 2003). "Improvements to NASA's Estimation of Ground Casualties from Reentering Space Debris," 54th International Astronautical Congress of the International Astronautical Federation, the International Academy of Astronautics, and the International Institute of Space Law, Bremen. Germany.

3. United States Bureau of the Census, "International Data Base." Available at: https://www.census.gov/population/internation al/data/idb/. Accessed 16 June 2017.

4. Center for International Earth Science Information Network - CIESIN - Columbia University. (2016). Gridded Population of the World, Version 4 (GPWv4): Population Count Adjusted to Match 2015 Revision of UN WPP Country Totals. Palisades, NY: NASA Socioeconomic Data and Applications Center

(SEDAC). Available at: http://dx.doi.org/10.7927/H4SF2T42. Accessed 16 June 2017.

5. CIESIN (Center for International Earth Science Information Network), Columbia University; International Food Policy Research Institute (IFPRI); and World Resources Institute (WRI). 2000. Gridded Population of the World (GPW), Version 2. Palisades, NY: CIESIN, Columbia University. Available at: http://sedac.cisin.columbia.edu/plue/gpw. Accessed 16 June 2017.

6. United States Bureau of the Census, "International Data Base: Population Estimates and Projections Methodology". Available at: http://www.census.gov/population/international/data/idb/estandproj.pdf. Accessed 16 June 2017.

7. Bacon, J.B., Matney, M.J.(October 2017). "Oblate-Earth Effects on the Calculation of Ec During Spacecraft Reentry", 9th International Association for the Advancement of Space Safety Conference, Toulouse, France.