Quantitative Assessment of a Threshold for Risk Mitigation Actions

Theodore H. Sweetser[(1)], Barbara M. Braun[(2)], Michael Acocella[(3)], and Mark A. Vincent[(4)]

(1) Jet Propulsion Laboratory, California Institute of Technology, 4800 Oak Grove Dr. Pasadena, CA, USA 91109
(2) The Aerospace Corporation, 2155 Louisiana Blvd. NE, Suite 5100, Albuquerque, NM, USA 87110
(3) Northrop Grumman, 45101 Warp Dr., Dulles, VA, USA 20166
(4) Raytheon Corp

ABSTRACT

Many low-Earth-orbit missions have a policy that if a future conjunction with a secondary object such as a piece of orbital debris is detected, a go/no go meeting will be held to decide about a risk mitigation action before the time of closest approach. Commonly, the policy is that a probability of collision (Pc) above a predetermined action threshold at the time of the meeting means the mission will take action to reduce the risk. The value to which the action threshold is set is a compromise—if it is higher, then there is a higher probability that a collision might occur when action is not taken; if it is lower, then more actions will be taken, increasing the cumulative costs and risks of the actions themselves.

Up to now, the basis for setting the action threshold has been engineering judgment, usually with reference to the NASA requirement concerning collisions with large objects. This requirement is that at launch the estimated cumulative probability of such a collision over the orbital lifetime of the mission's spacecraft shall be less than 0.001. The CloudSat and OCO-2 missions, for example, currently have an action threshold of 0.0001. This paper shows how a policy using an action threshold affects the overall mission risk of a collision with a large object.

The approved method for estimating the total mission risk of a collision with a large object is to run NASA's Debris Assessment Software (DAS), which can be used to find the *a priori* risk during each phase of the orbital lifetime, i.e., during operations and after the end of the mission if the spacecraft is left passive in orbit until atmospheric drag causes reentry into Earth's atmosphere. DAS does not include consideration of risk mitigation during operations, but we show how to estimate the fraction by which the risk during operations is reduced as a function of the value of the action threshold. This can be combined with the DAS results to give the total risk with risk mitigation included.

The key to estimating the risk reduction from an action-threshold policy is answering the question: given that the spacecraft is on a collision course, how likely is the mission to take action to prevent the collision? That likelihood is the fraction of risk that will be removed during operations because this policy is followed. The value of that likelihood is the product of the probability that the Pc will be greater than the action threshold at the go/no go meeting given that the spacecraft is on a collision course and the probability that the action will be successfully performed if the action threshold is exceeded. This paper tells how to estimate the first of those two probabilities.

The distribution of possible orbit determinations around the actual trajectory is the negative of the distribution of possible trajectories around an orbit determination, which is the same if the distribution is symmetric. We assume this distribution gives a bivariate random vector in the conjunction plane, which is centered on the spacecraft and is perpendicular to the relative velocity of the secondary with respect to the spacecraft. The covariance of this distribution is derived from the combined covariances of the orbit determinations of the spacecraft and the secondary. We first find the contour of the probability distribution function (pdf) which corresponds to a Pc that equals the action threshold—this depends on the expected value of the combined hard-body radius for the spacecraft and the secondary and the expected value of the covariance in the conjunction plane. The Pc of any possible orbit determination is the cumulative distribution within the combined hard-body radius of the point being considered. This can be calculated by using the Rice distribution, but instead we approximate it by multiplying the pdf at the point by the area given by the hard-body radius—the error from this approximation is shown to be small. With this approximation, the contour is at a constant Mahalanobis radius from the spacecraft and we show that the cumulative distribution function within this contour is given by Rayleigh's distribution. This gives the probability we sought.

We augment this with estimates of action success, expected hard-body radius, and expected covariance to obtain an algorithm for estimating the risk reduction associated with an action threshold policy. We apply this algorithm to the OCO-2 and CloudSat missions as examples, using historical conjunction data for these two missions.