

NASA/TM—2015–218214



NASA Meteoroid Engineering Model Release 2.0

*A.V. Moorhead, H.M. Koehler, and W.J. Cooke
Marshall Space Flight Center, Huntsville, Alabama*

October 2015

The NASA STI Program...in Profile

Since its founding, NASA has been dedicated to the advancement of aeronautics and space science. The NASA Scientific and Technical Information (STI) Program Office plays a key part in helping NASA maintain this important role.

The NASA STI Program Office is operated by Langley Research Center, the lead center for NASA's scientific and technical information. The NASA STI Program Office provides access to the NASA STI Database, the largest collection of aeronautical and space science STI in the world. The Program Office is also NASA's institutional mechanism for disseminating the results of its research and development activities. These results are published by NASA in the NASA STI Report Series, which includes the following report types:

- **TECHNICAL PUBLICATION.** Reports of completed research or a major significant phase of research that present the results of NASA programs and include extensive data or theoretical analysis. Includes compilations of significant scientific and technical data and information deemed to be of continuing reference value. NASA's counterpart of peer-reviewed formal professional papers but has less stringent limitations on manuscript length and extent of graphic presentations.
- **TECHNICAL MEMORANDUM.** Scientific and technical findings that are preliminary or of specialized interest, e.g., quick release reports, working papers, and bibliographies that contain minimal annotation. Does not contain extensive analysis.
- **CONTRACTOR REPORT.** Scientific and technical findings by NASA-sponsored contractors and grantees.
- **CONFERENCE PUBLICATION.** Collected papers from scientific and technical conferences, symposia, seminars, or other meetings sponsored or cosponsored by NASA.
- **SPECIAL PUBLICATION.** Scientific, technical, or historical information from NASA programs, projects, and mission, often concerned with subjects having substantial public interest.
- **TECHNICAL TRANSLATION.** English-language translations of foreign scientific and technical material pertinent to NASA's mission.

Specialized services that complement the STI Program Office's diverse offerings include creating custom thesauri, building customized databases, organizing and publishing research results...even providing videos.

For more information about the NASA STI Program Office, see the following:

- Access the NASA STI program home page at <<http://www.sti.nasa.gov>>
- E-mail your question via the Internet to <help@sti.nasa.gov>
- Phone the NASA STI Help Desk at 757-864-9658
- Write to:
NASA STI Information Desk
Mail Stop 148
NASA Langley Research Center
Hampton, VA 23681-2199, USA

NASA/TM—2015–218214



NASA Meteoroid Engineering Model Release 2.0

*A.V. Moorhead, H.M. Koehler, and W.J. Cooke
Marshall Space Flight Center, Huntsville, Alabama*

National Aeronautics and
Space Administration

Marshall Space Flight Center • Huntsville, Alabama 35812

October 2015

Acknowledgments

A.V. Moorhead and W.J. Cooke are indebted to H.M. Koehler, whose years of work developing and documenting the Meteoroid Engineering Model made this document possible.

Available from:

NASA STI Information Desk
Mail Stop 148
NASA Langley Research Center
Hampton, VA 23681-2199, USA
757-864-9658

This report is also available in electronic form at
<<http://www.sti.nasa.gov>>

TABLE OF CONTENTS

1. INTRODUCTION	1
1.1 History	1
1.2 Model Requirements	2
1.3 Model Limitations	3
1.4 Version History	4
2. THE MEM ENVIRONMENT MODEL	7
2.1 Flux	7
2.2 Directionality	8
2.3 Velocity Distribution	10
2.4 Density	10
3. SOFTWARE DESCRIPTION AND USER INSTRUCTIONS	12
3.1 Software Installation and Removal	12
3.2 Program Execution	13
3.3 Input Files	23
3.4 Output Files	26
4. INTERPRETING MEMR2 OUTPUTS	34
4.1 Viewing Results and Making Plots	34
4.2 Coordinate Frames	35
4.3 Flux Reporting	37
APPENDIX A—FAQ AND TROUBLESHOOTING	41
APPENDIX B—GENERATING INPUT FILES WITH SYSTEMS TOOL KIT	43
REFERENCES	44

LIST OF FIGURES

1.	Interplanetary meteoroid flux as a function of limiting particle mass	7
2.	Interplanetary meteoroid directionality as calculated by MEMR2 for (a) a 1-au orbit and (b) as observed by CMOR. Meteor radiants are shown in Sun-centered ecliptic coordinates, in which the center of the plot is aligned with the Earth's direction of motion. Southern radiants are not visible from CMOR's location	9
3.	The meteoroid velocity distribution at the top of the atmosphere (100 km altitude). The distribution as observed by CMOR (blue dots) and as modeled using MEM release 1.0c (red) is taken from figure 7.1-2 of Squire et al. The velocity distribution modeled using MEMR2 is overlaid in black	10
4.	The meteoroid density distribution observed by ALTAIR using (a) ultra-high frequency and (b) very high frequency modes. Originals from Suggs et al.	11
5.	MEMR2 program flow. Software initialization is shown in red, GUI interactions appear in yellow, internal calculations are shown in green, and output is shown in blue	14
6.	MEMR2 main user interface. The software requires the user to select a submodel before proceeding	17
7.	User interface for Earth-orbiting spacecraft	18
8.	User interface for lunar-orbiting spacecraft	19
9.	User interface for interplanetary spacecraft	20
10.	Example Cartesian state vector input file generated with STK. This file describes part of ISS trajectory and is therefore in ECI coordinates	24
11.	Example TLE input file	25
12.	Example main output file. The header (lines 1–11) lists the user's input file and parameter choices as well as the software version. The chosen output coordinate system (in this case, body-fixed) is apparent from the surfaces listed in line 18	27
13.	Example main output file. In this case, the chosen output coordinate system is ECI, and this choice is reflected in the surfaces listed in line 18	28

LIST OF FIGURES (Continued)

14.	Example main output file. In this case, the chosen output coordinate system is ECI, and the spacecraft is rotating about its angular momentum vector. Both of these choices are reflected in the surfaces listed in line 18	29
15.	Example average main output file ('AvgResults.out'). Note the similarity to figure 12 and the absence of state vector information. The last line of data in this example file is line 32	30
16.	Example standard deviation main output file ('StdDevResults.out'). The format is identical to that of the average results file ('AvgResults.out'; see fig. 15), but standard deviations are reported rather than averages. The last line of data in this example file is line 32	30
17.	Examples of (a) quasi-equal area threat igloo and (b) azimuth and elevation grid. These examples are for 5° angular resolution	31
18.	Example speed distribution plot generated within the MEMR2 main user interface after completion of a run	34
19.	Illustrations of (a) body-fixed and (b) inertial coordinate frames for the Earth and lunar submodels. The sphere in each diagram represents the central body (Earth or Moon), while the spacecraft is represented by a cube. For a prograde orbit, the y -axis will tend to point in the direction of the central body's north pole. For a retrograde orbit, the reverse is true, as shown in this diagram. For a perfectly circular orbit, $\hat{z} = \hat{r}$	35
20.	Illustrations of (a) body-fixed and (b) inertial coordinate frames for the interplanetary submodel. The sphere in each diagram represents the Sun, while the spacecraft is represented by a cube. For a prograde orbit, the z -axis will tend to point towards ecliptic north. For a retrograde orbit, the reverse is true, as shown in this diagram. For a perfectly circular orbit, $\hat{y} = -\hat{r}$	36
21.	A cube with unit side length viewed from three different directions: (a) face-on, (b) vertex-on, and (c) nearly edge-on, demonstrating how a 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	38

LIST OF TABLES

1.	Typical MEM output file sizes for each choice of resolution. The size of the main results file will vary depending on the number of state vectors used; more state vectors or a larger random draw will increase the file size	15
2.	Files located in the working directory upon installation and after a typical MEM run	16
3.	Cartesian state vector input file format. The required units are days for Julian dates, km for positional data, and km/s for velocity data	24
4.	Azimuth and elevation angles corresponding to the six cube faces reported for a body-fixed frame. Note that $\hat{h} = \hat{y}$ for the Earth and lunar submodels, while $\hat{h} = \hat{z}$ for the interplanetary submodel	37

LIST OF ACRONYMS

CMOR	Canadian Meteor Orbit Radar
ECI	Earth-centered inertial
GUI	graphical user interface
ISS	International Space Station
LEO	low-Earth orbit
MCI	Moon-centered inertial
MEM	Meteoroid Engineering Model
MEMR2	Meteoroid Engineering Model release 2.0
MEO	Meteoroid Environment Office
STK	Systems Tool Kit
TEME	true equator, mean equinox of epoch
TLE	two-line element
TM	Technical Memorandum

NOMENCLATURE

h	height
\hat{h}	angular momentum unit vector
i	state vector number; ring index
j	block index
r	radial distance
\hat{r}	position unit vector
s	circumference
\hat{v}	velocity unit vector
x	ordinate of a coordinate system
\hat{x}	ordinate unit vector
y	abscissa of a coordinate system
\hat{y}	abscissa unit vector
z	applicate of a coordinate system
\hat{z}	applicate unit vector
θ	azimuth
ϕ	elevation angle

TECHNICAL MEMORANDUM

NASA METEOROID ENGINEERING MODEL RELEASE 2.0

1. INTRODUCTION

The Meteoroid Engineering Model release 2.0 (MEMR2) software is NASA's most current and accurate model of the meteoroid environment. MEMR2 supersedes all previous versions of Meteoroid Engineering Model (MEM), including MEM release 1.0c 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 model¹ and its derivative, Space Station Specification SSP 30425.^{2,3} MEMR2 has been integrated into the Cross Program Design Specification for Natural Environments (SLS-SPEC-159, Revision B) and is being used to assess meteoroid impact risk by a number of NASA programs, including Commercial Crew (R. Suggs, Personal Communication, 2015).

MEMR2 offers several improvements over previous releases, one of which is an integrated user interface for spacecraft in orbit around the Earth, Moon, and Sun. Certain functionality found only in the former Constellation versions, MEMCxP and LunarMEM, has been incorporated into each of the three submodels packaged in MEM. MEMR2 does not include the penetrating flux calculation capability found in EarthMEM v2.1 and IPMEM v2.1. Because there are numerous situations where this information could be misused and misinterpreted, the development team decided to remove this capability at this time in favor of only providing engineering environment descriptions. The graphical user interface (GUI) has been updated to include a new output coordinate frame selection, a new output plotting capability, and three output file resolution choices.

MEMR2 also incorporates a refinement of the near-Earth meteoroid environment in the form of an updated particle speed distribution that better matches ground-based meteor radar observations. Previous releases of the model produced speed distributions that underrepresented particles faster than 40 km/s relative to radar observations. The speed distribution bins are also now uniform in width, having user-selected widths of 2, 4, and 5 km/s.

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 Grün et al.,¹ as described in Boeder et al.² and later in Smith³ (hereafter referred to as Technical Memorandum (TM) 4527). This expression described the meteoroid flux incident on a flat plate near 1 au. Technical Memorandum 4527 assumed 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. Technical Memorandum 4527 also introduced a crude, piecewise meteoroid speed distribution with an average velocity of 19 km/s for an orbiting spacecraft (based on Kessler⁵). Finally, TM 4527 assumed a three-step density distribution in which dust particles smaller than 10^{-6} g have a density of 2 g/cm^3 , micro-meteoroids between 10^{-6} g and 0.01 g have a density of 1 g/cm^3 , and meteoroids larger than 0.01 g have a density of 0.5 g/cm^3 . 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 SSP 30425.²

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 (LEO). 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 described in detail in section 2.

The MEO was established under the Office of Safety and Mission Assurance 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. In order to accomplish this task, the MEO funds and conducts research in various areas of meteor science in order 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 Observations, findings, and recommendations from 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.

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. In order 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 the spacecraft.

The risk of spacecraft penetration is higher when the number of incident particles is larger, making meteoroid flux one of the key outputs of MEM. 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, which take all of these properties as inputs (see Christiansen and Kerr⁸ for examples). 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 centimeters or millimeters. 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).

1.3 Model Limitations

Engineering environment models support programs and projects in the design phase of the spacecraft lifecycle. They are not meant to predict either the short-term perturbations that may occur during a specific year or month of a mission nor 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.

Although MEM models the dynamics of only sporadic meteors, meteor showers contribute $\approx 10\%$ of the total flux in the threat regime.^{9,10} MEM reports the total flux contributed by all meteors, including shower meteors, even though the short-term variations in the flux caused by these showers is not captured. The MEO models meteor showers, storms, and outbursts separately; while these models are not publicly available, the MEO does provide annual shower forecasts to programs and projects on request.

MEM also restricts its environment description to particle sizes that are considered to be potentially ‘damaging.’ Space shuttle radiators, for instance, were sensitive to impacts from debris particles as small as $100\ \mu\text{m}$ in diameter.¹¹ MEM takes these findings into account by modeling meteoroids as small as $10^{-6}\ \text{g}$, which corresponds to $124\ \mu\text{m}$ in diameter for a density of $1\ \text{g/cm}^3$. 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 should not be used to assess meteoroid impact risk outside this region. Gravitational focusing and shielding effects are computed only for the Earth and the Moon; no other planetary submodels are available at the time of writing.

1.4 Version History

The following is a history of MEM and details of its various versions from 2004 to 2015:

- MEM version 1.0, May 2004—The first version released was valid only for interplanetary spacecraft. The GUI was very simple and required only an input file of state vectors and an output file name. The model produced two output files. One output file described average fluxes and speeds for the surfaces of a basic cube-shaped spacecraft. The other output provided a composite non-normalized 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 submodels. 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 describes 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*i*.out output file. The word ‘normalized’ was removed from the velocity 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 January 14, 2008, indicating that the Sun-oriented surface average speed in the summary table of EarthMEM was incorrectly calculated. Users were instructed to use the distribution to find the average speed. The anti-sunward surface average speed in the summary table of IPMEM was also incorrectly calculated; users were again instructed to use the distribution to find the average speed.
- MEM release 1.0c, January 2008—Both IPMEM and EarthMEM were updated to fix the Sun-oriented and anti-Sun surface average speed calculation in the summary table of the main results file. This repaired the problem discussed in the special note sent to users about MEM release 1.0b and removed the need for a user workaround. Additionally, the ‘About’ dialogs in the GUIs and the help files were updated to display the correct version numbering.
- 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 reported 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 available in this version.
- MEMCxP v2.0, January 2008—As stated above, 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 with 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 available.
- LunarMEM v2.0, January 2008—As stated above, LunarMEM was a special version released to the Constellation Program and its support contractors. Version 2.0 fixed a bug in the averaging of distributions in the main output file.

- MEMR2.0, October 2013—MEMR2 packaged three submodels: EarthMEM, IPMEM, and LunarMEM. This release repackaged and updated the individual submodels 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 matched radar meteor observations. 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 submodel.
- MEMR2.0.2, March 2014—This point release introduced two additional improvements. First, it ensured that the main results file is overwritten for each new run, even if the user does not change the file name. This made it less likely that the user obtained 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 submodel choice after clicking the lunar submodel option.
- MEMR2.0.4, September 2014—This point release fixed two additional user-reported bugs. First, it fixed a bug in which the software quits without completing postprocessing when the random draw feature was used in conjunction with the interplanetary submodel. Second, it fixed a bug in which MEM processed only the first 48 two-line elements (TLEs) provided by the user.
- MEMR2.0.5, July 2015—This point release corrects the calculation of the meteoroid flux onto rotating surfaces. Prior versions simply reported the average of the flux on four sides of the stationary cube, which can over- or underreport portions of the meteoroid environment by up to 30%. MEMR2 now reports the flux on the rotating surface correctly (see sec. 4.3.3 for details). MEMR2.0.5 also corrects a minor bug in which the rotation mode was marked incorrectly in the output file headers, and improves the text alignment in the output files as well. The improved random number generation algorithm introduced in MEMR2 for state vector selection was applied throughout the code; users may see differences in the output values of $\approx 1\%$. Finally, all calculations now make use of double floating point precision.

2. THE MEM ENVIRONMENT MODEL

This section describes MEM's underlying environment model and its validation. As its name describes, MEM is an engineering model to be used in characterizing meteoroid particles considered a threat to manned and unmanned NASA spacecraft. The threat regime consists of 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. Thus, observations or measurements of particles outside this mass range pose little risk and are not used as validation datasets.

NASA programs and projects must consider the meteoroid environment when designing spacecraft. Risk assessments require environmental parameters such as 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 the flux, velocity, density, and directionality of MEMR2 output as compared to observations.

2.1 Flux

MEM fluxes are calibrated to the Grün interplanetary flux. For example, the cross-sectional flux of meteoroids 10^{-6} g and larger computed by MEMR2 for a circular, ecliptic orbit at 1 au is $5.71 \text{ m}^{-2} \text{ yr}^{-1}$. For comparison, the Grün flux, computed using the formula of TM 4527, is $5.95 \text{ m}^{-2} \text{ yr}^{-1}$. MEMR2 calculates flux as a function of mass using equation (7-4) of TM 4527. This mass dependence is depicted in figure 1.

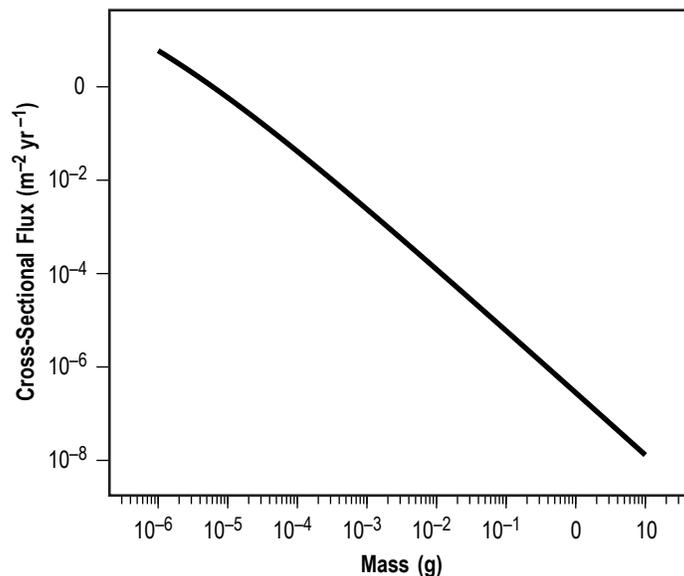


Figure 1. Interplanetary meteoroid flux as a function of limiting particle mass.

2.2 Directionality

The directionality of the sporadic environment has been known to be anisotropic for some time. Mid-twentieth century meteor radar surveys revealed concentrations of sporadic meteor radiants within the ecliptic plane.^{12,13} 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).¹⁴ The final two radiant concentrations are the north and south toroidal sources, which lie 60° north and south of the apex direction.¹⁵ 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.

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, for instance, could be substantially underestimated. Risk assessments therefore require a directional meteoroid model.

Early directional models were constructed in an empirical manner (e.g., Divine¹⁶); one major limitation to this approach is that most meteoroid surveys are Earth-based. Meteoroid data outside of near-Earth space is severely limited in comparison; impact detectors record comparatively few impacts and do not measure meteoroid directionality, while zodiacal light measurements probe a two-dimensional projection of a population of meteoroids that lie below the threat regime.

In contrast, the meteoroid model of Jones¹⁰ 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. Radiation pressure, Poynting-Robertson drag, and collisions affect the characteristics of this population and all are 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 on Earth by meteor radar surveys.

The Jones model¹⁰ forms the core of MEM. The sporadic directionality as modeled by MEMR2 reproduces the directionality observed by both historical meteor surveys and more recent surveys conducted by the Canadian Meteor Orbit Radar (CMOR) (fig. 2).

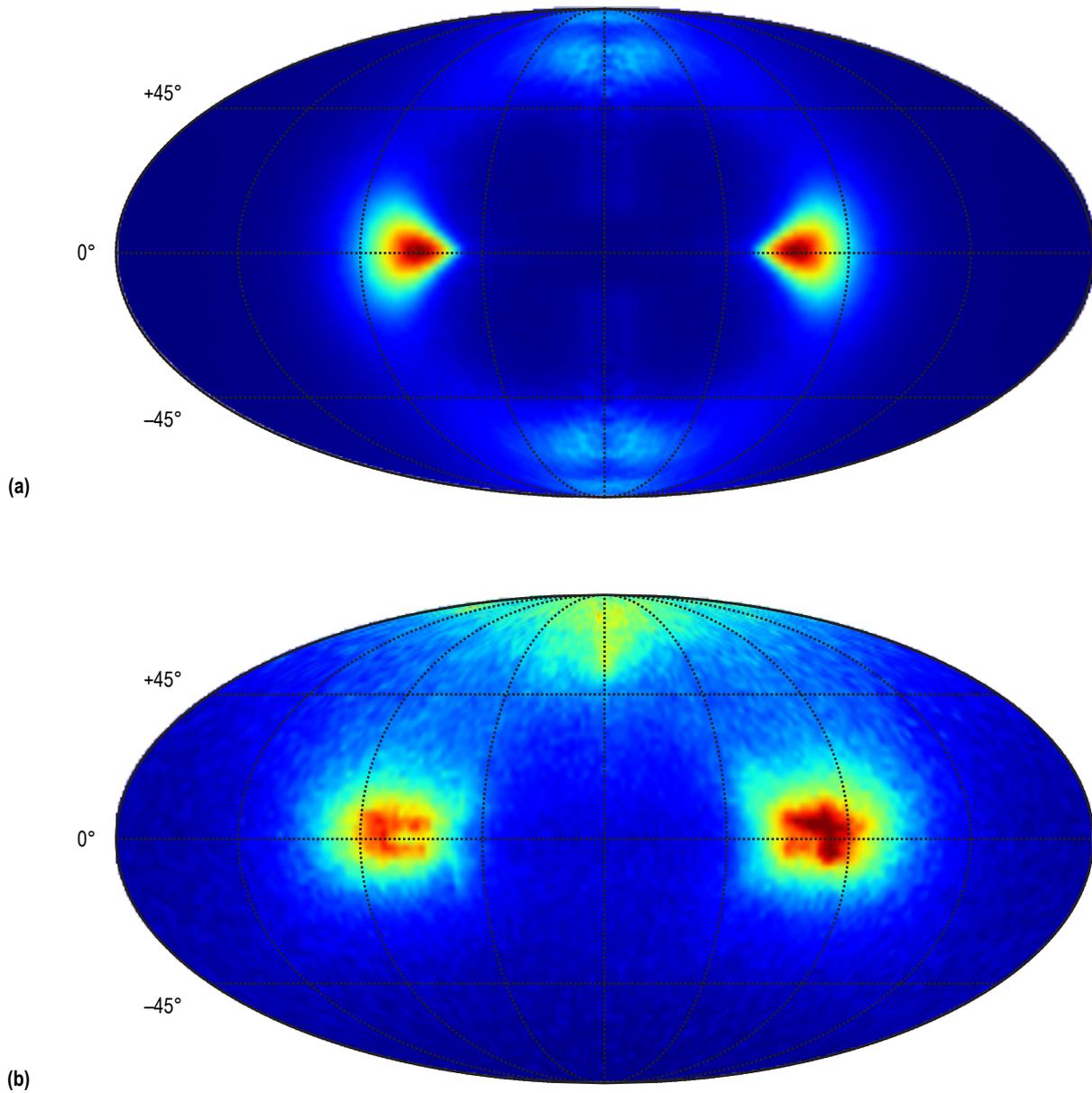


Figure 2. Interplanetary meteoroid directionality as calculated by MEMR2 for (a) a 1-au orbit and (b) as observed by CMOR. Meteor radiants are shown in Sun-centered ecliptic coordinates, in which the center of the plot is aligned with the Earth's direction of motion. Southern radiants are not visible from CMOR's location.

2.3 Velocity Distribution

The meteoroid environment has a distribution of speeds rather than a single representative velocity. Earlier versions of MEM produced a velocity distribution that resembled the observed distribution, albeit with an apparent underrepresentation of high-speed meteoroids (see fig. 3). Following a recommendation from Squire et al.,¹⁷ the Earth submodel of MEMR2 was adjusted to increase the proportion of high-speed meteoroids.

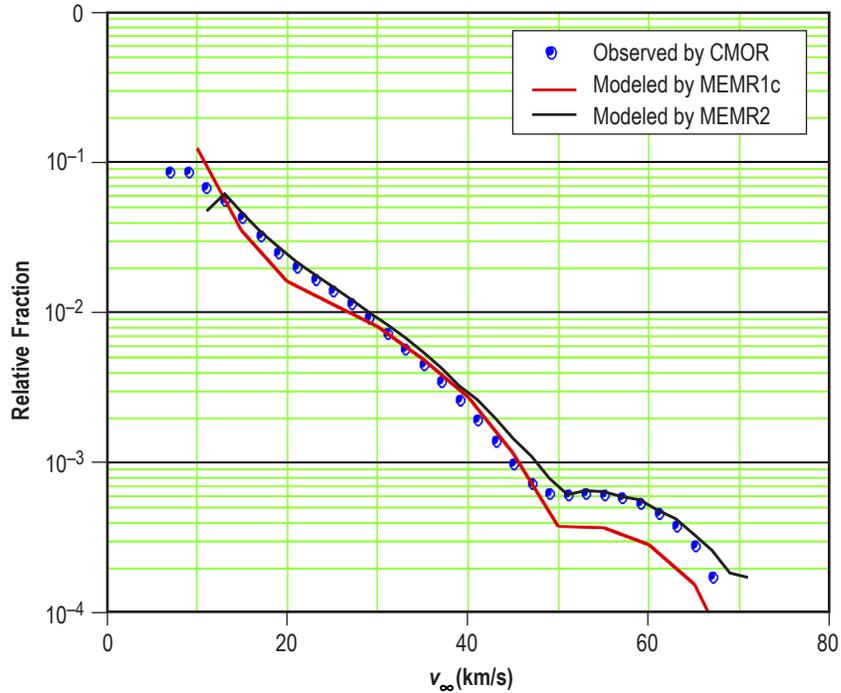


Figure 3. The meteoroid velocity distribution at the top of the atmosphere (100 km altitude). The distribution as observed by CMOR (blue dots) and as modeled using MEM release 1.0c (red) is taken from figure 7.1-2 of Squire et al.¹⁷ The velocity distribution modeled using MEMR2 is overlaid in black.

2.4 Density

Greater than 90% of sporadic meteoroids are cometary in origin. They are porous conglomerates of ice and dust with a mean bulk density close to that of water. Suggs et al.¹⁸ compiled a database of over 1,000 meteoroid densities derived from ALTAIR radar measurements of meteor atmospheric decelerations; the distribution is presented in figure 4.

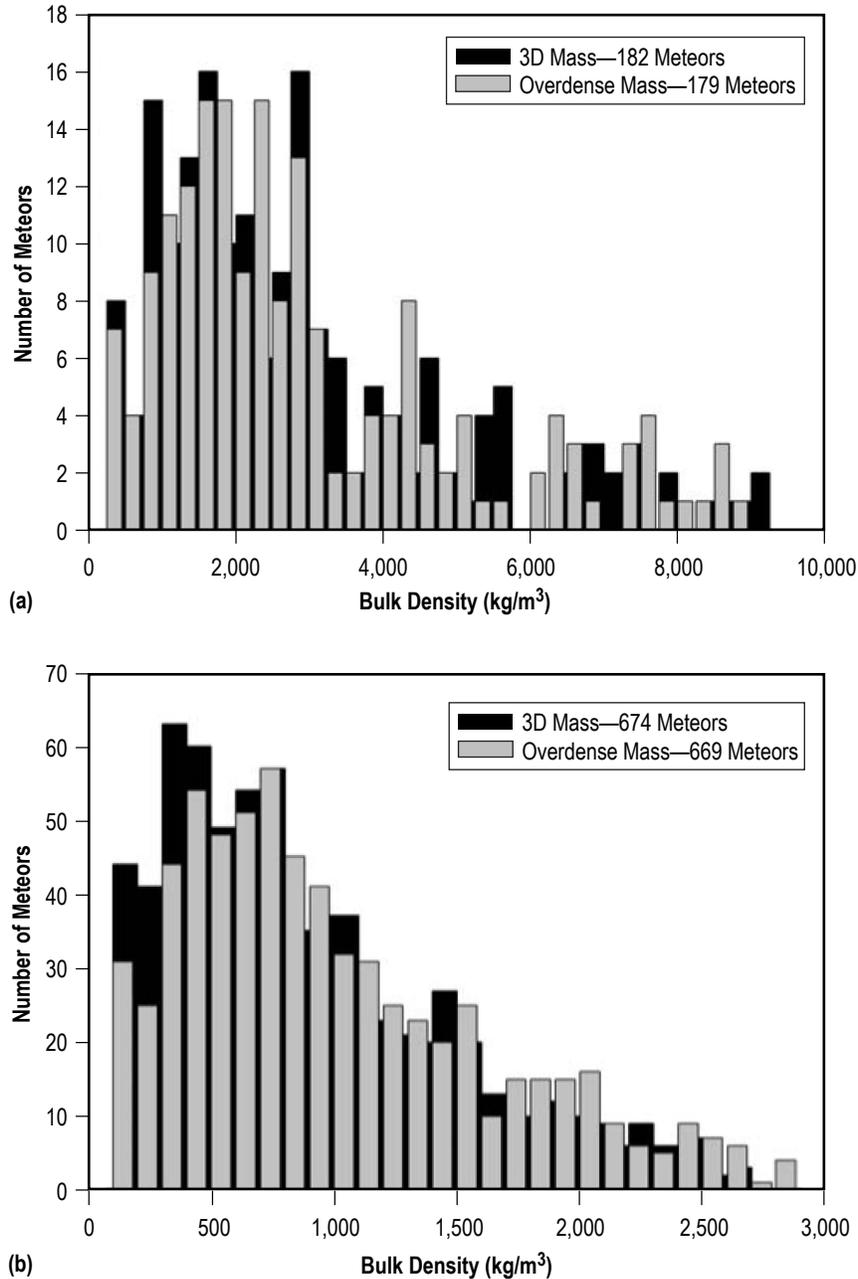


Figure 4. The meteoroid density distribution observed by ALTAIR using (a) ultra-high frequency and (b) very high frequency modes. Originals from Suggs et al.¹⁸

Mean bulk densities determined by the 3D spherical and overdense theories were $0.6 \pm 0.5 \text{ g/cm}^3$ and $0.7 \pm 0.6 \text{ g/cm}^3$, respectively. These data are valid over the 10^{-6} to 10^{-4} g mass range, which lies within the threat regime. These measured densities are consistent with those determined by other researchers, a summary of which is available in Suggs et al.¹⁸ MEMR2 uses a constant meteoroid density of 1 g/cm^3 , which is comparable to the ALTAIR values.

3. SOFTWARE DESCRIPTION AND USER INSTRUCTIONS

MEMR2 offers several new features that were previously available only in internally controlled versions, such as a random draw feature. Other features have been removed or simplified, and technical issues have been addressed. Unlike all previous releases, MEMR2 integrates three individual environment submodels that describe the meteoroid environment near the Earth, Moon, and in interplanetary space into one package. Each of these submodels is based on the same core meteoroid source distributions; however, the Earth and lunar submodels also take gravitational focusing and shielding into account.

Typical uses for MEM output files include spacecraft shield designs and risk assessments. These analyses may make use of the risk assessment tool known as BUMPER; MEM's threat igloo output files are consistent with the BUMPER input format (see sec. 3.4.3 for more information).

3.1 Software Installation and Removal

MEMR2 is distributed via the MEO website; users can request the software by completing the required web form. The software is delivered in the form of a zip file. After the file is unzipped, the user can run the included executable, setup.exe, to install the software and its support files and directories. This installer will place the model executable and binary source files in the Windows → Start Menu → Programs directory by default. However, successful execution of the software is dependent on the user having read-write privileges in the MEMR2 directory, and the user should select an installation directory that meets those requirements. Installation does not require a system reboot, and the user will receive an alert message when setup is complete.

Do not remove or rename the main executable or support files that are installed. This includes the program and its associated binary files (listed in table 2 in sec. 3.4). Model-generated output files can be freely moved, copied, or renamed; in fact, it is necessary to do so in order to keep them from being overwritten by subsequent runs.

MEMR2 also comes with an 'uninstall' option for cleanly removing the software. Before uninstalling the software, first move any desired output files to another location external to the MEM directory. To remove MEMR2, select the uninstall option from the Windows → Start Menu → Programs → NASA Meteoroid Engineering Model menu. This will remove the MEMR2 directory and all the files the directory contains.

Installing MEMR2 will not overwrite older versions of MEM or other MEO software products. Instead, the default installation option will place MEMR2 alongside these programs in the same NASA MEO folder under Windows → Start Menu → Programs. Older versions or other programs do not need to be uninstalled to run newer versions. However, the MEO advises discontinuing the use of older versions of MEM in favor of using MEMR2, and no longer supports older versions.

A list of common issues the user may encounter and the fixes for them are included in appendix A. MEMR2's minimum system requirements are as follows:

- Microsoft Windows XP or later.
- 512 MB RAM.
- 1.5 GB available disk space.
- A display resolution at least 768 pixels in height.

3.2 Program Execution

MEMR2's core files consist of a single executable and six binary source files that are used to calculate meteoroid fluxes. A user's guide is located in the MEMR2 directory in PDF format along with the executable and binary source files. All model-generated output files will be placed in this working directory as well. The user's input file must also be located in this main working directory in order for the model to run completely.

Users interact with the MEMR2 application through a GUI. This GUI will prompt the user to select one of three submodels, depending on whether the spacecraft is orbiting the Earth, the Moon, or is traveling through interplanetary space. Only one submodel can be used at a time; to run another submodel, the user must exit the active model and restart MEMR2. Once a submodel has been selected, a second window prompts the user for run parameters. During normal operation, some input fields will appear inactive or 'grayed-out' to ensure correct parameter combinations or selection order. Section 3.2.2 contains detailed instructions for input parameter choices. Figure 5 provides a high-level illustration of the order of inputs and program flow.

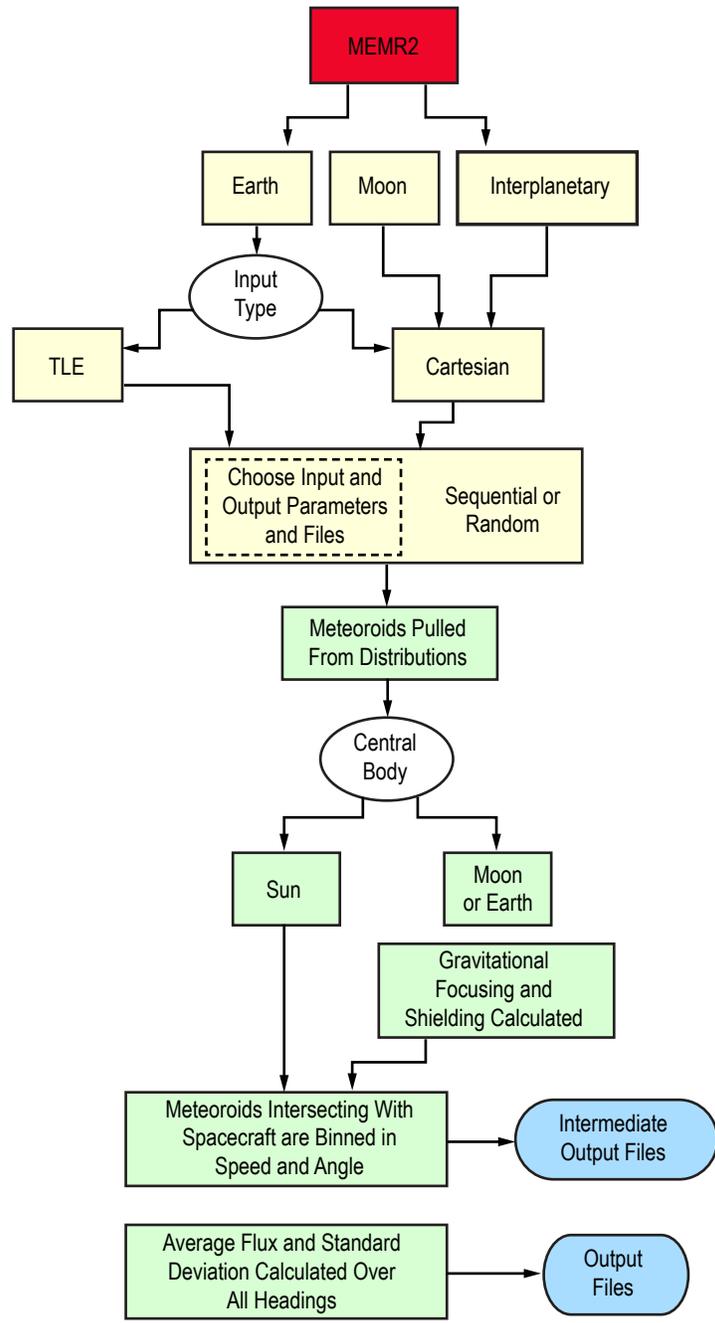


Figure 5. MEMR2 program flow. Software initialization is shown in red, GUI interactions appear in yellow, internal calculations are shown in green, and output is shown in blue.

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 MEMR2 has not been parallelized and will not take advantage of multiple processors. The number of state vectors also increases the disk space needed for output files; users can use table 1 to assess whether they have sufficient disk space for a MEM run. Users should be able to evaluate several thousand state vectors at once with MEMR2. For particularly long or detailed trajectories, users should consider dividing the trajectory into multiple input files or, if appropriate, using the random draw feature to analyze only a subset of the input state vectors.

Table 1. Typical MEM output file sizes for each choice of resolution. The size of the main results file will vary depending on the number of state vectors used; more state vectors or a larger random draw will increase the file size.

Output File	1°×1°×2 km/s	4°×4°×4 km/s	5°×5°×5 km/s
Main Results File	Variable	Variable	Variable
AvgResults.out	7–13 kB	4–7 kB	3–6 kB
AvgSpdDist.out	35–77 MB	1.1–2.4 MB	598 kB–1.2 MB
SpdDistMapX.out	35–77 MB	1.1–2.4 MB	598 kB–1.2 MB
AvgMEMIgllooDist.out	24–48 MB	835 kB–1.6 MB	468–852 kB

MEM generates several sets of output files (see sec. 3.4); these files will be stored in the MEMR2 directory and will follow the naming convention outlined in table 2. Some of these files, which appear in table 2 in gray, are deleted upon the completion of a run unless the user opts to ‘keep intermediate files.’ If the user wishes to permanently keep any output files generated by a particular run, he or she must move the files to another directory before using the software again.

Table 2. Files located in the working directory upon installation and after a typical MEM run.

File Name	Description
MEMR2.exe	MEMR2 executable.
bin1.dat, bin2.dat, bin3.dat, bin4.dat, bin5.dat, bin6.dat	Meteoroid population source files and fit files.
username.txt or *.in (e.g., MySatStateVectors.txt)	User-generated input file—Must have the format specified in section 3.2.2.2.
AvgMEMIgllooDist.out	Average threat igloo file—Reports flux averaged over all input state vectors.
userselctedname.out	Main output file—Reports average flux per speed bin and over the surfaces of a simple cube-shaped spacecraft for each input state vector.
AvgResults.out	Average results file—Reports flux averaged over all input state vectors.
SpdDistMapi.out	Intermediate speed distribution map files—These files list flux per chosen degree resolution in azimuth and elevation and by chosen speed resolution bin.
AvgResults.out	Average speed distribution map file—Average of all intermediate map files evaluated at each state vector from input file.
StdDevResults.out	Main standard deviations file—Reports standard deviations corresponding to the average fluxes in AvgResults.out.
StdDevSpdDist.out	Speed distribution standard deviation file—Reports standard deviations corresponding to the average fluxes per speed bin in AvgSpdDist.out. (The output of these two files will be suppressed if the user chooses not to output standard deviation files).

3.2.1 Choosing a Submodel

MEMR2 offers the user a choice of calculating the meteoroid environment near Earth, the Moon, or in interplanetary space (see fig. 6). A nearby planet or moon can gravitationally focus the meteoroid flux or shield a spacecraft from a portion of the environment. It is therefore important to choose the correct submodel. The user may use the following distances as a guide:

- Earth submodel: up to 925,000 km from the Earth’s center.
- Lunar submodel: up to 66,000 km from the Moon’s center.
- Interplanetary submodel: more than 925,000 km from the Earth and 66,000 km from the Moon.

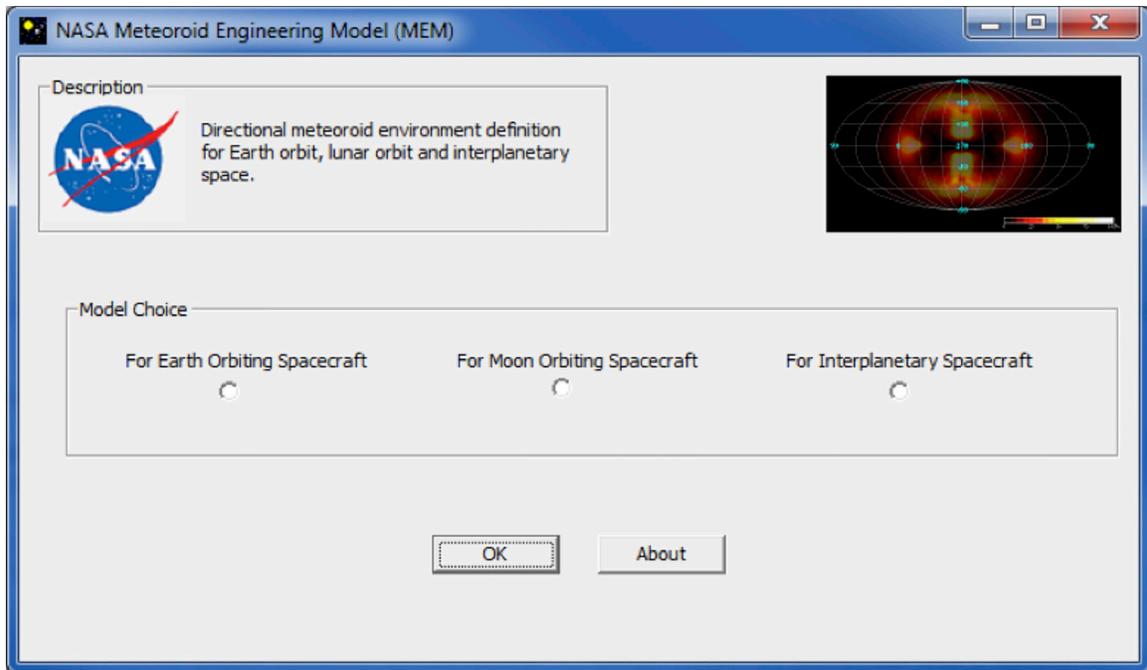


Figure 6. MEMR2 main user interface. The software requires the user to select a submodel before proceeding.

After choosing a submodel, the user will then be presented with a second GUI. Figure 7 shows the user interface for Earth-orbiting spacecraft, figure 8 shows the user interface for Moon-orbiting spacecraft, and figure 9 shows the user interface for interplanetary spacecraft trajectories. Transfer orbits (i.e., trajectories for spacecraft that pass from Earth orbit to lunar orbit or from Earth orbit to interplanetary space) require multiple MEM runs. The trajectory should be divided into pieces depending on whether the spacecraft lies near the Moon, the Earth, or neither.

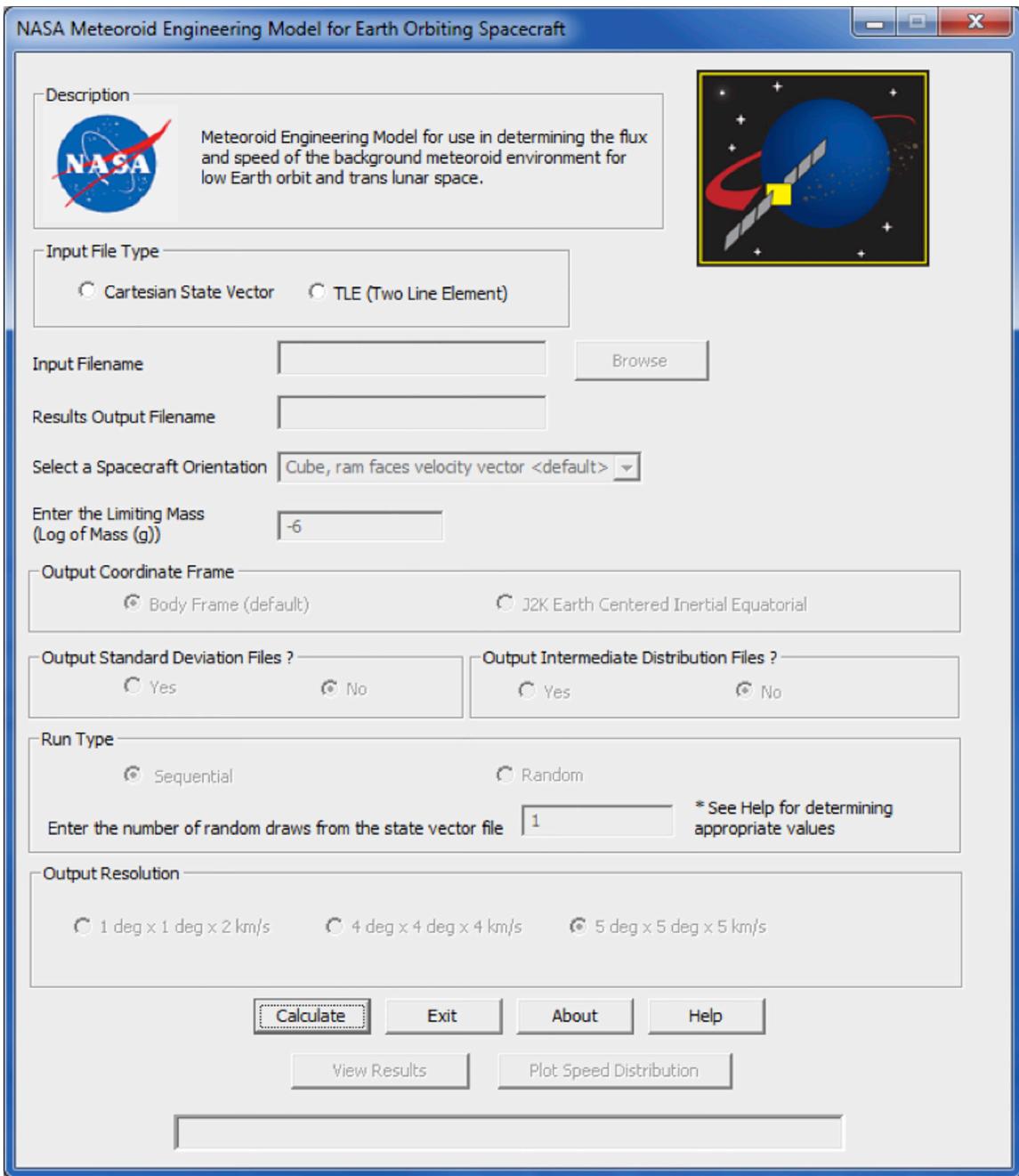


Figure 7. User interface for Earth-orbiting spacecraft.

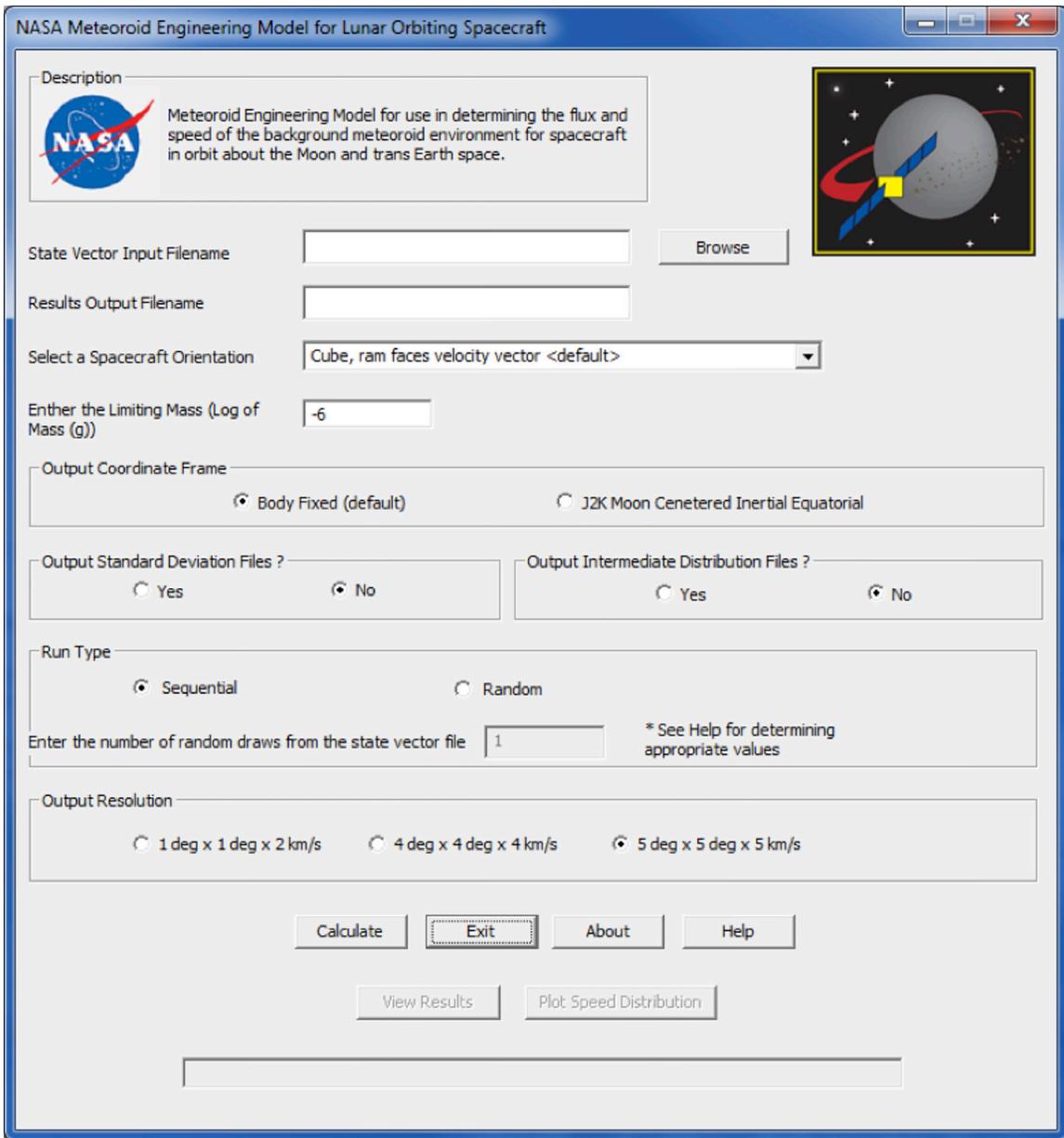


Figure 8. User interface for lunar-orbiting spacecraft.

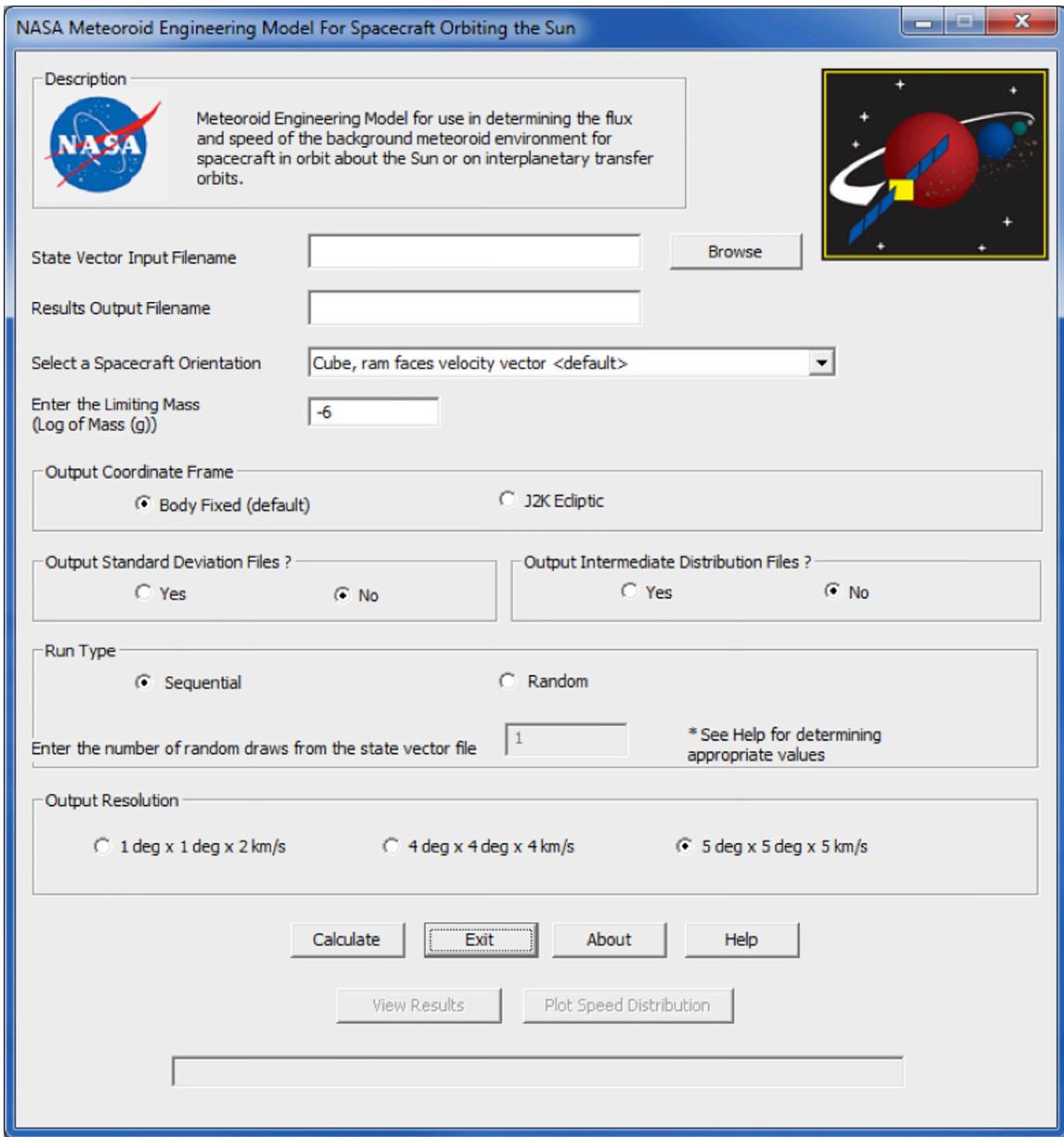


Figure 9. User interface for interplanetary spacecraft.

3.2.2 Input Parameter Choices

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.

3.2.2.1 Cartesian or Two-Line Element Input (Earth Orbit Only). In the case of a lunar or interplanetary orbit, trajectory information must be provided in the form of a series of Cartesian state vectors (see sec. 3.3.1 for more details). However, trajectories for Earth-orbiting satellites may be entered as a series of TLE sets. Note that the use of TLEs precludes the option to draw random state vectors from the user’s input file (sec. 3.2.2.9) and that the user should make sure that the orbit or trajectory is well-sampled (sec. 3.3.2).

3.2.2.2 Input Filename. The user may enter the absolute path of the input file or select it using the file browser. Please ensure that the input file lies in the same directory as the MEMR2 executable.

3.2.2.3 Output Filename. The user must enter the name of the primary output file; this will be the only output file with a user-determined filename. This file will be deposited in the same directory as the MEMR2 executable. MEM will not append a file extension; the user can choose ‘.out’ for the sake of consistency.

3.2.2.4 Spacecraft Orientation. The user may choose from three possible spacecraft orientations. In the first of these choices (‘cube, ram faces velocity vector’), the spacecraft maintains the same orientation relative to its instantaneous velocity vector and displacement from the submodel’s central body (Earth, Moon, or Sun; see sec. 4.2 for a depiction of coordinate frames). Alternatively, the user can choose to have the spacecraft rotate about its angular momentum or velocity vectors. The choice of orientation affects the flux columns reported in the primary, user-named output file; all other output files are unaffected. See section 3.4 for a discussion of output file content.

3.2.2.5 Limiting Mass. The user may specify the base-10 logarithm of the limiting mass. The user is restricted to choosing a value between -6 and 1 , corresponding to 10^{-6} and 10 g, respectively. The field is prepopulated with a default value of -6 . MEM will calculate the meteoroid flux for particles greater than or equal to the chosen limiting mass. See section 2.1 for an overview of the mass distribution. MEM assumes a constant meteoroid density of 1 g/cm^3 ; the user may use this density to convert between mass and size.

3.2.2.6 Output Coordinate Frame. The user may choose between two output coordinate frames: body-fixed and inertial. The body-fixed frame is determined by the velocity and position of the vehicle (see sec. 4.2). The inertial frame is the same as that for Cartesian state vector input files: J2000 Earth-centered inertial (ECI) for Earth-orbiting spacecraft, J2000 Moon-centered inertial (MCI) for Moon-orbiting spacecraft, and J2000 ecliptic for interplanetary spacecraft. Thus, the user may opt to receive MEM output in the same coordinate frame as the input files. This is a new feature of MEMR2.

3.2.2.7 Output Standard Deviation Files. The user may opt to output standard deviation files (described in sec. 3.4.1.3). The standard deviation files characterize the variation of the flux along the spacecraft’s trajectory; it does not provide information on environment uncertainty. The default is to suppress output.

3.2.2.8 Output Intermediate Distribution Files. For each state vector or heading in the input file, MEM computes the meteoroid environment relative to the spacecraft. MEM produces an output file for each state vector containing this instantaneous flux information. At the conclusion of a run, MEM averages the flux over these intermediate files to determine the average flux encountered by the spacecraft over its entire trajectory. Although the default option is to delete these intermediate files at the end of a run, the user does have the option to keep these files. However, maintaining these intermediate files for numerous long MEM runs can quickly deplete disk space.

3.2.2.9 Run Type. If the user has selected a Cartesian state vector input file (rather than TLEs), MEMR2 provides the option to compute the flux using a randomly selected subset of state vectors. Once the random run type has been selected, the user can enter the desired number of random draws. MEMR2 samples the state vectors with replacements; the selected subset may therefore contain duplicate state vectors.

The original input file will always cover the trajectory more fully than a randomly selected subsample drawn from it. Therefore, as with all run types, the user should take care 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.

The MEO has established random draw guidelines for selected basic missions that ensure adequate coverage of the variation in directionality. The MEO generated state vectors at 1-min intervals for these missions and determined the minimum number of random draws for which meteoroid flux results converged in testing. These guidelines will not cover every type of orbit or mission; if the user’s specific mission is not mentioned, use the above guidance for choosing an appropriate number of random draws. The minimum number of random draws established by the MEO are as follows:

- 1-year mission docked to the International Space Station (ISS): 4,000 random draws.
- 2-week mission docked to ISS: 1,500 random draws.
- 4-day lunar transit mission (typical Apollo trajectory): 1,500 random draws.
 - Note that this mission extends outward only to the Moon’s sphere of influence.
- 3-day LEO mission with 28.5° inclination and 300 km altitude: 1,500 random draws.

3.2.2.10 Output Resolution. The user can choose between three output resolutions in angle and speed. Choosing a coarser resolution will result in smaller output files and less detailed environment data. The default choice is the coarsest: 5° angular increments and 5 km/s speed increments. Table 1 gives approximate output file size for each choice of output resolution.

3.2.3 Computation of the Meteoroid Environment

Once all input parameters have been specified, the user can begin the environment calculation using the ‘Calculate’ button. Alternatively, the user may choose to exit the program, view application information, or view the help documentation.

Once ‘Calculate’ is chosen, MEMR2 begins to compute the meteoroid flux relative to the spacecraft for the provided or selected input state vectors. The program notifies the user via a pop-up window when the calculation is complete. Run time varies with system specifications, the length of the input files, and the choice of input parameters. It is recommended that new users use a short input file or small random draw number in conjunction with a coarse resolution in order to quickly become familiarized with the program.

3.2.4 Viewing Results

Once the calculation is complete, the user must press ‘OK’ in the notification window in order to return to the main GUI. At this point, the user may elect to view the primary output file or to plot the speed distribution. Section 3.4 describes the output files in more detail.

3.2.5 Notifications and Status Reporting

MEMR2 execution status and notifications are shown in two places. Model progress is indicated in the dialog menu bar, which will report the number of the state vector or TLE under evaluation. The menu bar will also indicate when the program is ‘idle.’ There is a second message bar beneath the ‘View Results’ and ‘Plot Speed Distribution’ buttons that alerts the user when the program has successfully completed. A small dialog box will also appear when calculations are complete, prompting user to accept the notification in order to return to the user interface and view results or make plots.

3.3 Input Files

Because MEMR2 provides trajectory-specific meteoroid environment data, the user must provide an input file containing trajectory information. This file can take the format of either a series of Cartesian state vectors or a series of TLE sets.

The state vectors in the input file can be sequential or correspond to random points in time. MEMR2 will produce a ‘snapshot’ of the meteoroid environment as seen from each state vector and construct an average environment using these snapshots. Each state vector will receive equal weight; therefore, sampling the spacecraft state vector at equal time intervals is recommended to avoid underweighting part of the trajectory.

3.3.1 Cartesian State Vector Input File Format

In order to accommodate trajectory data generated with the popular Systems Tool Kit (STK) (<<http://www.agi.com/products/stk/modules/default.aspx/id/stk-free>>), 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 x , y , z , v_x , v_y , and v_z coordinates 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 3, and an example input file is shown in figure 10.

Table 3. Cartesian state vector 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 No. 1	x_1	y_1	z_1	$v_{x,1}$	$v_{y,1}$	$v_{z,1}$
8	Julian Date No. 2	x_2	y_2	z_2	$v_{x,2}$	$v_{y,2}$	$v_{z,2}$
...
$N+6$	Julian Date No. N	x_N	y_N	z_N	$v_{x,N}$	$v_{y,N}$	$v_{z,N}$

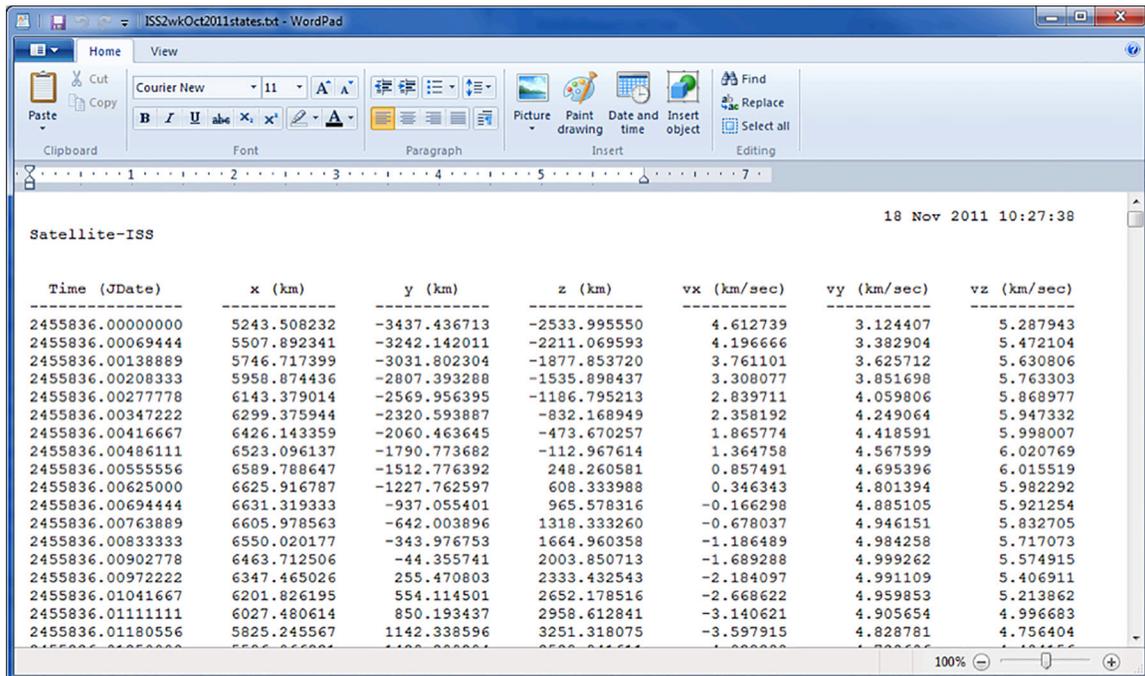


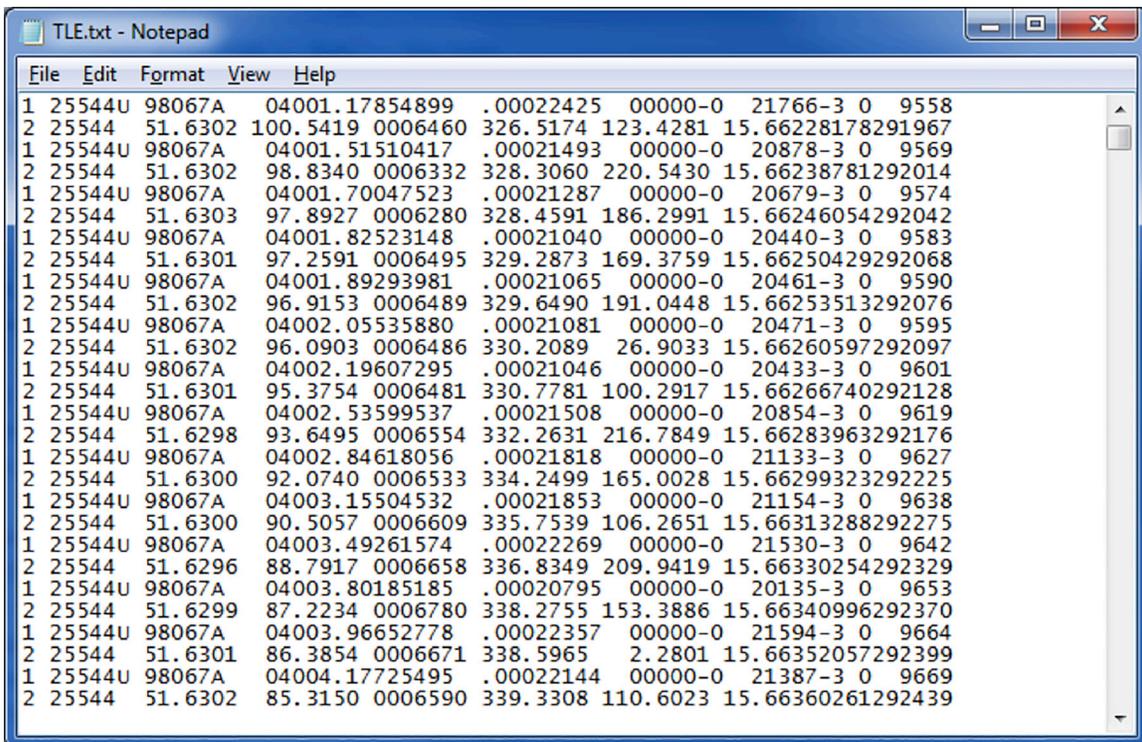
Figure 10. Example Cartesian state vector input file generated with STK. This file describes part of ISS trajectory and is therefore in ECI coordinates.

The input file must also satisfy the following requirements:

- State vectors should be in either J2000 ECI or equatorial coordinates.
- Outside of the header, there should be no commas, brackets, parentheses, or any other symbol or character other than the columns of numbers.
- Floating point, integers, scientific, or engineering representation are acceptable number formats.
- There should no 'return' character or spaces beyond the last digit of the last speed value. The cursor should end at the end of the state vector and not on the line following it.

3.3.2 Two-Line Element Input File Format

The Earth submodel of MEMR2 accepts TLE sets as input. TLE input files must start on line 1 and consist of TLE sets describing the spacecraft's orbit at an instant in time in a true equator, mean equinox of epoch (TEME) reference frame. While Cartesian state vector input files allot exactly one line to each point in time, TLE sets, by definition, require two lines. TLE format is very specific and is described in detail by Celestrak (<<http://celestrak.com/NORAD/documentation/tle-fmt.asp>>). An example TLE input file is shown in figure 11.



```
File Edit Format View Help
1 25544U 98067A 04001.17854899 .00022425 00000-0 21766-3 0 9558
2 25544 51.6302 100.5419 0006460 326.5174 123.4281 15.66228178291967
1 25544U 98067A 04001.51510417 .00021493 00000-0 20878-3 0 9569
2 25544 51.6302 98.8340 0006332 328.3060 220.5430 15.66238781292014
1 25544U 98067A 04001.70047523 .00021287 00000-0 20679-3 0 9574
2 25544 51.6303 97.8927 0006280 328.4591 186.2991 15.66246054292042
1 25544U 98067A 04001.82523148 .00021040 00000-0 20440-3 0 9583
2 25544 51.6301 97.2591 0006495 329.2873 169.3759 15.66250429292068
1 25544U 98067A 04001.89293981 .00021065 00000-0 20461-3 0 9590
2 25544 51.6302 96.9153 0006489 329.6490 191.0448 15.66253513292076
1 25544U 98067A 04002.05535880 .00021081 00000-0 20471-3 0 9595
2 25544 51.6302 96.0903 0006486 330.2089 26.9033 15.66260597292097
1 25544U 98067A 04002.19607295 .00021046 00000-0 20433-3 0 9601
2 25544 51.6301 95.3754 0006481 330.7781 100.2917 15.66266740292128
1 25544U 98067A 04002.53599537 .00021508 00000-0 20854-3 0 9619
2 25544 51.6298 93.6495 0006554 332.2631 216.7849 15.66283963292176
1 25544U 98067A 04002.84618056 .00021818 00000-0 21133-3 0 9627
2 25544 51.6300 92.0740 0006533 334.2499 165.0028 15.66299323292225
1 25544U 98067A 04003.15504532 .00021853 00000-0 21154-3 0 9638
2 25544 51.6300 90.5057 0006609 335.7539 106.2651 15.66313288292275
1 25544U 98067A 04003.49261574 .00022269 00000-0 21530-3 0 9642
2 25544 51.6296 88.7917 0006658 336.8349 209.9419 15.66330254292329
1 25544U 98067A 04003.80185185 .00020795 00000-0 20135-3 0 9653
2 25544 51.6299 87.2234 0006780 338.2755 153.3886 15.66340996292370
1 25544U 98067A 04003.96652778 .00022357 00000-0 21594-3 0 9664
2 25544 51.6301 86.3854 0006671 338.5965 2.2801 15.66352057292399
1 25544U 98067A 04004.17725495 .00022144 00000-0 21387-3 0 9669
2 25544 51.6302 85.3150 0006590 339.3308 110.6023 15.66360261292439
```

Figure 11. Example TLE input file.

The input file must also satisfy the following requirements:

- TLEs must be in a TEME reference frame (<<http://www.celestrak.com/columns/v04n05/index.asp#FAQ07>>).
- There should be no commas, brackets, parentheses, or any other symbol or character other than the columns of numbers as described in NORAD TLE documentation.
- There should no ‘return’ character or spaces beyond the last digit of the last TLE. The cursor should stop at the end of the last state vector and not on the following line.

MEMR2 will compute the meteoroid flux relative to each TLE provided. It does not ‘fill in’ the spacecraft’s trajectory between TLEs. The user should therefore carefully examine the set of available TLEs; if new TLEs are computed once per orbit, for example, the results will not be a good representation of the meteoroid environment seen along the entire orbit.

3.4 Output Files

MEMR2 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. These files and brief descriptions of their content are listed in table 2; the following sections describe each file in more detail.

In all cases, the flux and speed information presented in the output files are computed relative to the spacecraft. The output data also account for gravitational focusing and planetary shielding effects where applicable (i.e., for the Earth and lunar submodels). MEMR2 does not report environment uncertainties; the standard deviation output files report the observed variation in flux along the provided spacecraft trajectory.

3.4.1 Main Output, Average, and Standard Deviation Files

3.4.1.1 Main Output File. The main output file (which is named by the user during initialization; see sec. 3.2.2.2) contains all the information needed to repeat a calculation, including the MEM version number, submodel choice, input file name, limiting mass, spacecraft orientation, and the trajectory information itself. The main output file always returns trajectory information in the form of state vectors, regardless of whether the user provided state vectors or TLEs.

For each input state vector, the main output file reports the total cross-sectional meteoroid flux summed over all directions and speeds in units of particles per square meter per year (line 17 in fig. 12). This is equivalent to the meteoroid flux on a sphere per square meter of cross-sectional area (see sec. 4.3.1 for more discussion of this flux).

```

1  ***IMPORTANT NOTE - Use of average speeds in risk assessments may underestimate vehicle risk !
2  Speed distributions are recommended for detailed risk assessments, see documentation for explanation.
3
4  Earth Meteoroid Engineering Model Results
5  EarthMEM Version 3.0.5
6  File Written at 08:26:09 AM 02/04/15
7
8  User's Input File: Y:\MEMR2_0_5\test_tle.txt
9  Limiting mass was selected
10 Mass Value: 10^-6.0 grams
11 Orientation - Cube, ram faces velocity vector
12
13 Total Flux on Spacecraft
14 Heading #1
15 state vector 2454834.276563 4496.304754 -5473.676264 0.083115 -0.837208 -0.676458 7.425506
16
17 Cross Sectional Flux 7.213051e+000 /m^2/yr
18
19 Average Speed (km/s) +X Ram -X Wake +Y Port -Y Starboard +Z Zenith -Z Nadir -r Earth Sun Anti-Sun
20 Total Flux (#/m2/yr) 3.674e+000 7.252e-001 2.473e+000 8.891e-001 2.490e+000 3.909e-001 3.918e-001 2.369e+000 8.767e-001
21 V Bin Centered
22 2.5 1.250140E-002 2.496884E-003 6.080009E-003 2.692736E-003 6.045132E-003 1.182953E-003 1.185557E-003 5.068535E-003 2.781908E-003
23 7.5 2.952170E-001 5.883174E-002 1.499944E-001 6.484599E-002 1.508844E-001 2.807321E-002 2.813661E-002 1.293598E-001 6.644076E-002
24 12.5 6.407435E-001 1.264121E-001 3.880335E-001 1.529686E-001 4.065583E-001 6.229227E-002 6.244849E-002 3.748132E-001 1.514636E-001
25 17.5 1.101116E+000 2.162348E-001 7.132832E-001 2.723353E-001 7.590219E-001 1.077744E-001 1.080567E-001 7.155889E-001 2.658957E-001
26 22.5 6.863856E-001 1.339014E-001 4.913894E-001 1.784599E-001 5.304107E-001 6.854978E-002 6.873969E-002 5.145524E-001 1.709254E-001
27 27.5 3.825183E-001 7.477060E-002 2.709316E-001 9.828124E-002 2.893540E-001 3.860508E-002 3.871008E-002 2.798320E-001 9.457651E-002
28 32.5 2.199916E-001 4.305591E-002 1.577423E-001 5.626250E-002 1.661530E-001 2.273733E-002 2.279833E-002 1.611538E-001 5.425620E-002
29 37.5 1.245382E-001 2.448885E-002 9.141028E-002 3.118944E-002 9.218819E-002 1.374885E-002 1.378407E-002 8.989031E-002 3.035346E-002
30 42.5 6.814046E-002 1.358097E-002 5.216276E-002 1.594839E-002 4.665645E-002 8.758718E-003 8.778706E-003 4.595137E-002 1.598941E-002
31 47.5 6.028669E-002 1.232902E-002 4.004165E-002 1.163242E-002 2.812228E-002 8.608374E-003 8.624305E-003 2.606592E-002 1.271257E-002
32 52.5 3.123983E-002 6.842223E-003 3.211770E-002 3.585963E-003 9.220184E-003 8.318982E-003 8.330868E-003 1.099249E-002 5.273504E-003
33 57.5 2.042859E-002 4.792237E-003 2.992950E-002 6.871981E-004 2.924701E-003 8.268706E-003 8.279315E-003 6.305696E-003 2.563298E-003
34 62.5 1.495776E-002 3.576366E-003 2.380971E-002 1.511764E-004 1.482260E-003 6.654932E-003 6.663303E-003 4.429614E-003 1.688889E-003
35 67.5 8.581209E-003 2.059794E-003 1.388547E-002 4.477345E-005 7.717924E-004 3.889500E-003 3.894374E-003 2.518915E-003 9.465061E-004
36 72.5 7.522287E-003 1.805615E-003 1.217200E-002 3.924840E-005 6.765532E-004 3.409535E-003 3.413808E-003 2.208081E-003 8.297072E-004
37
38
39 Total Flux on Spacecraft
40 Heading #2
41 state vector 2456826.241543 -2715.925423 6542.343570 -0.104046 0.990887 0.401705 7.426504

```

Figure 12. Example main output file. The header (lines 1–11) lists the user’s input file and parameter choices as well as the software version. The chosen output coordinate system (in this case, body-fixed) is apparent from the surfaces listed in line 18.

The main output file also reports a table of the average meteoroid speed incident on each face of a cube with the spacecraft’s orientation (see sec. 4.3.2). The total flux incident on each surface is reported at the top (line 20 in fig. 12), followed by the flux in each speed interval (lines 22–36). Speed bins are labeled with the midpoint of the speed range, i.e., 2.5 km/s for meteoroids ranging from 0 to 5 km/s. The faces of the cube are aligned with the user’s chosen coordinate system (compare figs. 12 and 13). MEMR2 also reports the flux on surfaces facing the Earth, facing the Sun, and facing away from the Sun. These orientations may apply to communications equipment and solar panels, respectively. The lunar submodel reports the flux on the Moon-facing surface in place of an Earth-facing surface.

```

1  ***IMPORTANT NOTE - Use of average speeds in risk assessments may underestimate vehicle risk !
2  Speed distributions are recommended for detailed risk assessments, see documentation for explanation.
3
4  Earth Meteoroid Engineering Model Results
5  EarthMEM Version 3.0.5
6  File Written at 01:39:00 PM 02/09/15
7
8  User's Input File: Y:\MEMR2_0_5\test_tle.txt
9  Limiting mass was selected
10 Mass Value: 10^-6.0 grams
11 Orientation - Cube, ram faces velocity vector
12
13 Total Flux on Spacecraft
14 Heading #1
15 state vector 2454834.276563 4496.304754 -5473.676264 0.083115 -0.837208 -0.676458 7.425506
16
17 Cross Sectional Flux 7.213051e+000 /m^2/yr
18 +X(I)VerEqu -X +Y (J) -Y +Z(K)N.Pole -Z S.Pole Earth Sun Anti-Sun
19 Average Speed (km/s) 20.8 24.2 20.6 21.6 21.1 21.6 24.0 21.4 20.9
20 Total Flux (#/m2/yr) 1.086e+000 1.292e+000 4.793e-001 3.363e+000 3.515e+000 8.224e-001 3.900e-001 2.368e+000 8.754e-001
21 V Bin Centered
22 2.5 3.056753E-003 3.668604E-003 1.499015E-003 8.287549E-003 1.205246E-002 2.634790E-003 1.177953E-003 5.067852E-003 2.777069E-003
23 7.5 7.444148E-002 8.778821E-002 3.592203E-002 2.056594E-001 2.844525E-001 6.265832E-002 2.796030E-002 1.293416E-001 6.632732E-002
24 12.5 1.835153E-001 2.018391E-001 8.305019E-002 5.431853E-001 6.157867E-001 1.402650E-001 6.209746E-002 3.747532E-001 1.512253E-001
25 17.5 3.322314E-001 3.543537E-001 1.466747E-001 1.006817E+000 1.057138E+000 2.442078E-001 1.074765E-001 7.154724E-001 2.654911E-001
26 22.5 2.228575E-001 2.304506E-001 9.502438E-002 6.983808E-001 6.576638E-001 1.554383E-001 6.840228E-002 5.144622E-001 1.706803E-001
27 27.5 1.222846E-001 1.293765E-001 5.243716E-002 3.824384E-001 3.664318E-001 8.644461E-002 3.852132E-002 2.797799E-001 9.444095E-002
28 32.5 7.006494E-002 7.631464E-002 3.001588E-002 2.205554E-001 2.105276E-001 4.986741E-002 2.269155E-002 1.611201E-001 5.418000E-002
29 37.5 3.882283E-002 4.621388E-002 1.666132E-002 1.241271E-001 1.188514E-001 2.840868E-002 1.372605E-002 8.986541E-002 3.031315E-002
30 42.5 1.973116E-002 2.943737E-002 8.571730E-003 6.551690E-002 6.458028E-002 1.573943E-002 8.749984E-003 4.592968E-002 1.597129E-002
31 47.5 1.342142E-002 2.807931E-002 6.486564E-003 4.372111E-002 5.696397E-002 1.354866E-002 8.597417E-003 2.604260E-002 1.269883E-002
32 52.5 4.071601E-003 2.803093E-002 2.102916E-003 2.288514E-002 2.803225E-002 7.946341E-003 8.328576E-003 1.095435E-002 5.278943E-003
33 57.5 7.811242E-004 2.827984E-002 5.085509E-004 1.611261E-002 1.723092E-002 5.914857E-003 8.286629E-003 6.261535E-003 2.576100E-003
34 62.5 1.724627E-004 2.281900E-002 1.883559E-004 1.204123E-002 1.238284E-002 4.483404E-003 6.670530E-003 4.393199E-003 1.700226E-003
35 67.5 5.132512E-005 1.334299E-002 8.612643E-005 6.937048E-003 7.076147E-003 2.590297E-003 3.898743E-003 2.497538E-003 9.532443E-004
36 72.5 4.499160E-005 1.169646E-002 7.549842E-005 6.081016E-003 6.202950E-003 2.270654E-003 3.417638E-003 2.189341E-003 8.356139E-004
37
38
39 Total Flux on Spacecraft
40 Heading #2
41 state vector 2456826.241543 -2715.925423 6542.343570 -0.104046 0.990887 0.401705 7.426504

```

Figure 13. Example main output file. In this case, the chosen output coordinate system is ECI, and this choice is reflected in the surfaces listed in line 18.

The user may specify that the spacecraft is rotating about either the velocity or angular momentum vector. In these cases, MEM reports the flux on the two nonrotating surfaces (i.e., the ram and flux directions for a spacecraft rotating about its velocity vector) as well as that on the rotating surfaces. See figure 14 for an example.

Each line of input used by MEM has a corresponding flux table regardless of whether the inputs were processed sequentially from the input file or using a randomly drawn selection of state vectors from the input file. For random sample runs, the state vector numbering in the main results file reflects the MEMR2 processing order and does not correspond to their ordering in the input file. The use of average speeds in risk assessment may underestimate vehicle risk. The MEO recommends the use of meteoroid speed distributions.

```

1 ***IMPORTANT NOTE - Use of average speeds in risk assessments may underestimate vehicle risk !
2     Speed distributions are recommended for detailed risk assessments, see documentation for explanation.
3
4 Earth Meteoroid Engineering Model Results
5 EarthMEM Version 3.0.5
6 File Written at 08:25:32 AM 02/04/15
7
8 User's Input File: Y:\MEMR2_0_5\test_tle.txt
9 Limiting mass was selected
10 Mass Value: 10^-6.0 grams
11 Orientation - Rotating about angular momentum vector
12
13 Total Flux on Spacecraft
14 Heading #1
15 state vector 2454834.276563 4496.304754 -5473.676264 0.083115 -0.837208 -0.676458 7.425506
16
17 Cross Sectional Flux      7.213051e+000 /m^2/yr
18 Rotating Surf  +Y Port      -Y Starboard      -r Earth      Sun      Anti-Sun
19 Average Speed (km/s)      21.3      22.8      20.7      23.9      21.5      20.9
20 Total Flux (#/m2/yr)      5.936e+000      2.473e+000      8.891e-001      3.918e-001      2.369e+000      8.767e-001
21 V Bin Centered
22 2.5      1.807276E-002 6.080009E-003 2.692736E-003 1.185557E-003 5.068535E-003 2.781908E-003
23 7.5      4.336038E-001 1.499944E-001 6.484599E-002 2.813661E-002 1.293598E-001 6.644076E-002
24 12.5     1.007454E+000 3.880335E-001 1.529686E-001 6.244849E-002 3.748132E-001 1.514636E-001
25 17.5     1.781687E+000 7.132832E-001 2.723353E-001 1.080567E-001 7.155889E-001 2.658957E-001
26 22.5     1.158997E+000 4.913894E-001 1.784599E-001 6.873969E-002 5.145524E-001 1.709254E-001
27 27.5     6.410901E-001 2.709316E-001 9.828124E-002 3.871008E-002 2.798320E-001 9.457651E-002
28 32.5     3.689322E-001 1.577423E-001 5.626250E-002 2.279833E-002 1.611538E-001 5.425620E-002
29 37.5     2.080408E-001 9.141028E-002 3.118944E-002 1.378407E-002 8.989031E-002 3.035346E-002
30 42.5     1.117372E-001 5.216276E-002 1.594839E-002 8.778706E-003 4.595137E-002 1.598941E-002
31 47.5     8.872294E-002 4.004165E-002 1.163242E-002 8.624305E-003 2.606592E-002 1.271257E-002
32 52.5     4.477380E-002 3.211770E-002 3.585963E-003 8.330868E-003 1.099249E-002 5.273504E-003
33 57.5     2.907399E-002 2.992950E-002 6.871981E-004 8.279315E-003 6.305696E-003 2.563298E-003
34 62.5     2.124440E-002 2.380971E-002 1.511764E-004 6.663303E-003 4.429614E-003 1.688889E-003
35 67.5     1.218265E-002 1.388547E-002 4.477345E-005 3.894374E-003 2.518915E-003 9.465061E-004
36 72.5     1.067931E-002 1.217200E-002 3.924840E-005 3.413808E-003 2.208081E-003 8.297072E-004
37
38 Total Flux on Spacecraft
39 Heading #2
40 state vector 2456826.241543 -2715.925423 6542.343570 -0.104046 0.990887 0.401705 7.426504

```

Figure 14. Example main output file. In this case, the chosen output coordinate system is ECI, and the spacecraft is rotating about its angular momentum vector. Both of these choices are reflected in the surfaces listed in line 18.

3.4.1.2 AvgResults.out. The average main output file reports the numerical ‘average’ of all flux values presented in the main output file. Unlike the main results file, which is named by the user, this file is always named ‘AvgResults.out.’ The format (see fig. 15) is similar to that of the main results file, but only one average environment is presented and the individual state vectors are not listed.

3.4.1.3 StdDevResults.out. The user can also opt to ‘output standard deviation files.’ The first of these is the main standard deviation file (‘StdDevResults.out’; see fig. 16). This file mimics the format of the main and average results files, but reports the standard deviation in the flux.

```

AvgResults.out
1 Earth Meteoroid Engineering Model Results - AVERAGES
2 EarthMEM version 3.0.5
3 File Written at 08:26:25 AM 02/04/15
4
5 User's Input File: Y:\MEMR2_0_5\test_tle.txt
6 Limiting mass was selected
7 Mass Value: 10^-6.000000 grams
8
9 Orientation - Cube, ram faces velocity vector
10
11 Total Flux on Spacecraft
12 Average of All States
13 Cross Sectional Flux 6.837930e+000 /m^2/yr
14
15 +X Ram -X Wake +Y Port -Y Starboard +Z Zenith -Z Nadir -r Earth Sun Anti-Sun
16 Average Speed (km/s) 21.0 22.2 22.3 21.8 21.3 23.1 23.1 21.4
17 Total Flux (#/m^2/yr) 3.511e+000 6.807e-001 1.877e+000 1.229e+000 2.591e+000 3.114e-001 3.120e-001 3.372e+000 4.732e-001
18 V Bin Centered
19 2.5 1.216316E-002 2.567967E-003 5.590021E-003 3.960319E-003 7.375106E-003 1.073419E-003 1.075552E-003 9.609722E-003 1.549854E-003
20 7.5 2.451214E-001 4.865546E-002 1.135115E-001 8.061154E-002 1.571656E-001 2.086224E-002 2.090089E-002 1.996171E-001 3.353215E-002
21 12.5 6.130459E-001 1.187776E-001 3.093433E-001 2.062398E-001 4.288083E-001 5.187788E-002 5.197478E-002 5.560424E-001 8.163403E-002
22 17.5 1.054160E+000 2.017466E-001 5.473920E-001 3.571724E-001 7.610142E-001 8.901303E-002 8.918385E-002 9.858503E-001 1.421713E-001
23 22.5 6.734972E-001 1.215954E-001 3.606747E-001 2.354861E-001 5.225881E-001 5.532740E-002 5.543325E-002 6.792993E-001 9.149498E-002
24 27.5 3.926074E-001 6.690308E-002 2.072241E-001 1.374690E-001 3.098983E-001 3.145622E-002 3.151549E-002 4.075379E-001 5.203595E-002
25 32.5 2.359117E-001 3.851033E-002 1.248764E-001 8.320264E-002 1.903420E-001 1.869927E-002 1.873339E-002 2.526460E-001 3.068665E-002
26 37.5 1.361197E-001 2.289465E-002 7.407475E-002 4.952032E-002 1.116436E-001 1.126013E-002 1.127887E-002 1.488088E-001 1.760494E-002
27 42.5 6.979789E-002 1.552872E-002 4.252957E-002 2.844225E-002 5.664833E-002 7.340168E-003 7.351073E-003 7.499046E-002 9.418075E-003
28 47.5 3.802769E-002 1.381232E-002 2.696600E-002 1.848059E-002 2.602370E-002 6.040789E-003 6.048614E-003 3.153889E-002 6.305331E-003
29 52.5 1.635870E-002 1.224046E-002 1.996661E-002 1.348661E-002 9.932751E-003 5.761545E-003 5.767889E-003 1.166165E-002 3.045514E-003
30 57.5 1.055512E-002 9.139995E-003 1.842323E-002 8.848452E-003 5.282689E-003 3.398862E-003 3.396254E-003 7.294139E-003 1.772940E-003
31 62.5 7.337372E-003 5.579039E-003 1.378223E-002 4.750885E-003 2.867118E-003 3.958350E-003 3.962366E-003 4.583398E-003 1.101889E-003
32 67.5 3.919775E-003 2.053346E-003 7.535108E-003 1.141742E-003 9.221409E-004 2.075138E-003 2.077331E-003 2.024574E-003 4.962301E-004
33 72.5 2.706556E-003 7.272206E-004 4.648195E-003 1.608546E-005 2.665109E-004 1.278444E-003 1.279978E-003 9.130735E-004 2.972258E-004

```

Figure 15. Example average main output file ('AvgResults.out'). Note the similarity to figure 12 and the absence of state vector information. The last line of data in this example file is line 32.

```

StdDevResults.out
1 Earth Meteoroid Engineering Model Results - STANDARD DEVIATIONS
2 EarthMEM version 3.0.5
3 File Written at 02:32:20 PM 02/09/15
4
5 User's Input File: Y:\MEMR2_0_5\test_tle.txt
6 Limiting mass was selected
7 Mass Value: 10^-6.000000 grams
8
9 Orientation - Cube, ram faces velocity vector
10
11 Total Flux on Spacecraft
12 Average of All States
13 Cross Sectional Flux 3.716670e-001 /m^2/yr
14
15 +X Ram -X Wake +Y Port -Y Starboard +Z Zenith -Z Nadir -r Earth Sun Anti-Sun
16 Average Speed (km/s) 0.2 1.6 1.8 1.5 0.2 1.2 1.2 0.1 0.5
17 Total Flux (#/m^2/yr) 4.081e-001 4.538e-002 7.614e-001 5.907e-001 2.685e-001 1.053e-001 1.060e-001 8.697e-001 3.503e-001
18 V Bin Centered
19 2.5 2.321764E-003 3.189737E-004 1.434562E-003 1.402768E-003 1.229157E-003 3.582728E-004 3.616088E-004 3.965068E-003 1.076672E-003
20 7.5 4.565306E-002 8.828423E-003 3.758345E-002 3.269669E-002 2.760183E-002 7.536717E-003 7.582942E-003 6.390100E-002 2.850924E-002
21 12.5 7.574578E-002 7.057709E-003 1.013148E-001 8.367510E-002 4.242957E-002 1.567205E-002 1.580955E-002 1.569506E-001 6.065501E-002
22 17.5 1.361993E-001 1.365773E-002 1.988053E-001 1.402762E-001 5.901423E-002 2.779740E-002 2.803361E-002 2.341618E-001 1.075037E-001
23 22.5 5.522326E-002 1.072089E-002 1.481404E-001 1.080904E-001 5.900634E-002 1.713395E-002 1.727259E-002 1.452060E-001 6.890378E-002
24 27.5 3.812676E-002 6.836853E-003 8.957144E-002 6.839761E-002 3.487658E-002 1.032517E-002 1.039811E-002 1.110207E-001 3.697173E-002
25 32.5 2.856113E-002 3.936695E-003 5.802823E-002 4.495135E-002 2.606680E-002 6.385363E-003 6.424842E-003 7.925390E-002 2.053050E-002
26 37.5 1.772910E-002 2.700700E-003 3.639226E-002 3.062940E-002 1.893943E-002 3.810478E-003 3.831637E-003 5.102923E-002 1.110228E-002
27 42.5 1.294911E-002 4.895623E-003 2.453354E-002 2.115473E-002 9.009212E-003 2.694039E-003 2.704938E-003 2.588211E-002 5.720013E-003
28 47.5 2.109715E-002 7.481652E-003 1.861232E-002 1.671263E-002 2.797959E-003 2.770285E-003 2.778406E-003 6.925990E-003 5.551012E-003
29 52.5 1.379040E-002 1.003585E-002 1.631204E-002 1.889659E-002 5.272951E-003 2.777071E-003 2.782509E-003 7.941415E-004 2.039566E-003
30 57.5 9.187004E-003 7.093780E-003 1.552965E-002 1.443932E-002 4.802203E-003 3.157664E-003 3.162465E-003 8.732297E-004 8.301902E-004
31 62.5 7.022446E-003 3.396603E-003 1.208174E-002 7.984644E-003 2.580381E-003 2.781578E-003 2.785503E-003 6.200782E-004 5.456495E-004
32 67.5 4.247236E-003 2.189942E-004 6.963772E-003 1.900792E-003 4.191885E-004 1.813524E-003 1.815908E-003 9.153254E-004 3.911554E-004
33 72.5 4.181227E-003 9.526561E-004 6.575808E-003 2.055911E-005 3.603915E-004 1.857818E-003 1.860193E-003 1.152524E-003 4.621822E-004

```

Figure 16. Example standard deviation main output file ('StdDevResults.out'). The format is identical to that of the average results file ('AvgResults.out'; see fig. 15), but standard deviations are reported rather than averages. The last line of data in this example file is line 32.

3.4.2 Individual Speed Distributions and Associated Files

For each spacecraft state vector or TLE used, MEMR2 outputs the flux within a 3D grid in azimuth, elevation, and velocity. The resolution and orientation of this grid is chosen by the user at the beginning of a run (see secs. 3.2.2.10 and 3.2.2.4). 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 and the last value 355, 356, or 399. Each of the remaining columns corresponds to a speed bin. Speed values are not reported in the speed distribution files, but are listed in the main results file. These files have the following additional characteristics:

- Unlike the main results files, these files have no header. The user may keep a copy of the main output file as a record of the calculation.
- For some runs, the first few lines may contain zero meteoroid flux. This is normal for a spacecraft in LEO when the body-fixed output coordinate frame is selected. In this case, the Earth shields the spacecraft from nadir-originating meteoroids.
- These files report the meteoroid flux per angular bin. These bins are not equal in area and cover smaller portions of the sky in the zenith and nadir directions (see fig. 17). If the user wishes to generate plots of meteoroid flux as a function of direction, he or she will need to convert flux per angular bin to flux per square degree or, alternatively, use the igloo output files (sec. 3.4.3).

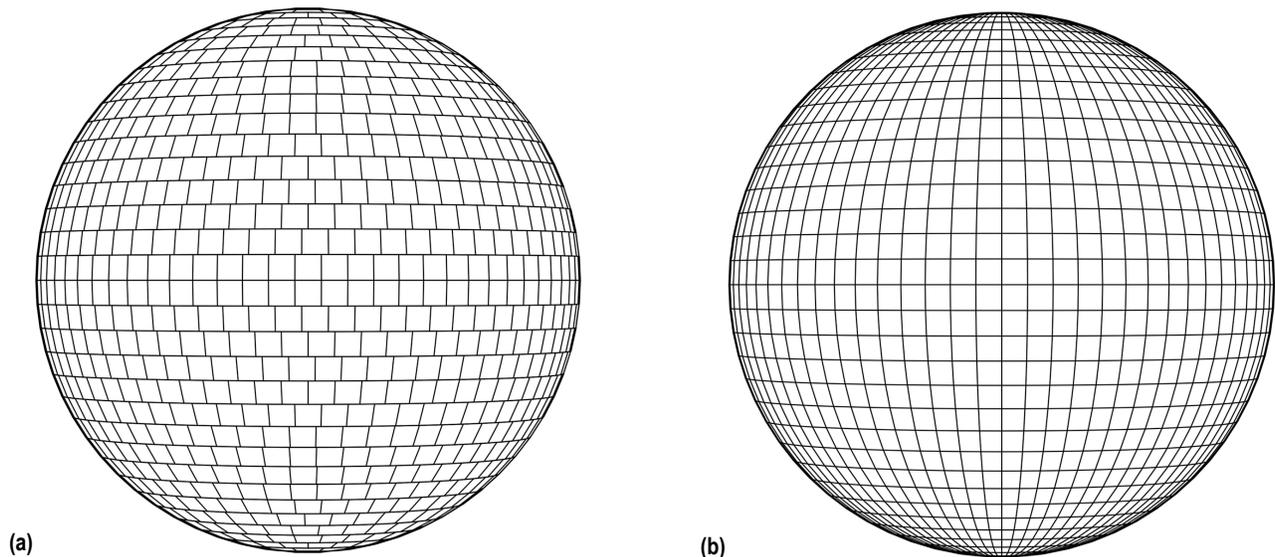


Figure 17. Examples of (a) quasi-equal area threat igloo and (b) azimuth and elevation grid. These examples are for 5° angular resolution.

3.4.2.1 SpdDistMap*i*.out. As MEM analyzes the meteoroid environment along a given trajectory, it produces a series of files named SpdDistMap*i*.out, where *i* is the state vector number. The number of individual speed distribution files should be equal to the number of input state vectors or TLEs, or, if the random draw option is used, the number of random draws. These files are used to compute all other output files, and are by default deleted at the end of a run. If the user wishes to keep all individual speed distribution files, each of which corresponds to a state vector or TLE, the user can opt to ‘output intermediate distribution files.’

3.4.2.2 AvgSpdDistMap.out. This file reports the average of all SpdDistMap*i*.out file data; it is analogous to AvgResults.out but reports the flux to the chosen angle and speed resolution. The format is identical to that of the SpdDistMap*i*.out files.

3.4.2.3 StdDevSpdDist.out. This file reports the standard deviation of the flux values in the speed distribution files; these standard deviations correspond to the averages in AvgSpdDist.out. These standard deviations quantify the variation in the meteoroid environment along the given trajectory and do not provide information regarding the uncertainty of the environment model. The format is identical to that of the SpdDistMap*i*.out and AvgSpdDistMap.out files.

3.4.3 Threat Igloo Files

The speed distribution files 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 1 square degree in size. As elevation increases, the number of blocks in a ring decreases in order to maintain an angular area similar to that in the 0° ring. Figure 17 illustrates this threat igloo concept. These igloo distribution files are used by BUMPER, the Johnson Space Center risk assessment tool.

Igloo files begin with nine columns of information specifying block location within the igloo. The first three columns are block indices: the first column is an element identification 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. Finally, the eighth and ninth columns contain the midpoint value for elevation and azimuth. Fluxes are reported in columns 10 and greater; the number of columns is determined by the chosen speed resolution.

3.4.3.1 AvgMEMIgllooDist.out. MEMR2 does not produce individual igloo files for each state vector. However, the average environment is reported in AvgMEMIgllooDist.out.

3.4.3.2 StdDevMEMIgllooDist.out. If the user chooses to ‘output standard deviation files,’ MEM will produce a standard deviation file in the igloo format. This file contains the standard deviation of the flux in each igloo bin, computed over the entire spacecraft trajectory in line 18.

4. INTERPRETING MEMR2 OUTPUTS

The MEMR2 software offers the user a choice of multiple coordinate frames and spacecraft orientations, and also reports meteoroid fluxes to varying levels of detail. This section aids the user in the correct interpretation and use of MEMR2 outputs.

4.1 Viewing Results and Making Plots

Once MEMR2 has completed its calculations and the user has clicked ‘OK’ in the pop-up notification to return to the main GUI, the user has several options to view results from within the application. The user may opt to ‘View Results,’ prompting the software to open the main output file using the WordPad text editor. If WordPad is not installed, the plain-text results file can be opened with another text editor.

The user can also choose to ‘Make Plot,’ which will prompt MEMR2 to plot the average flux per speed bin (see fig. 18 for an example). The number of points plotted is determined by the velocity resolution choice made by the user, but the user can adjust the plot limits by right-clicking on the graph. There is no option to save the plot aside from a screen capture, but the graph can be reproduced from the AvgSpdDistMap.out file. Each column in this file corresponds to a speed bin and each row corresponds to a direction; the overall speed distribution can thus be obtained by summing over all rows.

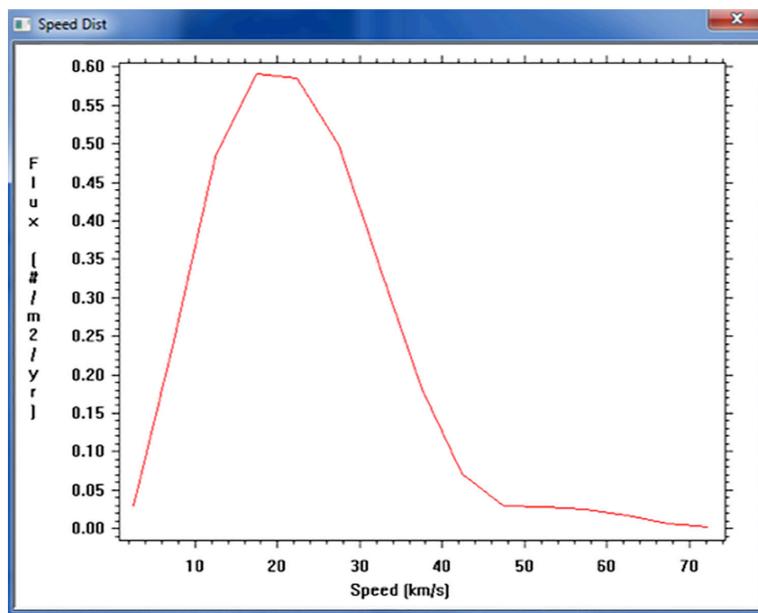


Figure 18. Example speed distribution plot generated within the MEMR2 main user interface after completion of a run.

4.2 Coordinate Frames

For each submodel, the user can choose to receive output data in either a body-fixed or an inertial coordinate frame. In this section, each of these reference frames is described in detail, making frequent reference to a ‘central body.’ For Earth-orbiting spacecraft, the central body is the Earth; for lunar-orbiting spacecraft, the central body is the Moon; and for interplanetary spacecraft, the central body is the Sun.

Users should note that the meteoroid environment is directional and, as the spacecraft changes directions relative to the Sun, the meteoroid directionality will change as well. Earth- and Moon-orbiting spacecraft may benefit from shielding effects, where the central body blocks a portion of the meteoroid environment. As the spacecraft changes position relative to the central body, the section of the environment that is blocked will shift, possibly resulting in noticeable changes in meteoroid directionality and flux.

4.2.1 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 $-\hat{x}$. For Earth- and lunar-orbiting spacecraft, the spacecraft’s angular momentum vector about the central body defines \hat{y} ; i.e., $\hat{y} = \hat{h} = \hat{r} \times \hat{x}$. The \hat{z} direction is then defined by the cross product of the \hat{x} and \hat{y} directions. The body-fixed coordinate frame is defined differently for interplanetary spacecraft; in this submodel, $\hat{z} = \hat{h} = \hat{r} \times \hat{x}$, while $\hat{y} = \hat{z} \times \hat{x}$ (see fig. 20). This difference in coordinate frame definition tends to align the z -axis with ecliptic north for interplanetary spacecraft.

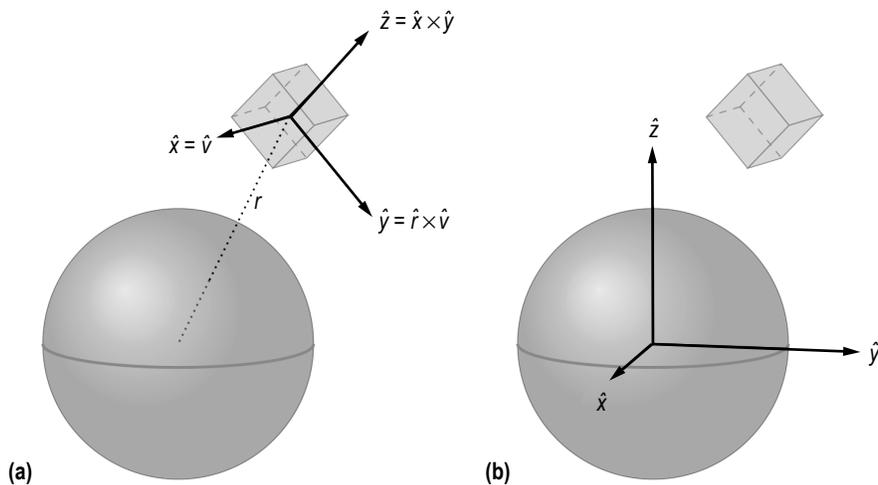


Figure 19. Illustrations of (a) body-fixed and (b) inertial coordinate frames for the Earth and lunar submodels. The sphere in each diagram represents the central body (Earth or Moon), while the spacecraft is represented by a cube. For a prograde orbit, the y -axis will tend to point in the direction of the central body’s north pole. For a retrograde orbit, the reverse is true, as shown in this diagram. For a perfectly circular orbit, $\hat{z} = \hat{r}$.

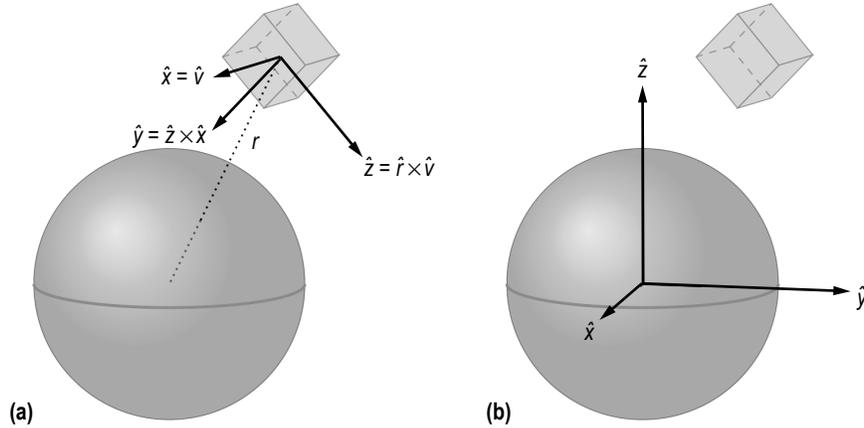


Figure 20. Illustrations of (a) body-fixed and (b) inertial coordinate frames for the interplanetary submodel. The sphere in each diagram represents the Sun, while the spacecraft is represented by a cube. For a prograde orbit, the z -axis will tend to point towards ecliptic north. For a retrograde orbit, the reverse is true, as shown in this diagram. For a perfectly circular orbit, $\hat{y} = -\hat{r}$.

Users should note that although \hat{r} and \hat{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).

4.2.2 Inertial Coordinate Frames

In an inertial reference frame, \hat{x} points in the direction of the vernal equinox at epoch J2000; this vector is identical for each central body and submodel. The x - y plane is then taken to be either the central body's equatorial plane (for Earth- and lunar-orbiting spacecraft) or the ecliptic plane (for interplanetary spacecraft). The \hat{z} is perpendicular to this plane and points toward geographic, selenographic, or ecliptic north. The inertial coordinate systems for the Earth, Moon, and interplanetary submodels are also known, respectively, as ECI, MCI, and ecliptic reference frames. The epoch in each case is 12:00 UT on January 1, 2000, or J2000.

4.2.3 Azimuth and Elevation

In addition to reporting the so-called 'cube fluxes' reported in the main output file, MEMR2 also reports the flux per angle interval in the speed distribution and igloo files. 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 4 gives the azimuth and elevation angles for the cube faces reported for a body-fixed frame.

Table 4. Azimuth and elevation angles corresponding to the six cube faces reported for a body-fixed frame. Note that $\hat{h} = \hat{y}$ for the Earth and lunar submodels, while $\hat{h} = \hat{z}$ for the interplanetary submodel.

		θ	φ
Ram	\hat{y}, \hat{x}	0°	0°
Wake	$-\hat{x}$	180°	0°
Port	\hat{y}	90°	0°
Starboard	$-\hat{y}$	270°	0°
Zenith or 'North'	\hat{z}	0°	90°
Nadir or 'South'	$-\hat{z}$	0°	-90°

4.2.4 Two-Line Element Coordinate Frame

All input state vectors are required to be in J2000 ECI, MCI, or ecliptic coordinates. However, TLEs are defined in a TEME reference frame (<<http://celestrak.com/columns/v04n03/>>). The SGP4 propagator, which is used by MEM to convert TLEs to state vectors, preserves this reference frame, resulting in a coordinate frame inconsistency.

This inconsistency in reference frame is thought to be insignificant compared to the accuracy limitations of TLEs.¹⁹ Nevertheless, the user should keep this issue in mind; for the most accurate results, users should convert TEME state vectors to J2000 state vectors using a tool such as STK (see appendix B for an example).

4.3 Flux Reporting

MEMR2 reports the meteoroid flux to several levels of fidelity; this section discusses the types of meteoroid flux reported so that the user can better determine which suits his or her needs.

4.3.1 Total Cross-Sectional Flux

The lowest fidelity flux describing the environment is the 'cross-sectional flux' reported in the main and average output 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. The flux is expressed per square meter of cross section.

This flux can easily be converted to the flux on one side of a randomly tumbling plate by dividing 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).

4.3.2 Cube Fluxes

The main and average results files also report the meteoroid fluxes incident on a cubic spacecraft. The normal vectors of the six cube faces (ram, wake, port, starboard, zenith, and nadir) are aligned with the axes of the body-fixed coordinate frame (described in sec. 4.2.1). In general, the sum of these ‘cube fluxes’ does not and should not equal the cross-sectional flux (sec. 4.3.1). 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).

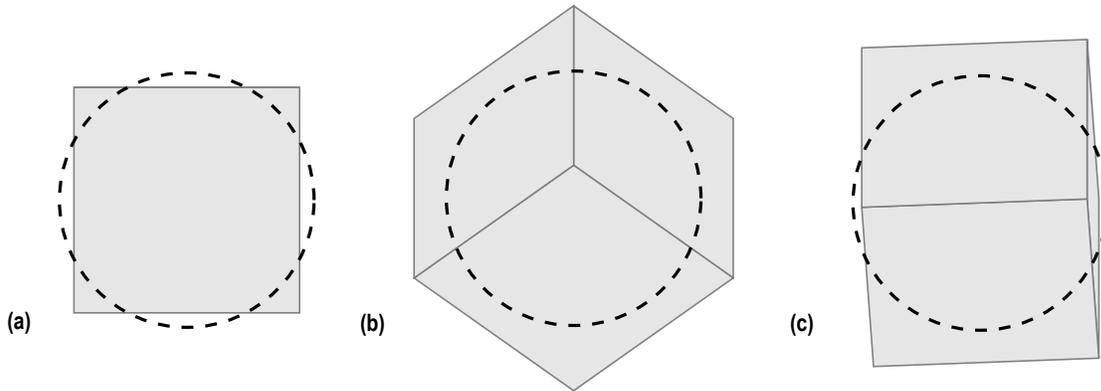


Figure 21. A cube with unit side length viewed from three different directions: (a) face-on, (b) vertex-on, and (c) nearly edge-on, demonstrating how a cross section varies with viewing angle. For the sake of comparison, the outline of a sphere of unit cross-sectional area is overlaid as a dashed black line.

In addition to the above surfaces, MEMR2 also calculates the flux on surfaces facing the Earth or Moon, facing the Sun, and facing away from the Sun. Communications equipment and solar panels may have surfaces with these alignments. For each surface, MEMR2 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.

4.3.3 Flux on a Rotating Spacecraft

If a spacecraft rotates as it moves along its trajectory, the cube surfaces discussed in section 4.3.2 may not be meaningful. Instead, the user can choose to calculate the flux for a spacecraft that is rotating about its angular momentum or velocity vector. If the spacecraft is rotating about the velocity vector, flux on the ram and wake surfaces will still be reported along with the flux on the rotating surface (all other directions). If the spacecraft is rotating about the angular momentum vector, flux on the zenith and nadir surfaces will be reported along with the flux on the rotating surface.

The user is cautioned that the flux on the rotating surface is not equivalent to the flux on four sides of a nonrotating cube. In the case of rotation about the angular momentum vector, for example, the incident flux per square meter of an azimuthally averaged cross section is reported. For a unit meter cube, this azimuthally averaged cross section is $4/\pi$ m², or roughly 1.273 m². More generally, the azimuthally averaged cross section of a non-concave generalized cylinder is $sh/2\pi$, where s is circumference and h is height. 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 MEMR2 is concerned, these rotation options correspond to 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 (Earth, Moon, or Sun). If the orientation of the spacecraft at each point in time is known, the user can perform postprocessing to extract more precise fluxes.

4.3.4 Igloo and Speed Distribution Files

For more detailed directional information, users can refer to the igloo and speed distribution files (AvgSpdDist.out and AvgMEMIgllooDist.out). These files are described in section 3.4; each provides the flux per speed interval and per solid angle interval. AvgSpdDist.out divides the flux into a regular grid in azimuth and elevation and the size of the directional bins is proportional to $\cos \phi$. AvgMEMIgllooDist.out, in contrast, divides the flux into azimuth and elevation bins that are approximately equal in size (see fig. 17).

4.3.5 Instantaneous Environment Information

For those users requiring high fidelity in speed, direction, and time, MEMR2 offers the option of saving the so-called 'intermediate files.' These files, named SpdDistMap*i*.out, give the instantaneous meteoroid environments corresponding to each input state vector. 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 (<<http://www.nasa.gov/centers/johnson/techtransfer/technology/MS-C-23774-1-bumper.html>>).

APPENDIX A—FAQ AND TROUBLESHOOTING

This section describes several common issues the user may encounter and the fixes for them.

If the program crashes, check to make sure there is enough RAM and available hard drive space for the program to run.

If the program still crashes, gather as much information as you can about the type of computer you have and the specific test case you are running. Most likely there will be intermediate files left in the directory; save these and notify the MEO.

Q. MEM exits immediately after the user hits ‘Calculate.’

A. Missing input or data files can cause MEMR2 to exit in this manner. Verify that all six binary data files (see table 2) and the user-generated input file are in the same directory as the MEMR2 executable.

Q. MEM exits immediately after the user hits ‘Calculate’ with a Windows dialog error ‘TODO:<File Description> has stopped working.’

A. The user may not have write permissions for the installed MEMR2 folder. If the permissions cannot be altered, the user can reinstall MEM in a less restricted directory. See section 3.1 for more information.

Q. State vectors or TLEs are missing from the main output file.

A. This can result from too short a header in the input file. If the data begin before line 7 in the input file, MEM will miscategorize the data as header text. Check that the header is exactly six lines long.

Q. The last state vector in the main output file is repeated.

A. This error may occur if there are empty lines at the end of the input file. Please ensure that there is no text in the input file following the last state vector value.

Q. The GUI is unresponsive.

A. Once the user clicks ‘Calculate,’ MEM begins its environment calculation. Control of the GUI is not returned to the user until calculations are complete and the user clicks ‘OK’ in the notification pop-up window. If the program is running, output files will regularly appear in the MEMR2 directory.

- Q. Output files do not appear in the MEMR2 directory.
- A. When using the Windows 7 operating system, the output files may not appear in the installation directory even though the program completes without error. If this occurs, look for a menu bar option called 'Compatibility Files' within File Explorer. Clicking this menu option will take you to a file path in a virtual store location. The output files are stored here, and the user can move these files to the MEMR2 directory or store them in a user-specified location.

APPENDIX B—GENERATING INPUT FILES WITH SYSTEMS TOOL KIT

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, the process for loading TLEs into STK (release 10) is described as follows:

- (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 to one orbital period.

To generate state vectors for this or any other user-defined trajectory, perform the following:

- (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.

REFERENCES

1. Grün, E.; Zook, H.A.; Fechtig, H.; and Giese, R.H.: “Collisional Balance of the Meteoritic Complex,” *Icarus* Vol. 62, No. 2, pp. 244–272, doi:10.1016/0019-1035(85)90121-6, June 1985.
2. Boeder, P.; Lambert, J.C.; Liemohn, H.; et al.: “Space Station Program Natural Environment Definition for Design,” SSP 30425, Rev. B, NASA Johnson Space Center, Houston, TX, 237 pp., February 1994.
3. Smith, R.E.: “Natural Orbital Environment Guidelines for Use in Aerospace Vehicle Development,” NASA-TM-4527, NASA Marshall Space Flight Center, Huntsville, AL, 162 pp., June 1994.
4. McDonnell, T.; McBride, N.; Green, S.F.; et al.: “Near Earth Environment,” in *Interplanetary Dust*, E. Grün, B.Å.S. Gustafon, S.F. Dermott, and H. Fechtig (eds.), Springer Berlin Heidelberg, Heidelberg, Germany, pp. 163–231, doi:10.1007/978-3-642-56428-4_4, 2001.
5. Kessler, D.J.: “Average Relative Velocity of Sporadic Meteoroids in Interplanetary Space,” *AIAA Journal*, Vol. 7, No. 12, pp. 2337–2338, doi:10.2514/3.5539, December 1969.
6. Scott, S.; Fisher, M.; Evans, H.; et al.: “BUMPER II Micrometeoroid and Orbital Debris Risk Assessment Independent Technical Inspection Report,” NESC-RP-05-66, NASA Langley Research Center, Hampton, VA, 833 pp., April 2005.
7. Gehman, H.W.; Barry, J.L.; Deal, D.W.; et al.: “Columbia Accident Investigation Board,” Vol. 1, NASA HQ, Washington, DC, 248 pp., August 2003.
8. Christiansen, E.L.; and Kerr, J.H.: “Ballistic limit equations for spacecraft shielding,” *Int. J. Impact. Eng.*, Vol. 26, Nos. 1–10, pp. 93–104, doi:10.1016/S0734-743X(01)00070-7, December 2001.
9. Campbell-Brown, M.D.: “High resolution radiant distribution and orbits of sporadic radar meteoroids,” *Icarus*, Vol. 196, No. 1, pp. 144–163, doi:10.1016/j.icarus.2008.02.022, July 2008.
10. Jones, J.: “Meteoroid Engineering Model – Final Report,” SEE/CR-2004-400, NASA Marshall Space Flight Center, Huntsville, AL, 48 pp., June 2004.
11. Christiansen, E.L.: “Meteoroid/Debris Shielding,” NASA/TP—2003–210788, NASA Johnson Space Center, Houston, TX, 114 pp., August 2003.
12. Hawkins, G.S.: “Variation in the occurrence rate of meteors,” *Astron. J.*, Vol. 61, No. 1243, p. 386, doi:10.1086/107367, November 1956.

13. Weiss, A.A.; and Smith, J.W.: "A southern hemisphere survey of the radiants of sporadic meteors," *Mon. Not. R. Astron. Soc.*, Vol. 121, No. 1, p. 5, doi:10.1093/mnras/121.1.5, July 1960.
14. Sekanina, Z.: "Statistical Model of Meteor Streams. IV. A Study of Radio Streams from the Synoptic Year," *Icarus*, Vol. 27, No. 2, pp. 265–321, doi:10.1016/0019-1035(76)90009-9, February 1976.
15. Jones, J.; and Brown, P.G.: "Sporadic meteor radiant distributions: orbital survey results," *Mon. Not. R. Astron. Soc.*, Vol. 265, No. 3, p. 524, doi:10.1093/mnras/265.3.524, December 1993.
16. Divine, N.: "Five populations of interplanetary meteoroids," *J. Geophys. Res.*, Vol. 98, No. E9, pp. 17,029–17,048, doi:10.1029/93JE01203, September 1993.
17. Squire, M.; Scott, S.; Mclay, T., et al.: "Independent Review of Constellation (Cx) Orion Vehicle Micrometeoroids and Orbital Debris (MMOD) Risk Analysis," NESC-RP-08-00468, NASA Langley Research Center, Hampton, VA, 315 pp., January 2009.
18. Suggs, R.M.; Cooke, W.J.; Brown, P.G.; et al.: "Meteor Properties Database - Final Report," SEE/TP-2004-400, NASA Marshall Space Flight Center, Huntsville, AL, 145 pp., August 2004.
19. Vallado, D.; Crawford, P.; Hujsak, R.; and Kelso, T.S.: "Revisiting Spacetrack Report #3," Paper Presented at AIAA/AAS Astrodynamics Specialist Conference and Exhibit, Keystone, CO, August 21–24, 2006.

REPORT DOCUMENTATION PAGE			Form Approved OMB No. 0704-0188		
<p>The public reporting burden for this collection of information is estimated to average 1 hour per response, including the time for reviewing instructions, searching existing data sources, gathering and maintaining the data needed, and completing and reviewing the collection of information. Send comments regarding this burden estimate or any other aspect of this collection of information, including suggestions for reducing this burden, to Department of Defense, Washington Headquarters Services, Directorate for Information Operation and Reports (0704-0188), 1215 Jefferson Davis Highway, Suite 1204, Arlington, VA 22202-4302. Respondents should be aware that notwithstanding any other provision of law, no person shall be subject to any penalty for failing to comply with a collection of information if it does not display a currently valid OMB control number.</p> <p>PLEASE DO NOT RETURN YOUR FORM TO THE ABOVE ADDRESS.</p>					
1. REPORT DATE (DD-MM-YYYY) 01-10-2015		2. REPORT TYPE Technical Memorandum		3. DATES COVERED (From - To)	
4. TITLE AND SUBTITLE NASA Meteoroid Engineering Model Release 2.0			5a. CONTRACT NUMBER		
			5b. GRANT NUMBER		
			5c. PROGRAM ELEMENT NUMBER		
6. AUTHOR(S) A.V. Moorhead, H.M. Koehler, and W.J. Cooke			5d. PROJECT NUMBER		
			5e. TASK NUMBER		
			5f. WORK UNIT NUMBER		
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) George C. Marshall Space Flight Center Huntsville, AL 35812			8. PERFORMING ORGANIZATION REPORT NUMBER M-1403		
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES) National Aeronautics and Space Administration Washington, DC 20546-0001			10. SPONSORING/MONITOR'S ACRONYM(S) NASA		
			11. SPONSORING/MONITORING REPORT NUMBER NASA/TM-2015-218214		
12. DISTRIBUTION/AVAILABILITY STATEMENT Unclassified-Unlimited Subject Category 16 Availability: NASA STI Information Desk (757-864-9658)					
13. SUPPLEMENTARY NOTES Prepared by the Spacecraft and Vehicle Systems Department, Engineering Directorate					
14. ABSTRACT The Meteoroid Engineering Model release 2.0 (MEMR2) software is NASA's most current and accurate model of the meteoroid environment. It enables the user to generate a trajectory-specific meteoroid environment for spacecraft traveling within the inner solar system. In addition to the total meteoroid flux, MEMR2 provides the user with meteoroid directionality and velocity information. Users have the ability to make a number of analysis and output choices that tailor the resulting environment to their needs. This Technical Memorandum outlines the history of MEMR2, the meteoroid environment it describes, and makes recommendations for the correct use of the software and interpretation of its results.					
15. SUBJECT TERMS meteoroids, spacecraft hazards, risk modeling, software					
16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT	b. ABSTRACT	c. THIS PAGE			STI Help Desk at email: help@sti.nasa.gov
U	U	U	UU	60	19b. TELEPHONE NUMBER (Include area code) STI Help Desk at: 757-864-9658

National Aeronautics and
Space Administration
IS20
George C. Marshall Space Flight Center
Huntsville, Alabama 35812