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NASA Meteoroid Engineering Model (MEM) Version 3

*A.V. Moorhead
Marshall Space Flight Center, Huntsville, Alabama*

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*A. V. Moorhead
Marshall Space Flight Center, Huntsville, Alabama*

National Aeronautics and
Space Administration

Marshall Space Flight Center • Huntsville, Alabama 35812

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LIST OF ACRONYMS

BLE	ballistic limit equation
CMOR	Canadian Meteor Orbit Radar
ECI	Earth-centered inertial
GUI	graphical user interface
ICRF	International Celestial Reference Frame
IMEM	Interplanetary Meteoroid Model
MEM	Meteoroid Engineering Model
MEO	Meteoroid Environment Office
SSP	Space Station Specification
STK	Systems Tool Kit
TLE	two-line element
TM 4527	Technical Memorandum 4527

NOMENCLATURE

c	multiplicative constant
$\text{flux}_{\text{effect}}$	flux of meteoroids that produce a particular impact effect
flux_{ijk}	flux in a particular angle and velocity bin
fraction_n	fraction of meteoroids that lie in a particular density bin
$g(m)$	Grün flux of particles larger than limiting mass m
\hat{h}	angular momentum unit vector
i	elevation bin index
j	azimuthal bin index
k	velocity bin index
l	length of a cylinder
m	limiting mass
m_{effect}	meteoroid limiting mass corresponding to a particular impact effect
m_{run}	limiting mass used in a MEM run
n	density bin index
P	probability
\hat{r}	position unit vector
s	circumference of a cylinder
v	meteoroid speed
v_k	velocity corresponding to a particular velocity bin
\hat{v}	velocity unit vector

NOMENCLATURE (Continued)

\hat{x}	ordinate of a 3D Cartesian coordinate system
\hat{y}	abscissa of a 3D Cartesian coordinate system
\hat{z}	applicate of a 3D Cartesian coordinate system
γ	exponential constant
θ	azimuthal angle
θ_j	azimuthal angle corresponding to a particular angular bin
μ	mean of a Gaussian distribution
ρ	meteoroid bulk density
σ	standard deviation of a Gaussian distribution
ϕ	elevation angle
ϕ_1	elevation angle of the first edge of an angular bin
ϕ_2	elevation angle of the second edge of an angular bin
ϕ_i	elevation angle corresponding to a particular angular bin
ϕ_m	elevation angle that divides an angular bin into two equal areas

TECHNICAL MEMORANDUM

NASA METEOROID ENGINEERING MODEL (MEM) VERSION 3

1 INTRODUCTION

The Meteoroid Engineering Model (MEM) version 3 is NASA's most current and accurate model of the meteoroid environment. MEM 3 supersedes all previous versions of MEM, including MEM Release 2.0 (MEMR2), MEM Release 1.0c (MEMR1c), and previously internally controlled and released versions of MEMCxP v2.0 and LunarMEM v2.0. Earlier versions of MEM superseded older models of the meteoroid environment such as the Grün model and its derivative, Technical Memo 4527 (hereafter abbreviated as TM 4527) [1].

1.1 History

Prior to the establishment of the NASA Meteoroid Environment Office (MEO), NASA's meteoroid environment models relied on a simple empirical expression derived from [2], as described in [3] and later in [1]. This expression describes the meteoroid flux incident on a flat plate near 1 au. TM 4527 assumes an isotropic environment, making the orientation of the plate irrelevant [4]. The flux was combined with scale factors to account for the reduction in flux occurring when the Earth shields the spacecraft from a portion of the meteoroid environment and the enhancement in flux due to the focusing effect of Earth's gravitational field. TM 4527 also introduced a crude, piecewise meteoroid speed distribution with an average velocity of 19 km/s for an orbiting spacecraft based on [5]. Finally, TM 4527 assumed a three-step density distribution in which dust particles smaller than 10^{-6} g have a density of 2 g/cm³, micrometeoroids between 10^{-6} g and 0.01 g have a density of 1 g/cm³, and meteoroids larger than 0.01 g have a density of 0.5 g/cm³. Thus, the meteoroid model presented in TM 4527 was assembled from multiple independent sources. The model of TM 4527 was also used for years in Space Station risk assessments, and is described in Space Station Specification (SSP) 30425.

Although TM 4527 was the first effort to build a comprehensive model of the meteoroid environment, it was never formally peer-reviewed and does not accurately reproduce crater counts on low-Earth-orbiting spacecraft [6]. As a result, TM 4527 underrepresents the risk of meteoroid impacts posed to spacecraft in low Earth orbit. The subsequent review of NASA's meteoroid models by several independent boards led to the development of a new model whose flux and speed were consistent with the observations and physics. This model forms the basis of MEM and is briefly described in section 2.

The MEO was established under the Office of Safety and Mission Assurance (OSMA) in October 2004 at Marshall Space Flight Center. The MEO is responsible for defining the meteoroid environment and providing support to NASA programs and projects for spacecraft engineering and operations. To accomplish this task, the MEO funds and conducts research in various areas of meteor science to develop engineering environment models for NASA programs and projects. The formation of this office is due in

large part to several independent study and panel recommendations such as the report of the Columbia Accident Investigation Board [7]. These reports agreed that current meteoroid environment models were inadequate and that a central NASA technical authority should be designated to coordinate the development and review of an agency-wide meteoroid model. MEM was developed to meet this need.

1.2 Model Requirements

MEM's target audience is spacecraft design engineers and analysts, and its intended purpose is to provide a meteoroid environment description suitable for performing risk assessments of particle penetration. To meet the needs of its target audience, MEM must provide an accurate description of the environment in a useful format and with minimal computation time. Like all engineering environment models, it must describe the environment in terms that are useful to the design engineer in the particle range considered threatening to spacecraft.

The risk of spacecraft penetration is higher when the number of incident particles is larger; thus, MEM's key output is meteoroid flux. However, the response of spacecraft shield materials to a meteoroid impact depends on the particle's size, density, relative speed, and impact angle. The smallest particle capable of damaging a spacecraft component is determined by ballistic limit equations (or BLEs), which take all of these properties as inputs; see [8] for example BLEs. Additionally, determining the directionality of the environment is critical for planning shield placement. To meet these needs, MEM reports not only the total meteoroid flux but also the flux as a function of speed and direction for a user-determined minimum meteoroid mass.

Note that meteoroid environments are typically described using grams for the unit of mass, whereas orbital debris environment descriptions use size in cm or mm. This is because the fundamental equations of meteor physics have mass as the primary variable, while orbital debris measurements are based on radar cross-section (size). However, if needed, users may convert mass to a range of sizes using MEM 3's bulk density distributions. The bulk density also factors into most ballistic limit equations and is thus a required output of the model.

1.3 Model Limitations

Engineering environment models support programs and projects in the design phase of the spacecraft life cycle. They are not meant to predict the short-term perturbations (such as meteor showers) that may occur during a specific year or month of a mission nor do they capture the long-term changes that take place as the environment evolves over tens of thousands of years. For the purposes of planning a mission, the meteoroid environment in the year 2020 is no different than the environment in the year 2000; the changes that take place over a 20-year period pale in comparison to the differences in the meteoroid flux relative to two different spacecraft trajectories. Therefore, MEM describes only the sporadic meteoroid complex, or background meteoroid environment, which is constant from year to year.

It was previously believed that MEM—and other models based on the Grün flux [2]—included meteor showers in an average sense. Recent work [9] indicates that this is not the case; showers pose an additional risk that is not captured by MEM. However, at MEM's lower mass limit of 1 μg , showers produce about 1% of the flux, which is well within the uncertainty in the sporadic flux. Showers contribute

a larger fraction of the flux when the limiting mass is larger, but the shower fraction is less than 10% for particles smaller than about half a centimeter in diameter. The MEO models meteor showers, storms, and outbursts separately; an annual meteor shower forecast for low Earth orbit is made publicly available through the NASA Technical Reports Server,¹ and the MEO produces custom forecasts for programs and projects on request.

MEM also restricts its environment description to particles sizes that are considered to be potentially damaging. Space shuttle radiators, for instance, were sensitive to impacts from debris particles as small as 100 microns in diameter [10]. MEM takes these findings into account by modeling meteoroids as small as 10^{-6} grams, which corresponds to 124 microns in diameter for a density of 1 g/cm^3 . Particles smaller than this limit are considered “dust” and are not modeled. Therefore, MEM is not an appropriate choice for modeling the degradation of sensitive surfaces such as optics or solar arrays by interplanetary dust.

MEM describes the meteoroid environment in the inner solar system between heliocentric distances of 0.2 and 2 au. It cannot be used to assess meteoroid impact risk outside this region. Gravitational focusing and shielding effects are computed for the Earth, Moon, Mercury, Venus, and Mars but not the Martian moons, comets, or asteroids.

1.4 Version History

MEM version 1.0, May 2004: The first version released was valid only for interplanetary spacecraft. The graphical user interface (GUI) was very simple and required only an input file name and output file name. The model produced two output files: one described average fluxes and speeds for the surfaces of a basic cube-shaped spacecraft, while the other file provided a composite speed distribution.

MEM version 1.5, September 2004: Version 1.5 was also valid only for interplanetary spacecraft. The GUI was updated to include new features. The output file formats and help files were both updated as well. The source code was revised to produce results for additional surfaces and the output file formatting was modified. The speed distribution output was changed to a normalized distribution.

MEM release 1.0, February 2007: Starting with MEM release 1.0, a single MEM release included two sub-models. This release contained an interplanetary meteoroid model (IPMEM version 1.6) and a newly developed EarthMEM model (version 1.0) for Earth-orbiting spacecraft. The output files were updated to include new output values and surface distributions. A new summary table was added at the end of the main results that described the average environment for all input states. A gravitational focusing algorithm and planet-centered state vector input coordinate frame option were introduced for EarthMEM. Users were given a choice of output angular resolution and velocity bin size for output data display. Errors were fixed in the velocity distribution output file rendering and penetration equation flux calculations. Memory allocation and array accessing improvements were included.

MEM release 1.0a, December 2007: IPMEM was updated to correct a variable initialization bug in the calculation of the `SpdDist.out` output file. The word “Normalized” was removed from the velocity

¹ For an example, visit <https://ntrs.nasa.gov/search.jsp?R=20180007899>

distribution output files in both IPMEM and EarthMEM. Both models' help files were updated. The IPMEM version number was incremented to 1.6a.

MEM release 1.0b, January 2008: The flux averaging technique used to produce the summary table in the main results file for both IPMEM and EarthMEM was changed to use a flux-weighted averaging scheme. All distributions in the main results file and velocity distribution file reported fractional fluxes rather than normalized fluxes. All average surface speed values in the summary table were calculated from their respective distributions. IPMEM received a bug fix to correct the use of a non-normalized unit vector to calculate the +z surface flux distribution. The velocity distribution output file calculation method was made consistent with the speed distribution and direction output file. Both help files were updated. IPMEM and EarthMEM model numbers were incremented to 2.0.

A special note was sent to users on Jan 14, 2008, indicating that the average speed on sunward and anti-sunward surfaces was incorrectly calculated in the summary tables produced by EarthMEM and IPMEM. Users were instructed to use the distribution to find the average speed.

MEM Release 1.0c, January 2008: IPMEM and EarthMEM were updated to fix the sunward and anti-sunward surface speeds in the main results file. This repaired the problem discussed in the special note sent to users about MEMR1b and removed the need for a user workaround. Additionally, the “About” dialogs in the GUI and the help files were updated to display the correct version numbering.

In 2016, a user alerted us to a possible error in the penetrating fluxes calculated by MEMR1c. Further investigation revealed that an internal error in the source code resulted in penetrating flux values that are nearly an order of magnitude too small. While users were always advised to use MEM's penetrating flux calculations for preliminary risk estimates only, the magnitude of this error compelled us to advise against using MEM's penetrating flux values entirely (a notification was sent to all known MEM users on March 30, 2016). This error is known to be present in the Cour-Palais penetrating flux option in MEMR1c, but is thought to affect all older versions of MEM that compute penetrating fluxes. Later versions of MEM, starting with MEMR2, do not report penetrating fluxes and are unaffected by this error.

MEMCxP v1.0, May 2007: MEMCxP denotes a special version of MEM released to the Constellation Program and its support contractors. This version was a variation of the EarthMEM model from MEM Release 1.0c. A random draw routine was developed to randomly sample points from the input state vector file (saving run time for month- or year-long missions). The random-draw feature enabled the computation of basic statistical quantities such as the average and standard deviation of the flux. Note that this standard deviation does not represent the uncertainty in the environment; rather, it quantifies the variation in flux experienced along the chosen trajectory. A new output file was developed to support the use of MEM results with the risk assessment code BUMPER. This output file reported fluxes within a “threat igloo”; i.e., it reports the flux per speed bin for quasi-equal area igloo bins in azimuth and elevation in the body-centered frame. User options to select output file resolution for the igloo maps and speed distribution maps were made available in this version.

MEMCxP v2.0, January 2008: This version included several additional enhancements. A sequential read option was added to allow users to choose between reading states sequentially or randomly selecting points

from the input state vector. Memory allocation was improved, and a bug was fixed in the averaging of distributions for the main output file.

LunarMEM v1.0, November 2007: LunarMEM was a special version released to the Constellation Program and its support contractors. This new lunar model described the meteoroid environment for spacecraft orbiting the Moon. It provided a sequential state vector selection option and a random draw routine as described in MEMCXP. Variable output file resolution options for the speed distribution map and threat igloo files were made available.

LunarMEM v2.0, January 2008: This version fixed a bug in the averaging of distributions in the main output file.

MEMR2.0, October 2013: MEMR2 included three sub-models: EarthMEM, IPMEM, and LunarMEM. This release repackaged and updated these individual sub-models with new user options for turning off output files, improved random number generation, threat igloo output files, combined output resolution selection, speed distribution plotting, an expanded user's guide, and a speed distribution correction for EarthMEM that better matches radar meteor observations. MEMR2 did not include the penetrating flux calculation capability found in MEMR1c. MEMR2.0 was the first version of MEMR2 and was provided only to a select group of beta testers.

MEMR2.0.1, January 2014: This point release repaired a software bug in which occasional negative fluxes occurred in the Earth sub-model.

MEMR2.0.2, March 2014: This point release included one improvement and one bug fix. First, it ensured that the main results file was overwritten for each new run, even if the user did not change the file name. This made it less likely that the user would obtain erroneous fluxes by leaving the results of previous runs in the working directory. Second, MEMR2.0.1 fixed a GUI bug in which it was impossible to change the sub-model choice after clicking the lunar sub-model option.

MEMR2.0.4, September 2014: This point release fixed two additional user-reported bugs. First, it fixed a bug in which the software quit without completing post-processing when the random draw feature was used in conjunction with the interplanetary sub-model. Second, it fixed a bug in which MEM processed only the first 48 TLEs provided by the user.

MEMR2.0.5, July 2015: This point release corrected the calculation of the meteoroid flux onto rotating surfaces. Prior versions simply reported the average of the flux on four sides of a stationary cube, which can over- or underreport portions of the meteoroid environment by up to 30%. MEMR2.0.5 reported the flux on the rotating surface correctly (see sec. 4.2.3). MEMR2.0.5 also corrected a minor bug in which the rotation mode was marked incorrectly in the output file headers, and also improved the text alignment in the output files. The improved random number generation algorithm introduced in MEMR2 for state vector selection was applied throughout the code; users may have seen differences in the output values of approximately 1%. Finally, the code was changed to make use of double floating point precision for all calculations.

MEM 3.0, May 2019: MEM 3 offers far more than an incremental improvement over previous versions. The code base was completely refactored and simplified. The modeling algorithms were corrected and new density distributions were added. Submodels were completely eliminated in favor of a more

streamlined approach. A new GUI was designed from scratch and a separate command-line executable was generated. Section 1.5 lists the most significant changes between MEM 3 and MEMR2.

MEM 3.0.1, July 2019: This minor point release ensures that no meteoroid flux is encountered at locations inside a planet or Moon.

1.5 Key Differences between MEM 3 and MEMR2

MEM 3 offers many improvements over previous releases; in fact, there are arguably more differences between MEM 3 and MEMR2 than there are between any two previous subsequent releases. These differences range from superficial (such as a redesigned GUI) to fundamental (such as a corrected gravitational focusing model). A detailed description of these changes is the focus of a separate publication [11], but this section briefly describes the most significant differences between MEMR2 and MEM 3.

These changes include a shift in our abbreviation convention. The previous version of MEM was typically abbreviated as “MEMR2,” where the “R2” stood for “Release 2.” Starting with MEM 3, we are using a more conventional abbreviation format in which the version number is separated from the code name by a space. “MEM 3” refers to all point releases whose version number starts with 3.

1.5.1 More Accurate Environment Modeling

MEM 3 contains a number of modeling improvements, such as more accurate planetary ephemerides, a corrected gravitational focusing model, and better preservation of correlations between speed and directionality. These algorithmic improvements are discussed in depth in a separate paper [11].

1.5.2 Meteoroid Bulk Densities

MEMR2 assumes a uniform meteoroid bulk density of 1000 kg/m^3 , while MEM 3 divides the meteoroid environment into two—low-density and high-density—populations [12, 13]. MEM 3 generates two sets of environment files corresponding to these two populations, including two density distribution files. This adds a new dimension to the data, although, within a population, the density is independent of speed, directionality, and mass.

1.5.3 Streamlined Execution

Previous versions of MEM required the user to select a “sub-model” depending on the trajectory type; for instance, the Earth sub-model was used to compute the meteoroid flux on spacecraft orbiting the Earth. This approach is not used in MEM 3. Instead, users simply specify the origin and axis alignment of their spacecraft trajectory file, and MEM determines whether a planet (or moon) is nearby. Thus, transfer trajectories can now be analyzed in a single MEM run.

1.5.4 Mercury, Venus, and Mars Environments

MEM 3 includes the planets Mercury, Venus, and Mars as well as the Earth and Moon. This allows users to generate environments for spacecraft orbiting or passing near any of the planets in the inner solar system.

Like earlier versions, MEM 3 models the meteoroid environment between 0.2 and 2 au and does not model the asteroid belt or outer solar system bodies.

1.5.5 Reduced Run Time and File Input/Output

MEM 3 runs approximately three times faster than MEMR2 in low-fidelity mode (which is equivalent to the level of fidelity offered by MEMR2), although the increase in speed depends on the chosen run parameters. This increase in speed is due in part to reduced file input and output: intermediate files are only written at the user's request and are never read back in.

1.5.6 Optional High-fidelity Mode

MEM 3's decreased run time allows us to offer users a high-fidelity run mode. This mode is about as fast as MEMR2 but includes four times as many meteoroid trajectories.

1.5.7 Cross-platform Command-line Support

MEM 3 can either be run in a command-line environment or via a GUI. Like previous versions of MEM, the GUI supports only Windows, but command-line executables exist for Windows, Mac, and Linux operating systems.

1.5.8 Increased User Assistance

MEM 3 offers more user assistance than MEMR2. Like MEMR2, MEM 3 is packaged with a user guide (this document); however, the MEM 3 GUI also offers mouse-over help tips, a preliminary estimate of the needed disk space, and pre-run checks and warnings. Both the MEM 3 GUI and the command-line executable include a progress bar.

1.5.9 Improved Error Handling

MEM 3 also attempts to provide more robust error handling. For instance, the code is now less sensitive to minor formatting issues in the spacecraft trajectory file, such as the presence of trailing empty lines.

MEM 3 conducts a series of initial checks on the trajectory file and the combination of options the user has selected. The GUI reports any errors or warnings to the user in a pop-up window before proceeding with execution. Both the GUI and the command-line executable also create a log file that contains a summary of any errors and warnings.

1.5.10 Sensible File Organization

MEM's capabilities have expanded since it was first released in 2004, but as additional output files were added, they were not necessarily given the same naming scheme, content structure, or file organization. MEM 3 "cleans up" the output files and places them in a single, user-named output directory.

1.5.11 Smoother Angular Distributions

All previous versions of MEM sometimes produced anomalous "hot pixels," in which a particular bin showed an anomalously high flux, sometimes dwarfing the rest of the flux distribution. This behavior was traced back to a singularity in the meteoroid spatial density calculation; it has been repaired using a small smoothing factor.

1.5.12 Removal of the TLE Input Option

MEMR2 allowed users to specify the trajectories of Earth-orbiting spacecraft using two-line element (TLE) sets. MEMR2 did *not* propagate these TLEs, but rather converted each TLE to a single state vector. If users download TLEs from, for example, the CelesTrak website, these TLEs tend to have epochs that correspond to the same value of mean anomaly and are generated once per orbit or every few orbits. Without propagation, these TLEs do not fully "cover" the orbit and are inappropriate for use with MEM.

Thus, most TLEs required user modification before they could be inserted into MEMR2. We have found that many users do not realize this and that using TLEs thus tends to lead to a poor modeling result. We have therefore removed the TLE input option in MEM 3.

1.5.13 Different Velocity Resolution Options

MEM 3 offers 1 km/s and 2 km/s velocity resolutions, and the velocity resolution can be chosen separately from the angular resolution. In contrast, MEMR2 offered resolutions of 2, 4, or 5 km/s, and the velocity resolution was tied to the angular resolution, making it impossible to combine a coarse angular resolution with a fine velocity resolution.

It has long been the opinion of the MEO that the velocity resolution should be no coarser than 2 km/s in order to accurately describe the velocity distribution. Characterizing the effect of the angular, velocity, and density resolutions on typical damage predictions is an area of ongoing work.

1.5.14 Removal of the Lunar Coordinate System

MEMR2 included a lunar coordinate system that was tilted 1.5424° away from the ecliptic plane about the vernal equinox. However, the vernal equinox does not, in fact, lie within the Moon's equatorial plane, and thus MEMR2's lunar coordinate system does not conform to any standard lunar coordinate frame. We also found that some trajectory and ephemeris tools do not offer, or at least do not unambiguously describe, a lunar coordinate frame; this problem is more pronounced for other planets. Thus, MEM 3 does away with the lunar coordinate frame entirely and requires users to prepare their input trajectory in either an ecliptic or Earth-equatorial coordinate frame.

2 THE ENVIRONMENT ACCORDING TO MEM 3

NASA programs and projects must consider the meteoroid environment when designing spacecraft. Risk assessments require descriptions of the meteoroid flux, velocity, density, and directionality to compute the probability of no penetration or impact. A valid meteoroid model must therefore accurately represent the observations and measurements in these four areas.

This section describes MEM's underlying environment model and its validation. As its name indicates, MEM is an engineering model and is intended to be used in characterizing meteoroid particles considered a threat to manned and unmanned NASA spacecraft. We define the threat regime as particles with masses between 10^{-6} g and 10 g; particles smaller than 10^{-6} g are unlikely to penetrate spacecraft materials and particles larger than 10 g are too rare to pose significant risk. Furthermore, dust particle measurements are not a useful probe of the properties of potentially hazardous meteoroids because the dynamics of natural particles is a function of particle size [14, 15]. Thus, observations or measurements of particles outside this mass range (10^{-6} –10 g) are not used as validation datasets.

2.1 Flux

Larger meteoroids are less numerous than smaller meteoroids; thus, when users choose a larger limiting mass they will obtain noticeably smaller fluxes. MEM 3 models this behavior using the mass scaling specified by the Grün interplanetary flux equation [2]:

$$g(m) = (c_4 m^{\gamma_4} + c_5)^{\gamma_5} + c_6 (m + c_7 m^{\gamma_6} + c_8 m^{\gamma_7})^{\gamma_8} + c_9 (m + c_{10} m^{\gamma_9})^{\gamma_{10}} \quad (1)$$

where $g(m)$ is the flux of particles larger than a limiting mass m ; the constants are $c_4 = 2.2 \times 10^3$, $c_5 = 15$, $c_6 = 1.3 \times 10^{-9}$, $c_7 = 10^{-11}$, $c_8 = 10^{27}$, $c_9 = 1.3 \times 10^{-16}$, $c_{10} = 10^6$; and the exponents are $\gamma_4 = 0.306$, $\gamma_5 = -4.38$, $\gamma_6 = 2$, $\gamma_7 = 4$, $\gamma_8 = -0.36$, $\gamma_9 = 2$, and $\gamma_{10} = -0.85$. This equation is applied to MEM's mass range in figure 1.

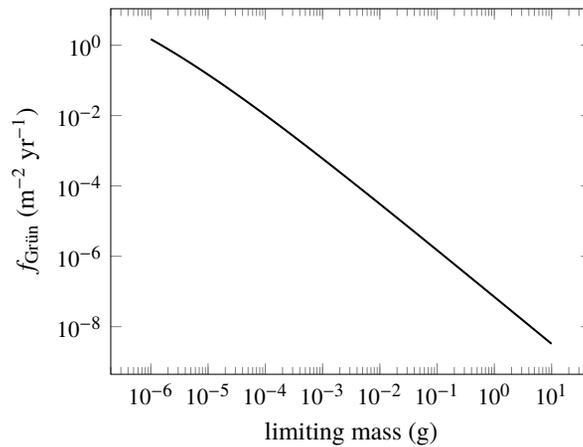


Figure 1. The Grün interplanetary meteoroid flux as a function of limiting particle mass.

The magnitude of the flux is a function of both the heliocentric distance and the distance to the nearest gravitational body and thus may not exactly equal the Grün flux at any particular point. However, the flux is always *proportional* to equation A3 of [2] or Equation 1 of this document, and this equation can be used to rescale a given set of MEM outputs to a different limiting mass if desired.

Users sometimes ask how they can scale MEM results to smaller particles. However, MEM has a minimum meteoroid mass of 10^{-6} g for several reasons. The first reason is that particles smaller than 10^{-6} g are not likely to be dangerous to properly shielded spacecraft components. Second, MEM is tied to meteor observations from the Canadian Meteor Orbit Radar (CMOR), which does not observe meteoroids below this mass limit. The third reason is that below 10^{-6} g, radiative forces such as radiation pressure and Poynting-Robertson drag become significant. As a result, the directionality and speed distribution are likely different below 10^{-6} g [14, 15], and one cannot model these particles by applying a multiplicative factor to MEM results. This also means it is not possible to validate or invalidate MEM using sub-microgram meteoroid crater data.

If information on the sub-microgram meteoroid environment is needed, there are several codes that attempt to model this population. One is the European Space Agency’s Interplanetary Meteoroid Model (IMEM). IMEM is a physics-based meteoroid environment model that is tied to zodiacal cloud data instead of meteor survey data and models particles down to 10^{-12} g. IMEM may therefore be a better model choice for particles below the threat regime.

2.2 Directionality

The directionality of the sporadic environment has been known to be anisotropic for many decades; mid-twentieth century meteor radar surveys revealed concentrations of sporadic meteor radiants within the ecliptic plane [16, 17]. These radiant concentrations are separated from the sunward and anti-sunward directions by about 20° and have been termed the “helion” and “antihelion” sporadic sources. Later surveys uncovered additional concentrations just north and south of the apex direction (i.e., the “north apex” and “south apex” sources [18]). The final two radiant concentrations are the north and south toroidal sources, which lie 60° north and south of the apex direction [19]. In all cases, these sources are named according to their location relative to the Earth’s motion within the ecliptic plane: “apex” refers to the Earth’s ram direction, while “north” and “south” refer specifically to ecliptic north and ecliptic south. Figure 2 presents the directionality distribution of each of these source populations.

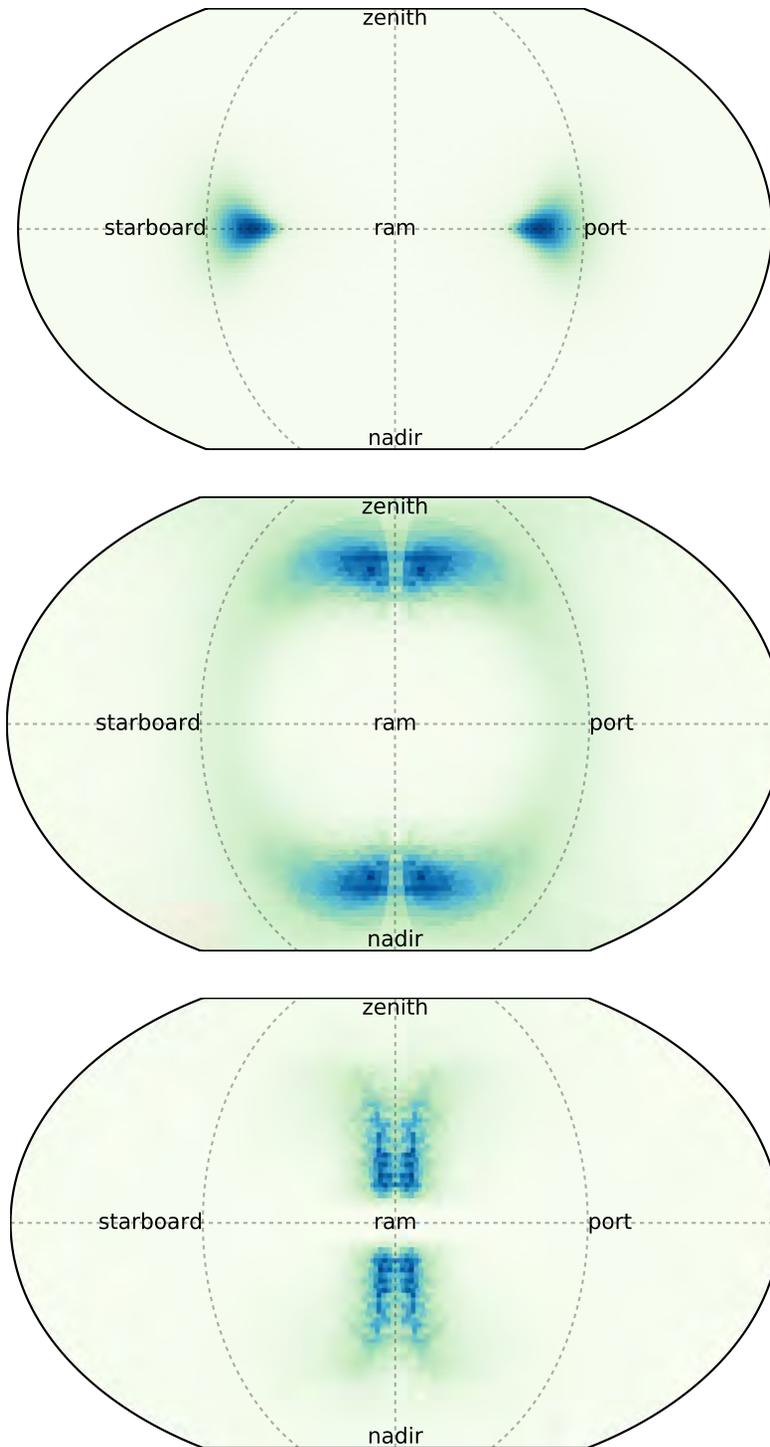


Figure 2. Interplanetary meteoroid directionality as calculated by MEM 3 for a spacecraft that is orbiting the Sun at 1 au but is not near the Earth. The top plot shows the directionality of the helion and antihelion sources, the middle plot corresponds to the toroidal source, and the bottom plot shows the apex source. The directionality is plotted in a body-fixed frame, in which the center (0° in azimuth and 0° in altitude) corresponds to the spacecraft's direction of motion.

It is clear from these surveys that the meteoroid environment cannot be accurately described using an isotropic model. Directionality must be taken into account, or meteoroid impact risk on sunward-facing surfaces, such as solar panels, could be substantially underestimated. Risk assessments therefore require a directional meteoroid model. Early directional models were constructed in an empirical manner [20]; one major limitation to this approach is that most meteoroid surveys are Earth-based, as the quantity of available meteoroid data outside of near-Earth space is severely limited. Impact detectors record comparatively few impacts and do not measure meteoroid directionality, and zodiacal light measurements probe a two-dimensional projection of a population of meteoroids that are far too small to be hazardous.

MEM is based on the meteoroid model of [21], which is a physics-based model calibrated to match Earth-based meteoroid surveys. This model uses the orbits of known comets to generate a dynamically plausible meteoroid population. The effects of radiation pressure, Poynting-Robertson drag, and collisions on meteoroid orbits are all taken into account. The model is constrained using the particle distribution as a function of heliocentric distance derived from zodiacal light and the directionality and particle size distribution observed at Earth by meteor radar surveys. The resulting sporadic directionality reproduces the directionality observed by both historical meteor surveys and more recent surveys conducted by CMOR.

2.3 Velocity Distribution

The meteoroid environment has a distribution of speeds rather than a single representative velocity. The exact form of this distribution is being frequently revised, with some studies arguing for substantial numbers of slow meteoroids [15] and others for a much faster distribution [22]. The observed velocity distribution requires careful debiasing and is very sensitive at low speeds to small changes in methodology [23, 24].

MEMR2 re-weighted the velocity distribution, applying heavier weights to faster meteoroids, to bring it into agreement with [22]. This re-weighting was applied to the Earth sub-model only. We discard this approach in MEM 3, which has a naturally faster speed distribution. MEM 3's speed distribution at the top of the atmosphere is shown in figure 3.

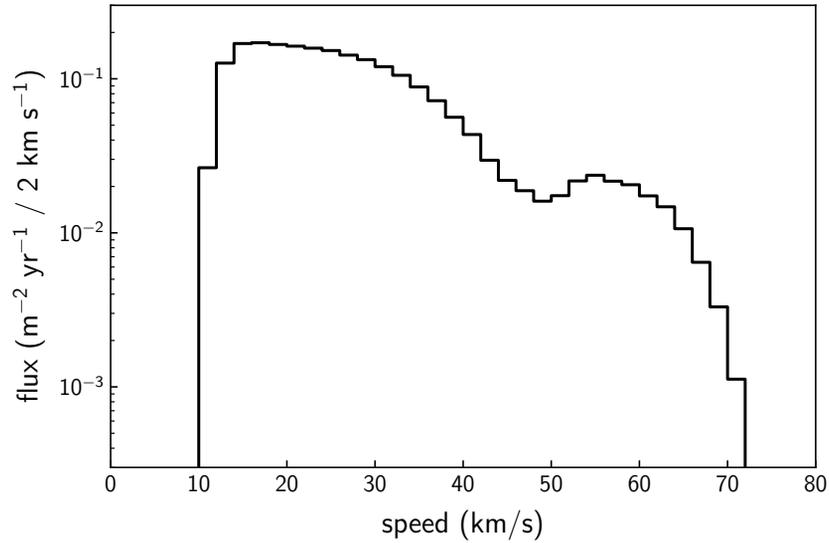


Figure 3. Meteoroid speed distribution relative to the Earth at the top of the atmosphere as calculated by MEM 3.

MEM 3 also fully preserves the correlation between directionality and speed. The orbits of the source populations produce correlations between meteoroid directionality and speed. Furthermore, meteoroids striking the ram-facing side of a spacecraft will generally have higher relative speeds than those striking the wake-facing side. This correlation is depicted in figure 4.

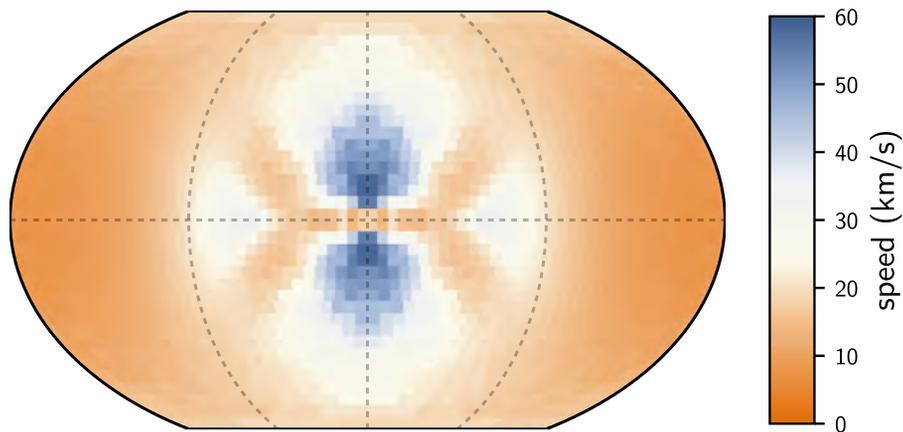


Figure 4. Average interplanetary meteoroid speed as calculated by MEM 3 for a spacecraft that is orbiting the Sun at 1 au but is not near the Earth. Color indicates the average speed of all meteoroids originating from a particular direction, where blue areas correspond to higher speeds and red to lower. The directionality is plotted in a body-fixed frame, in which the center (0° in azimuth and 0° in altitude) corresponds to the spacecraft's direction of motion.

2.4 Density

Nearly all meteoroids are thought to be cometary in origin. At birth, such particles may be either fluffy conglomerates of ice and dust, or they may be compact particles [25]. Over time, exposure to solar radiation is thought to increase the density of these particles. Thus, meteoroids on short orbits, which frequently pass close to the Sun, are expected to have higher bulk densities than those on long orbits. This is supported by recent measurements, which find that meteoroids whose orbits resemble those of asteroids or short-period comets are denser than those whose orbits resemble those of long-period comets [12].

MEM 3 divides the meteoroid environment into two density populations based on [12]. Helion and anti-helion meteoroids constitute the high-density population, while toroidal and apex meteoroids make up the low-density population [13]. Within each population, density is assumed to be independent of mass, speed, and directionality and follows a log-normal distribution (see fig. 5).

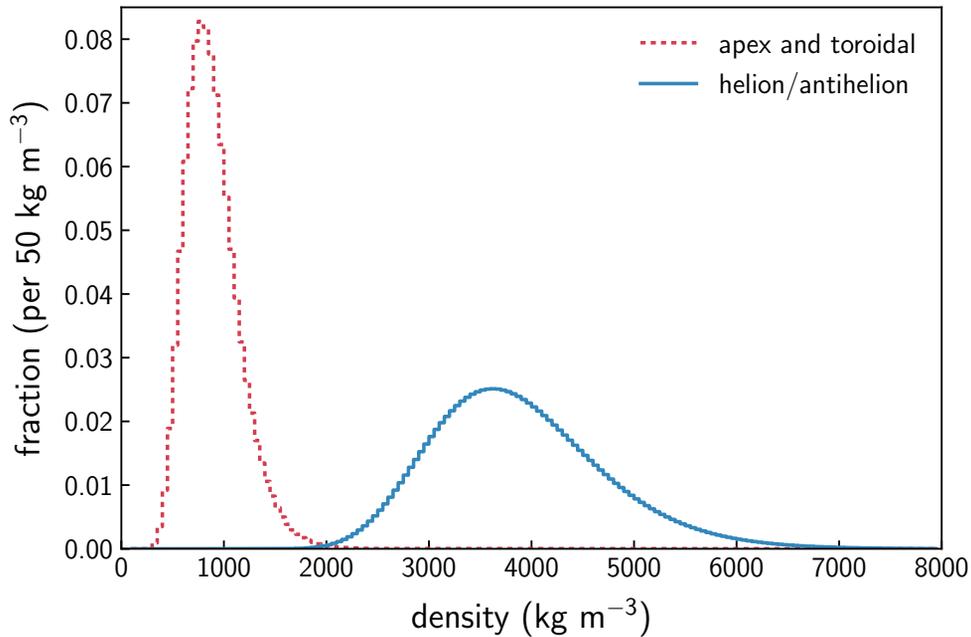


Figure 5. Meteoroid density distribution according to MEM 3. The apex and toroidal meteoroid sources constitute the low-density population, while the helion/antihelion source constitutes the high-density population. Each set of densities follows a log-normal distribution.

3 SOFTWARE DESCRIPTION AND USER INSTRUCTIONS

3.1 Software Installation and Removal

MEM 3 is distributed via the MEO website; users can request the software by completing the required web form² and captcha. The software then downloads in the form of a zip file, usually to the user's "Downloads" directory.

The user can unzip the downloaded file to obtain a directory containing MEM 3 and all files required for its execution. The folder or its contents can be moved to a location of the user's choice, so long as all files are located within the same directory and the user has write privileges to that directory. These files include the program—both command-line and GUI, if applicable—and its associated binary files (listed in table 1.) Most of these files are required to run MEM 3, although there are exceptions: `ISSEexample.txt` is provided simply as an example trajectory file for the user, for instance, and can be removed if the user wishes.

Table 1. A listing of the files typically included with an MEM 3 installation.

MEM 3 data file	Description
bin1.dat bin2.dat bin3.dat de430	Binary data files
ISSEexample.txt	Example trajectory file
MEM3Help.pdf	User guide (this document)
MEM3GUI.exe	GUI application: present only in Windows installations
MEM3.exe <i>or</i> mem3cl	Windows command-line executable Mac or Linux command-line executable
options.txt	Example options file
rho1.txt rho2.txt	Density data files

Unlike earlier versions of MEM, the Windows version of MEM 3 does not come with an installation executable that places the code within the user's Program Files. Recent versions of Windows typically do not give the user write access to the Program Files directory and thus it is no longer an appropriate location for MEM.

² https://www.nasa.gov/offices/meo/software/meo_form.html

Installing MEM 3 will not overwrite older versions of MEM or other MEO software products. However, the MEO advises discontinuing the use of older versions of MEM in favor of using MEM 3 and does not provide support for older versions.

3.1.1 Installing MEM 3 on a Virtual Machine

Users can, if they wish, install and run the MEM 3 GUI application on a virtual machine. However, the user must in that case select a location within a lettered drive as the output location. The MEM 3 GUI cannot determine the size of a virtual drive and thus cannot determine whether enough space is available for the run. It is possible to temporarily assign a letter to a virtual drive, but *the MEO does not provide general IT support and cannot help users with this task.*

3.2 Program Execution

The core components of MEM 3 consist of a command-line executable (named either `MEM3.exe` or `mem3cl`, depending on the operating system), four binary source files (`bin1.dat`, `bin2.dat`, `bin3.dat`, and `de430`), two text files (`rho1.txt` and `rho2.txt`), and a user's manual (this document), all of which are located and must remain located in the same directory.

Before executing either the MEM 3 GUI or the command-line executable, users must prepare an input file that describes their spacecraft trajectory. The required format of this file is described further in Section 3.3, but in brief: it consists of a six-line header, followed by a series of state vectors describing a spacecraft trajectory. The trajectory file can have any alphanumeric name (characters such as dashes and underscores are also permitted) and can be located outside the MEM 3 program directory. The MEM 3 directory includes an example trajectory file named `ISSEexample.txt` and an example options file named `options.txt`.

Depending on the number of state vectors in the input file, MEM run times can vary from minutes to hours. A faster CPU will reduce the runtime, but MEM has not been parallelized and will not take advantage of multiple processors. A larger number of state vectors will also increase the disk space needed for output files if the user has chosen to “output intermediate files,” which causes the code to generate and save flux files corresponding to each individual state vector.

3.2.1 Using the MEM 3 Command-line Executable

Certain Windows users may wish to run MEM 3 directly on the command line, and Mac and Linux users can only run MEM 3 on the command line. The command-line version is not interactive and users must prepare an options file specifying all run parameters. The options file must be named `options.txt` and it must be located in the same directory as the command-line executable. This file specifies the user's desired run options, which are described in detail in section 3.2.3. A sample options file is included with MEM 3; this sample file is shown in figure 6. Note that the full or relative path from the MEM command-line executable to the input trajectory file must be specified in the options file.

```

#####
# Input file for the command line version of MEM 3, must be named "options.txt"
# The following files must be located in the same directory :
# - MEM3Windows.exe (Windows) or mem3cl (Mac or Linux)
# - bin*.dat (3 files)
# - de430
# - options.txt, rho1.txt, and rho2.txt
#
#####
# This input file must contain the following lines
# Line 1 - name of input file
# Line 2 - input origin: (su)n, (ea)rth, (mo)on, (me)rcury, (ve)nus, (ma)rs
# Line 3 - input axes: (eq)uatorial or (ec)liptic
# Line 4 - use (a)ll state vectors, a (r)andom selection, or the (f)irst n
# Line 5 - integer number of state vectors to be used (ignored if using all)
# Line 6 - log10 of the desired minimum particle mass, within [-6, 1]
# Line 7 - high fidelity run (y for yes)
# Line 8 - directory within which results will be placed
# Line 9 - run name (will be used to name results folder)
# Line 10 - output origin: (su)n, (ea)rth, (mo)on, (me)rcury, (ve)nus, (ma)rs
# Line 11 - output axes: (eq)uatorial, (ec)liptic, or (bo)dy-fixed
# Line 12 - desired output resolution in degrees (1, 2, 3, 4, or 5)
# Line 13 - desired output resolution in km/s (1 or 2)
# Line 14 - output intermediate files (y for yes)
# Line 15 - output igloo files (y for yes)
# Line 16 - output standard deviation files (y for yes)
#
#####
ISSEExample.txt
Earth
equatorial
all
1
-6
no high fidelity
.
MyRun
Earth
body-fixed
5 degree angular resolution
1 km/s velocity resolution
no intermediate files
no igloo files
no standard deviations

```

Figure 6. Sample options file. Notice that line 8 is blank after the leading pound sign. An options file created by the MEM 3 GUI application will instead specify what version of the MEM 3 GUI created it on line 8.

Once the trajectory and options files have both been prepared, users can execute the MEM command-line executable. The code will provide the user with a rudimentary progress bar and estimation of time left (see fig. 7).



Figure 7. Screen capture of a command-line MEM 3 run in the Terminal application on a Mac.

3.2.2 Using the MEM 3 GUI

Windows users can choose to invoke a GUI program (MEM3GUI.exe) that constructs the options.txt file and invokes the command-line executable “behind the scenes.” This GUI (see fig. 8) provides users with early checks and warnings regarding the validity of their run choices. Some input fields may appear inactive or “grayed-out” to ensure correct parameter combinations or selection order. Section 3.2.3 contains detailed instructions for run options.

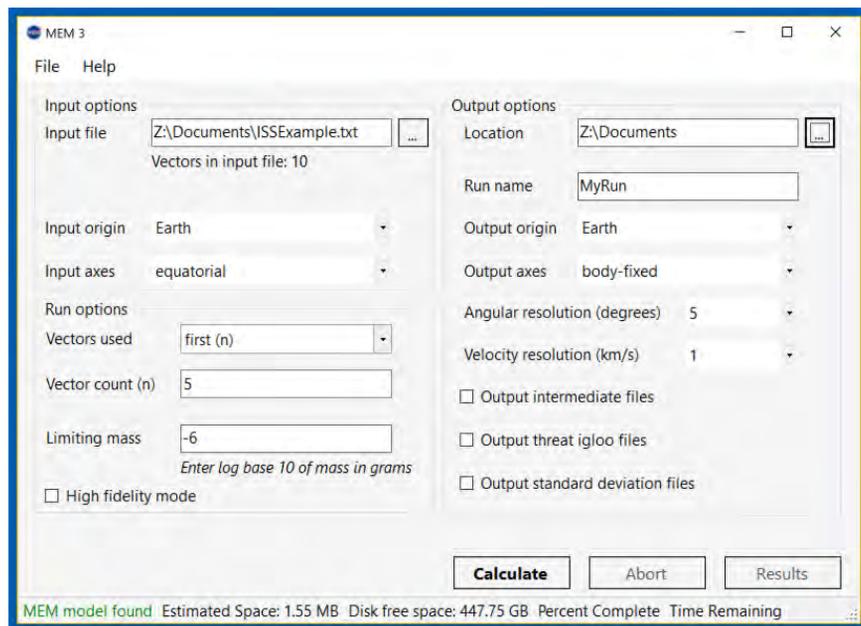


Figure 8. A screen capture of the MEM 3 GUI.

The GUI provides users with an estimate of the maximum disk space needed (actual disk space used may be less) and compares it with that available; it does not allow the user to proceed with a run that may exceed the available disk space. No such estimates are provided for the command-line version.

Users can click “Calculate” when they are ready to begin an MEM run. This will prompt the application to open a second window that reports any errors or warnings that arise from the user’s selected options or input file (see fig. 9). If errors are present, the user cannot proceed with the run but must instead return to the options window and correct any errors. If no errors are present, the user can proceed with the run.

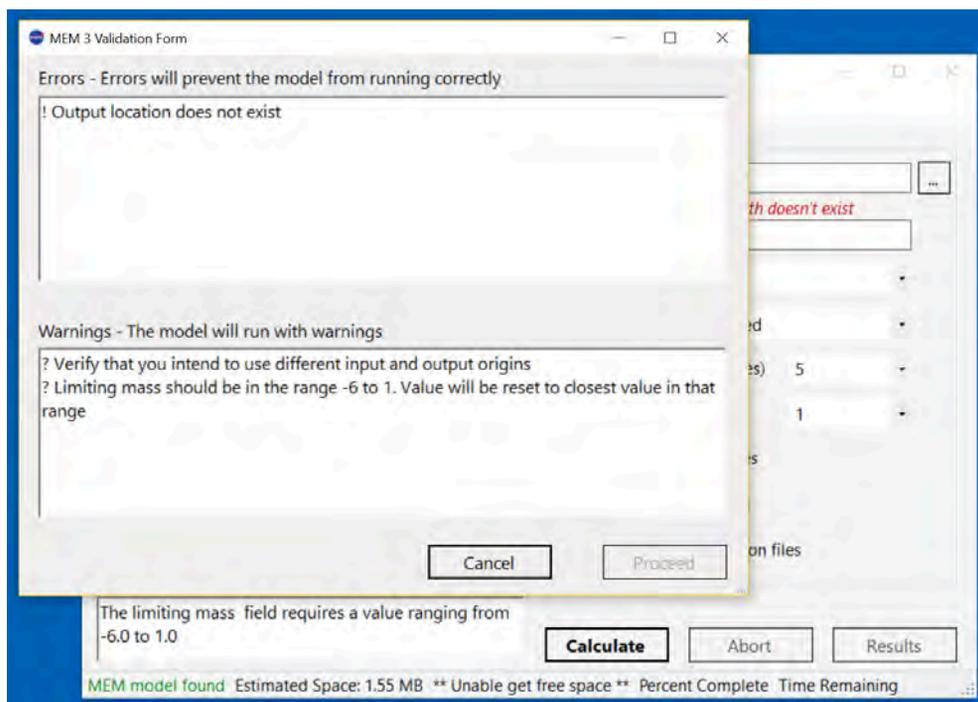


Figure 9. A screen capture of the MEM 3 GUI at the error checking stage.

The GUI will provide the user with a progress bar and an estimate of the time remaining (see fig. 10). The users can use the “Abort” button to terminate the run before it is complete. Once the run has completed (fig. 11), users can click the “Results” button to open the output directory.

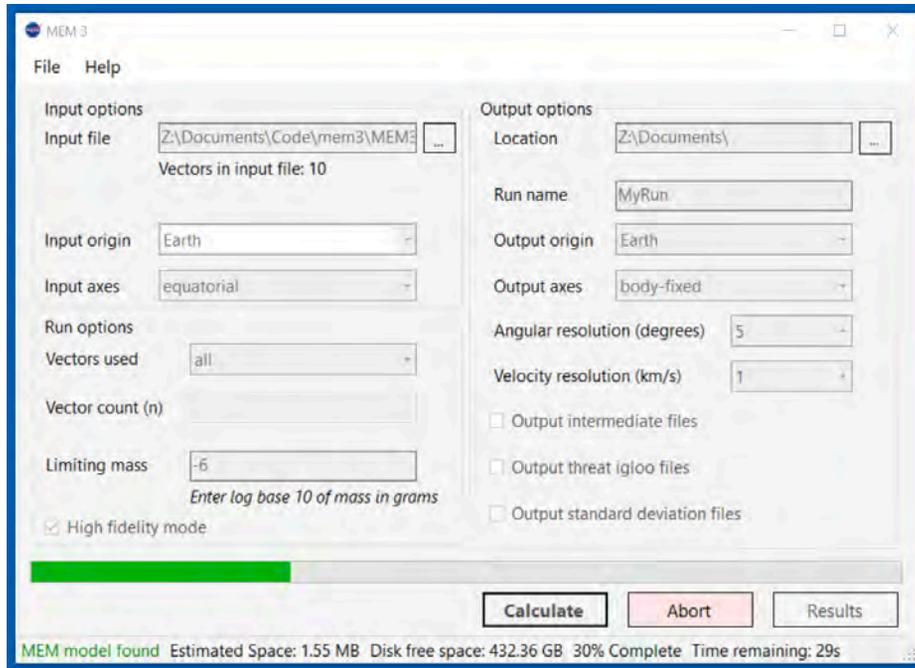


Figure 10. A screen capture of the MEM 3 GUI while the code is running. Note the green progress bar towards the bottom of the window.

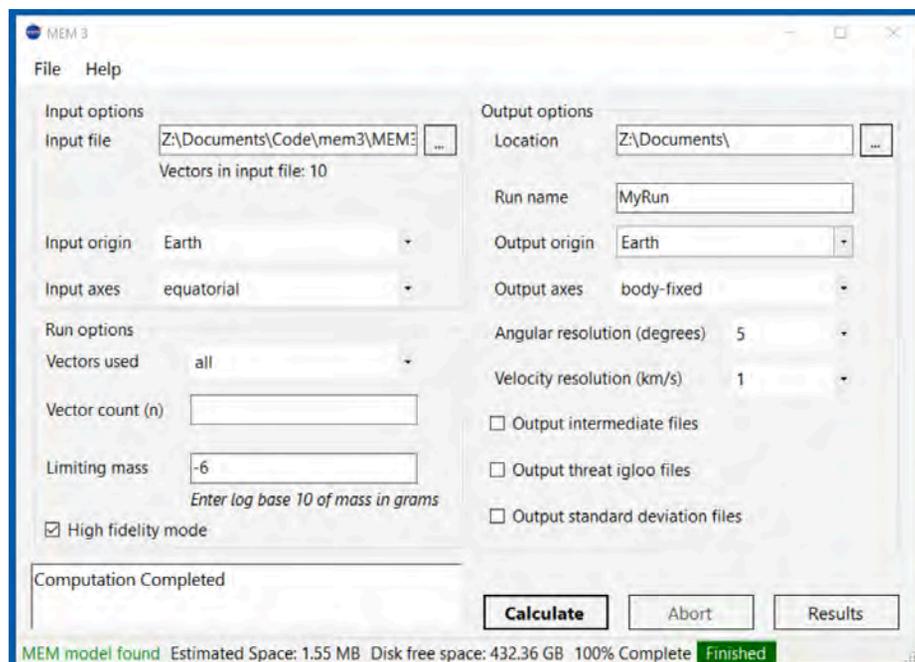


Figure 11. A screen capture of the MEM 3 GUI after the code has completed a run. Note the text “Computation Completed” in the lower left, the green box with the word “Finished” in the lower right, and the activation of the “Results” button.

3.2.3 Run Options

The user has the ability to make a number of choices that influence MEM’s calculations and outputs. The following subsections describe each of these options in the order that they appear in the options file (see fig. 6) and the MEM 3 GUI (see fig. 8).

Input file name:

The user must first provide the name of a file that specifies a spacecraft trajectory. The user may manually enter the file name into either the options file (when using the command-line executable directly) or the input file field (when using the GUI). The user may enter either the absolute path to the input trajectory or the relative path from the MEM directory to the trajectory file.

The GUI allows the user to browse their files and select the desired input file; click the “. . .” button next to the input file field to do so. If the GUI is able to read the input file, it will display the number of state vectors below the input file name text field.

Input origin:

This variable specifies the origin or center of the user’s input trajectory file. For instance, Earth-centered inertial (ECI) coordinates will have “Earth” as their origin. Users may also use the Sun, Moon, Mercury, Venus, or Mars as the origin of their spacecraft trajectory coordinate system.

The origin will often be the nearest massive body, but this is not required. Thus, users can analyze a transfer trajectory in a single run, using any of the possible choices as the origin of their entire trajectory. MEM will automatically detect whether the spacecraft passes near a massive body and takes any such encounters into account.

Input axes:

This variable specifies the axis alignment used by the user’s input trajectory file. Options are “equatorial,” or aligned with the Earth’s equator, and “ecliptic,” or aligned with the ecliptic plane of the Solar System. For instance, ECI coordinates have “equatorial” axes.

Note that “equatorial” *always* refers to the Earth’s equator, regardless of the input origin.

Vectors used:

Users can opt to use a subset of the state vectors listed in their input trajectory file. They may choose to use all state vectors (“all”), a random selection (“random (n)”), or the first few (“first (n)”). If the random option is chosen, state vectors are randomly chosen without replacement from the full list; duplicate state vectors are not used.

The original input file will always cover the trajectory more fully than a randomly selected subsample drawn from it. Therefore, as with all runs, the user should ensure that the input file covers the trajectory well and that a large enough subsample is drawn. Users are advised to vary the number of random draws; if a large enough sample has been drawn, the results will not vary significantly. Note, however, that passing this test does not guarantee that the original input file adequately covers the trajectory.

Vector count:

Users may use this text field to specify the number of state vectors to analyze when using the “random” or “first few” run types. If this number matches or exceeds the number of state vectors in the input file, a warning may be issued by the GUI. Users may proceed (or run the code on the command line), but MEM 3 will set the number of state vectors used to the number of state vectors it is able to read from the input file.

Limiting mass:

The user may specify the base-10 logarithm of the limiting mass in grams. The user is restricted to choosing a value between -6 and 1, corresponding to 10^{-6} and 10 g, respectively. The field is pre-populated with a default value of -6. MEM will calculate the meteoroid flux for particles greater than or equal to the chosen limiting mass.

High-fidelity mode:

If the user chooses to run in high-fidelity mode, four times as many meteoroid orbit realizations are used in the flux calculations. This reduces noise in the resulting flux values and is required for a standard deviation calculation. When high-fidelity mode is “off,” the number of orbits is equivalent to MEMR2. The code runs more slowly in high-fidelity mode (by approximately a factor of 3 to 4, depending on other run parameters).

Output location:

This text field specifies the directory within which the results may be placed. The user may type the absolute or relative path into either the output “Location” text field in the GUI or the corresponding line in the options file.

The GUI also allows the user to browse their files and select the desired directory; click the “. . .” button next to the output location field to do so.

The GUI attempts to determine the space available on the drive within which the output location resides. If the GUI cannot determine a drive letter, it will not allow the user to proceed; this is to ensure that MEM’s outputs do not completely fill the user’s hard drive. However, this may prevent users from running the MEM GUI on virtual folders. The command-line executable does not perform this check.

Run name:

Users are required to provide a run name; a directory of this name will be created within the specified output location. All output files, log files, and copies of input files will be placed within this directory. If a directory with the given run name already exists within the specified output location, a warning is issued and output files may be overwritten.

Output origin:

This variable specifies the origin the user wishes MEM to use for all output files. Allowed choices are the Sun, Earth, Moon, Mercury, Venus, or Mars. In most cases, we expect that users will want to use the same origin for their output files as they do for their spacecraft trajectory, but this is not required.

Output axes:

This variable specifies the axis alignment the user wishes MEM to use for all output files. A “body-fixed” option, in which the $+x$ axis is aligned with the spacecraft’s direction of motion, is available in addition to the “equatorial” and “ecliptic” options.

Angular resolution:

Users may select an angular resolution of “1°,” “2°,” “3°,” “4°,” or “5°” for their output files. A coarser angular resolution will reduce run time and file size.

Velocity resolution:

Users may select a velocity resolution of “1 km/s” or “2 km/s” for their output files. A coarser resolution will reduce run time and file size, but we recommend the “1 km/s” option in most cases. The velocity resolution is not tied to the angular resolution.

Output intermediate files:

If users select this option, MEM will output flux files for each spacecraft state vector used. If this option is not selected, no flux files will be generated until the end of the run.

Output igloo files:

If users select this option, MEM will output a “threat igloo” file in which the flux is divided into quasi-equal area angular bins. If both this option and the intermediate file option are selected, MEM will output an igloo file for each state vector used.

Output standard deviation files:

If users select this option, MEM will output standard deviation files in addition to the average flux files. If the igloo file option has been chosen, MEM will also output the standard deviation of the flux in igloo file format. Note that this simply describes the variation along the user-provided spacecraft trajectory and does not describe the uncertainty in the model.

This option requires the use of the high-fidelity mode.

3.3 Input Files

Because MEM provides trajectory-specific meteoroid environment data, the user must provide an input file containing trajectory information. This file must contain a series of Cartesian state vectors. The state vectors in the input file can be sequential or correspond to random points in time. Each state vector will receive equal weight; we therefore recommend sampling the spacecraft state vector at equal time intervals to avoid underweighting part of the trajectory.

3.3.1 Options File

The options file must be named `options.txt` and it must be located in the same directory as the MEM command-line executable. If the user chooses to run the command-line version of MEM directly, they must take care to preserve the name, placement, and formatting of this file. If the user makes use of the GUI program, there is no need to edit or handle the options file directly.

3.3.2 Input Trajectory File

To accommodate trajectory data generated with the popular Systems Tool Kit³ (STK), MEM assumes that the first six lines of an input file are header. The contents of this header are irrelevant and may be left empty, but no data will be used prior to line 7 of the input file. Starting on line 7, the input file lines must consist of a Julian date (in units of days) followed by the Cartesian position and velocity of the spacecraft (in units of km and km/s, respectively). Individual numbers must be separated by whitespace; the required format is shown in table 2, and an example input file is shown in figure 12.

Table 2. Trajectory input file format. The required units are days for Julian dates, km for positional data, and km/s for velocity data.

1	Header text – no required format other than six line requirement						
2							
3							
4							
5							
6							
7	Julian Date #1	x_1	y_1	z_1	$v_{x,1}$	$v_{y,1}$	$v_{z,1}$
8	Julian Date #2	x_2	y_2	z_2	$v_{x,2}$	$v_{y,2}$	$v_{z,2}$
...
$N + 6$	Julian Date # N	x_N	y_N	z_N	$v_{x,N}$	$v_{y,N}$	$v_{z,N}$

³ <http://www.agi.com/products/stk/modules/default.aspx/id/stk-free>

18 Nov 2011 10:27:38

Satellite-ISS

Time (JDate)	x (km)	y (km)	z (km)	vx (km/sec)	vy (km/sec)	vz (km/sec)
2455836.00000000	5243.508232	-3437.436713	-2533.995550	4.612739	3.124407	5.287943
2455836.00069444	5507.892341	-3242.142011	-2211.069593	4.196666	3.382904	5.472104
2455836.00138889	5746.717399	-3031.802304	-1877.853720	3.761101	3.625712	5.630806
2455836.00208333	5958.874436	-2807.393288	-1535.898437	3.308077	3.851698	5.763303
2455836.00277778	6143.379014	-2569.956395	-1186.795213	2.839711	4.059806	5.868977
2455836.00347222	6299.375944	-2320.593887	-832.168949	2.358192	4.249064	5.947332
2455836.00416667	6426.143359	-2060.463645	-473.670257	1.865774	4.418591	5.998007
2455836.00486111	6523.096137	-1790.773682	-112.967614	1.364758	4.567599	6.020769
2455836.00555556	6589.788647	-1512.776392	248.260581	0.857491	4.695396	6.015519
2455836.00625000	6625.916787	-1227.762597	608.333988	0.346343	4.801394	5.982292
2455836.00694444	6631.319333	-937.055401	965.578316	-0.166298	4.885105	5.921254
2455836.00763889	6605.978563	-642.003896	1318.333260	-0.678037	4.946151	5.832705
2455836.00833333	6550.020177	-343.976753	1664.960358	-1.186489	4.984258	5.717073
2455836.00902778	6463.712506	-44.355741	2003.850713	-1.689288	4.999262	5.574915
2455836.00972222	6347.465026	255.470803	2333.432543	-2.184097	4.991109	5.406911
2455836.01041667	6201.826195	554.114501	2652.178516	-2.668622	4.959853	5.213862
2455836.01111111	6027.480614	850.193437	2958.612841	-3.140621	4.905654	4.996683
2455836.01180556	5825.245567	1142.338596	3251.318075	-3.597915	4.828781	4.756404

Figure 12. Example trajectory input file generated with STK. This file describes part of the ISS trajectory and is in ECI coordinates (i.e., the coordinate origin is “Earth” and the axes are “equatorial”).

The input file must also satisfy the following requirements:

- State vectors should be in either J2000/ICRF ecliptic or equatorial coordinates, with the origin located at the Sun, Earth, Moon, Mercury, Venus, or Mars.
- Outside of the header, there should not be any commas, brackets, parentheses, or any other symbol or character other than the columns of numbers.
- Floating point numbers, integers, and scientific or engineering representation are acceptable number formats.
- While MEM 3 is able to handle trailing empty lines better than previous versions, we recommend keeping extraneous whitespace to a minimum.

J2000 or ICRF?

Technically, “J2000” and “ICRF” are distinct coordinate frames. The J2000 coordinate frame may also be referred to as the FK5/J2000 frame; furthermore, there are at least three iterations on the International Celestial Reference Frame (ICRF): ICRF1, ICRF2, and ICRF3. In practice, the differences between these reference frames are extremely small, and, as a result, some tools may not distinguish between them. The JPL HORIZONS ephemeris website and the SPICE ephemeris toolkit consider the J2000 and ICRF frames to be indistinguishable, and “J2000” data from SPICE are actually referenced to the ICRF frame.

Some tools (such as STK) do distinguish between the two frames. Users may use either, although “ICRF” is technically more consistent with the SPICE-based ephemerides used by MEM.

Please ensure that the trajectory file does not inadvertently place the spacecraft *inside* a planet or the Moon. If this occurs, all meteoroids will be shielded and all flux components will be zero; this will also occur when a spacecraft is inside a planet’s atmosphere. MEM 3 models the planets and the Moon as spheres with the radii and atmospheric depth specified in table 3.

Table 3. Meteoroid-blocking radius assumed by MEM 3 for each body in the inner Solar System. Mercury and the Moon are airless bodies, but Venus has about 120 km of meteoroid-blocking atmosphere, the Earth has 100 km, and Mars has 90 km.

body	radius + atmosphere
Mercury	2439.7 km
Venus	6172 km
Earth	6471 km
Moon	1737.4 km
Mars	3480 km

3.4 Output Files

MEM 3 produces a collection of output files that describe both the aggregate meteoroid environment along the entire provided trajectory and the instantaneous environments corresponding to each input state vector or TLE. In all cases, the flux and speed information presented in the output files are computed relative to the spacecraft. The output data include the effects of gravitational focusing and planetary shielding where applicable (i.e., when the spacecraft is near a planet or the Moon). MEM 3 does not report environment uncertainties; the standard deviation output files report the observed variation in flux along the provided spacecraft trajectory.

Output files are placed into a directory whose name matches the run name specified by the user in either the `options.txt` file or the GUI. The cube, flux, and igloo files are further organized into `HiDensity` and `LoDensity` subdirectories.

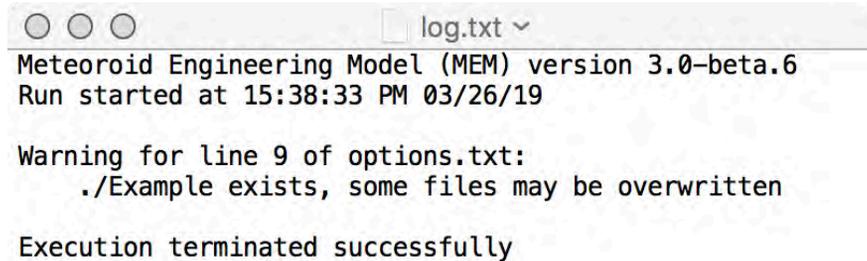
For users who have experience with MEMR2, table 4 lists each output file produced by MEM 3 and its MEMR2 equivalent, if any.

Table 4. The list of output files generated by a MEM 3 run and, where applicable, their MEMR2 equivalent.

MEM 3 output file	MEMR2 equivalent
MyRun\info.txt MyRun\input.txt MyRun\log.txt MyRun\options.txt	
MyRun\HiDensity\cube_avg.txt MyRun\LoDensity\cube_avg.txt	AvgResults.out
MyRun\HiDensity\cube_std.txt MyRun\LoDensity\cube_std.txt	StdDevResults.out
MyRun\HiDensity\cube_01.txt ... MyRun\HiDensity\cube_NN.txt MyRun\LoDensity\cube_01.txt ... MyRun\LoDensity\cube_NN.txt	main results file (user-chosen file name)
MyRun\HiDensity\flux_avg.txt MyRun\LoDensity\flux_avg.txt	AvgSpdDist.out
MyRun\HiDensity\flux_std.txt MyRun\LoDensity\flux_std.txt	StdDevSpdDist.out
MyRun\HiDensity\flux_01.txt ... MyRun\HiDensity\flux_NN.txt MyRun\LoDensity\flux_01.txt ... MyRun\LoDensity\flux_NN.txt	SpdDistMap1.out ... SpdDistMapNN.out
MyRun\HiDensity\igloo_avg.txt MyRun\LoDensity\igloo_avg.txt	AvgMEMIglooDist.out
MyRun\HiDensity\igloo_std.txt MyRun\LoDensity\igloo_std.txt	StdDevMEMIglooDist.out
MyRun\HiDensity\igloo_01.txt ... MyRun\HiDensity\igloo_NN.txt MyRun\LoDensity\igloo_01.txt ... MyRun\LoDensity\igloo_NN.txt	
MyRun\hidensity.txt MyRun\lodensity.txt	

3.4.1 Log, Information, and Options Files

MEM 3 logs errors, warnings, and other information to a log file named `log.txt` (see fig. 13). MEM 3 initially creates this file in the same location where the MEM 3 command-line executable resides. If it is able to create a run directory, the log file is moved to that location. Users should check these two locations for the `log.txt` file if they are unable to start a run.



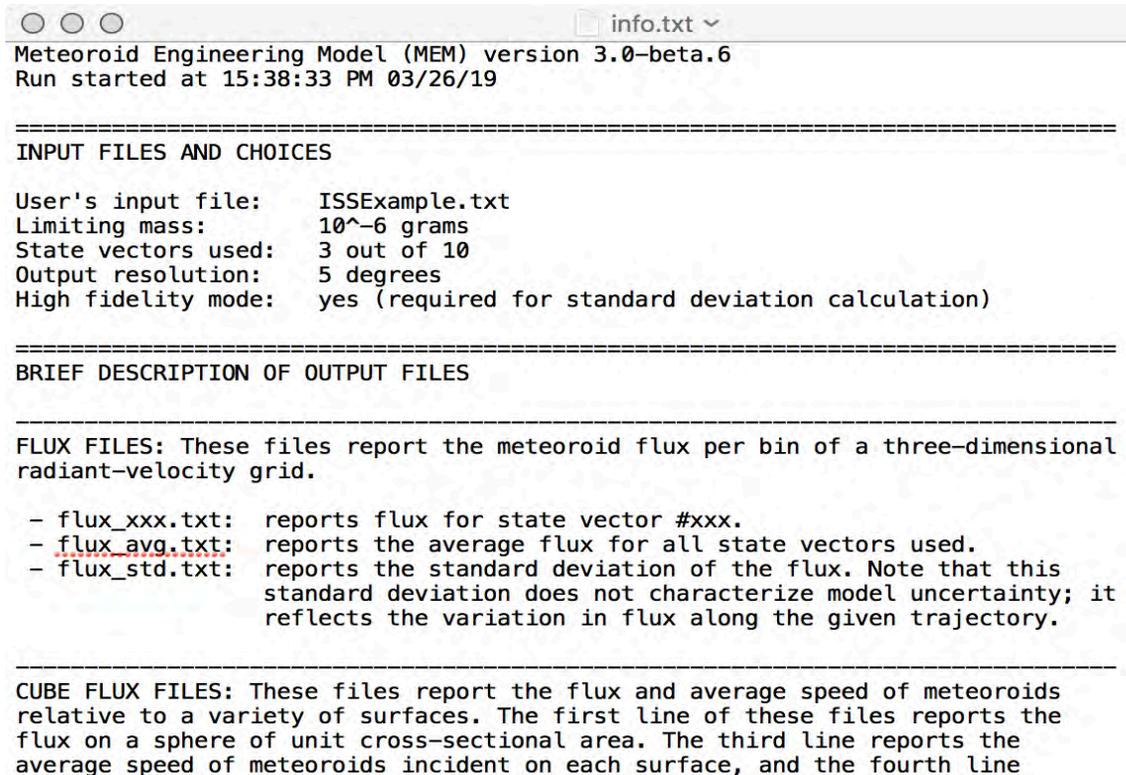
```
log.txt
Meteoroid Engineering Model (MEM) version 3.0-beta.6
Run started at 15:38:33 PM 03/26/19

Warning for line 9 of options.txt:
  ./Example exists, some files may be overwritten

Execution terminated successfully
```

Figure 13. Example log file.

MEM 3 also creates a file named `info.txt` (see fig. 14) that provides a description of the primary output files. Users can refer to the information file to refresh their memory of what each file type contains.



```
info.txt
Meteoroid Engineering Model (MEM) version 3.0-beta.6
Run started at 15:38:33 PM 03/26/19

=====
INPUT FILES AND CHOICES

User's input file:  ISSEExample.txt
Limiting mass:     10^-6 grams
State vectors used: 3 out of 10
Output resolution: 5 degrees
High fidelity mode: yes (required for standard deviation calculation)

=====
BRIEF DESCRIPTION OF OUTPUT FILES

=====
FLUX FILES: These files report the meteoroid flux per bin of a three-dimensional
radiant-velocity grid.

- flux_xxx.txt: reports flux for state vector #xxx.
- flux_avg.txt: reports the average flux for all state vectors used.
- flux_std.txt: reports the standard deviation of the flux. Note that this
standard deviation does not characterize model uncertainty; it
reflects the variation in flux along the given trajectory.

=====
CUBE FLUX FILES: These files report the flux and average speed of meteoroids
relative to a variety of surfaces. The first line of these files reports the
flux on a sphere of unit cross-sectional area. The third line reports the
average speed of meteoroids incident on each surface, and the fourth line
```

Figure 14. Example information file.

Finally, MEM 3 also copies the trajectory input file (which will be renamed `input.txt`) and options file (`options.txt`) to the run directory. Thus, the run directory contains not only the output of a MEM 3 run but also the set of files that allow the user to replicate that run.

3.4.2 Cube Files

The “cube” files report meteoroid fluxes and velocities relative to a series of flat surfaces with different orientations. A cube file begins with a nine-line header that first reports the number of rows (line 1) and columns (line 2) of flux data, not including velocity labels. Next, the file reports the total cross-sectional meteoroid flux summed over all directions and speeds in units of particles per square meter per year (line 4). This is equivalent to the meteoroid flux on a sphere per square meter of cross-sectional area. The cube files next provide a table of the average meteoroid speed incident on each face of a cube with the spacecraft’s orientation (line 7). We warn that the use of average speeds in risk assessments may underestimate vehicle risk and recommend the use of the full meteoroid speed distributions (see sec. 3.4.3). The total flux incident on each surface is reported next (line 8).

The flux in each speed interval is reported immediately after the header and beginning on line 10. Speed bins are labeled with the midpoint of the speed range in the first column: 0.5 km/s for meteoroids ranging from 0 to 1 km/s. The next six columns of data report the corresponding flux component on each side of a cube whose faces are aligned with the user’s chosen coordinate system. The next three columns report the flux on surfaces facing the Earth, facing the Sun, and facing away from the Sun. These orientations may be relevant to communications equipment and solar panels, respectively. Finally, the last three columns report the flux on surfaces rotating about the three axes of the user’s chosen coordinate system. These fluxes are quoted per unit of average cross-sectional area perpendicular to the axis of rotation. Part of a sample cube file is shown in figure 15.

```

# 40 rows of flux data
# 12 columns of flux data
#
# total cross-sectional flux 4.237290e+00 /m^2/yr
#
#
#          +x ram      -x wake      +y port  -y starboard      +z zenith      -z nadir      Earth
# average speed (km/s)      27.71      13.18      27.83      27.50      25.56      26.40      26.40
# total flux (#/m2/yr) 1.818891e+00 5.829470e-02 1.978173e+00 1.227293e+00 1.141148e+00 1.023061e-01 1.008805e-01
# velocity (km/s)
  1.0      0.000000e+00 0.000000e+00 0.000000e+00 0.000000e+00 0.000000e+00 0.000000e+00 0.000000e+00
  3.0      0.000000e+00 0.000000e+00 0.000000e+00 0.000000e+00 0.000000e+00 0.000000e+00 0.000000e+00
  5.0      0.000000e+00 1.119981e-03 2.533877e-04 1.790183e-04 1.725092e-04 2.185151e-04 2.187359e-04
  7.0      0.000000e+00 7.752284e-03 2.395943e-03 2.568004e-03 3.523747e-03 7.234954e-04 7.275788e-04
  9.0      3.099916e-05 1.170573e-02 6.917215e-03 7.311624e-03 1.025895e-02 1.039799e-03 1.051928e-03
 11.0     9.456655e-04 9.466546e-03 1.468845e-02 1.302404e-02 1.847857e-02 1.160379e-03 1.169966e-03
 13.0     6.992635e-03 7.141426e-03 2.852543e-02 2.066533e-02 3.208855e-02 1.466117e-03 1.471160e-03
 15.0     2.818314e-02 5.534890e-03 5.563756e-02 3.390890e-02 5.636522e-02 2.226676e-03 2.221709e-03
 17.0     7.860090e-02 4.457798e-03 9.970797e-02 5.593179e-02 8.585962e-02 3.637910e-03 3.600351e-03
 19.0     1.726435e-01 3.559988e-03 1.422722e-01 8.763606e-02 1.124429e-01 6.336028e-03 6.211276e-03
 21.0     2.109265e-01 2.693630e-03 1.637522e-01 1.076950e-01 1.156100e-01 8.902242e-03 8.699666e-03
 23.0     1.997184e-01 2.014260e-03 1.748386e-01 1.146737e-01 1.084794e-01 1.017958e-02 9.974463e-03
 25.0     1.768586e-01 1.322799e-03 1.778195e-01 1.162446e-01 9.835226e-02 1.140343e-02 1.121166e-02
 27.0     1.597479e-01 8.075919e-04 1.771548e-01 1.125325e-01 8.993370e-02 1.166562e-02 1.148955e-02
 29.0     1.426704e-01 4.266777e-04 1.698725e-01 1.063815e-01 8.076744e-02 1.130381e-02 1.115496e-02
 31.0     1.289667e-01 1.960155e-04 1.586826e-01 9.703555e-02 7.195065e-02 1.024273e-02 1.011985e-02

```

Figure 15. Section of an example cube file. This example uses a body-fixed output coordinate system. Cube files contain a nine-line header that includes the total cross-sectional flux, the average speed on each surface considered, and the total flux on each surface considered. A more detailed breakdown of the flux on each surface in each speed bin begins on line 10.

All MEM 3 runs produce an average cube file, `cube_avg.txt`, which reports each flux component averaged over the spacecraft trajectory. If users opt to generate standard deviation files, a standard deviation file named `cube_std.txt` will also be produced. Finally, if users choose to output intermediate files, a cube flux file will be produced for each state vector used and will be named `cube_NN.txt`, where NN is the number of the state vector in the trajectory input file.

3.4.3 Flux Files

For each spacecraft state vector, MEM 3 calculates the meteoroid flux within a three-dimensional grid in azimuth, elevation, and velocity; the resolution and orientation of this grid is chosen by the user at the beginning of a run. The resulting grid of data is written to what we call the “flux files.”

A flux file begins with an eight-line header that first reports the number of rows (line 1) and columns (line 2) of flux data, not including angular labels. A description of the bin labeling is provided in lines 4-6 of the header. The last line of the header provides labels for each column of data.

Flux data begins immediately after the header, starting on line 9 of the flux file. The first column in the file reports the lower elevation limit for a grid cell. Therefore, the first value will always be -90 and the last value will be 85, 86, or 89, depending on the chosen resolution. The second column in the file reports the low value for azimuth; the first value will always be 0. Each of the remaining columns

corresponds to a speed bin, and the midpoint of each velocity bin appears as a column label (line 8 of the header). Part of an example flux file is shown in figure 16.

```
# 2592 rows of flux data
# 40 columns of flux data
#
# flux is distributed by angle and speed:
# angle values give minimum value of angular range (degrees)
# numeric column labels give midpoint of speed range (km/s)
#
# PHI1 THETA1      1      3      5      7      9      11      13      :
-90      0 0.000000e+00 0.000000e+00 0.000000e+00 0.000000e+00 0.000000e+00 0.000000e+00 0.000000e+00 0.000000e+
-90      5 0.000000e+00 0.000000e+00 0.000000e+00 0.000000e+00 0.000000e+00 0.000000e+00 0.000000e+00 0.000000e+
-90     10 0.000000e+00 0.000000e+00 0.000000e+00 0.000000e+00 0.000000e+00 0.000000e+00 0.000000e+00 0.000000e+
-90     15 0.000000e+00 0.000000e+00 0.000000e+00 0.000000e+00 0.000000e+00 0.000000e+00 0.000000e+00 0.000000e+
-90     20 0.000000e+00 0.000000e+00 0.000000e+00 0.000000e+00 0.000000e+00 0.000000e+00 0.000000e+00 0.000000e+
-90     25 0.000000e+00 0.000000e+00 0.000000e+00 0.000000e+00 0.000000e+00 0.000000e+00 0.000000e+00 0.000000e+
-90     30 0.000000e+00 0.000000e+00 0.000000e+00 0.000000e+00 0.000000e+00 0.000000e+00 0.000000e+00 0.000000e+
-90     35 0.000000e+00 0.000000e+00 0.000000e+00 0.000000e+00 0.000000e+00 0.000000e+00 0.000000e+00 0.000000e+
-90     40 0.000000e+00 0.000000e+00 0.000000e+00 0.000000e+00 0.000000e+00 0.000000e+00 0.000000e+00 0.000000e+
-90     45 0.000000e+00 0.000000e+00 0.000000e+00 0.000000e+00 0.000000e+00 0.000000e+00 0.000000e+00 0.000000e+
-90     50 0.000000e+00 0.000000e+00 0.000000e+00 0.000000e+00 0.000000e+00 0.000000e+00 0.000000e+00 0.000000e+
-90     55 0.000000e+00 0.000000e+00 0.000000e+00 0.000000e+00 0.000000e+00 0.000000e+00 0.000000e+00 0.000000e+
-90     60 0.000000e+00 0.000000e+00 0.000000e+00 0.000000e+00 0.000000e+00 0.000000e+00 0.000000e+00 0.000000e+
```

Figure 16. Section of an example flux file. The number of columns is determined by the number of speed bins. Not all rows and columns are shown here. As is typical for spacecraft in low Earth orbit, the flux in low-velocity or nadir-facing bins is zero.

All MEM 3 runs produce an average flux file, `flux_avg.txt`, which reports each flux component averaged over the spacecraft trajectory. If users opt to generate standard deviation files, a standard deviation file named `flux_std.txt` will also be produced. Finally, if users choose to output intermediate files, a flux file will be produced for each state vector used and will be named `flux_NN.txt`, where NN is the number of the state vector in the trajectory input file.

For some runs, the first few lines or columns may contain zero meteoroid flux (this is the case in fig. 16). This is normal for a spacecraft in low Earth orbit when the body-fixed output coordinate frame is selected. In this case, the Earth shields the spacecraft from nadir-originating meteoroids. Low-velocity bins will also typically be empty; meteoroids do not orbit the Earth and thus their speeds necessarily exceed the local escape speed.

Please also note that these files report the meteoroid flux per angular bin. These bins are not equal in area and cover smaller portions of the sky towards the zenith and nadir directions (see fig. 17). If the user wishes to generate plots of meteoroid flux as a function of direction, we recommend converting flux per angular bin to flux per square degree, or, alternatively, using the igloo output files (sec. 3.4.4).

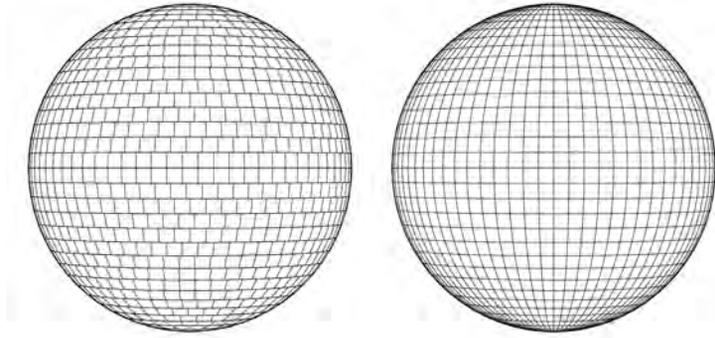


Figure 17. Quasi-equal-area threat igloo (left) and azimuth and elevation grid (right). These examples correspond to a 5° angular resolution.

3.4.4 Igloo Files

The flux files described in section 3.4.3 completely describe the meteoroid environment along the given trajectory to the user-specified resolution. However, the angular bins in the azimuth and elevation grid vary in size. Therefore, MEM also provides the user with an alternate description of the environment in which flux is divided into an “igloo” of quasi-equal area angular bins. The azimuthal width of these bins varies such that the solid angle subtended stays roughly constant; for example, the angular area of the 5° igloo bins ranges from 24.35 to 26.17 square degrees.

These igloo files provide a quasi-equal area projection of the meteoroid environment as seen by the spacecraft. Blocks in the “equator,” or 0° elevation row, span equivalent ranges in elevation and azimuth. For a 1° resolution choice, these blocks will be approximately one square degree in size. As elevation increases, the number of blocks in a ring decreases to maintain an angular area similar to that in the 0° ring. Figure 17 illustrates this threat igloo concept.

Like the flux files, the igloo files begin with an eight-line header that first reports the number of rows (line 1) and columns (line 2) of flux data, not including angular labels. A description of the bin labeling is provided in lines 4-6 of the header. The last line of the header provides labels for each column of data.

The first nine columns of an igloo file specify the location of each angular block within the igloo. The first three columns are block indices: the first column is an element id number, the second column is the elevation “ring” index (i), and the third column is the block index within that ring (j). The next four columns report the lower and upper bounds on elevation angle for the given block followed by the lower and upper bounds on azimuth.

The eighth and ninth columns contain the value of elevation and azimuth that divide the igloo bin into four equal-area quadrants. The azimuthal angle corresponding to this areal midpoint is simply the average of the two bounding azimuth values. However, the elevation angle is given by:

$$\sin \phi_m = \frac{1}{2}(\sin \phi_1 + \sin \phi_2) \quad (2)$$

where ϕ_1 and ϕ_2 are the two bounding elevation angles of the igloo bin. For resolutions of 5° or finer, these midpoint angles lie very close, but are not identical, to the centroid of the bin.

Finally, flux values are reported in columns 10 and greater; the number of columns is determined by the chosen speed resolution. Part of an example igloo file is shown in figure 18.

```
# 1652 rows of flux data
# 40 columns of flux data
#
# flux is distributed by angle and speed:
# angle values give boundaries and center of angular bin (degrees)
# numeric column labels give midpoint of speed range (km/s)
#
#
# ID  I  J  PHI1  PHI2  THETA1  THETA2  PHIavg  THETAavg  1.0  3.0  5.0
1  1  1  -90.00  -85.00  0.00  120.00  -86.47  60.00  0.000000e+00  0.000000e+00  0.000000e+00  0.000E
2  1  2  -90.00  -85.00  120.00  240.00  -86.47  180.00  0.000000e+00  0.000000e+00  0.000000e+00  0.000E
3  1  3  -90.00  -85.00  240.00  360.00  -86.47  300.00  0.000000e+00  0.000000e+00  0.000000e+00  0.000E
4  2  1  -85.00  -80.00  0.00  40.00  -82.10  20.00  0.000000e+00  0.000000e+00  0.000000e+00  0.000E
5  2  2  -85.00  -80.00  40.00  80.00  -82.10  60.00  0.000000e+00  0.000000e+00  0.000000e+00  0.000E
6  2  3  -85.00  -80.00  80.00  120.00  -82.10  100.00  0.000000e+00  0.000000e+00  0.000000e+00  0.000E
7  2  4  -85.00  -80.00  120.00  160.00  -82.10  140.00  0.000000e+00  0.000000e+00  0.000000e+00  0.000E
8  2  5  -85.00  -80.00  160.00  200.00  -82.10  180.00  0.000000e+00  0.000000e+00  0.000000e+00  0.000E
9  2  6  -85.00  -80.00  200.00  240.00  -82.10  220.00  0.000000e+00  0.000000e+00  0.000000e+00  0.000E
10 2  7  -85.00  -80.00  240.00  280.00  -82.10  260.00  0.000000e+00  0.000000e+00  0.000000e+00  0.000E
11 2  8  -85.00  -80.00  280.00  320.00  -82.10  300.00  0.000000e+00  0.000000e+00  0.000000e+00  0.000E
12 2  9  -85.00  -80.00  320.00  360.00  -82.10  340.00  0.000000e+00  0.000000e+00  0.000000e+00  0.000E
13 3  1  -80.00  -75.00  0.00  22.50  -77.26  11.25  0.000000e+00  0.000000e+00  0.000000e+00  0.000E
14 3  2  -80.00  -75.00  22.50  45.00  -77.26  33.75  0.000000e+00  0.000000e+00  0.000000e+00  0.000E
15 3  3  -80.00  -75.00  45.00  67.50  -77.26  56.25  0.000000e+00  0.000000e+00  0.000000e+00  0.000E
16 3  4  -80.00  -75.00  67.50  90.00  -77.26  78.75  0.000000e+00  0.000000e+00  0.000000e+00  0.000E
```

Figure 18. Section of an example igloo file. The header (lines 1-8) describes and provides labels for the data columns. Data begins on line 9, and the number of columns is determined by the number of speed bins. Not all rows and columns are shown.

Igloo files are an optional output. If the user chooses to output igloo files, MEM 3 runs will produce an average igloo file, `igloo_avg.txt`, which reports each flux component averaged over the spacecraft trajectory. If users also opt to generate standard deviation files, a standard deviation file named `igloo_std.txt` will also be produced. Finally, if users choose to output both igloo and intermediate files, an igloo file will be produced for each state vector used and will be named `igloo_NN.txt`, where NN is the number of the state vector in the trajectory input file.

3.4.5 Density Files

MEM 3 produces two density distribution files (`hidensity.txt` and `lodensity.txt`) for each run. The names of these files correspond to the cube and flux files in the directory of the same name. For instance, `hidensity.txt` applies to `HiDensity\flux_avg.txt`. These files provide the *fraction* of the flux in each density bin for two meteoroid populations and do not change between runs. Per population, the density is independent of the speed and directionality. Users may therefore multiply the cube or flux files by the corresponding density file to add a density dimension to their results.

4 INTERPRETING MEM RESULTS

4.1 Coordinate Frames

The user can choose to receive output in either a body-fixed or inertial coordinate frame; in this section, we describe each of these reference frames. When discussing MEM 3 output, it is important to distinguish between (a) a nearby massive body and (b) the origin of the output coordinate system. Users have the freedom to choose any major body in the inner solar system as the origin of their output coordinate system, regardless of whether it is a sensible choice. For instance, it is possible, but not recommended, to select the planet Mercury as the output coordinate origin for a spacecraft orbiting Mars.

A spacecraft's position relative to a *nearby massive body* will tend to affect the flux. For instance, spacecraft near a planet or the Moon can experience shielding effects, in which the massive body blocks a portion of the meteoroid environment. As the spacecraft changes position relative to a nearby massive body, the section of the environment that is blocked will shift, resulting in noticeable changes in meteoroid directionality and flux.

A spacecraft's position relative to the chosen *output origin* will not affect the overall flux. However, it will affect the apparent directionality of the flux—if and only if the user has opted to use a body-fixed output frame. This is because the body-fixed frame is not an inertial reference frame but is instead defined by the spacecraft's instantaneous position and velocity relative to the output origin.

4.1.1 Body-fixed Coordinate Frames

In a body-fixed reference frame, the spacecraft's velocity vector relative to the central body defines the \hat{x} direction (see fig. 19). Thus, \hat{x} points in the spacecraft's ram direction, while the wake direction corresponds to $-\hat{x}$.

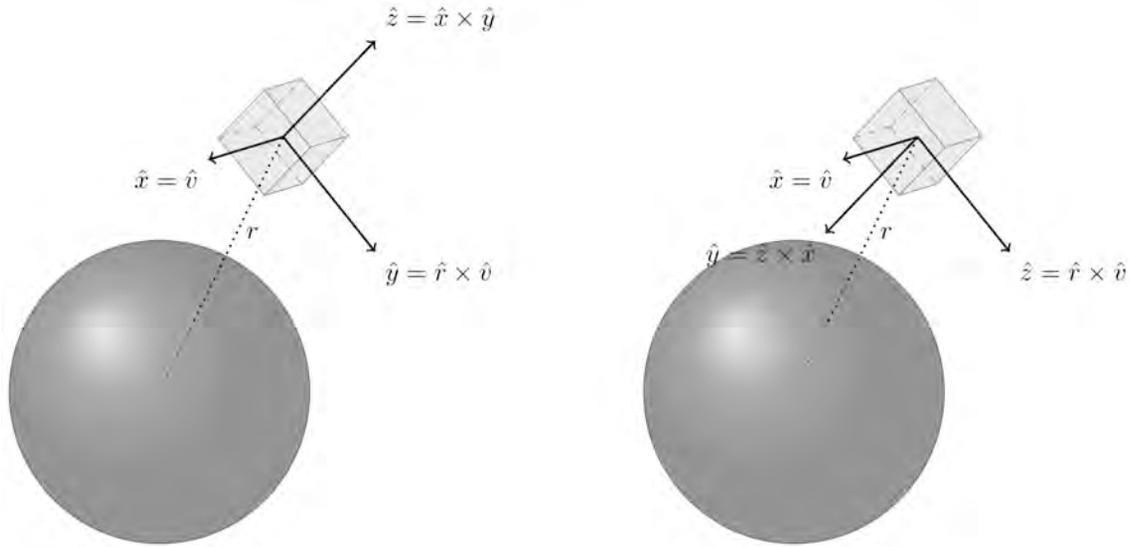


Figure 19. Illustrations of body-fixed coordinate frames in which a planet or the Moon has been chosen as the output origin (left) and in which the Sun has been chosen as the output origin (right). Note that in both cases the \hat{x} vector points in the direction of motion.

If a planet or Moon has been selected as the origin of the output coordinate frame, the spacecraft's angular momentum vector about that body defines \hat{y} ; that is, $\hat{y} = \hat{h} = \hat{r} \times \hat{x}$. The \hat{z} direction is then defined by the cross product of the \hat{x} and \hat{y} directions (see fig. 19). If the spacecraft is in a prograde orbit around the output origin, the y axis will tend to point in the direction of the output origin's north pole. For a retrograde orbit, the reverse is true. For a perfectly circular orbit, $\hat{z} = \hat{r}$.

If, instead, the Sun has been selected as the origin of the output coordinate frame, the y and z axes are defined differently. In this case, the z axis is aligned with the angular momentum vector: $\hat{z} = \hat{h} = \hat{r} \times \hat{x}$. Then, $\hat{y} = \hat{z} \times \hat{x}$ (see fig. 19). This difference in coordinate frame definition tends to align the z axis with ecliptic north when the spacecraft is near the ecliptic plane and orbiting the Sun in a prograde direction. For a perfectly circular orbit, $\hat{y} = -\hat{r}$.

Users should note that although \vec{r} and \vec{v} are perpendicular for a spacecraft on a circular orbit, this is not the case for eccentric or transfer orbits. For near-circular orbits, the main output file will show similar if not identical fluxes and speeds for certain surfaces (for example, Earth-facing and nadir surfaces).

The body-fixed frame is often the best choice for a spacecraft that orbits a planet or Moon and maintains a fixed orientation relative to its orbit. In such a case, the body being orbited should be selected as the origin of the output coordinate system.

4.1.2 Inertial Coordinate Frames

Two inertial coordinate frames are available in MEM 3: ecliptic and equatorial. The choice of origin in this case has no effect; meteoroid velocities are always reported relative to the spacecraft.

In both the ecliptic and equatorial reference frames, \hat{x} points in the direction of the vernal equinox at epoch J2000. In the ecliptic reference frame, \hat{z} points toward ecliptic north; both \hat{x} and \hat{y} are parallel to the Earth's orbital plane. See the left panel of figure 20 for an illustration.

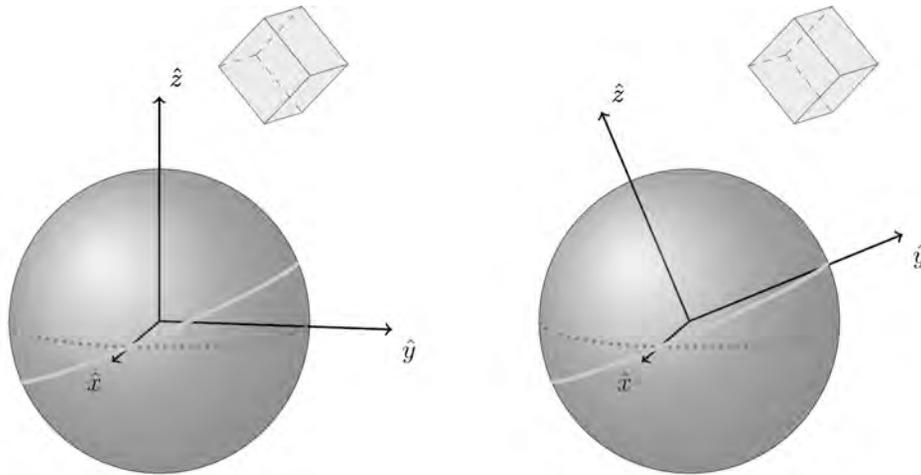


Figure 20. Illustrations of inertial coordinate frames. In the ecliptic frame (left), the x - y plane is parallel to the ecliptic (dotted gray arc). In the equatorial frame (right), the x - y plane is parallel to the Earth's equator (light gray arc). Note that in both cases the x vector points in the direction of the vernal equinox.

In the equatorial reference frame, \hat{z} points toward celestial north and is aligned with the Earth's rotational axis. The \hat{x} and \hat{y} vectors are parallel to the Earth's equatorial plane. See the right panel of figure 4.2 for an illustration.

An inertial output coordinate frame may be more useful for a spacecraft that changes its orientation relative to its direction of motion.

4.1.3 Azimuth and Elevation

The flux and igloo output files divide the meteoroid flux into directional bins; each bin spans a range in azimuth (θ) and elevation (ϕ). These angles, ϕ and θ , are defined relative to the chosen output reference frame. The azimuth, θ , measures position within the $x - y$ plane, where $\theta = 0^\circ$ along the $+x$ axis and $\theta = 90^\circ$ along the $+y$ axis. The elevation angle, ϕ , measures displacement from the $x - y$ plane: $\phi = 90^\circ$ along the $+z$ axis, $\phi = 0^\circ$ in the $x - y$ plane, and $\phi = -90^\circ$ along the $-z$ axis. For the user's reference,

table 5 gives the azimuth and elevation angles for the normal vectors of the cube faces reported for a body-fixed frame.

Table 5. Azimuth and elevation angles corresponding to the normal vector of each “cube” face reported for a body-fixed frame.

		θ	ϕ
ram	$\hat{v}, +\hat{x}$	0°	0°
wake	$-\hat{x}$	180°	0°
port	$+\hat{y}$	90°	0°
starboard	$-\hat{y}$	270°	0°
zenith or “north”	$+\hat{z}$	any	+90°
nadir or “south”	$-\hat{z}$	any	-90°

4.2 Flux Reporting

MEM 3 reports the meteoroid flux to several levels of fidelity; this section discusses the types of meteoroid flux reported, so the user can better determine which suits their needs.

4.2.1 Total Cross-sectional Flux

The lowest-fidelity flux describing the environment is the “total cross-sectional flux” reported in the cube files. This quantity is simply the sum of the meteoroid flux over all directions and speeds. It is equivalent to the total flux incident on a spherical spacecraft and is expressed per square meter of cross-section.

To obtain the flux on one side of a randomly tumbling plate, you can divide the total cross-sectional flux by four. This factor of four arises from the ratio of the cross-sectional area to surface area of a plate (which is unity) relative to that of a sphere (which is 1/4). *This applies if and only if your spacecraft is randomly tumbling.* If your spacecraft’s orientation is known, please use the cube fluxes or calculate their equivalent from the flux or igloo files.

4.2.2 Cube Fluxes

The cube files also report the meteoroid flux incident on the sides of a cubic spacecraft. In a body-fixed frame, these normal vectors are aligned with the ram, wake, port, starboard, zenith, and nadir directions (see sec. 4.1.1). In an inertial reference frame, they are aligned with the axes of the coordinate system. In general, the sum of these “cube fluxes” does not and should not equal the “cross-sectional flux” (sec. 4.2.1). While a sphere presents the same cross-sectional area in all directions, the apparent cross-sectional area of a cube varies with viewing angle (see fig. 21).

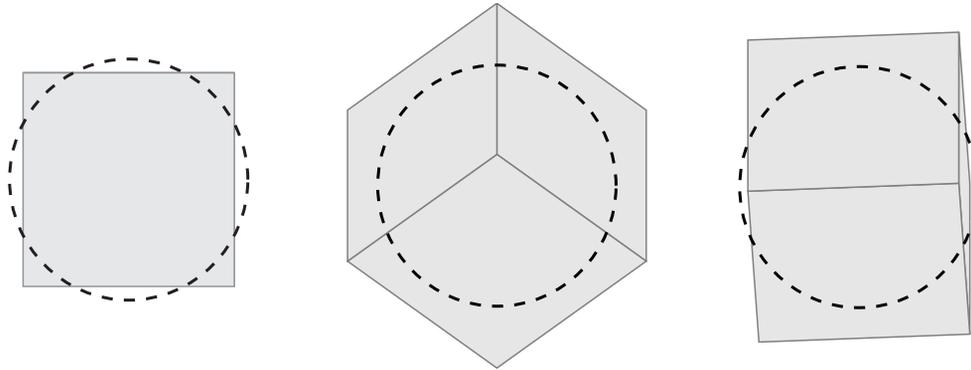


Figure 21. A cube with unit side length viewed from three different directions, demonstrating how cross-section varies with viewing angle. For the sake of comparison, the outline of a sphere of unit cross-sectional area is overlaid as a dashed black line.

In addition to the above surfaces, MEM 3 also calculates the flux on surfaces facing the Earth, facing the Sun, and facing away from the Sun. Communications equipment and solar panels may have surfaces with these alignments. For each surface, MEM 3 reports not only the total flux (denoted “total flux”) but also the flux per speed interval, where the size of these intervals is determined by the user’s resolution choice.

Note that these “cube” fluxes are mass-limited, not damage-limited. While they are useful as a “quick look” at the environment, they are not useful for a full risk analysis.

4.2.3 Flux on Rotating Surfaces

If a spacecraft rotates as it moves along its trajectory, the cube surfaces discussed in section 4.2.2 may not be meaningful. Thus, MEM 3 also reports the flux on surfaces that are rotating about each axis of the output coordinate system; these fluxes are given in the last three columns of the cube files.

We caution the user that the flux on the rotating surface is not equivalent to the flux on four sides of a non-rotating cube. In the case of rotation about the z -axis, for example, we report the incident flux per square meter of azimuthally-averaged cross-section. For a unit meter cube, this azimuthally-averaged cross-section is $4/\pi \text{ m}^2$ or roughly 1.273 m^2 . More generally, the azimuthally-averaged cross-section of a non-concave generalized cylinder is $sl/2\pi$, where s is circumference and l is length. Although performing this conversion may seem inconvenient, it is the cross-sectional area that determines how many meteoroids impact the spacecraft, while the ratio of the circumference to cross-section depends on spacecraft shape.

As far as MEM 3 is concerned, these rotation modes are the equivalent of the spacecraft randomly changing its orientation about the rotation axis. There is no option to specify the rotation rate; the speed of spacecraft surfaces due to rotation is assumed to be negligible compared to the spacecraft’s speed relative to the central body (planet, Moon, or Sun.) If the orientation of the spacecraft at each point in time is known, the user can perform post-processing to extract more precise fluxes.

4.2.4 Igloo and Flux Files

For more detailed directional information, users can refer to the igloo and flux files (described in sec. 3.4); both report the flux per speed interval and per solid angle interval. The flux files divide the flux into a regular grid in azimuth and elevation and the angular size of the bins is proportional to $\cos\phi$. The igloo files, in contrast, divide the flux into azimuth and elevation bins that are approximately equal in angular size (see fig. 17).

The flux files, with their constant number of azimuthal bins, are typically easier to use when generating visualizations. For instance, the data can be read in, summed across the velocity columns, and then reshaped into a two-dimensional grid for plotting. However, it is important to remember that the bin size is smaller near the poles and that a correction of $1/\cos\phi$ must be applied to obtain the flux per square degree (see fig. 22).

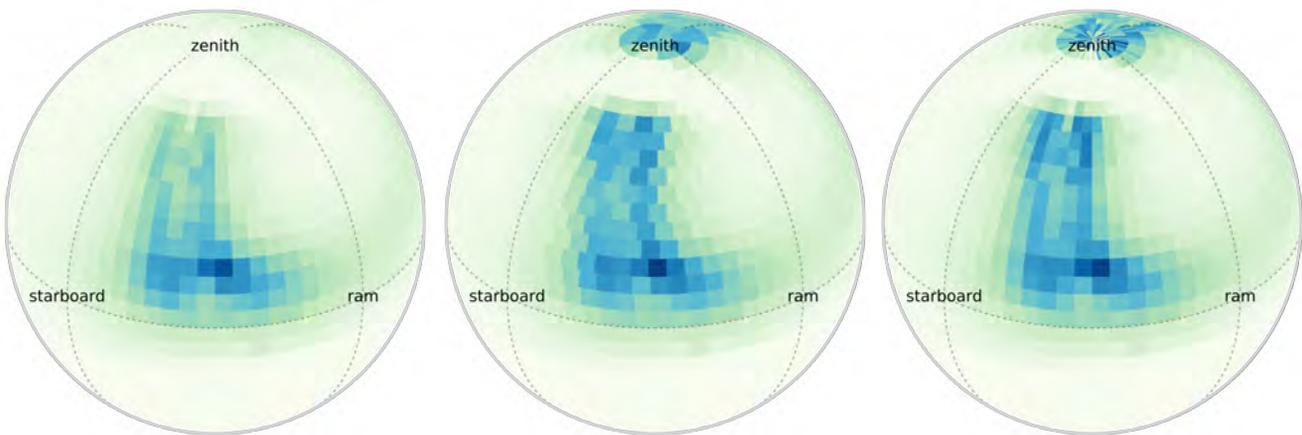


Figure 22. Meteoroid directionality relative to a single state vector for a spacecraft in low Earth orbit, plotted as a heat map on an orthographic projection. In this particular case, there is a significant flux component coming from the zenith direction. If we use the flux file to create a heat map of the flux, the small bins near the poles tend to visually suppress the flux (left). If we apply a crude correction of $1/\cos\phi$, the magnitude of the flux near the poles is closer to reality, albeit noisy (middle). The igloo file, with its quasi-equal-area bins, requires no such correction (right).

The igloo files, with their quasi-equal-area bins, are difficult to render into plots (although this is not impossible; see fig. 22). However, the smaller number of bins in the igloo files tends to conserve disk space—the igloo files are about 36% smaller than the flux files for any given choice of angular resolution. As a result, users will also find the igloo files to be faster than the flux files to process for any ballistic limit calculations.

4.2.5 Instantaneous Environment Information

For those users requiring high fidelity in speed, direction, and time, MEM 3 offers the option of creating a set of output files corresponding to each state vector in the input trajectory file. If desired, the user can convolve each environment with the spacecraft's geometry, taking its attitude into account. Alternatively, the user can feed these environments, along with spacecraft shape and orientation information, into a risk assessment tool such as BUMPER.⁴

4.3 Density Distributions

As modeled by MEM 3, all meteoroids belong to either a high-density population or a low-density population. Within each population, the mass, speed, and angular distributions are independent of density. Thus, density is *not* included as a fourth dimension in the flux files; instead, the density distribution is provided separately in two files named `hidensity.txt` and `lodensity.txt`.

The third row of each density file does not contain a flux value; instead, it reports the *fraction* of the flux contained in the given bin. Thus, any flux component in the cube, flux, or igloo files can be multiplied by the density fraction to obtain the flux value in that density, velocity, and directional bin.

The density files have a fairly fine resolution and users may therefore wish to reduce the number of bins. One approach is to use only those bins that contain at least a certain fraction of the total (selection of this threshold is up to the user). If users prefer to take a Monte-Carlo approach, they can draw densities from log-normal distributions, where the probability P of drawing a particular density value is:

$$P(\log_{10} \rho) = \frac{1}{\sqrt{2\pi\sigma^2}} e^{-(\log_{10} \rho - \mu)^2 / 2\sigma^2} \quad (3)$$

where ρ is density. For the low-density population, $\mu = 2.933$ and $\sigma = 0.127$; for the high-density population, $\mu = 3.579$ and $\sigma = 0.093$.

4.3.1 Mass Scaling and Risk Assessment

MEM 3 reports meteoroid flux to a constant limiting mass, chosen by the user. This means that the reported fluxes include particles of the specified size and larger. MEM 3 uses the Grün et al. mass scaling relation [2]; this relation can also be used to rescale the results of a MEM run to a different limiting mass (see sec. 2.1).

Most impact effects are not mass-limited. Instead, the limiting quantity may be penetration depth, kinetic energy, charge produced, or angular momentum imparted. In order to compute an impact-effect-limited flux, one must first determine the equation that governs the limiting effect and then invert this equation to obtain the limiting mass as a function of speed, impact angle, and meteoroid density. Let us refer to this mass as $m_{\text{effect}}(\phi, \theta, v, \rho)$. Then, the effect-limited-flux is given by:

$$\text{flux}_{\text{effect}} = \sum_{i,j,k,n} \text{flux}_{i,j,k} \times \text{fraction}_n \times \frac{g(m_{\text{effect}}(\phi_i, \theta_j, v_k, \rho_n))}{g(m_{\text{run}})} \quad (4)$$

⁴<http://www.nasa.gov/centers/johnson/techtransfer/technology/MS-C-23774-1-bumper.html>

where i is used to number the elevation bins, j is used to number the azimuthal bins, k is used to number the velocity bins, and n is used to number the density bins. Thus, $\text{flux}_{i,j,k}$ is the flux in a particular angle and velocity bin in a flux or igloo file and ϕ_i , θ_j , and v_k are the elevation, azimuth, and velocity corresponding to that bin. Similarly, fraction_n is the fraction of the flux in a given density bin, where ρ_n is the corresponding density. The function g refers to the Grün flux; see equation 1 of this document.

Determination of the correct equation for m_{effect} is the responsibility of the user. Note also that the above equation does not take shadowing effects into account; if the spacecraft has any concavities, one part of the spacecraft's surface can shield other parts from a portion of the environment. For assistance with either 3D spacecraft modeling or impact effects, please contact the Hypervelocity Impact Technology⁵ team at Johnson Space Center.

⁵ <https://hvit.jsc.nasa.gov/risk-assessment/>

APPENDIX A—TROUBLESHOOTING

This section gives a few brief troubleshooting tips. MEM 3 addresses most of the common problems users encountered with MEMR2, but users may still encounter problems or require help. When this occurs, please try the following:

- After installing MEM, first try a run with the example file (`ISSEexample.txt`) as your trajectory file.
- If you are running MEM on Windows, we recommend using the GUI rather than the command-line executable at first. The GUI provides more immediate feedback on your run choices and input file and thus can help uncover problems sooner.
- If you receive a security warning stating that “we can’t verify who created this file,” try clicking “Run” in the security warning box, or, alternatively, running MEM as administrator.
- Before executing any lengthy run, first try a short run using the “first few” or “random selection” option to analyze, say, 5-10 state vectors. If the run completes successfully and produces the desired outputs, then proceed to running the full trajectory.
- If you run into file permission errors, try moving the code directory to an alternate location, such as the Desktop.
- The code comes with an example trajectory file (`ISSEexample.txt`) and an example options file (`options.txt`). However, please note that the MEM GUI will overwrite the options file. Options files written by the MEM GUI will contain a short comment specifying which version of the GUI wrote the file.
- If you need assistance, you can contact the MEM developer.⁶ If you are writing to ask for help with a particular run, please include a copy of the options file and log file in your email. If possible, consider also including a copy of your trajectory file.

⁶ althea.moorhead@nasa.gov

APPENDIX B—GENERATING INPUT FILES WITH STK

MEM users may use TLEs to describe a spacecraft's trajectory. In some cases, however, TLEs are only available at times corresponding to a single point in an orbit and thus do not adequately cover the spacecraft's trajectory. To avoid this problem, the user can convert TLEs to state vectors. As an example, we describe the process for loading TLEs into STK (release 10):

1. Create a new scenario; STK offers this option on startup by default. The "Insert STK Objects" dialog should appear.
2. Choose "Satellite" and "From TLE File."
3. Select the TLE file and click "Insert." The satellite should appear in the scenario.
4. Adjust the time span of the scenario to the desired interval, such as one orbital period.

To generate state vectors for this or any other user-defined trajectory:

1. Click on the "Report & Graph Manager" button.
2. On the right, click the "New Report Style" button, enter a name such as "MEM Input Format," and hit return.
 - (a) In the panel at left, scroll down to "Cartesian Position" and click to expand.
 - (b) Click to expand "J2000."
 - (c) Select "Time," "x," "y," and "z" and click the arrow icon to add these fields to your report style.
 - (d) Click to expand "Cartesian Velocity."
 - (e) Click to expand "J2000."
 - (f) Add "x," "y," and "z."
 - (g) Click on "Time" in your report style, then "Units ..."
 - (h) Uncheck "Use Defaults."
 - (i) Choose "Julian Date (JDate)" from the menu on the right. Click "OK."

- (j) Click “OK” again to close the report style. You can save this report style for future use and thus skip step 2 from now on.
3. Select your style, the “Report/Graph” option, and click “Generate.” The resulting text should have a 6-line header followed by time, position, and velocity values. This report should be formatted for MEM input.
4. Click the save icon in the report window to “Save as text.” This will be your MEM input file.

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