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Title: Space Vehicle Reliability Modeling in DIORAMA

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Space Vehicle Reliability Modeling in DIORAMA

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1 Introduction

When modeling system performance of space based detection systems it is important to consider spacecraft reliability [1, 2]. As space vehicles age the components become prone to failure for a variety of reasons such as radiation damage. Additionally, some vehicles may lose the ability to maneuver once they exhaust fuel supplies. Typically failure is divided into two categories: engineering mistakes and technology surprise. This document will report on a method of simulating space vehicle reliability in the DIORAMA framework.

2 Reliability

Reliability is commonly referred to as the ability of a system or component to function under stated conditions for a specified period of time. For space vehicles the specified period of time may be referred to as the Mean Mission Duration (MMD), or the average time an on-orbit space system is operational before a mission critical failure occurs. The MMD is determined by (1) where $R(t)$ is the mission reliability model and T_D is the design life of the vehicle.

$$MMD = \int_0^{T_D} R(t)dt \tag{1}$$

Often times for on-orbit systems the reliability model (R) is specified using a Weibull distribution. The Weibull distribution is an exponential function in which the reliability of a vehicle decreases as a function of time. Equation 2 shows the Weibull distribution as a function of time, t, where α is the scale parameter and β is the shape parameter. Both t and α share the same units of time (*e.g.* hours, months, years) and β is dimensionless. For space vehicle reliability the β parameter is typically between 1.2 and 1.7.

$$R(t) = e^{-(t/\alpha)^\beta} \tag{2}$$

The shape parameter (β) has 3 possible ranges all with interesting meaning. Values of β less than 1 indicate decreasing failure rates, or infant mortality. This could be caused by uncertainties during launch (e.g. failure) or changes to the vehicle during a burn-in period. Values of β greater than 1 indicates increasing failure rate, or wear out. This could apply to individual components, fuel levels, damage, etc. Finally, a β value of 1 indicates a constant failure rate (exponential decay). Another quantity of interest to reliability studies is the Mean Time To Failure (MTTF) or the average time a vehicle is expected to operate before it fails. This is sometimes also called the Mean Time to First Failure (MTTFF). The calculation of the MTTF is shown in (3).

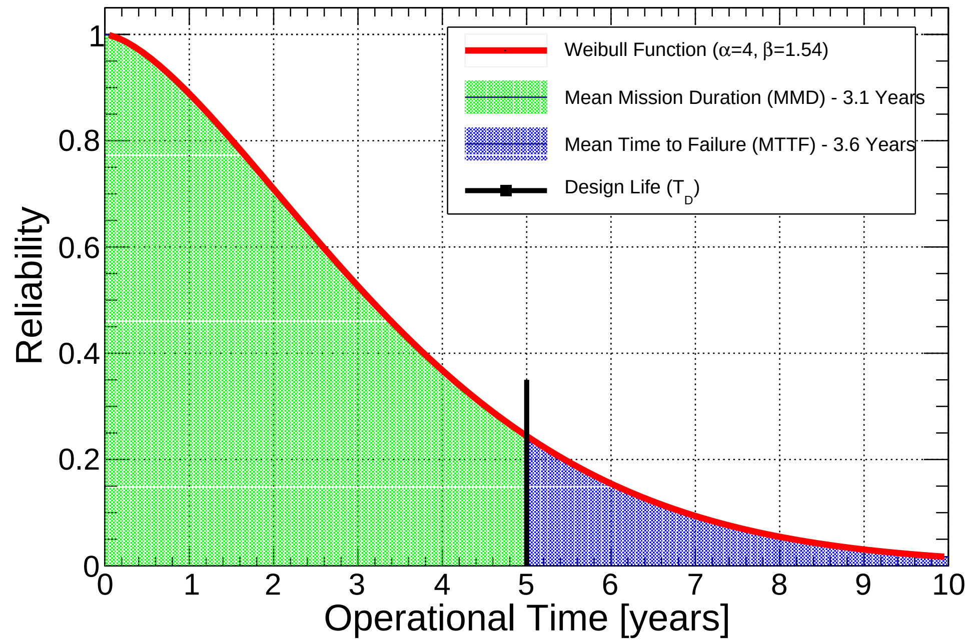

Figure 1: Notional space vehicle reliability versus time curve.

$$MTTF = \int_0^\infty R(t)dt \tag{3}$$

Consider a notional space vehicle which has $\alpha = 5$ years, $\beta = 1.54$ and a design lifetime of 5 years. Figure 1 shows the associated Weibull distribution, $R(t)$.

In Fig. 1 the Weibull distribution is shown in red where the MMD is the area under the distribution up to the design life and the MTTF is the total area under the curve (green + blue).

3 Implementation in DIORAMA

The DIORAMA framework allows for specification of a constellation of space vehicles using an XML description of the arrangement. Additionally, users can specify the start and end dates (e.g. launch and retire) of each space vehicle. Using these dates, DIORAMA first determines if a satellite was present in the constellation at the time of a given event. Next, if the satellite has clear line of sight to the event (e.g. not Earth blocked) it will be incorporated into the simulation of that event.

In order to add spacecraft reliability to the DIORAMA framework, several additional parameters were added to the duration element of the XML schema; the alpha and beta parameters. Listing 1 shows and example XML specification of a single satellite that was launched on 2016-07-01 and assumed to be present in the constellation until 2030-07-01. Additionally, the alpha and beta parameters are specified to be 4 and 1.54 respectively.

Listing 1: Example XML duration element with Weibull parameters specified.

```
<body id="SV-1" type="satellite">
  ...
  <duration>
    <begin value="2016-07-01T00:00:00.00Z"/>
    <end value="2030-07-01T00:00:00.00Z"/>
    <alpha value="4.0"/>
    <beta value="1.54"/>
  </duration>
  ...
</body>
```

In this case, an event simulated in DIORAMA on 2017-07-01 will decide that satellite SV-1 is in the current constellation, check if the event is in view of the satellite and if so, then calculate the reliability parameters. This is accomplished by evaluating the Weibull distribution with the given alpha and beta parameters at the time of the event, with respect to the launch date of the satellite (e.g. in this case 1 year into the distribution). This will produce a number in the range of 0 to 1 indicating the probability of failure of the vehicle. A random number is generated on the same range and if the random number is less than the probability of failure, then the satellite is taken out of the simulation. This logic is applied on an event by event basis, meaning the reliability is not applied for all time given a single sampling.

4 Example Calculations

It is useful for validation of the codes to envision a test case where the affect of reliability can be easily observed. In this section, an example single satellite constellation will be considered. Using the satellite definition from Listing 1, a static location can be added along with a single look angle respondent (geometric) sensor model and a terminator processor. Listing 2 shows the full satellite description in the DIORAMA XML format.

Here, the satellite is launched in July of 2016 and slated for retirement in July of 2030. The Weibull parameters for alpha and beta are 4.0 years and 1.54 respectively. The satellite has been placed at (0, 0) in latitude and longitude and 20,200 km altitude (*i.e.* GPS orbit). The location of the satellite is not changing with time. The satellite has a single X-ray sensor on-board with a hypothetical look angle constraint of 90 degrees, *i.e.* any satellite that is within ±90 degrees of the event will trigger the sensor. The terminator processor is a requirement of DIORAMA such that the simulator knows when events are complete.

The next step in the simulation is to define an event or set of events. For this test case, since the performance of the sensor over the course of many years is required, a set of event clusters will be defined. Listing 3 shows the event cluster definition. Here, 11 dates will be evaluated starting on July 1 of 2016 and each additional date is specified 1 year later. On each date evaluated 1000 events will be simulated over the course of the day, randomly in time (*n_sample*). The event is located at (0, 0) in latitude and longitude at 100 km altitude (i.e. directly below the satellite), therefore the sensor should always trigger on the event because the look angle is 0 degrees.

Listing 2: Example XML body definition for a single satellite.

```
<body id="SV-1" type="satellite">
  <duration>
    <begin value="2016-07-01T00:00:00.00Z"/>
    <end value="2030-07-01T00:00:00.00Z"/>
    <alpha value="4.0"/>
    <beta value="1.54"/>
  </duration>
  <location>
    <geographic>
      <latitude value="0.0"/>
      <longitude value="0.0"/>
      <altitude value="20200.0"/>
    </geographic>
  </location>
  <sensors>
    <sensor class="lar" id="SENSOR1"/>
      <parameters>
        <parameter name="acceptance_angle" value="90.0"/>
        <parameter name="phenomenology" value="XRAY"/>
      </parameters>
    </sensor>
    <processors>
      <processor class="terminator" id="TERMINATOR">
        <inputs>
          <input><class source="lar" include_same_body="true"/></input>
        </inputs>
      </processor>
    </processors>
  </sensors>
</body>
```

Listing 3: Example event clusters definition.

```
<event_clusters>
  <event_cluster>
    <events>
      <event class="sample" id="EVENT" type="nudet">
        <parameters>
          <parameter name="yield" value="1.0"/>
        </parameters>
        <location>
          <geographic>
            <latitude value="0.0"/>
            <longitude value="0.0"/>
            <altitude value="100.0"/>
          </geographic>
        </location>
      </event>
    </events>
  </event_cluster>
</event_clusters>
```

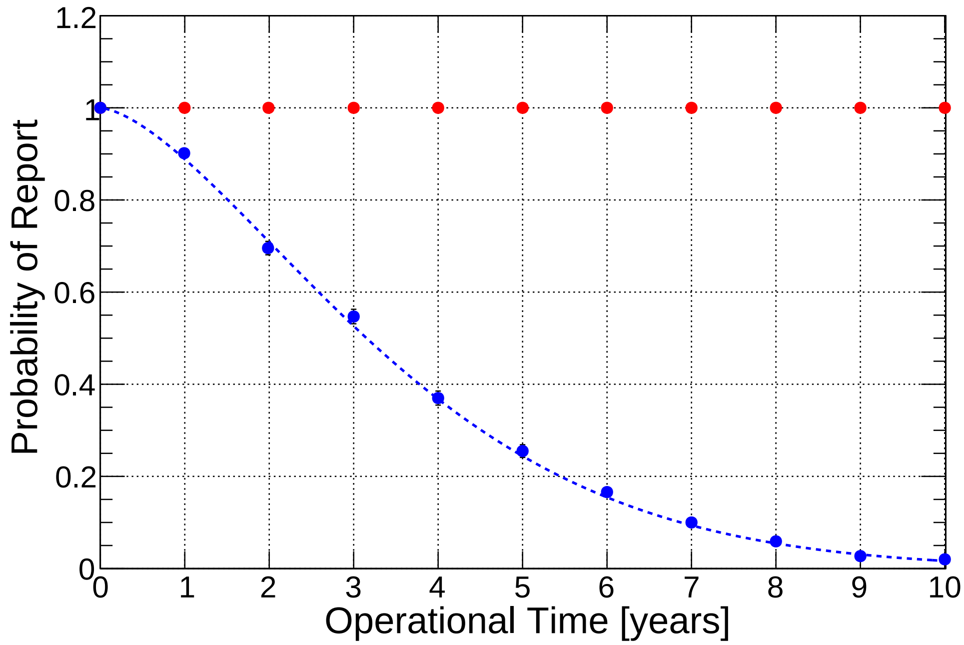

Figure 2: DIORAMA results for a single satellite's probability of report as a function of operational time. The red points show the simulation without including spacecraft availability, the blue dots show the same calculation including the Weibull distribution and the dashed blue line shows the expected Weibull distribution.

If the scenario is run without the alpha and beta parameters defined for the satellite, the sensor should always trigger on the event, and since the reliability of the satellite is always 1, the probability of report for a single satellite should always be 1. Once the Weibull parameters are included the probability of triggering on the event is still a constant 1, however, the satellite is not always available and the probability of report should fall off following the distribution. Figure 2 shows the results of the simulation before (red dots) and after (green dots) including spacecraft availability. The Weibull distribution is shown by the dashed green line and it can be seen that the probability of report follows the Weibull distribution as expected (within the statistical error bars).

It may also be interesting to see the affect of adding another, identical, satellite 3 years into the operational period. This is useful in the case of studying a full constellation and effects on system performance over many years with many different spacecraft. Figure 3 shows the probability of report for the 2 satellite constellation (both at the same location) when the second satellite is launched 3 years into the operations period. It can be seen that the addition of a second satellite adds redundancy to the probability of detection but as both satellites begin to age the probability falls off with a combination of both Weibull distributions.

5 Summary

In this document a description of spacecraft reliability has been presented. Given a two parameter Weibull distribution, the probability of spacecraft failure can be calculated at an arbitrary date into the operational period. These distribution functions have been added to the DIORAMA framework

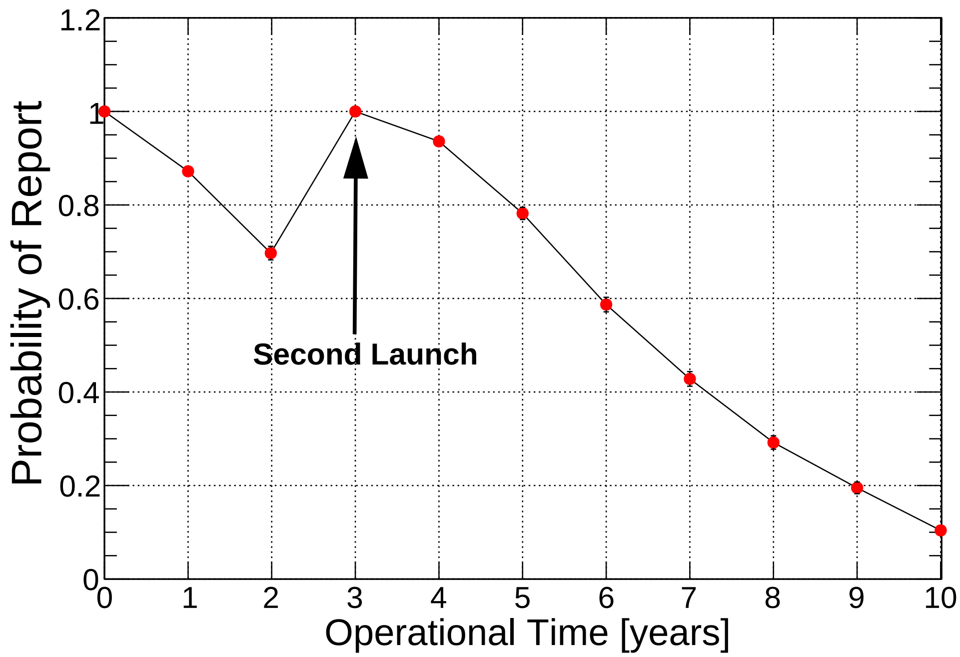

Figure 3: DIORAMA results for a two satellite constellation robability of report as a function of operational time.

so that the effects of reliability can be considered in simulations of constellation performance. Examples of how to specify the parameters and demonstration of functionality has been given.

References

[1] Duphily, R. J., *Space Vehicle Reliability Engineering Tutorial for SMC-University* Aerospace Corporation TOR-2009(8583)-8929. 2009

[2] *Reliability Engineering Resources* http://www.weibull.com Accessed 12 July 2016