Empirical Tests of the Predicted Footprint for Uncontrolled Satellite Reentry Hazards

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A number of statistical tools have been developed over the years for assessing the risk of reentering object to human populations. These tools make use of the characteristics (e.g., mass, material, shape, size) of debris that are predicted by aerothermal models to survive reentry. The statistical tools use this information to compute the probability that one or more of the surviving debris might hit a person on the ground and cause one or more casualties.

The statistical portion of the analysis relies on a number of assumptions about how the debris footprint and the human population are distributed in latitude and longitude, and how to use that information to arrive at realistic risk numbers. Because this information is used in making policy and engineering decisions, it is important that these assumptions be tested using empirical data.

This study uses the latest database of known uncontrolled reentry locations measured by the United States Department of Defense. The predicted ground footprint distributions of these objects are based on the theory that their orbits behave basically like simple Kepler orbits. However, there are a number of factors in the final stages of reentry - including the effects of gravitational harmonics, the effects of the Earth’s equatorial bulge on the atmosphere, and the rotation of the Earth and atmosphere - that could cause them to diverge from simple Kepler orbit behavior and possibly change the probability of reentering over a given location. In this paper, the measured latitude and longitude distributions of these objects are directly compared with the predicted distributions, providing a fundamental empirical test of the model assumptions.

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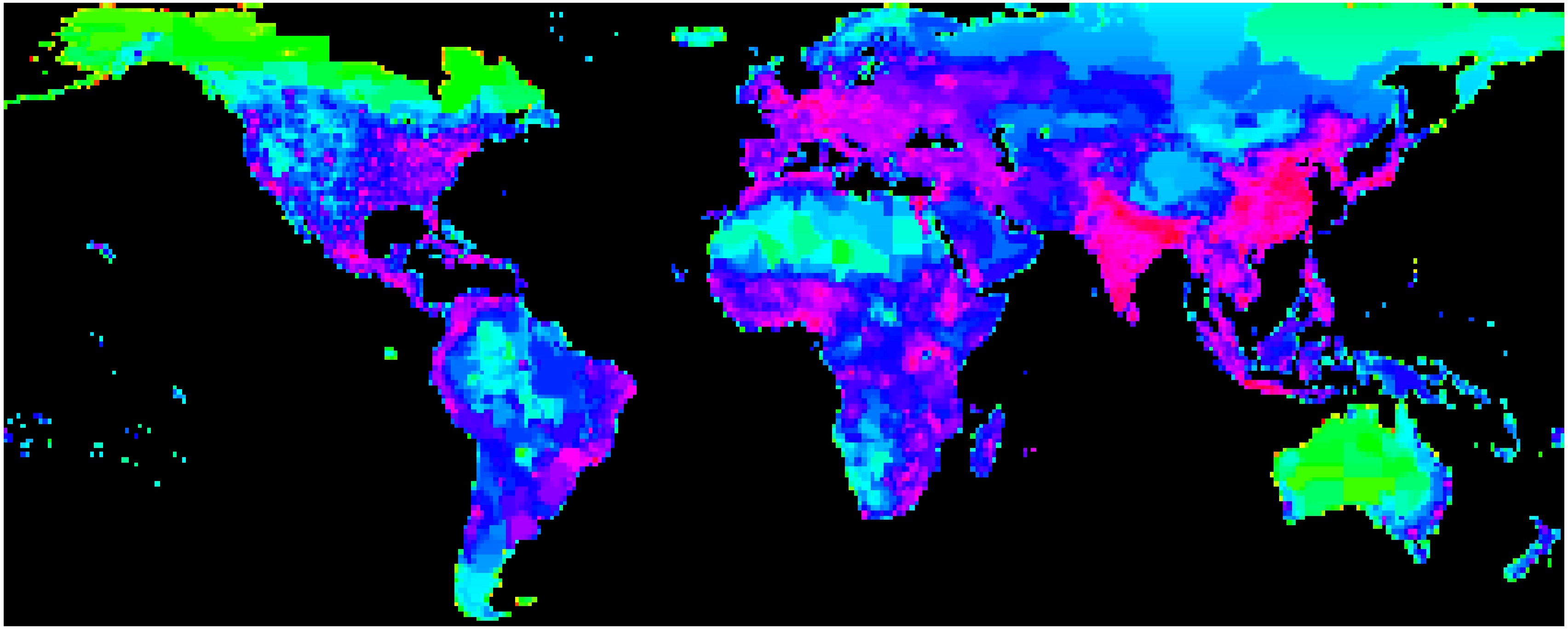
Reentry Risks

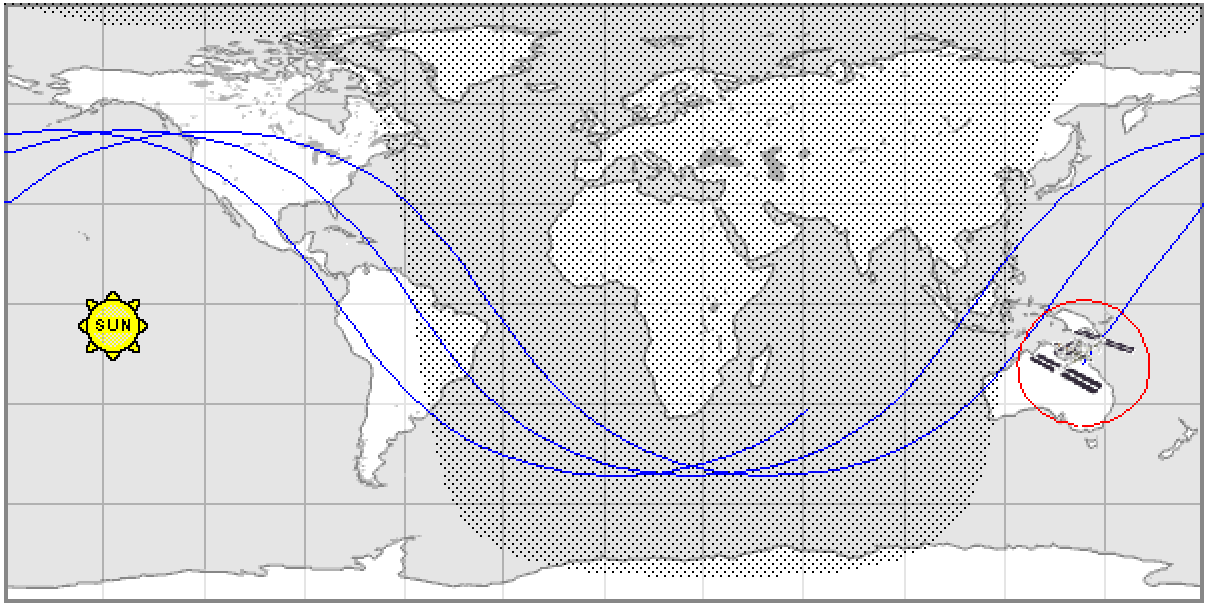
- Uncontrolled reentry of satellites pose a potential risk to people on the ground
  - Satellite pieces survive reentry
    - ORSAT/DAS
    - SCARAB
  - Toxic substances
- Risk calculation
  - Population density under ground track
  - Size of human beings
  - What fraction of humans are sheltered
  - Size of surviving debris
    - Does it “bounce”?
    - Size of zone where exposure to toxic substances is a hazard
  - Energy of impact
    - 15 Joules

Population Distribution on the Earth



- Gridded Population of the World, version 3 (GPWv3)
- Socioeconomic Data and Applications Center (SEDAC) at Columbia University
- 2.5×2.5 arc minute cells = 4.6 km×4.6 km cells at the Equator
- Reference years 1990-2015 in 5-year intervals

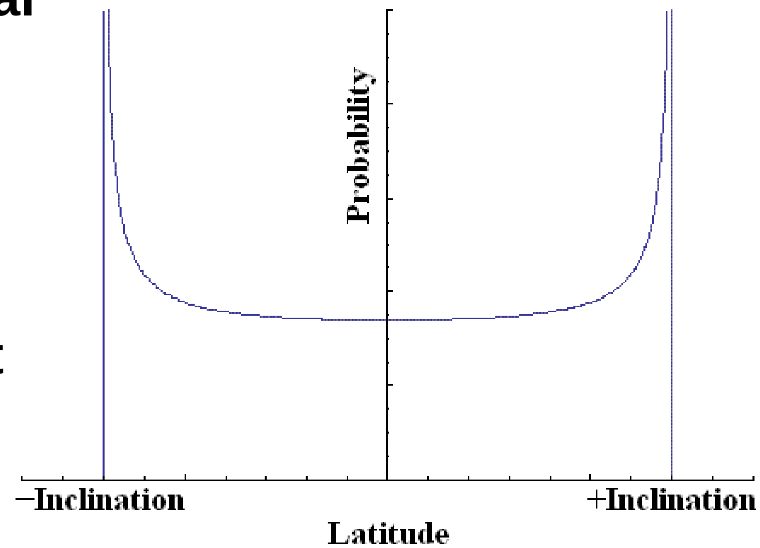
Geographic Distribution of ISS Orbit



- **Satellite does not overfly latitudes beyond ± orbit inclination**
- **Satellite spends a disproportionate amount of time near northernmost and southernmost parts of the orbit**
- **Rotation of the Earth and precession of orbit plane result in randomized longitude**

Latitude Distributions

- **Under the assumption that the orbit is an ideal circular Kepler orbit, reentry latitude probability is not uniformly distributed**

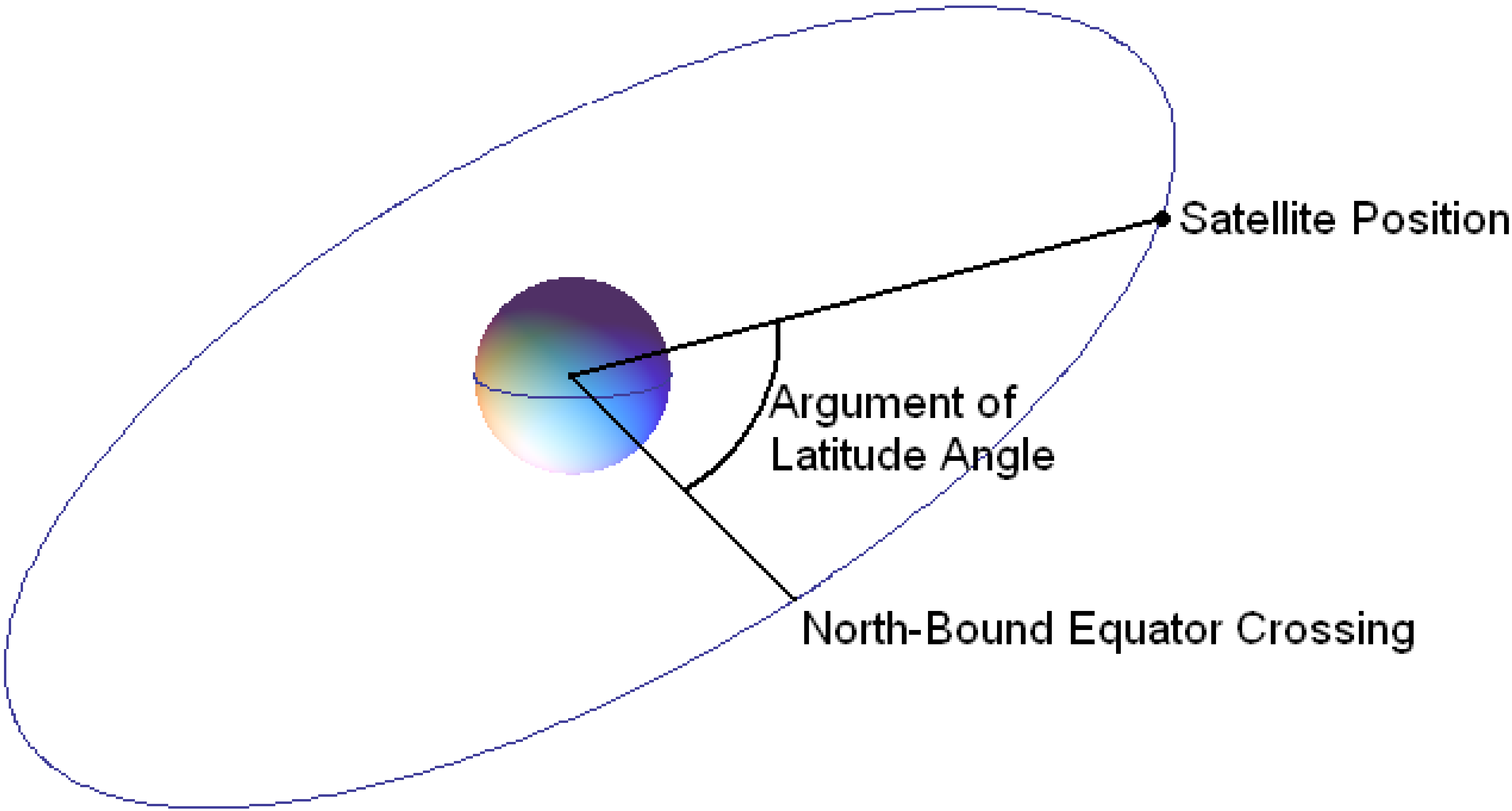


- **Instead, the argument of latitude (= argument of perigee + true anomaly) is assumed to be uniformly randomly distributed**

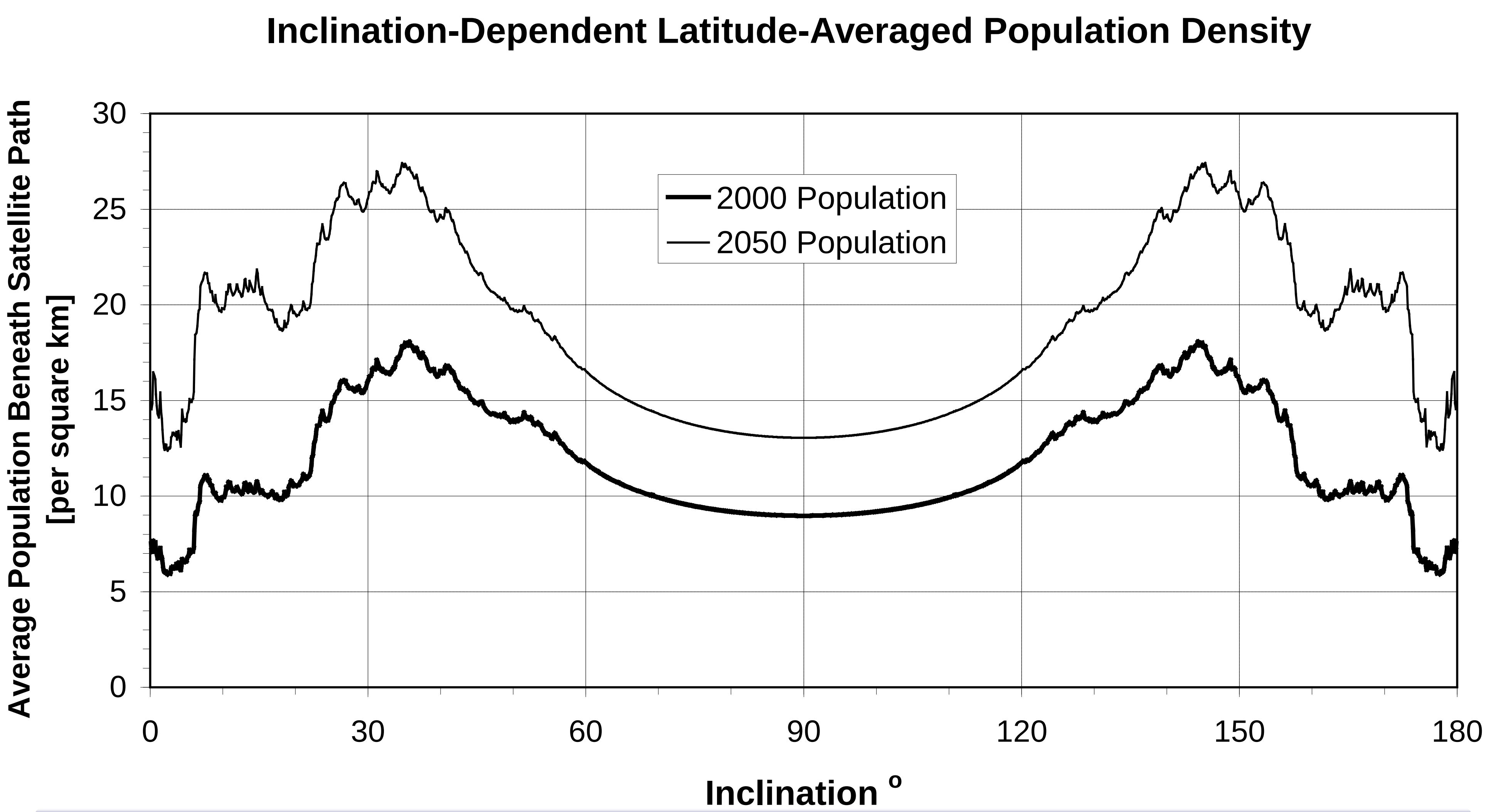
- **Relationship between argument of latitude *u*, latitude *lat*, and inclination *inc* (quadrant must be set according to whether orbits is ascending – going north – or descending – going south – at time of reentry)**

$$\sin u = \frac{\sin lat}{\sin inc}$$

Argument of Latitude



Average Density of People Below Satellite Path



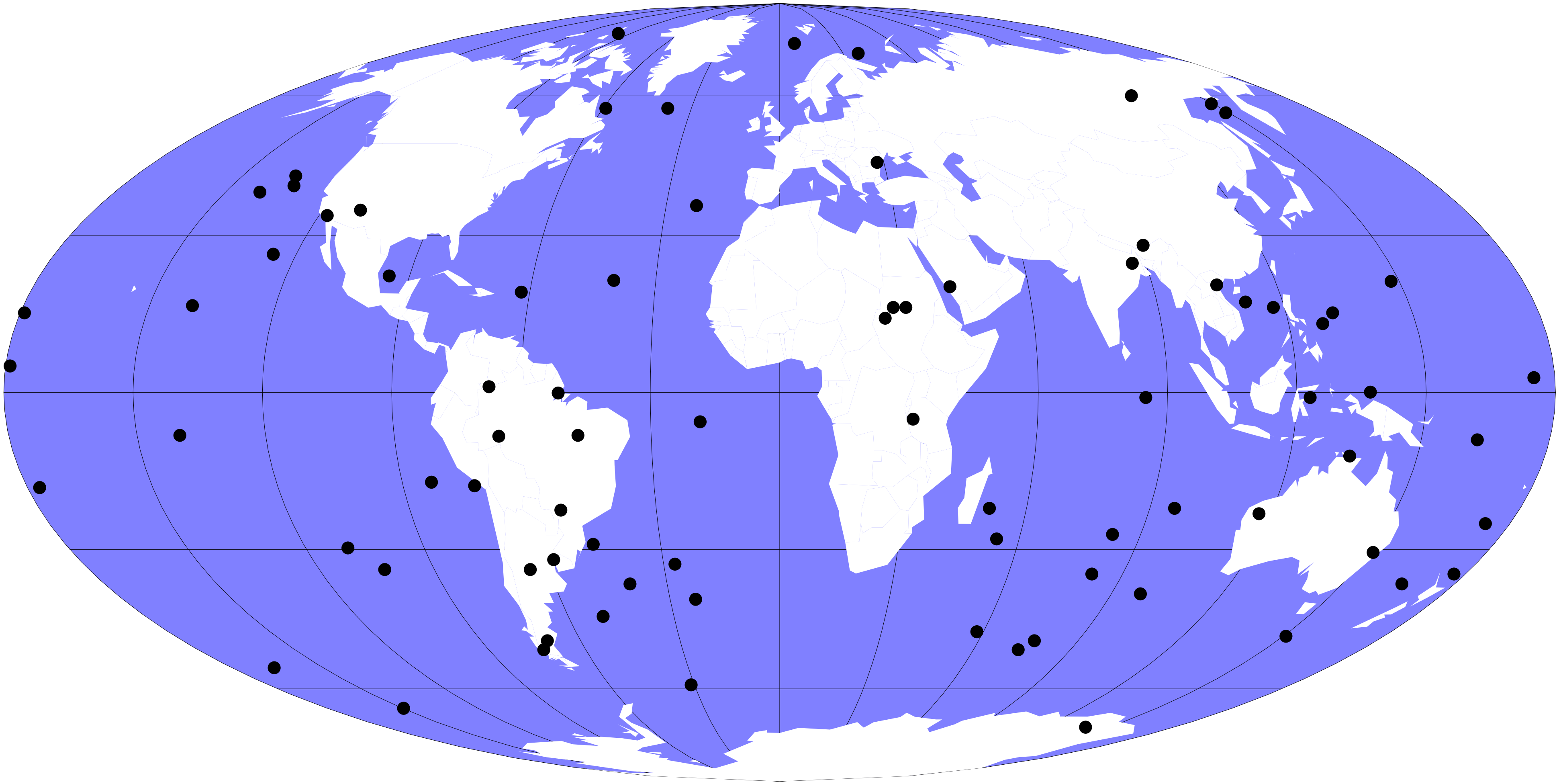
Latitude/Longitude Distributions

- **Computation of risk assumes satellite reentries are distributed randomly in argument of latitude and longitude. How do we know this assumption correct?**

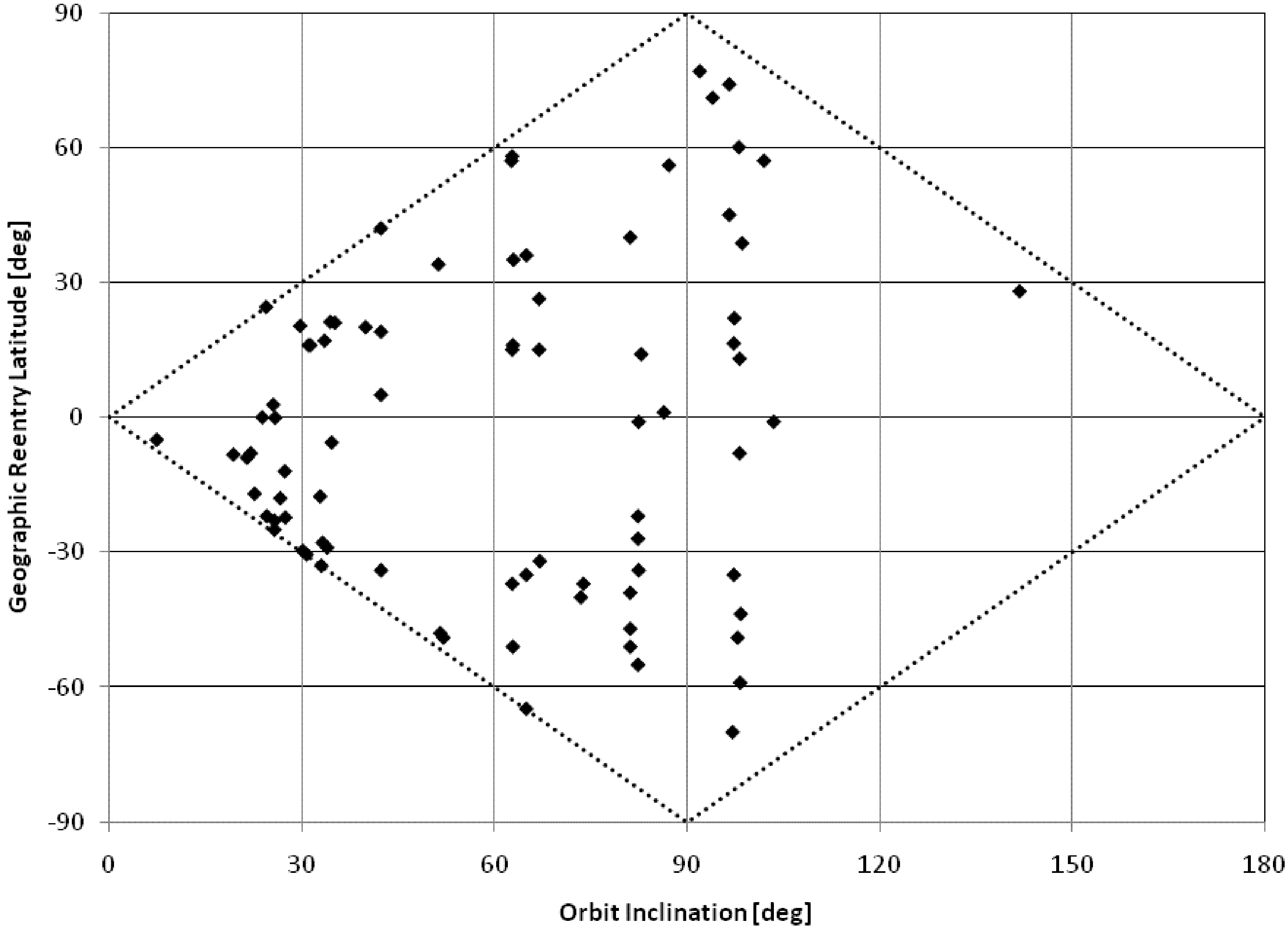
- **This talk is a follow-up to that given at the 3rd IAASS Symposium in Rome for 47 reentries**

- **Reentry database**
  - **81 intact satellites (both rocket bodies and spacecraft) that reentered between 2003 and 2011 (including UARS)**
  - **Near-circular orbits (final orbit eccentricity < 0.0075, corresponding to a difference between apogee and perigee less than 100 km)**
  - **Objects in orbit >15 days**
  - **Reentry latitude/longitude accurately measured by US DoD**
  - **Believed to be no geographical observation biases**

Global Distribution of 81 Circular Orbit Reentries



Reentry Latitude of 81 Circular Orbit Satellites as a Function of Inclination



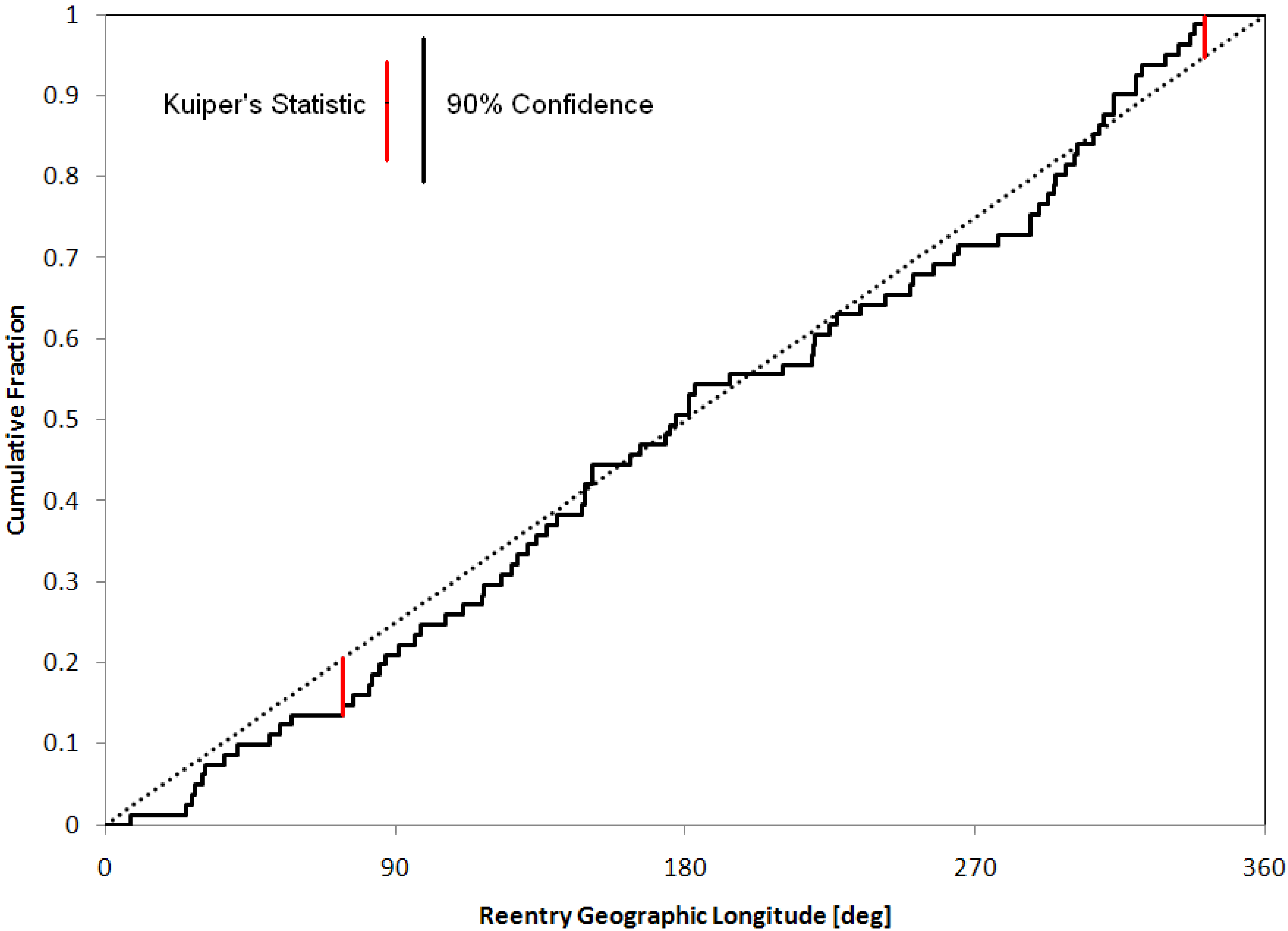
Statistical Tests

- **Longitude is believed to be randomly distributed**
  - **How do we test this assumption?**

- **Kuiper's test**
  - **Plot cumulative distribution of both data and theoretical distribution**
  - **Measure maximum difference between the two both above and below the theoretical distribution**
  - **Compare the sum of these two values to the range of possible values for a random draw from the theoretical uniform distribution**

  - **Similar to Kolmogorov-Smirnov test**
  - **It is a better measure near the "ends" than the K-S test**
  - **Works better than the K-S test with "wrap-around"/periodic distributions, but is applicable for any distribution**

Longitude Distribution for 81 Circular Orbit Reentries



Statistical Tests

- **Using Kuiper's test, we can conclude that the measured distribution was indeed randomly distributed in longitude well within the 90% confidence bounds, as expected**
  - **In other words, the measured distribution is consistent with a random sample from a uniform distribution in longitude, within statistical bounds**
- **For latitude analysis, use argument of latitude distribution**
  - **Should be distributed uniformly if assumptions hold**

Argument of Latitude Distribution

- **Why might we expect that the reentry argument of latitude distribution to vary from a perfect Kepler orbit?**

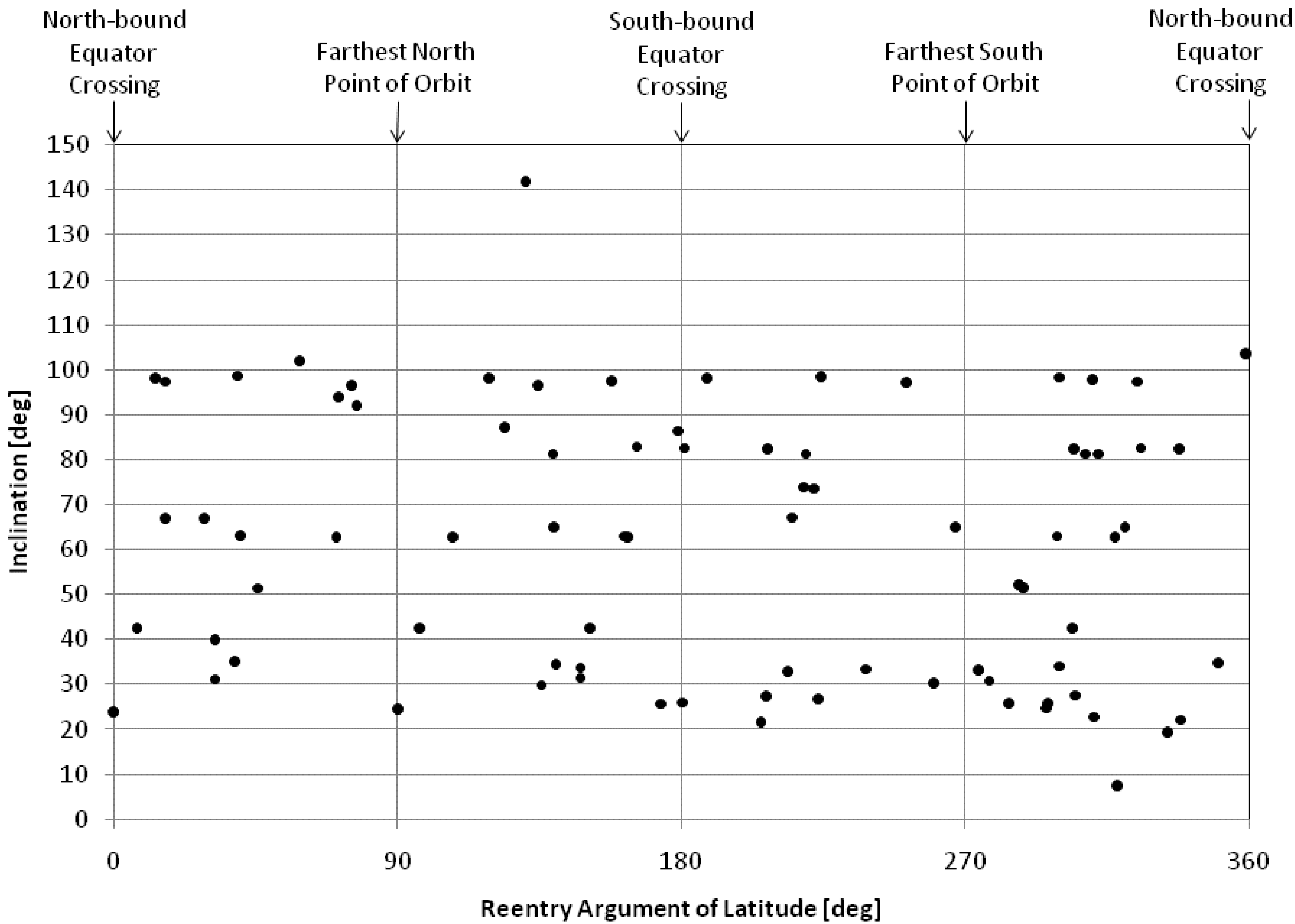
1. **J_2 gravitational term changes orbit speed and azimuth near the equator**

2. **Earth is not perfectly spherical**
   - **The equatorial radius is larger than the polar radius**
   - **The atmosphere at the equator is correspondingly denser at a given radius**

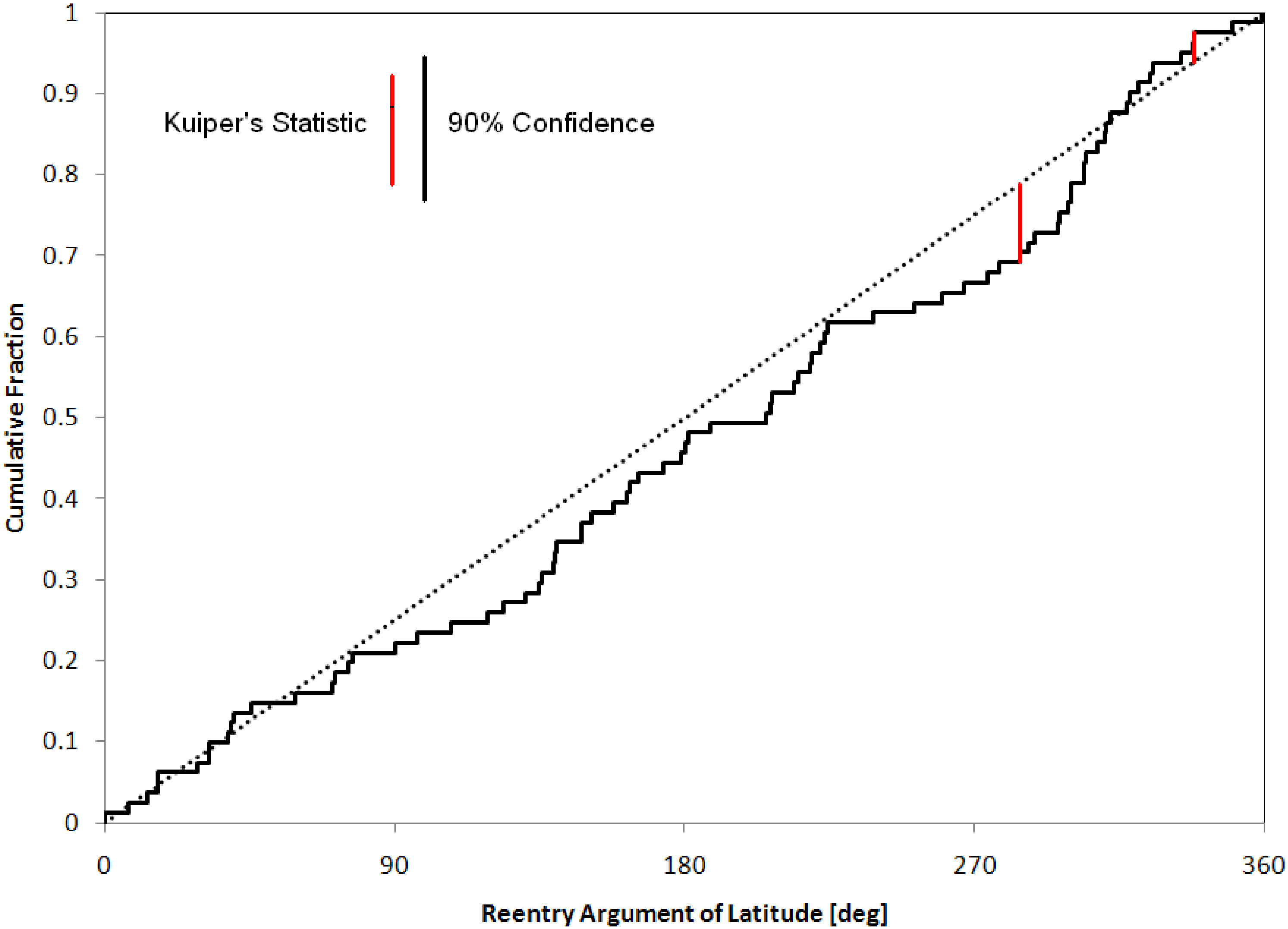
3. **Differential heating of the atmosphere**
   - **Subsolar point always in the tropics**
   - **Magnetospheric heating near the poles**

4. **The atmosphere rotates with the Earth**
   - **Drag is a function of the relative velocity of the satellite and the atmosphere**
   - **Different relative velocity**
     - **As satellite crosses the equator**
     - **At northernmost and southernmost regions of the orbit**

Argument of Latitude Distribution for 81 Circular Orbit Reentries



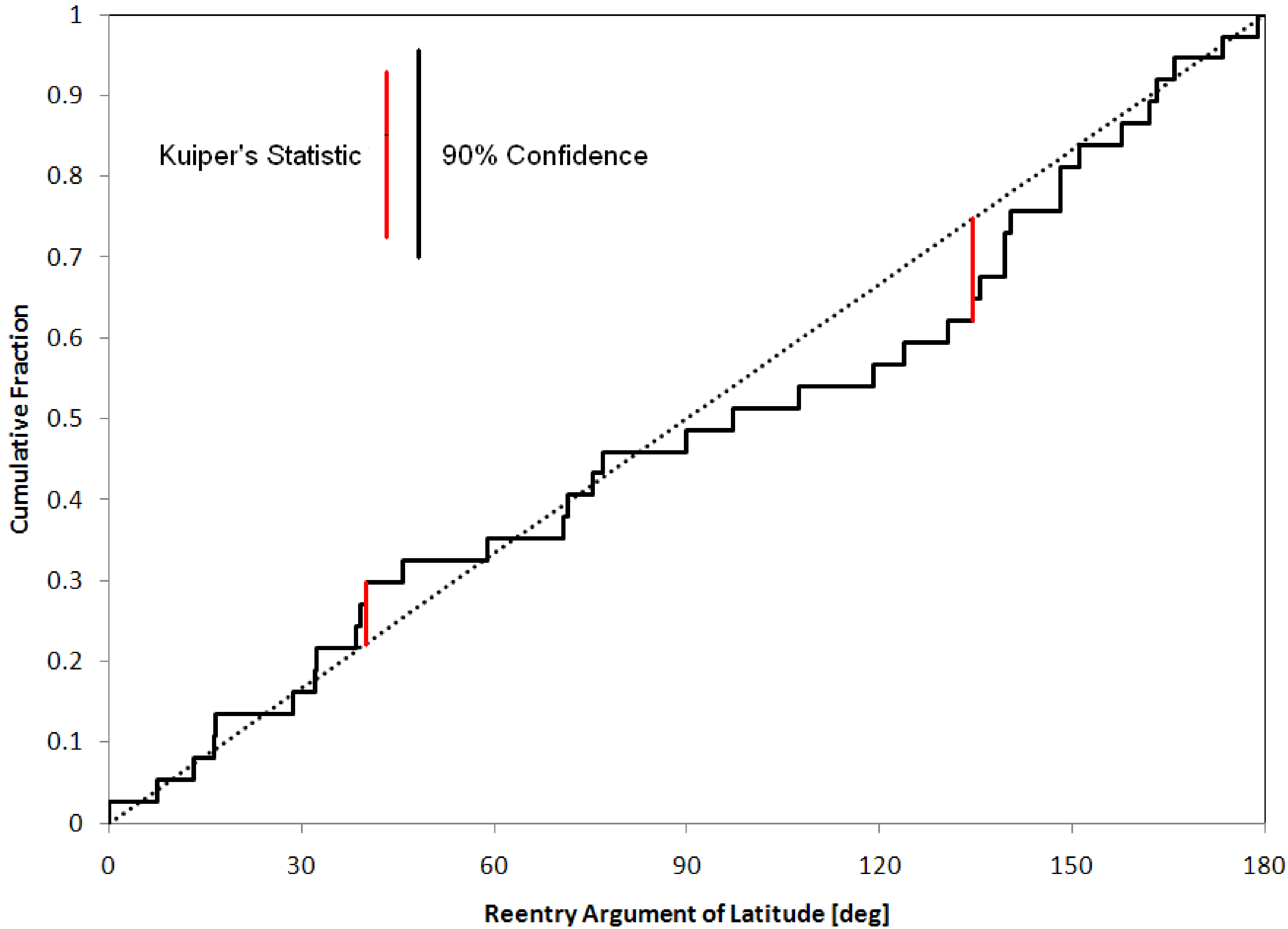
Argument of Latitude Distribution for 81 Circular Orbit Reentries



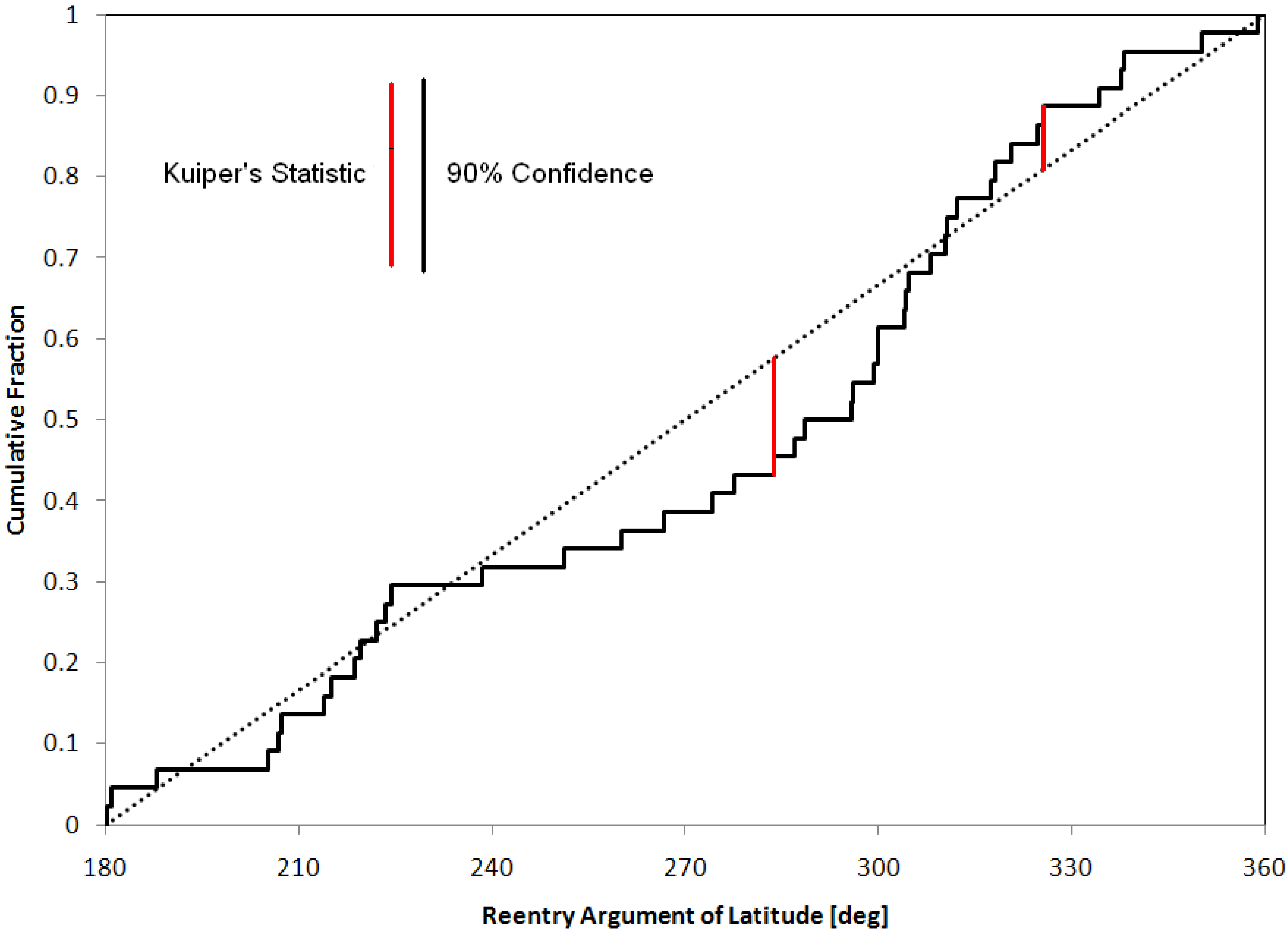
Argument of Latitude Distribution

- **Overall Argument of Latitude distribution consistent with uniform distribution**
- **However, northern hemisphere reentries (0° to 180°) and southern hemisphere reentries (180° to 360°) appear to show biases**

Argument of Latitude Distribution for 37 Northern Hemisphere Circular Orbit Reentries



Argument of Latitude Distribution for 44 Southern Hemisphere Circular Orbit Reentries

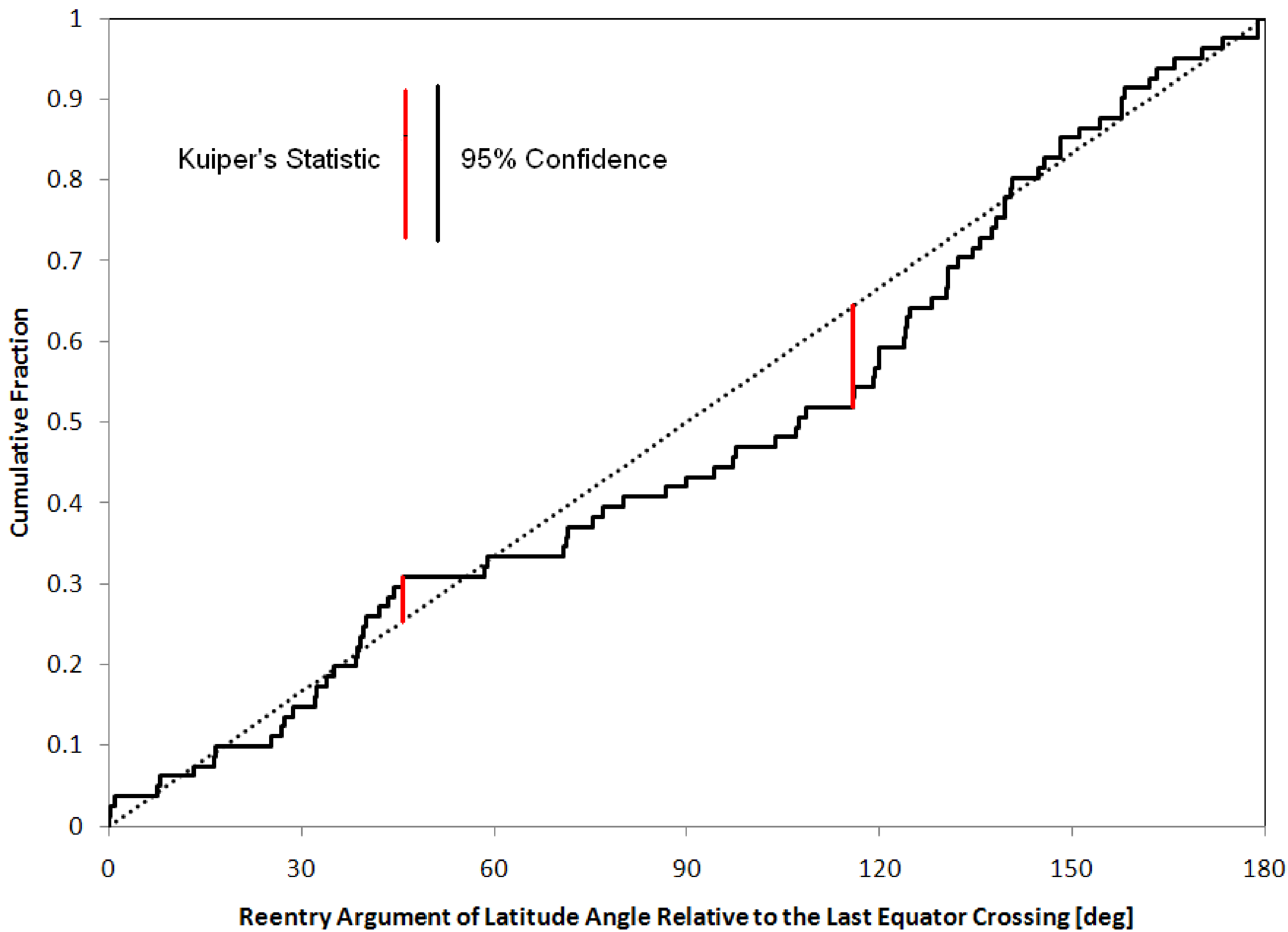


Modified Argument of Latitude Distribution

- Despite the apparent biases in the northern and southern hemisphere reentries, the overall Argument of Latitude distribution is consistent with uniform distribution

- Nevertheless, the similarities of the northern and southern hemisphere reentry distribution warrants a second look
  - Plot the distribution of the Argument of Latitude angle from the last Equator crossing (north-bound or south-bound)
  - If Argument of Latitude < 180°, use Argument of Latitude
  - If Argument of Latitude > 180°, use Argument of Latitude - 180°

Distribution in Angle from Last Equator Crossing (North-Bound or South-Bound) for 81 Circular Orbit Reentries



Modified Argument of Latitude Distribution

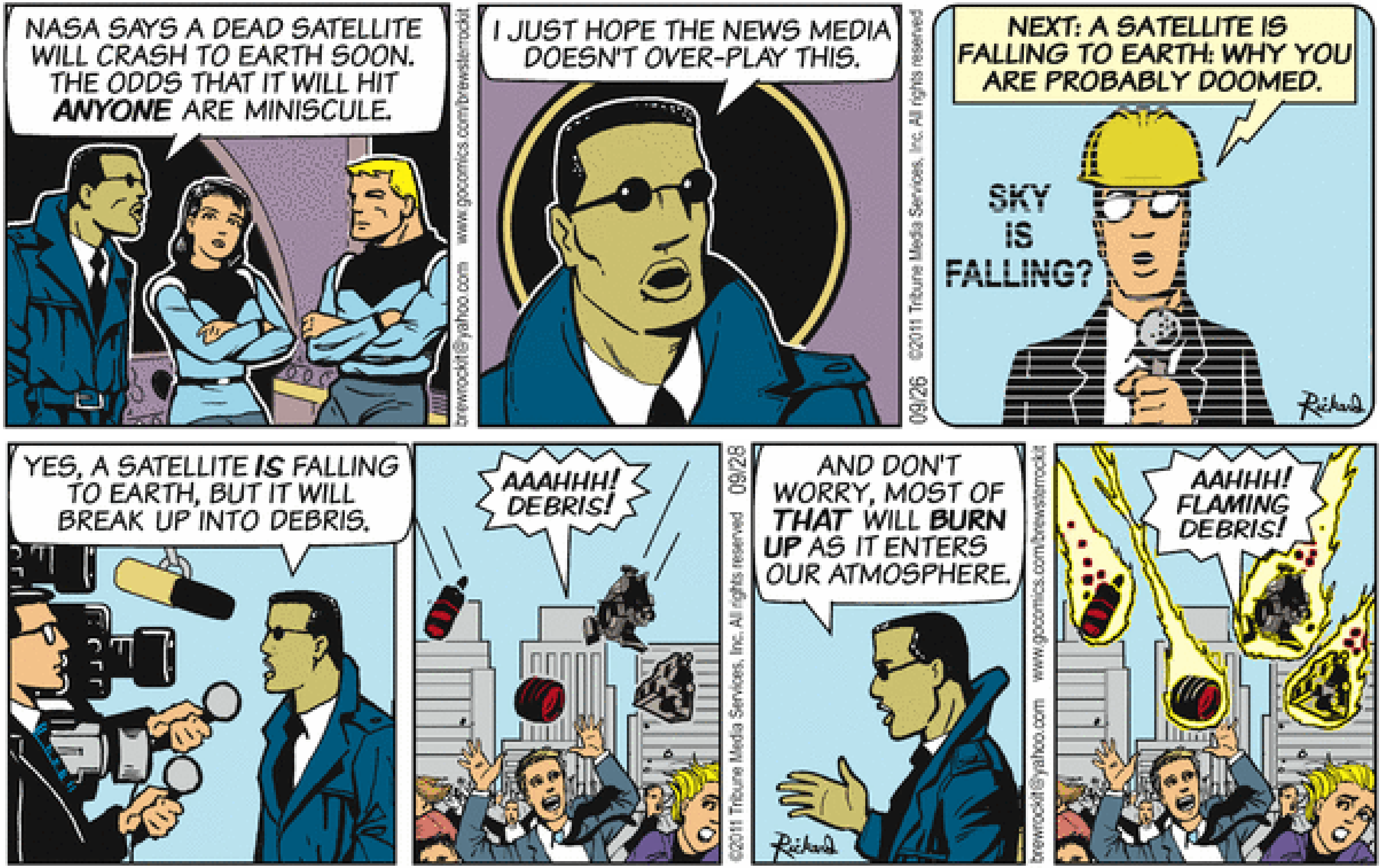
- **Kuiper's statistic for this distribution exceeds 90% confidence limits, but remains within 95% confidence limits**

- **Data possibly hints at non-uniform distribution in argument of latitude, but more data needed to resolve**

Conclusions

- **Random distribution of reentry parameters for circular orbit reentries consistent with model assumptions within statistical bounds**
  - **Hints that there may be biases in the argument of latitude position in each hemisphere, but sample size not large enough to resolve**
  - **At this point, there is no justification for altering our reentry risk assumptions on the geographic distribution of debris**
- **Future work**
  - **Need even larger data base – preferably hundreds of reentries**
  - **Investigate behavior of decay of elliptical orbits – driven more by gravitational perturbations than by atmosphere?**
  - **Careful modeling of generalized reentries**

Questions?


NASA SAYS A DEAD SATELLITE WILL CRASH TO EARTH SOON. THE ODDS THAT IT WILL HIT ANYONE ARE MINISCULE.
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SKY IS FALLING?
YES, A SATELLITE IS FALLING TO EARTH, BUT IT WILL BREAK UP INTO DEBRIS.
AAAHHH! DEBRIS!
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