National Aeronautics and
Space Administration


# Bumper 3 Update for IADC Protection Manual

34th Interagency Space Debris Coordination Committee (IADC)

March-April 2016

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# Bumper Status


- NASA's risk assessment code (Bumper) has been updated to version 3
  - Program structure modified into two sections
    - Common core: environment models, shadowing, etc.
    - Ballistic limit equations: tailored for specific customers
  - 4 orbital debris and 2 meteoroid environments available
    - OD = NASA 91, ORDEM 2000, ORDEM 3, MASTER 2009
    - MM = NASA 91, MEM R2
  - Distributed as a 64 bit Windows installer package
- After the Bumper 3 release in 2014, Bumper II code support was suspended

# Proposed Protection Manual Updates


- NASA has prepared updates for two sections in the Protection Manual
  - Recommend that the Bumper II description in Section 2.3 be replaced with updated content on Bumper 3
  - Recommend that Bumper II calibration results in Section 2.4 be replaced with Bumper 3 calibration results
    - Results provided for 3 OD & 2 MM environments
      - OD = NASA 91, ORDEM 2000, ORDEM 3
      - MM = NASA 91, MEM R2
    - Tables 2.4-1 (cube), 2.4.-2 (space station), 2.4-3 (sphere)
    - Table 2.4-5 (cube detail), 2.4-6 (space station detail)

## 2.3 Impact Risk Assessment Codes

### 2.3.1 BUMPER 3

The Bumper code has been the standard in use by NASA and contractors to perform meteoroid/debris risk assessments since 1990. It has undergone extensive revisions and updates [NASA JSC HITF website; Christiansen *et al*., 1992, 1997]. NASA Johnson Space Center (JSC) has applied BUMPER to risk assessments for Space Station, Shuttle, Mir, Extravehicular Mobility Units (EMU) space suits, and other spacecraft (e.g., LDEF, Iridium, TDRS, and Hubble Space Telescope). Bumper continues to be updated with changes in the ballistic limit equations describing failure threshold of various spacecraft components, as well as changes in the meteoroid and debris environment models. Significant efforts are expended to validate Bumper and benchmark it to other meteoroid/debris risk assessment codes.
Bumper 3 is a refactored version of Bumper II. The structure of the code was extensively modified to improve maintenance, performance and flexibility. The architecture was changed to separate the frequently updated ballistic limit equations from the relatively stable common core functions of the program. These updates allow NASA to produce specific editions of the Bumper 3 that are tailored for specific customer requirements. The core consists of common code necessary to process the MMOD environment models, assess shadowing and calculate MMOD risk. The library of target response subroutines includes a board range of different types of MMOD shield ballistic limit equations as well as equations describing damage to various spacecraft subsystems or hardware (thermal protection materials, windows, radiators, solar arrays, cables, etc.). The core and library of ballistic response subroutines are maintained under configuration control. A change in the core will affect all editions of the code, whereas a change in one or more of the response subroutines will affect all editions of the code that contain the particular response subroutines which are modified. Note that the Bumper II program is no longer maintained or distributed by NASA.

#### *2.3.1.1 References*

[Christiansen *et al*., 1992, 1997; Prior *et al*., 2001, Bjorkman et al, 2014]

#### *2.3.1.2 Procedure*

Figure 2.3-1 illustrates the analysis methodology implemented in BUMPER. A finite element model (FEM) that describes the spacecraft geometry is created in IDEAS. In conducting International Space Station (ISS) risk assessments, a number of FEMs are required to describe the geometry of each assembly stage. Figure 2.3-2 illustrates the ISS FEM for an assembly complete configuration. This model has over 1,000,000 finite elements and nearly 1,000 different shield types.

BUMPER calculates the number of failures by determining the number of meteoroid/debris particles that exceed the ballistic limits for each element of the FEM, then summing failures over all elements and/or particular regions of interest in the FEM. The number of failures is determined by assigning environment specific threat directions for each element of the FEM. Each threat direction has a distribution of velocities, and a unique impact angle for each element is determined for each threat direction. The environment models define the fraction

of total flux that impacts at each threat direction/velocity combination. Those threat directions that are shadowed by other elements in the FEM are removed from the calculation. The calculation of number of particles that exceed the ballistic limit is done at the element level.

The probability of no failure (PNF) is determined from Poisson statistics, i.e., PNF = exp(-N), where N is the number of failures. PNF is equivalent to PNP (Probability of No Penetration) when the ballistic limits used in the assessment define shield threshold penetration. Failure criteria and risk calculations are made for functional failures, system degradation, or spacecraft mission abort cases. BUMPER is also used to assess probability of no impact from certain size meteoroid/debris particles and larger.

BUMPER outputs the number of failures (and risk of failure) for the entire FEM or pieces of the FEM as desired by the user. Risk per unit area can produced as an output from BUMPER, which can be used to produce contour plots where colors are used to highlight high risk and low risk areas on the spacecraft. Relative meteoroid/debris risks as a function of impact angle and velocity can also be plotted from BUMPER output. This feature is particularly important for planning the most likely impact angle and velocity, which can be used in designing hypervelocity impact tests.

#### *2.3.1.3 Flux Models Implemented*

***Meteoroids***

- NASA 91 [NASA SSP-30425, Rev. B, 1994]
- MEM R2, (includes EarthMEM, LunarMEM and Interplantary MEM) [Cooke, et al, 2013]

***Space Debris***

- NASA 91 [NASA SSP-30425, Rev.B, 1994]
- NASA ORDEM 2000 [Liou *et al*., 2002]
- MASTER 2009, via STENVI files [Institute for Aerospace Systems, 2011]
- NASA ORDEM 3 [Stansbery et al, 2014]

***MEM R2 and ORDEM 3 are the current NASA MMOD environments for risk assessment. The use of older environments should be avoided, unless dictated by program requirements.***

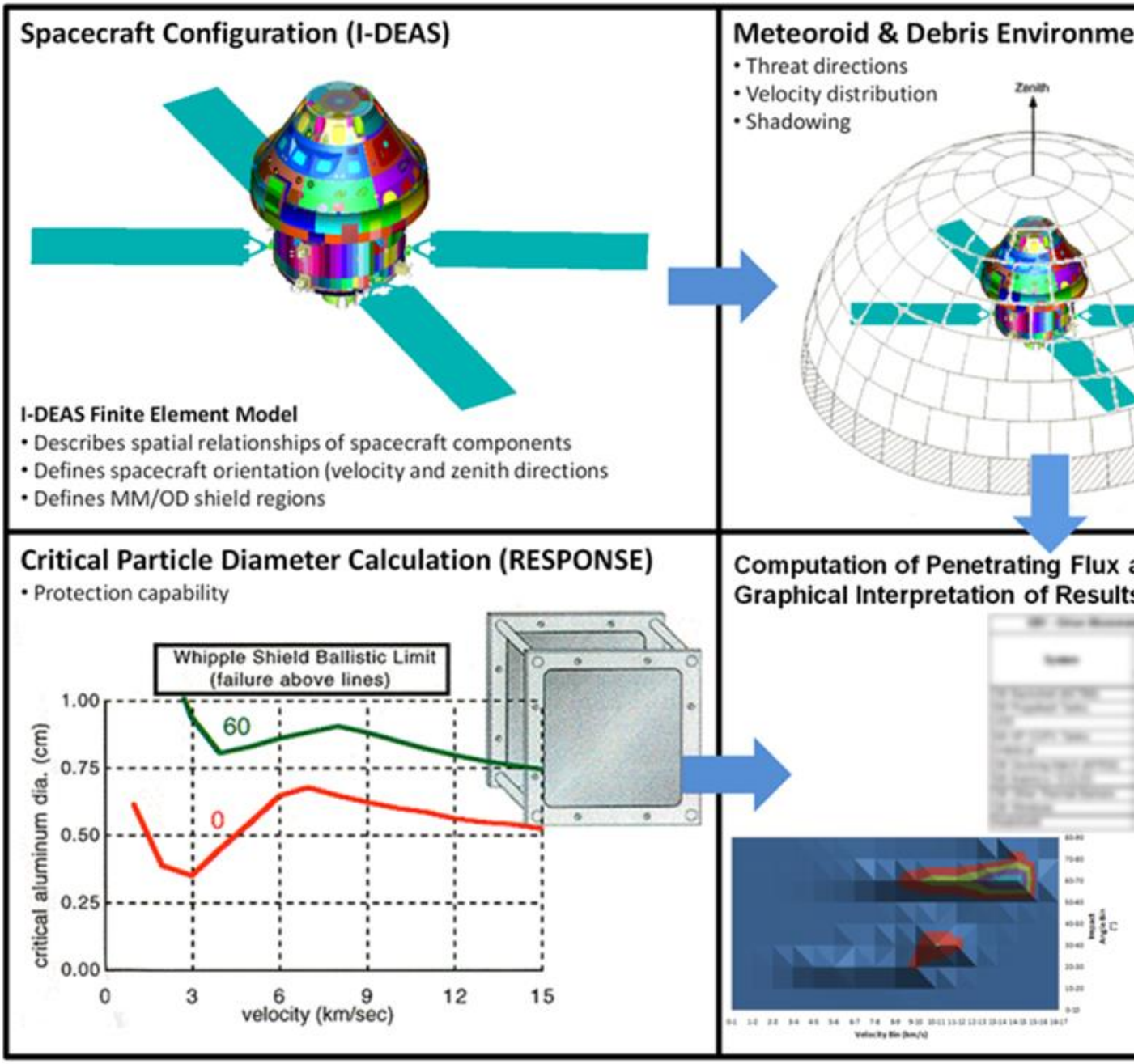


***Figure 2.3-1**: BUMPER Code diagram*

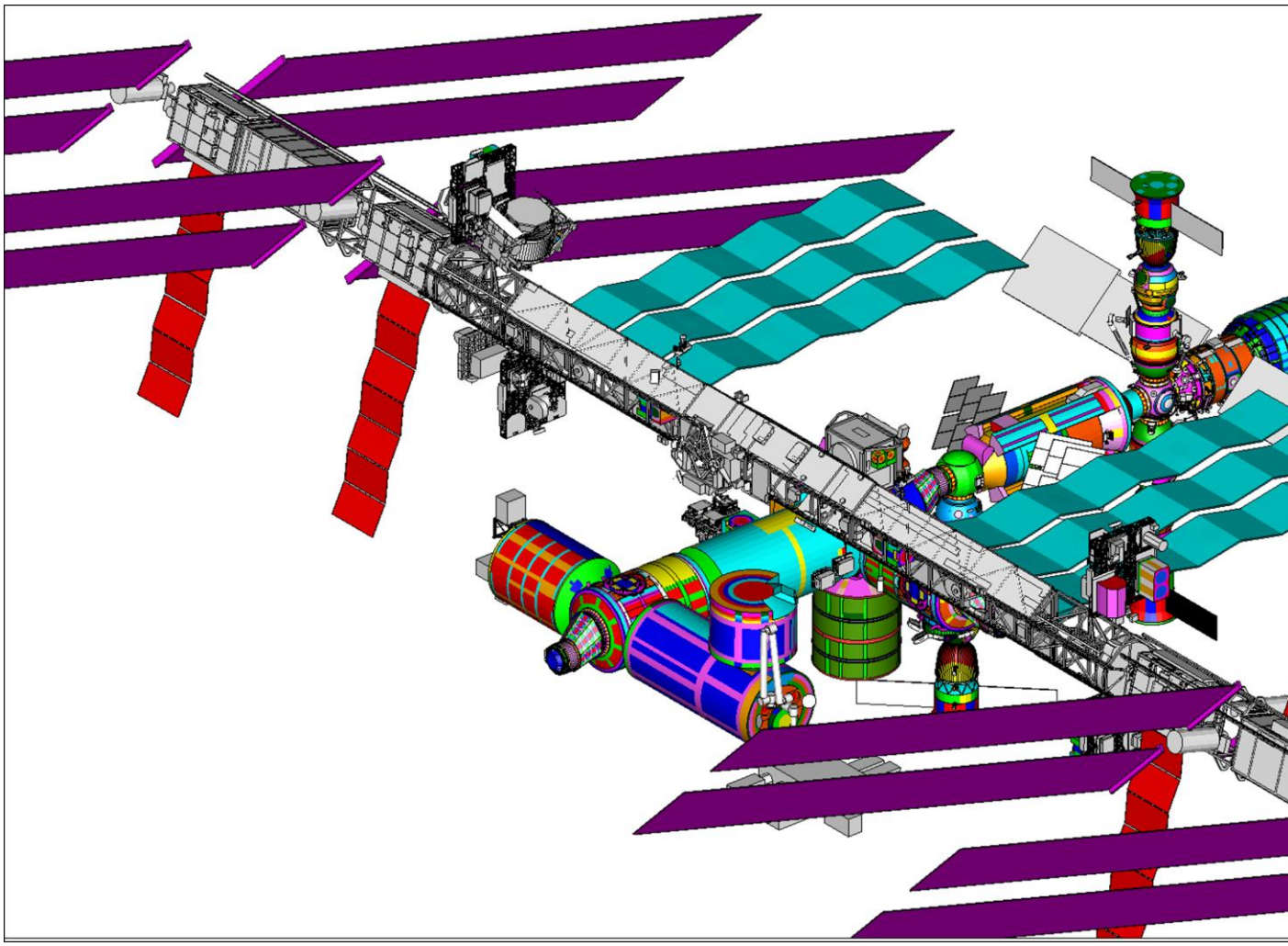

***Figure 2.3-2**: Finite Element Model (FEM) of the International Space Station (ISS).*

#### *2.3.1.4 Damage Equations Implemented*

Parameter equations are included for single walls, multiple walls and crater/hole sizes. Any damage or hole size equation can be specified in the form of a subroutine.

#### *2.3.1.5 Special Features/Comments*

Probabilistic risk assessments may be performed using environment and ballistic limit equation uncertainty distributions. The NASA SP-8013 lunar ejecta environment is available for analyzing spacecraft on the lunar surface. Partial shadowing from solar arrays, radiators or other “thin”, non-conformal hardware can be assessed using a 3-part method, or more directly using a semi-shadowing algorithm.

| | Bench mark | BUMPER 3 | ESABASE /Debris | ESABASE 3.0 /Debris | MDPANTO | COLLO | MODAOST |
|---|---|---|---|---|---|---|---|
| **NASA 91** | d > 0.1 mm | 4.464E+00 | 4.56E+00 | 4.516E+00 | 4.473E+00 | 4.52E+00 | 4.476E+00 |
| | d > 1.0 cm | 5.689E-05 | 6.20E-05 | 6.110E-05 | 5.702E-05 | 6.27E-05 | 5.706E-05 |
| | p > 1.0 mm | 8.053E-02 | 8.90E-02 | 8.116E-02 | 8.094E-02 | 8.23E-02 | 8.051E-02 |
| | single | 3.240E-01 | 3.60E-01 | 3.364E-01 | 3.256E-01 | 3.19E-01 | 3.239E-01 |
| | double | 2.025E-04 | 2.10E-04 | 2.060E-04 | 2.034E-04 | 2.12E-04 | 2.081E-04 |
| **NASA 2000** | d > 0.1 mm | 2.131E+01 | | 2.096E+01 | 2.139E+01 | 2.16E+01 | 2.143E+01 |
| | d > 1.0 cm | 2.874E-06 | | 2.667E-06 | 2.872E-06 | 2.87E-06 | 2.873E-06 |
| | p > 1.0 mm | 3.445E-01 | | 1.654E-01 | 3.360E-01 | 4.00E-01 | 3.368E-01 |
| | single | 1.669E+00 | | 7.829E-01 | 1.642E+00 | 1.90E+00 | 1.639E+00 |
| | double | 2.330E-05 | | 3.016E-05 | 2.257E-05 | 1.62E-05 | 2.303E-05 |
| **ORDEM 3.0** | d > 0.1 mm | 4.788E+00 | | | | | |
| | d > 1.0 cm | 1.977E-06 | | | | | |
| | p > 1.0 mm | 1.742E-01 | | | | | |
| | single | 5.283E-01 | | | | | |
| | double | 1.066E-05 | | | | | |
| **MASTER2005** | d > 0.1 mm | | | 5.069E+00 | | | |
| | d > 1.0 cm | | | 1.681E-05 | | | |
| | p > 1.0 mm | | | 1.053E-02 | | | |
| | single | | | 1.530E-01 | | | |
| | double | | | 5.076E-05 | | | |
| **Meteoroid 91** | d > 0.1 mm | 2.342E+01 | 2.12E+01 | 2.124E+01 | 2.164E+01 | 3.50E+01 | 2.164E+01 |
| | d > 1.0 cm | 1.474E-06 | 1.30E-06 | 1.336E-06 | 1.360E-06 | 2.21E-06 | 1.362E-06 |
| | p > 1.0 mm | 1.003E-01 | 8.30E-02 | 8.595E-02 | 9.064E-02 | 1.67E-01 | 8.812E-02 |
| | single | 6.725E-01 | 6.00E-01 | 6.164E-01 | 6.204E-01 | 1.04E+00 | 6.018E-01 |
| | double | 1.383E-05 | 1.20E-05 | 1.146E-05 | 1.142E-05 | 2.47E-05 | 1.142E-05 |
| **MEM R2** | d > 0.1 mm | 1.920E+01 | | | | | |
| | d > 1.0 cm | 1.283E-06 | | | | | |
| | p > 1.0 mm | 1.301E-01 | | | | | |
| | single | 8.274E-01 | | | | | |
| | double | 1.982E-05 | | | | | |

* See Section 2.4.3.2 for discussion of these results

***Table 0-1**: Calibration results for the cube*

| | Bench mark | BUMPER 3 | ESABASE /Debris | ESABASE 3.0 | MDPANTO | COLLO | MODAOST |
|---|---|---|---|---|---|---|---|
| **NASA 91** | d > 0.1 mm | 1.758E+01 | 1.70E+01 | 1.769E+01 | 1.761E+01 | 1.77E+01 | 1.763E+01 |
| | d > 1.0 cm | 2.240E-04 | 2.30E-04 | 2.394E-04 | 2.245E-04 | 2.45E-04 | 2.247E-04 |
| | p > 1.0 mm | 2.858E-01 | 3.10E-01 | 2.849E-01 | 2.920E-01 | 2.91E-01 | 2.855E-01 |
| | single | 1.150E+00 | 1.24E+00 | 1.181E+00 | 1.175E+00 | 1.13E+00 | 1.149E+00 |
| | double | 7.595E-04 | 7.40E-04 | 7.477E-04 | 7.654E-04 | 7.87E-04 | 7.861E-04 |
| **NASA 2000** | d > 0.1 mm | 9.176E+01 | | 9.167E+01 | 9.165E+01 | 9.09E+01 | 9.193E+01 |
| | d > 1.0 cm | 1.150E-05 | | 1.094E-05 | 1.149E-05 | 1.13E-05 | 1.151E-05 |
| | p > 1.0 mm | 1.149E+00 | | 5.586E-01 | 1.148E+00 | 1.48E+00 | 1.125E+00 |
| | single | 5.725E+00 | | 2.699E+00 | 5.787E+00 | 7.95E+00 | 5.629E+00 |
| | double | 8.586E-05 | | 1.213E-04 | 9.054E-05 | 5.98E-05 | 8.581E-05 |
| **ORDEM 3.0** | d > 0.1 mm | 1.922E+01 | | | | | |
| | d > 1.0 cm | 7.889E-06 | | | | | |
| | p > 1.0 mm | 6.292E-01 | | | | | |
| | single | 1.896E+00 | | | | | |
| | double | 3.819E-05 | | | | | |
| **MASTER2005** | d > 0.1 mm | | | 2.107E+01 | | | |
| | d > 1.0 cm | | | 6.790E-05 | | | |
| | p > 1.0 mm | | | 3.686E-02 | | | |
| | single | | | 5.386E-01 | | | |
| | double | | | 2.034E-04 | | | |
| **Meteoroid 91** | d > 0.1 mm | 1.001E+02 | 8.96E+01 | 8.991E+01 | 9.247E+01 | 7.21E+01 | 9.246E+01 |
| | d > 1.0 cm | 6.296E-06 | 5.60E-06 | 5.656E-06 | 5.820E-06 | 1.02E-05 | 5.819E-06 |
| | p > 1.0 mm | 4.157E-01 | 3.40E-01 | 3.521E-01 | 3.732E-01 | 7.28E-01 | 3.639E-01 |
| | single | 2.796E+00 | 2.47E+00 | 2.534E+00 | 2.564E+00 | 4.50E+00 | 2.495E+00 |
| | double | 5.670E-05 | 4.90E-05 | 4.659E-05 | 4.657E-05 | 1.09E-04 | 4.660E-05 |
| **MEM R2** | d > 0.1 mm | 8.234E+01 | | | | | |
| | d > 1.0 cm | 5.503E-06 | | | | | |
| | p > 1.0 mm | 5.515E-01 | | | | | |
| | single | 3.513E+00 | | | | | |
| | double | 8.348E-05 | | | | | |

***Table 0-2**: Calibration results for the simple space-station model*

| | Bench mark | BUMPER 3 | ESABASE /Debris | ESABASE 3.0 /Debris | MDPANTO | COLLO | MODAOST |
|---|---|---|---|---|---|---|---|
| **NASA 91** | d > 0.1 mm | 3.307E+00 | | 3.341E+00 | 3.302E+00 | 3.34E+00 | 3.314E+00 |
| | d > 1.0 cm | 4.215E-05 | | 4.520E-05 | 4.209E-05 | 4.63E-05 | 4.225E-05 |
| | p > 1.0 mm | 5.201E-02 | | 5.270E-02 | 5.355E-02 | 8.23E-02 | 5.201E-02 |
| | single | 2.093E-01 | | 2.160E-01 | 2.154E-01 | 3.19E-01 | 2.092E-01 |
| | double | 1.393E-04 | | 1.360E-04 | 1.394E-04 | 2.12E-04 | 1.440E-04 |
| **NASA 2000** | d > 0.1 mm | 1.705E+01 | | 1.696E+01 | 1.699E+01 | 1.71E+01 | 1.698E+01 |
| | d > 1.0 cm | 2.145E-06 | | 2.019E-06 | 2.141E-06 | 2.14E-06 | 2.143E-06 |
| | p > 1.0 mm | 2.044E-01 | | 9.624E-02 | 2.050E-01 | 2.41E-01 | 2.009E-01 |
| | single | 1.019E+00 | | 4.680E-01 | 1.033E+00 | 1.20E+00 | 1.005E+00 |
| | double | 1.504E-05 | | 2.093E-05 | 1.607E-05 | 1.08E-05 | 1.509E-05 |
| **ORDEM 3.0** | d > 0.1 mm | 3.576E+00 | | | | | |
| | d > 1.0 cm | 1.482E-06 | | | | | |
| | p > 1.0 mm | 1.147E-01 | | | | | |
| | single | 3.458E-01 | | | | | |
| | double | 6.499E-06 | | | | | |
| **MASTER2005** | d > 0.1 mm | | | 3.725E+00 | | | |
| | d > 1.0 cm | | | 1.233E-05 | | | |
| | p > 1.0 mm | | | 6.864E-03 | | | |
| | single | | | 9.282E-02 | | | |
| | double | | | 3.809E-05 | | | |
| **Meteoroid 91** | d > 0.1 mm | 1.585E+01 | | 1.416E+01 | 1.457E+01 | 2.37E+01 | 1.461E+01 |
| | d > 1.0 cm | 9.971E-07 | | 8.910E-07 | 9.200E-07 | 1.50E-06 | 9.196E-07 |
| | p > 1.0 mm | 6.433E-02 | | 5.426E-02 | 5.779E-02 | 1.07E-01 | 5.647E-02 |
| | single | 4.336E-01 | | 3.913E-01 | 3.976E-01 | 6.66E-01 | 3.878E-01 |
| | double | 8.734E-06 | | 7.145E-06 | 7.180E-06 | 1.56E-05 | 7.210E-06 |
| **MEM R2** | d > 0.1 mm | 1.297E+01 | | | | | |
| | d > 1.0 cm | 8.667E-07 | | | | | |
| | p > 1.0 mm | 8.475E-02 | | | | | |
| | single | 5.409E-01 | | | | | |
| | double | 1.279E-05 | | | | | |

***Table 0-3**: Calibration results for the sphere*

## Case 1: Cube

### MDPANTO

| | | Fwd | Stbd | Port | Back | Space | Earth | Total |
|---|---|---|---|---|---|---|---|---|
| **NASA** | d>0.1 mm | 2.327E+00 | 1.073E+00 | 1.073E+00 | 0.000E+00 | 0.000E+00 | 0.000E+00 | **4.473E+00** |
| **91** | d>1 cm | 2.966E-05 | 1.368E-05 | 1.368E-05 | 0.000E+00 | 0.000E+00 | 0.000E+00 | **5.702E-05** |
| | p>1 mm | 5.506E-02 | 1.294E-02 | 1.294E-02 | 0.000E+00 | 0.000E+00 | 0.000E+00 | **8.094E-02** |
| **Debris** | single | 2.215E-01 | 5.207E-02 | 5.207E-02 | 0.000E+00 | 0.000E+00 | 0.000E+00 | **3.256E-01** |
| **ρ = 2.8** | double | 1.198E-04 | 4.178E-05 | 4.178E-05 | 0.000E+00 | 0.000E+00 | 0.000E+00 | **2.034E-04** |
| **NASA** | d>0.1 mm | 5.284E+00 | 7.757E+00 | 7.785E+00 | 5.643E-01 | 0.000E+00 | 0.000E+00 | **2.139E+01** |
| **2000** | d>1 cm | 1.306E-06 | 7.733E-07 | 7.743E-07 | 1.824E-08 | 0.000E+00 | 0.000E+00 | **2.872E-06** |
| | p>1 mm | 5.232E-02 | 1.433E-01 | 1.399E-01 | 4.711E-04 | 0.000E+00 | 0.000E+00 | **3.360E-01** |
| **Debris** | single | 2.729E-01 | 6.903E-01 | 6.749E-01 | 3.985E-03 | 0.000E+00 | 0.000E+00 | **1.642E+00** |
| **ρ = 2.8** | double | 3.189E-06 | 9.557E-06 | 9.716E-06 | 1.047E-07 | 0.000E+00 | 0.000E+00 | **2.257E-05** |
| **NASA** | d>0.1 mm | 7.692E+00 | 3.626E+00 | 3.626E+00 | 9.851E-01 | 5.177E+00 | 5.313E-01 | **2.164E+01** |
| **91** | d>1 cm | 4.840E-07 | 2.282E-07 | 2.282E-07 | 6.198E-08 | 3.257E-07 | 3.343E-08 | **1.360E-06** |
| | p>1 mm | 5.247E-02 | 1.047E-02 | 1.047E-02 | 7.178E-04 | 1.370E-02 | 1.064E-04 | **8.794E-02** |
| **Meteoroid** | single | 3.515E-01 | 7.770E-02 | 7.770E-02 | 5.938E-03 | 1.025E-01 | 5.095E-03 | **6.204E-01** |
| **ρ = 1.0** | double | 7.063E-06 | 1.275E-06 | 1.275E-06 | 8.077E-08 | 1.658E-06 | 7.030E-08 | **1.142E-05** |

### BUMPER 3

| | | Fwd | Stbd | Port | Back | Space | Earth | Total |
|---|---|---|---|---|---|---|---|---|
| **NASA** | d>0.1 mm | 2.320E+00 | 1.072E+00 | 1.072E+00 | 0.000E+00 | 0.000E+00 | 0.000E+00 | **4.464E+00** |
| **91** | d>1 cm | 2.957E-05 | 1.366E-05 | 1.366E-05 | 0.000E+00 | 0.000E+00 | 0.000E+00 | **5.689E-05** |
| | p>1 mm | 5.500E-02 | 1.276E-02 | 1.276E-02 | 0.000E+00 | 0.000E+00 | 0.000E+00 | **8.053E-02** |
| **Debris** | single | 2.213E-01 | 5.135E-02 | 5.135E-02 | 0.000E+00 | 0.000E+00 | 0.000E+00 | **3.240E-01** |
| **ρ = 2.8** | double | 1.197E-04 | 4.142E-05 | 4.142E-05 | 0.000E+00 | 0.000E+00 | 0.000E+00 | **2.025E-04** |
| **NASA** | d>0.1 mm | 5.162E+00 | 7.901E+00 | 7.790E+00 | 4.570E-01 | 0.000E+00 | 0.000E+00 | **2.131E+01** |
| **ORDEM2000** | d>1 cm | 1.315E-06 | 7.721E-07 | 7.698E-07 | 1.724E-08 | 0.000E+00 | 0.000E+00 | **2.874E-06** |
| | p>1 mm | 5.195E-02 | 1.480E-01 | 1.445E-01 | 8.291E-05 | 0.000E+00 | 0.000E+00 | **3.445E-01** |
| **Debris** | single | 2.591E-01 | 7.123E-01 | 6.964E-01 | 9.071E-04 | 0.000E+00 | 0.000E+00 | **1.669E+00** |
| **ρ = 2.8** | double | 8.550E-06 | 7.354E-06 | 7.354E-06 | 4.707E-08 | 0.000E+00 | 0.000E+00 | **2.330E-05** |
| **NASA** | d>0.1 mm | 2.090E+00 | 1.302E+00 | 1.302E+00 | 3.709E-02 | 2.861E-02 | 2.861E-02 | **4.788E+00** |
| **ORDEM 3.0** | d>1 cm | 9.961E-07 | 4.751E-07 | 4.751E-07 | 1.634E-08 | 7.026E-09 | 7.026E-09 | **1.977E-06** |
| | p>1 mm | 9.388E-02 | 3.994E-02 | 3.994E-02 | 8.286E-05 | 1.872E-04 | 1.872E-04 | **1.742E-01** |
| **Debris** | single | 2.916E-01 | 1.177E-01 | 1.177E-01 | 2.699E-04 | 5.277E-04 | 5.277E-04 | **5.283E-01** |
| **5 groups** | double | 5.664E-06 | 2.463E-06 | 2.463E-06 | 4.502E-08 | 9.745E-09 | 9.745E-09 | **1.066E-05** |
| **NASA** | d>0.1 mm | 8.769E+00 | 3.842E+00 | 3.842E+00 | 9.637E-01 | 5.445E+00 | 5.574E-01 | **2.342E+01** |
| **91** | d>1 cm | 5.518E-07 | 2.418E-07 | 2.418E-07 | 6.064E-08 | 3.426E-07 | 3.507E-08 | **1.474E-06** |
| | p>1 mm | 5.715E-02 | 1.248E-02 | 1.248E-02 | 1.933E-03 | 1.619E-02 | 9.606E-05 | **1.003E-01** |
| **Meteoroid** | single | 3.777E-01 | 8.508E-02 | 8.508E-02 | 1.295E-02 | 1.109E-01 | 7.710E-04 | **6.725E-01** |
| **ρ = 1.0** | double | 7.910E-06 | 1.690E-06 | 1.690E-06 | 2.993E-07 | 2.158E-06 | 7.945E-08 | **1.383E-05** |
| **NASA** | d>0.1 mm | 6.534E+00 | 3.241E+00 | 3.188E+00 | 1.135E+00 | 4.678E+00 | 4.201E-01 | **1.920E+01** |
| **MEM R2** | d>1 cm | 4.367E-07 | 2.166E-07 | 2.131E-07 | 7.584E-08 | 3.127E-07 | 2.808E-08 | **1.283E-06** |
| | p>1 mm | 5.194E-02 | 2.135E-02 | 2.088E-02 | 7.918E-03 | 2.783E-02 | 2.359E-04 | **1.301E-01** |
| **Meteoroid** | single | 3.285E-01 | 1.359E-01 | 1.330E-01 | 4.976E-02 | 1.784E-01 | 1.746E-03 | **8.274E-01** |
| **ρ = 1.0** | double | 7.869E-06 | 3.244E-06 | 3.165E-06 | 1.248E-06 | 4.199E-06 | 9.498E-08 | **1.982E-05** |

### MODAOST

| | | Fwd | Stbd | Port | Back | Space | Earth | Total |
|---|---|---|---|---|---|---|---|---|
| **NASA** | d>0.1 mm | 2.328E+00 | 1.074E+00 | 1.074E+00 | 0.000E+00 | 0.000E+00 | 0.000E+00 | **4.476E+00** |
| **91** | d>1 cm | 2.968E-05 | 1.369E-05 | 1.369E-05 | 0.000E+00 | 0.000E+00 | 0.000E+00 | **5.706E-05** |
| | p>1 mm | 5.503E-02 | 1.274E-02 | 1.274E-02 | 0.000E+00 | 0.000E+00 | 0.000E+00 | **8.051E-02** |
| **Debris** | single | 2.214E-01 | 5.124E-02 | 5.124E-02 | 0.000E+00 | 0.000E+00 | 0.000E+00 | **3.239E-01** |
| **ρ = 2.8** | double | 1.223E-04 | 4.288E-05 | 4.288E-05 | 0.000E+00 | 0.000E+00 | 0.000E+00 | **2.081E-04** |
| **NASA** | d>0.1 mm | 5.311E+00 | 7.731E+00 | 7.843E+00 | 5.402E-01 | 0.000E+00 | 0.000E+00 | **2.143E+01** |
| **2000** | d>1 cm | 1.307E-06 | 7.732E-07 | 7.742E-07 | 1.826E-08 | 0.000E+00 | 0.000E+00 | **2.873E-06** |
| | p>1 mm | 5.432E-02 | 1.394E-01 | 1.430E-01 | 9.303E-05 | 0.000E+00 | 0.000E+00 | **3.368E-01** |
| **Debris** | single | 2.713E-01 | 6.755E-01 | 6.915E-01 | 1.068E-03 | 0.000E+00 | 0.000E+00 | **1.639E+00** |
| **ρ = 2.8** | double | 8.430E-06 | 7.322E-06 | 7.229E-06 | 4.446E-08 | 0.000E+00 | 0.000E+00 | **2.303E-05** |
| **NASA** | d>0.1 mm | 7.699E+00 | 3.598E+00 | 3.598E+00 | 1.025E+00 | 5.186E+00 | 5.325E-01 | **2.164E+01** |
| **91** | d>1 cm | 4.845E-07 | 2.265E-07 | 2.265E-07 | 6.451E-08 | 3.264E-07 | 3.351E-08 | **1.362E-06** |
| | p>1 mm | 5.242E-02 | 1.052E-02 | 1.052E-02 | 7.271E-04 | 1.383E-02 | 1.146E-04 | **8.812E-02** |
| **Meteoroid** | single | 3.491E-01 | 7.416E-02 | 7.416E-02 | 5.534E-03 | 9.794E-02 | 9.105E-04 | **6.018E-01** |
| **ρ = 1.0** | double | 7.049E-06 | 1.275E-06 | 1.275E-06 | 8.391E-08 | 1.668E-06 | 7.028E-08 | **1.142E-05** |

### COLLO

| | | Fwd | Stbd | Port | Back | Space | Earth | Total |
|---|---|---|---|---|---|---|---|---|
| **NASA** | d>0.1 mm | 2.35E+00 | 1.09E+00 | 1.09E+00 | 0.000E+00 | 0.000E+00 | 0.000E+00 | **4.52E+00** |
| **91** | d>1 cm | 3.26E-05 | 1.51E-05 | 1.51E-05 | 0.000E+00 | 0.000E+00 | 0.000E+00 | **6.27E-05** |
| | p>1 mm | 5.58E-02 | 1.32E-02 | 1.32E-02 | 0.000E+00 | 0.000E+00 | 0.000E+00 | **8.23E-02** |
| **Debris** | single | 2.16E-01 | 5.13E-02 | 5.13E-02 | 0.000E+00 | 0.000E+00 | 0.000E+00 | **3.19E-01** |
| **ρ = 2.8** | double | 1.24E-04 | 4.38E-05 | 4.38E-05 | 0.000E+00 | 0.000E+00 | 0.000E+00 | **2.12E-04** |

| | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| **NASA** | d>0.1 mm | 5.33E+00 | 7.78E+00 | 7.91E+00 | 5.33E-01 | 0.000E+00 | 0.000E+00 | **2.16E+01** |
| **2000** | d>1 cm | 1.30E-06 | 7.73E-07 | 7.72E-07 | 1.83E-08 | 0.000E+00 | 0.000E+00 | **2.87E-06** |
| | p>1 mm | 5.53E-02 | 1.69E-01 | 1.75E-01 | 4.05E-04 | 0.000E+00 | 0.000E+00 | **4.00E-01** |
| **Debris** | single | 2.91E-01 | 7.91E-01 | 8.16E-01 | 4.26E-03 | 0.000E+00 | 0.000E+00 | **1.90E+00** |
| **ρ = 2.8** | double | 6.02E-06 | 5.07E-06 | 5.02E-06 | 5.60E-08 | 0.000E+00 | 0.000E+00 | **1.62E-05** |
| **NASA** | d>0.1 mm | 1.40E+01 | 5.11E+00 | 4.75E+00 | 1.09E+00 | 7.30E+00 | 2.81E+00 | **3.50E+01** |
| **91** | d>1 cm | 8.84E-07 | 3.22E-07 | 3.00E-07 | 6.87E-08 | 4.61E-07 | 1.77E-07 | **2.21E-06** |
| | p>1 mm | 9.14E-02 | 1.76E-02 | 1.94E-02 | 8.61E-03 | 2.44E-02 | 5.94E-03 | **1.67E-01** |
| **Meteoroid** | single | 5.62E-01 | 1.11E-01 | 1.20E-01 | 4.94E-02 | 1.55E-01 | 4.09E-02 | **1.04E+00** |
| **ρ = 1.0** | double | 1.37E-05 | 2.54E-06 | 2.88E-06 | 1.55E-06 | 3.40E-06 | 6.47E-07 | **2.47E-05** |

***Table 0-4**: Number of impacts/penetrations for "cube" calibration*

## Case 2: Simple Space Station

### MDPANTO

| | | Box | Stbd | Port | Trailing | Earth | Total |
|---|---|---|---|---|---|---|---|
| **NASA** | d>0.1 mm | 2.569E+00 | 3.042E+00 | 5.367E+00 | 3.325E+00 | 3.309E+00 | **1.761E+01** |
| **91** | d>1 cm | 3.275E-05 | 3.878E-05 | 6.841E-05 | 4.239E-05 | 4.217E-05 | **2.245E-04** |
| | p>1 mm | 5.796E-02 | 4.942E-02 | 8.980E-02 | 2.792E-02 | 6.688E-02 | **2.920E-01** |
| **Debris** | single | 2.332E-01 | 1.988E-01 | 3.613E-01 | 1.123E-01 | 2.691E-01 | **1.175E+00** |
| **ρ = 2.8** | double | 1.293E-04 | 1.229E-04 | 2.165E-04 | 1.324E-04 | 1.643E-04 | **7.654E-04** |
| **NASA** | d>0.1 mm | 7.276E+00 | 1.098E+01 | 1.652E+01 | 3.989E+01 | 1.698E+01 | **9.165E+01** |
| **2000** | d>1 cm | 1.485E-06 | 1.834E-06 | 3.149E-06 | 2.878E-06 | 2.140E-06 | **1.149E-05** |
| | p>1 mm | 8.616E-02 | 1.496E-01 | 1.881E-01 | 4.549E-01 | 2.689E-01 | **1.148E+00** |
| **Debris** | single | 4.372E-01 | 7.462E-01 | 9.615E-01 | 2.344E+00 | 1.298E+00 | **5.787E+00** |
| **ρ = 2.8** | double | 5.672E-06 | 9.915E-06 | 1.275E-05 | 4.280E-05 | 1.940E-05 | **9.054E-05** |
| **NASA** | d>0.1 mm | 1.410E+01 | 1.386E+01 | 2.527E+01 | 2.782E+01 | 1.142E+01 | **9.247E+01** |
| **91** | d>1 cm | 8.870E-07 | 8.722E-07 | 1.590E-06 | 1.750E-06 | 7.183E-07 | **5.820E-06** |
| | p>1 mm | 7.046E-02 | 5.912E-02 | 1.105E-01 | 7.639E-02 | 5.672E-02 | **3.732E-01** |
| **Meteoroid** | single | 4.773E-01 | 4.048E-01 | 7.546E-01 | 5.421E-01 | 3.849E-01 | **2.564E+00** |
| **ρ = 1.0** | double | 9.098E-06 | 7.439E-06 | 1.398E-05 | 8.775E-06 | 7.281E-06 | **4.657E-05** |

### BUMPER 3

| | | Box | Stbd | Port | Trailing | Earth | Total |
|---|---|---|---|---|---|---|---|
| **NASA** | d>0.1 mm | 2.556E+00 | 3.048E+00 | 5.366E+00 | 3.302E+00 | 3.306E+00 | **1.758E+01** |
| **91** | d>1 cm | 3.258E-05 | 3.885E-05 | 6.839E-05 | 4.209E-05 | 4.213E-05 | **2.240E-04** |
| | p>1 mm | 5.780E-02 | 4.825E-02 | 8.717E-02 | 2.648E-02 | 6.610E-02 | **2.858E-01** |
| **Debris** | single | 2.325E-01 | 1.941E-01 | 3.507E-01 | 1.065E-01 | 2.660E-01 | **1.150E+00** |
| **ρ = 2.8** | double | 1.289E-04 | 1.221E-04 | 2.145E-04 | 1.300E-04 | 1.640E-04 | **7.595E-04** |
| **NASA** | d>0.1 mm | 7.154E+00 | 1.087E+01 | 1.631E+01 | 4.038E+01 | 1.704E+01 | **9.176E+01** |
| **ORDEM 2000** | d>1 cm | 1.489E-06 | 1.849E-06 | 3.174E-06 | 2.844E-06 | 2.144E-06 | **1.150E-05** |
| | p>1 mm | 8.641E-02 | 1.458E-01 | 1.827E-01 | 4.600E-01 | 2.738E-01 | **1.149E+00** |
| **Debris** | single | 4.264E-01 | 7.155E-01 | 9.069E-01 | 2.366E+00 | 1.310E+00 | **5.725E+00** |
| **ρ = 2.8** | double | 1.032E-05 | 1.166E-05 | 1.776E-05 | 2.692E-05 | 1.920E-05 | **8.586E-05** |
| **NASA** | d>0.1 mm | 2.429E+00 | 3.026E+00 | 5.157E+00 | 5.039E+00 | 3.566E+00 | **1.922E+01** |
| **ORDEM 3.0** | d>1 cm | 1.114E-06 | 1.338E-06 | 2.350E-06 | 1.610E-06 | 1.477E-06 | **7.889E-06** |
| | p>1 mm | 1.034E-01 | 1.007E-01 | 1.718E-01 | 1.148E-01 | 1.384E-01 | **6.292E-01** |
| **Debris** | single | 3.196E-01 | 3.026E-01 | 5.179E-01 | 3.314E-01 | 4.250E-01 | **1.896E+00** |
| **5 populations** | double | 6.272E-06 | 5.957E-06 | 1.009E-05 | 7.879E-06 | 7.988E-06 | **3.819E-05** |
| **NASA** | d>0.1 mm | 1.545E+01 | 1.516E+01 | 2.767E+01 | 2.914E+01 | 1.263E+01 | **1.001E+02** |
| **91** | d>1 cm | 9.723E-07 | 9.541E-07 | 1.741E-06 | 1.833E-06 | 7.948E-07 | **6.296E-06** |
| | p>1 mm | 7.706E-02 | 6.560E-02 | 1.221E-01 | 8.814E-02 | 6.285E-02 | **4.157E-01** |
| **Meteoroid** | single | 5.139E-01 | 4.408E-01 | 8.197E-01 | 6.024E-01 | 4.194E-01 | **2.796E+00** |
| **ρ = 1.0** | double | 1.058E-05 | 8.944E-06 | 1.666E-05 | 1.184E-05 | 8.674E-06 | **5.670E-05** |
| **NASA** | d>0.1 mm | 1.230E+01 | 1.227E+01 | 2.240E+01 | 2.528E+01 | 1.009E+01 | **8.234E+01** |
| **MEM R2** | d>1 cm | 8.221E-07 | 8.198E-07 | 1.497E-06 | 1.690E-06 | 6.744E-07 | **5.503E-06** |
| | p>1 mm | 8.679E-02 | 8.193E-02 | 1.492E-01 | 1.588E-01 | 7.479E-02 | **5.515E-01** |
| **Meteoroid** | single | 5.516E-01 | 5.221E-01 | 9.507E-01 | 1.015E+00 | 4.735E-01 | **3.513E+00** |
| **ρ = 1.0** | double | 1.315E-05 | 1.238E-05 | 2.255E-05 | 2.399E-05 | 1.141E-05 | **8.348E-05** |

### MODAOST

| | | Box | Stbd | Port | Trailing | Earth | Total |
|---|---|---|---|---|---|---|---|
| **NASA** | d>0.1 mm | 2.583E+00 | 3.044E+00 | 5.371E+00 | 3.318E+00 | 3.308E+00 | **1.763E+01** |
| **91** | d>1 cm | 3.292E-05 | 3.881E-05 | 6.846E-05 | 4.230E-05 | 4.217E-05 | **2.247E-04** |
| | p>1 mm | 5.803E-02 | 4.803E-02 | 8.698E-02 | 2.653E-02 | 6.594E-02 | **2.855E-01** |
| **Debris** | single | 2.335E-01 | 1.932E-01 | 3.499E-01 | 1.067E-01 | 2.653E-01 | **1.149E+00** |
| **ρ = 2.8** | double | 1.326E-04 | 1.262E-04 | 2.223E-04 | 1.370E-04 | 1.681E-04 | **7.861E-04** |
| **NASA** | d>0.1 mm | 7.401E+00 | 1.106E+01 | 1.650E+01 | 3.998E+01 | 1.698E+01 | **9.193E+01** |
| **2000** | d>1 cm | 1.495E-06 | 1.836E-06 | 3.152E-06 | 2.880E-06 | 2.142E-06 | **1.151E-05** |
| | p>1 mm | 8.970E-02 | 1.454E-01 | 1.783E-01 | 4.424E-01 | 2.689E-01 | **1.125E+00** |
| **Debris** | single | 4.437E-01 | 7.166E-01 | 8.915E-01 | 2.287E+00 | 1.290E+00 | **5.629E+00** |
| **ρ = 2.8** | double | 1.029E-05 | 1.150E-05 | 1.768E-05 | 2.725E-05 | 1.908E-05 | **8.581E-05** |

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| **NASA** | d>0.1 mm | 1.414E+01 | 1.384E+01 | 2.525E+01 | 2.784E+01 | 1.140E+01 | **9.246E+01** |
| **91** | d>1 cm | 8.898E-07 | 8.710E-07 | 1.589E-06 | 1.752E-06 | 7.176E-07 | **5.819E-06** |
| | p>1 mm | 6.939E-02 | 5.776E-02 | 1.080E-01 | 7.323E-02 | 5.550E-02 | **3.639E-01** |
| **Meteoroid** | single | 4.692E-01 | 3.947E-01 | 7.364E-01 | 5.189E-01 | 3.759E-01 | **2.495E+00** |
| **ρ = 1.0** | double | 9.106E-06 | 7.439E-06 | 1.397E-05 | 8.802E-06 | 7.281E-06 | **4.660E-05** |
| **COLLO** | | | | | | | |
| | | **Box** | **Stbd** | **Port** | **Trailing** | **Earth** | **Total** |
| **NASA** | d>0.1 mm | 2.55E+00 | 3.05E+00 | 5.37E+00 | 3.36E+00 | 3.32E+00 | **1.77E+01** |
| **91** | d>1 cm | 3.53E-05 | 4.23E-05 | 7.45E-05 | 4.65E-05 | 4.60E-05 | **2.45E-04** |
| | p>1 mm | 5.71E-02 | 4.91E-02 | 8.95E-02 | 2.85E-02 | 6.69E-02 | **2.91E-01** |
| **Debris** | single | 2.21E-01 | 1.90E-01 | 3.47E-01 | 1.11E-01 | 2.59E-01 | **1.13E+00** |
| **ρ = 2.8** | double | 1.30E-04 | 1.26E-04 | 2.22E-04 | 1.39E-04 | 1.69E-04 | **7.87E-04** |
| **NASA** | d>0.1 mm | 7.27E+00 | 1.13E+01 | 1.69E+01 | 3.84E+01 | 1.71E+01 | **9.09E+01** |
| **2000** | d>1 cm | 1.47E-06 | 1.85E-06 | 3.18E-06 | 2.66E-06 | 2.12E-06 | **1.13E-05** |
| | p>1 mm | 1.02E-01 | 1.98E-01 | 2.40E-01 | 5.78E-01 | 3.59E-01 | **1.48E+00** |
| **Debris** | single | 5.60E-01 | 1.05E+00 | 1.31E+00 | 3.22E+00 | 1.82E+00 | **7.95E+00** |
| **ρ = 2.8** | double | 7.26E-06 | 8.48E-06 | 1.32E-05 | 1.76E-05 | 1.32E-05 | **5.98E-05** |
| **NASA** | d>0.1 mm | 1.01E+01 | 1.07E+01 | 1.92E+01 | 2.31E+01 | 9.05E+00 | **7.21E+01** |
| **91** | d>1 cm | 1.50E-06 | 1.56E-06 | 2.82E-06 | 2.83E-06 | 1.45E-06 | **1.02E-05** |
| | p>1 mm | 1.27E-01 | 1.18E-01 | 2.11E-01 | 1.60E-01 | 1.13E-01 | **7.28E-01** |
| **Meteoroid** | single | 7.83E-01 | 7.29E-01 | 1.31E+00 | 9.88E-01 | 6.93E-01 | **4.50E+00** |
| **ρ = 1.0** | double | 1.91E-05 | 1.74E-05 | 3.15E-05 | 2.44E-05 | 1.71E-05 | **1.09E-04** |

***Table 0-5**: Number of impacts/penetrations for "simple space station" calibration*

## 2.4
## 2.5
## 2.6
## 2.7 References

Bjorkman M.D., E.L. Christiansen, D.M. Lear, Bumper 3 Software User Manual, *NASA TM-2014-218559*, October 2014.