

Simulation of Micron-Sized Debris Populations in Low Earth Orbit

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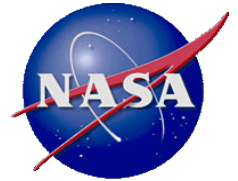
Abstract

The update of ORDEM2000, the NASA Orbital Debris Engineering Model, to its new version – ORDEM2010, is nearly complete. As a part of the ORDEM upgrade, this paper addresses the simulation of micro-debris (greater than 10 μm and smaller than 1 mm in size) populations in low Earth orbit. The principal data used in the modeling of the micron-sized debris populations are in-situ hypervelocity impact records, accumulated in post-flight damage surveys on the space-exposed surfaces of returned spacecrafts. The development of the micro-debris model populations follows the general approach to deriving other ORDEM2010-required input populations for various components and types of debris. This paper describes the key elements and major steps in the statistical inference of the ORDEM2010 micro-debris populations. A crucial step is the construction of a degradation/ejecta source model to provide prior information on the micron-sized objects (such as orbital and object-size distributions). Another critical step is to link model populations with data, which is rather involved. It demands detailed information on area-time/directionality for all the space-exposed elements of a shuttle orbiter and damage laws, which relate impact damage with the physical properties of a projectile and impact conditions such as impact angle and velocity. Also needed are model-predicted debris fluxes as a function of object size and impact velocity from all possible directions. In spite of the very limited quantity of the available shuttle impact data, the population-derivation process is satisfactorily stable. Final modeling results obtained from shuttle window and radiator impact data are reasonably convergent and consistent, especially for the debris populations with object-size thresholds at 10 and 100 μm .

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Paper Outline

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 - a. Window data
 - b. Radiator data
3. The construction of a reference degradation/ejecta source model
 - a. Major assumptions
 - b. Orbital elements and the surface area of a large-size space-resident object
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4. Prediction of STS impacts from the reference degradation/ejecta model
 - a. Damage laws
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 - c. Butterfly-type directional debris fluxes
5. Statistical inference of the new ORDEM micro-debris populations
 - a. Definition of model parameters
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 - c. Population modeling for debris objects of MD (medium-density) material type
 - d. Population modeling for debris objects of HD (high-density) material type
 - e. Consistency analysis for models based on different types of data
6. Discussions on the modeling results
7. Concluding remarks and future work



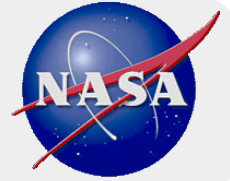
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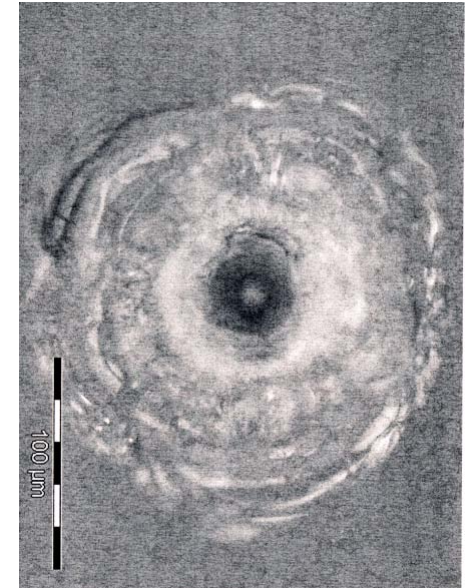
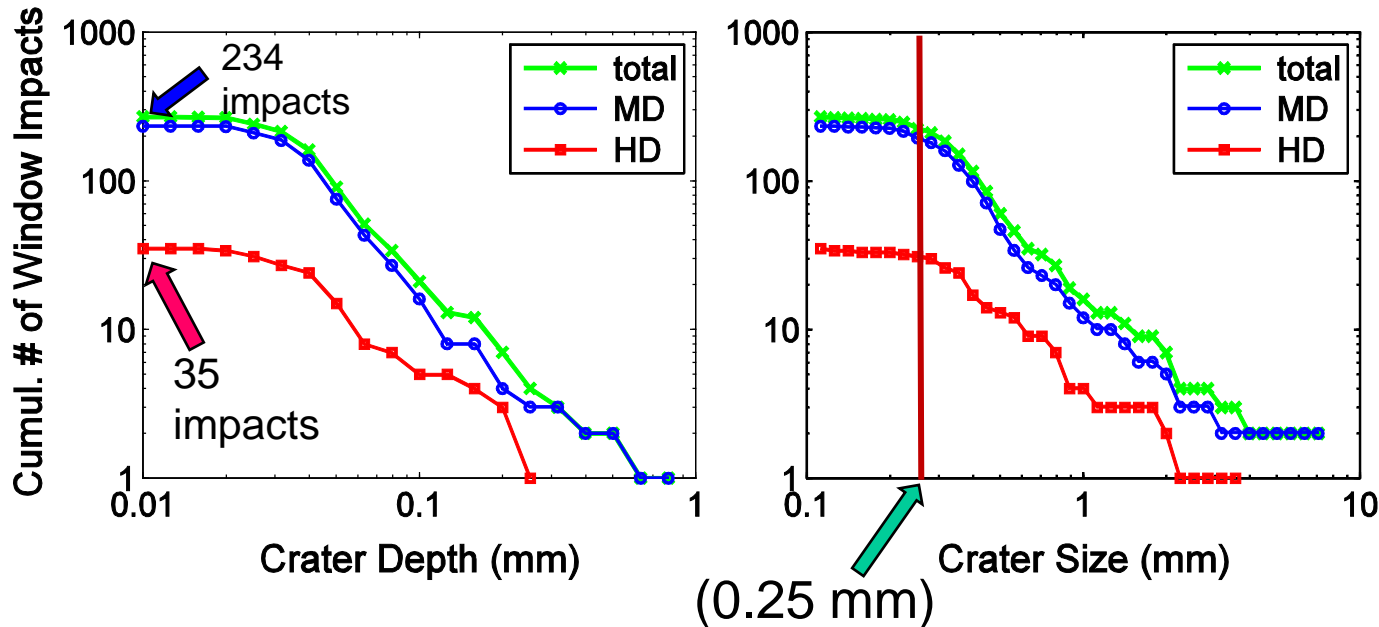
STS impact data and the development of ORDEM2010 sub-millimeter populations (in LEO)

- **To use newly collected OD data and to take advantage of newly developed analytical techniques and supporting models, NASA has recently updated the Orbital Debris Engineering Model, ORDEM2000, to its new version, ORDEM2010.**
- **ORDEM2010 micro-debris (greater than 10 μm and smaller than 1 mm in size) populations are statistically estimated from space shuttle (window and radiator) impact data that are collected from post-flight visual damage inspections of space-exposed shuttle orbiter surfaces.**
- **The development of the model micro-debris populations follows the general procedure of statistical inference used in ORDEM2010. It takes the following key steps:**
 - Data analysis,
 - Construction of reference populations,
 - Definition of model parameters in terms of the reference populations,
 - Linking model parameters with data,
 - Searching for best estimates of the model parameters based on data; updating reference populations using the best estimated parameters, and
 - Assessment of the modeling results and repeating the above two steps until satisfactory results are obtained.



Example window data with a material-type breakdown

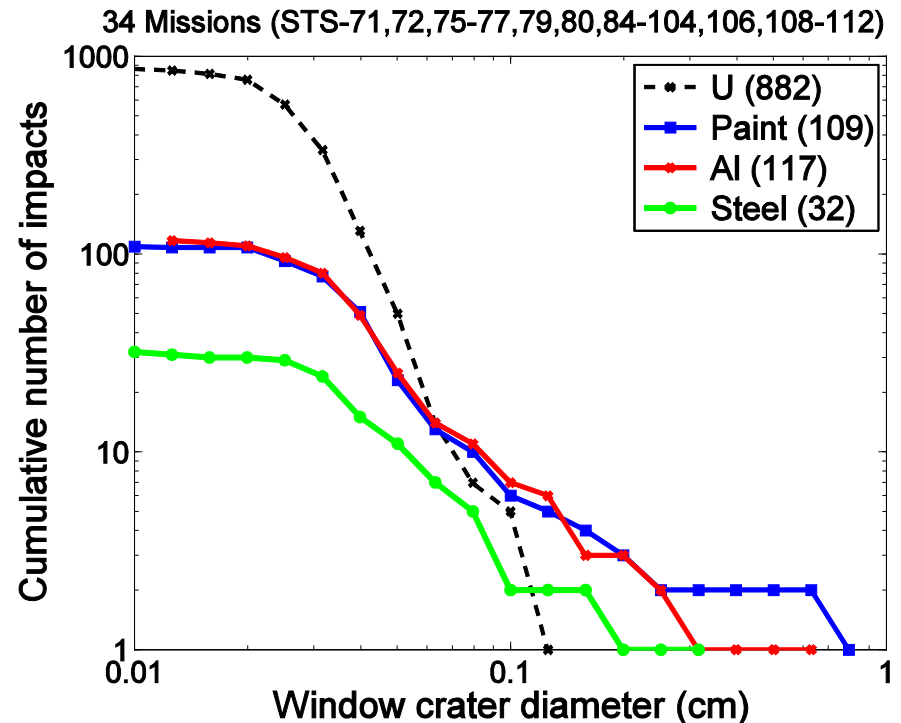
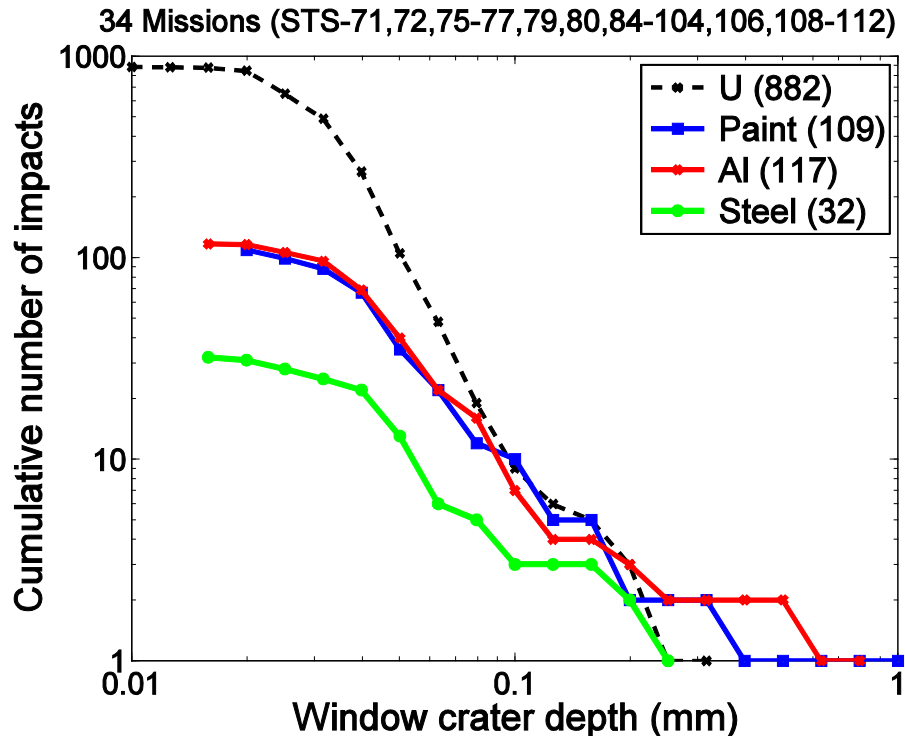
34 Missions (STS-71,72,75-77,79,80,84-104,106,108-112)



- Cumulative crater depth and size (diameter) distributions of STS window impacts from medium-density (MD) and high-density (HD) OD impactors as identified in post-flight surveys of 34 mission flights (STS-71, 72, 75-77, 79, 80, 84-104, 106, 108-112). Steel, Cu, and Ag are considered to be HD and all others MD. (*Note that MD includes two impacts from low-density plastic impactors.*)
- MD and HD data are used separately to derive respective MD & HD populations.



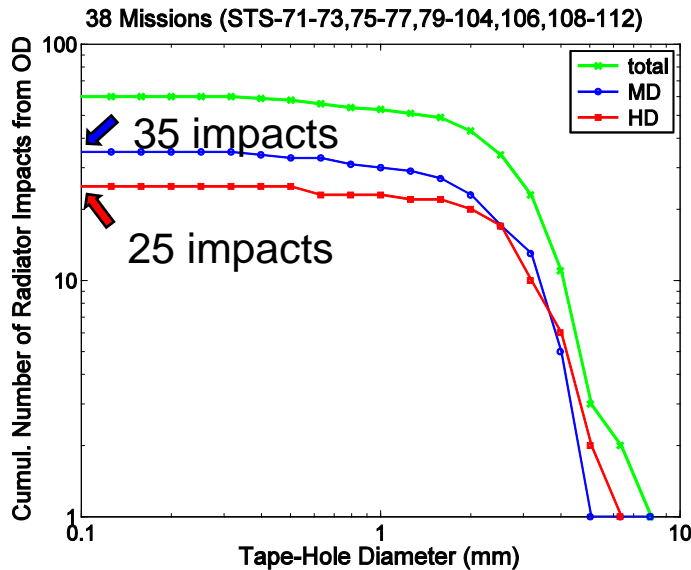
Window data: crater diameter and depth distributions of paint, Al, & steel impacts



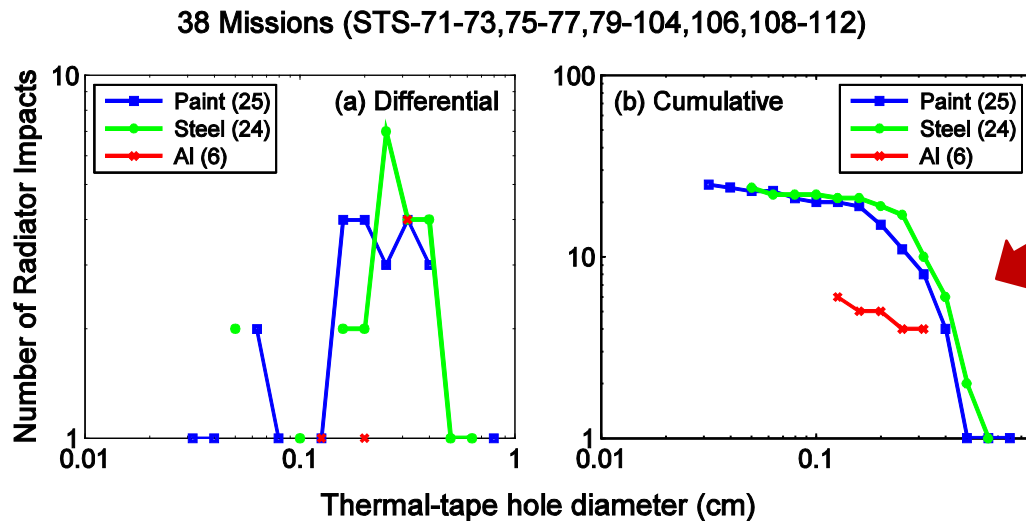
- Note the close resemblance between the total numbers and cumulative crater depth and size (diameter) distributions of window impacts from Paint and Al (Aluminum) objects. This is a useful information on the abundance of Paint and Al particles in the debris environment.



Radiator data with a material-type breakdown



- **Cumulative tape-hole diameter distributions of STS radiator impacts from medium-density (MD) and high-density (HD) impactors as identified in post-flight surveys of 38 mission flights (STS-71-73, 75-77, 79-104, 106, 108-112).**

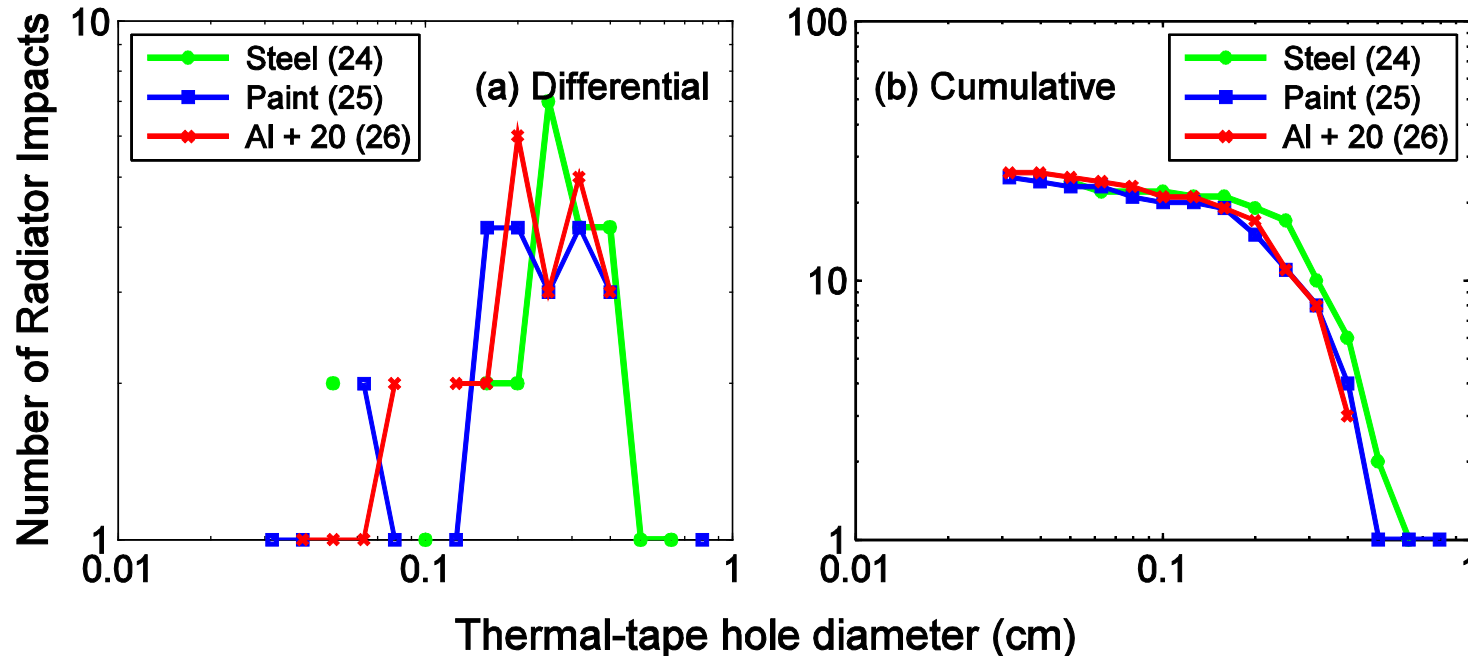


There is **an aluminum-on-aluminum issue** for the radiator impacts. Some unknowns are assumed to be missing Al impacts.



Extraction of missing Al impacts from unknowns

38 Missions (STS-71-73,75-77,79-104,106,108-112)



- **Missing Al impacts are picked up from unknowns using the “rejection method” (with a minor modification) based on the known distributions of unknowns, paint, and Al impacts**
 - A description of the “rejection method” can be found in “Numerical Recipe”



A degradation/ejecta model: general considerations and assumptions

- An ORDEM2010 model debris population consists of a large group of representative orbits. It is practically infeasible to obtain micron-sized debris populations from the STS impact data *directly* without providing adequate prior information on the debris populations (i.e., reference populations).
 - Small objects in the debris environment are believed to generate mostly due to some regular, non-violent processes of surface material degradation.
 - A degradation/ejecta source model is constructed to provide the desired reference populations for the micro-debris population derivations.
 - Catalog (>10 cm) objects are taken as parent bodies of the small micron-sized particles.
- **Two major assumptions in the construction of the degradation/ejecta model.**
 - Number of micro-debris objects created by a surface degradation process is proportional to the surface area of a parent body. (*Note that the production rates for different material types are to be determined by the data of different material types during the population derivation process.*)
 - Micro-debris objects created in a surface degradation process share the same orbit with its parent body *at the creation time*. Every orbit of the degradation/ejecta particles is propagated independently under the influence of solar radiation pressure and atmospheric drag, in addition to gravitational perturbations.

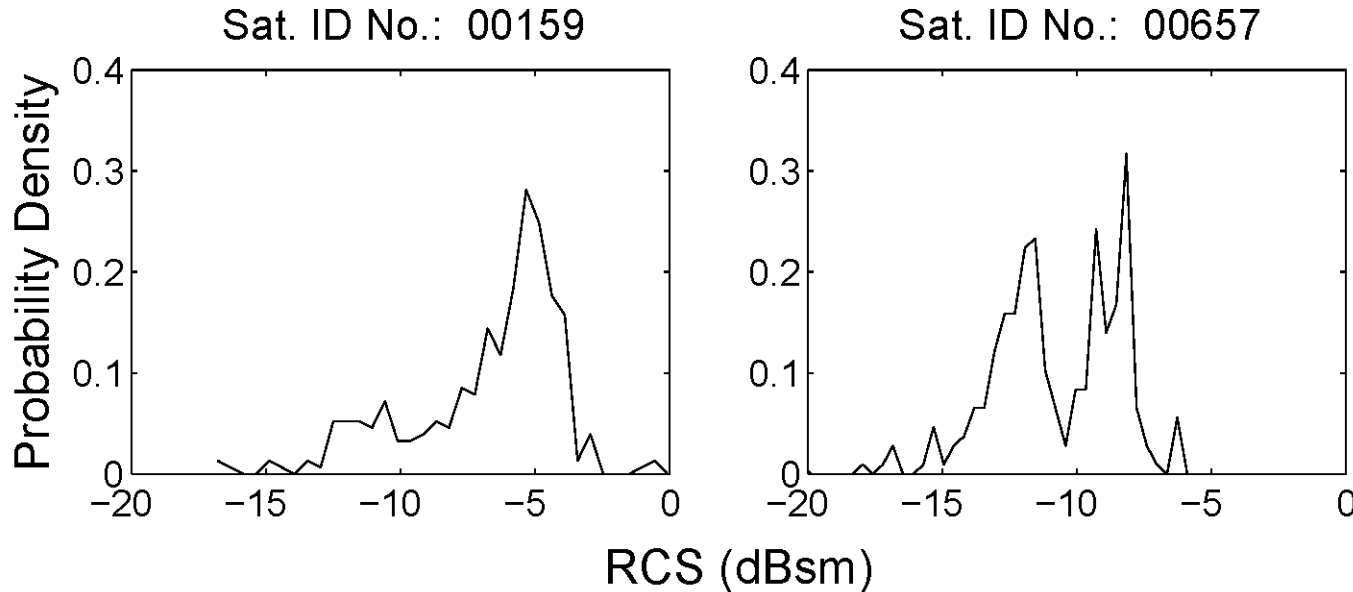


A degradation/ejecta model: orbital parameters and surface area of parent bodies

- **The building of a degradation/ejecta source model requires detailed information on the orbital parameters and surface areas of parent bodies.**
- **The SSN catalog maintains a historical record of orbital parameters for every tracked object, known as Two Line Element (TLE) set data. Orbital elements of an individual SSN cataloged object can be conveniently extracted from the TLE sets for any reference time as long as the object is in orbit at that time.**
- **SSN products do not explicitly provide a surface area for a cataloged object, though an area-to-mass ratio could be estimated from the information contained in the SSN catalog. There are different sources to obtain approximate surface areas for SSN catalog objects.**
 - The detailed dimensions of some intact satellites are known. For these objects, their surface area may be computed from the physical dimensions measured before launch.
 - For objects with known mass, an approximate surface area may be obtained from the area-to-mass ratio estimated from the TLE records.
 - However, both physical dimensions and mass of the majority of the catalog objects, breakup fragments in particular, cannot be directly measured. In general, the information on the physical and geometrical properties of such an SSN cataloged object is embedded in its radar cross section (RCS) measurements.

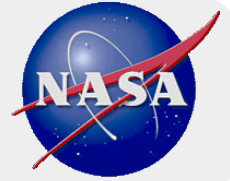


Observed RCSs of SSN cataloged objects: two examples



- The probability density distributions of RCS shown left are based on 320 measured RCSs for #00159 and 284 values for #00657

- The “size” (or “characteristic length”) of an OD object is usually estimated from the mean (or median) of the measured RCSs.
- The conversion from RCS to object size is an intricate inverse problem in fundamental radiative scattering theories, requiring an accurate interpretation of returned radar signals originating from the complicated interaction of electromagnetic radiation with an object of arbitrary morphology. NASA uses SEM (Size Estimation Model) to convert RCS to object size. SEM is developed using static laboratory RCS measurements of a representative set of debris objects.



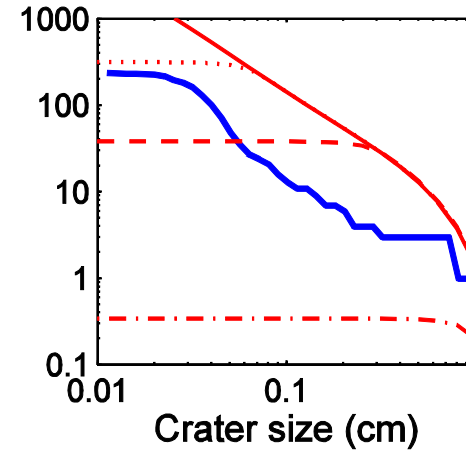
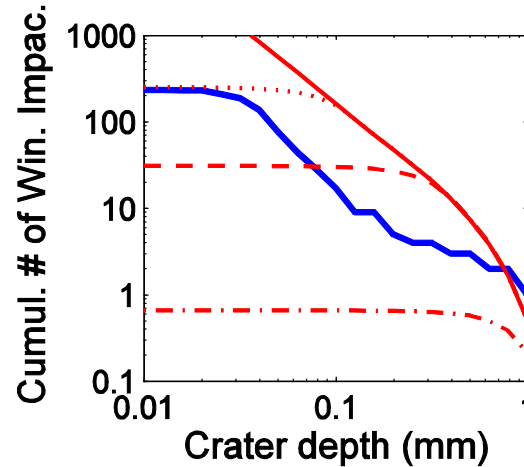
Linking model populations with data

- **When data and reference model populations are available, the next critical step is to link data with model populations.**
- **The model prediction of STS impacts demands three major elements**
 - 1) Damage equations (or damage laws) to predict impact damage characteristics, given physical size and material density of a projectile and impact conditions,
 - 2) Detailed information on STS flight timeline and space-exposed area-time/directionality of each window and radiator element of a shuttle orbiter (i.e., the so-called Mark-files) for every altitude session of each involved space mission, and
 - 3) Detailed information on directional debris fluxes (of “butterfly” type) on every orbit of involved space missions, calculated using the reference and updated model populations.



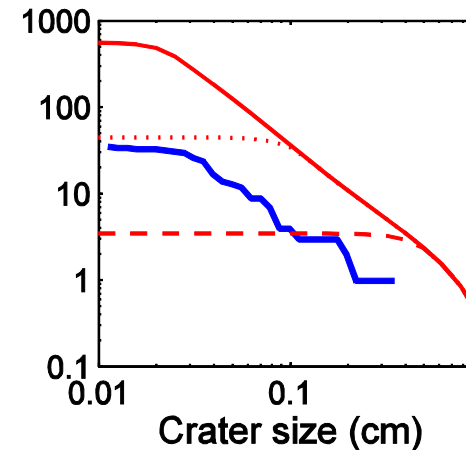
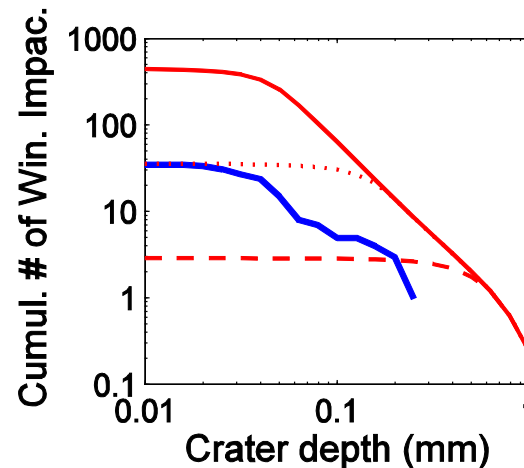
STS impacts predicted from reference populations in the degradation/ejecta model

Window impacts predicted from MD objects in reference populations



— STS data (MD)
 — $\geq 10 \mu\text{m}$, (MD)
 ... $\geq 31.6 \mu\text{m}$, (MD)
 - - $\geq 100 \mu\text{m}$, (MD)
 - · $\geq 316 \mu\text{m}$, (MD)

Window impacts predicted from HD objects in reference populations



— STS data (HD)
 — $\geq 10 \mu\text{m}$, (HD)
 ... $\geq 31.6 \mu\text{m}$, (HD)
 - - $\geq 100 \mu\text{m}$, (HD)
 - · $\geq 316 \mu\text{m}$, (HD)

- A Bayesian statistical process refines reference populations based on data!



Estimation of model populations from data

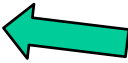
- **When data and reference populations are available and the connection between data and model populations is established (i.e., the model matrix calculated), model populations (more strictly speaking, model parameters) are estimated from data through an appropriate statistical approach.**
- **STS data are in the form of counts (i.e., number of impacts). The Poisson distribution is the nominal distribution for discrete data in much the same way that the Gaussian distribution is the bench-mark for continuous data.**
- **Since we have only one single data set (i.e., we are unable to repeat the random sampling process for the OD impacts), it is impossible to investigate the “actual” frequency distribution of the impacts. It simply assumes that the OD impacts follow a Poisson-like distribution. This means that the random mechanism of the OD impacts is assumed to be known to us, which is approximately Poisson.**




First-step best-estimated model parameters

Orbital Group	Model Estimates	
	adjust. factor	sigma (%)
MD, 10-31.6 um	0.18	7
MD, 31.6-100 um	0.45	15
MD, 100-316 um	1.15	21
MD, 316um-1mm	3.69	19

(MD)
 Power law (cumulative)
 size distribution in initial
 reference populations:
 $\sim (\text{object-size})^{-2.6}$



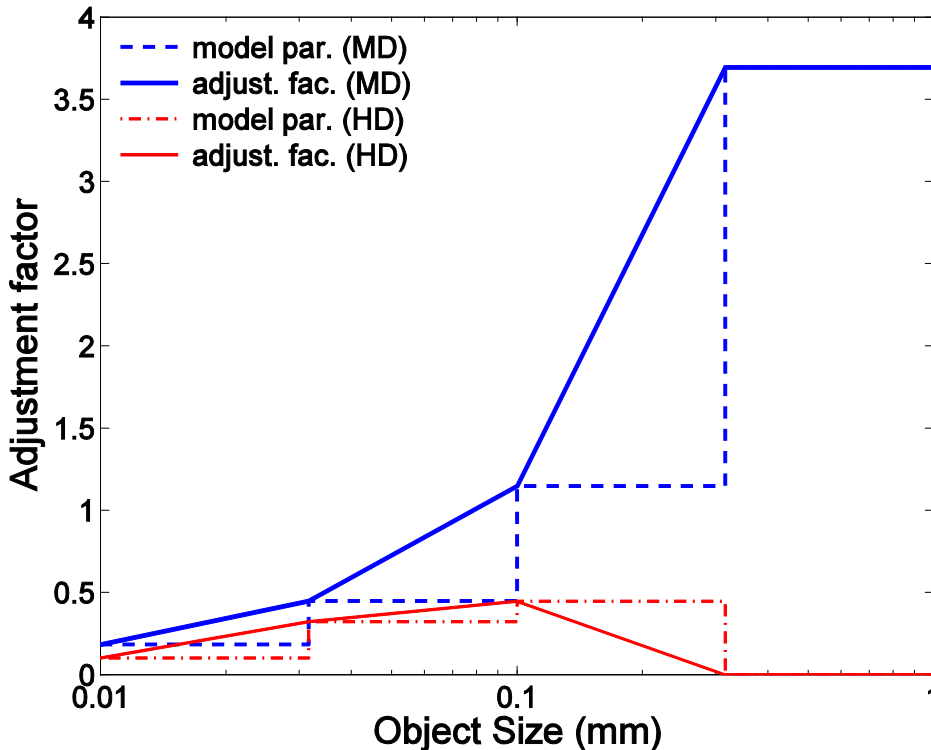
(HD)
 Power law (cumulative)
 size distribution in initial
 reference populations:
 $\sim (\text{object-size})^{-2.8}$



Orbital Group	Model Estimates	
	adjust. factor	sigma (%)
HD, 10-31.6 um	0.10	18
HD, 31.6-100 um	0.32	36
HD, 100-316 um	0.45	40
HD, 316um-1mm	0.00	38



Update of reference populations: first iteration

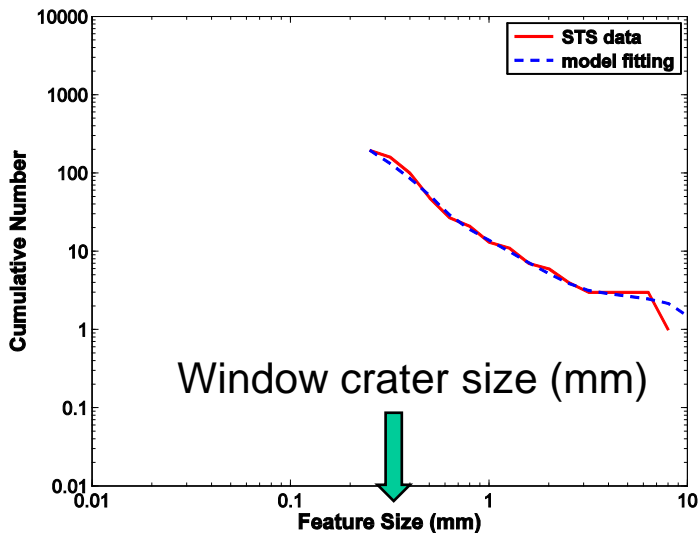
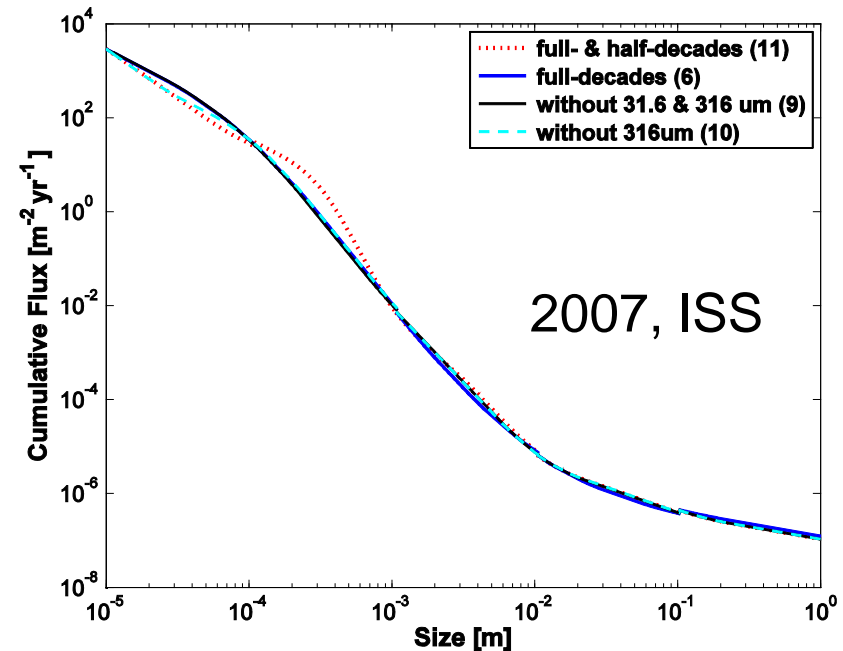
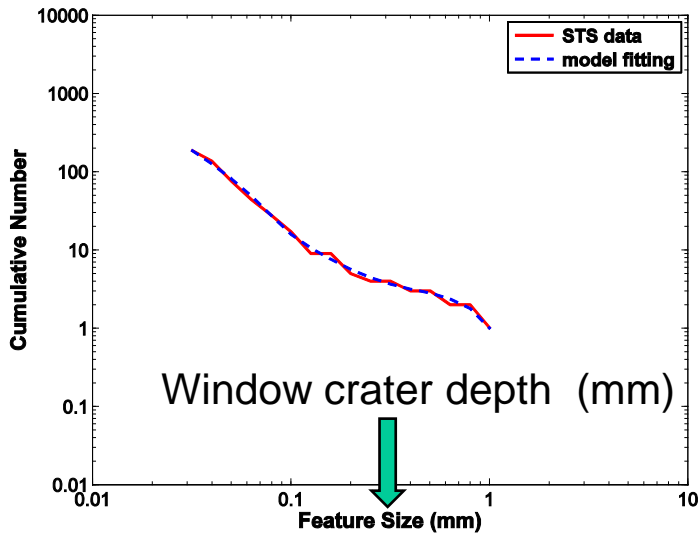


Note that other numerical schemes can also be used to construct adjustment factors from model parameters as a function of object size. As practical calculation results show, what scheme to use is not critical since all final adjustment factors will converge to ~ 1 .

- The adjustment factors used to update reference populations are obtained from model parameters through a simple numerical scheme as shown.
- Note the important difference between model parameters and adjustment factors applied to update reference populations. Only for a single parameter model, the model parameter will be identical to the single adjustment factor.
- The updated reference populations are to be used to recalculate model matrices and to re-derive a new set of model parameters. Such a procedure is repeated until all model parameters become sufficiently close to 1.



An issue with data fitting

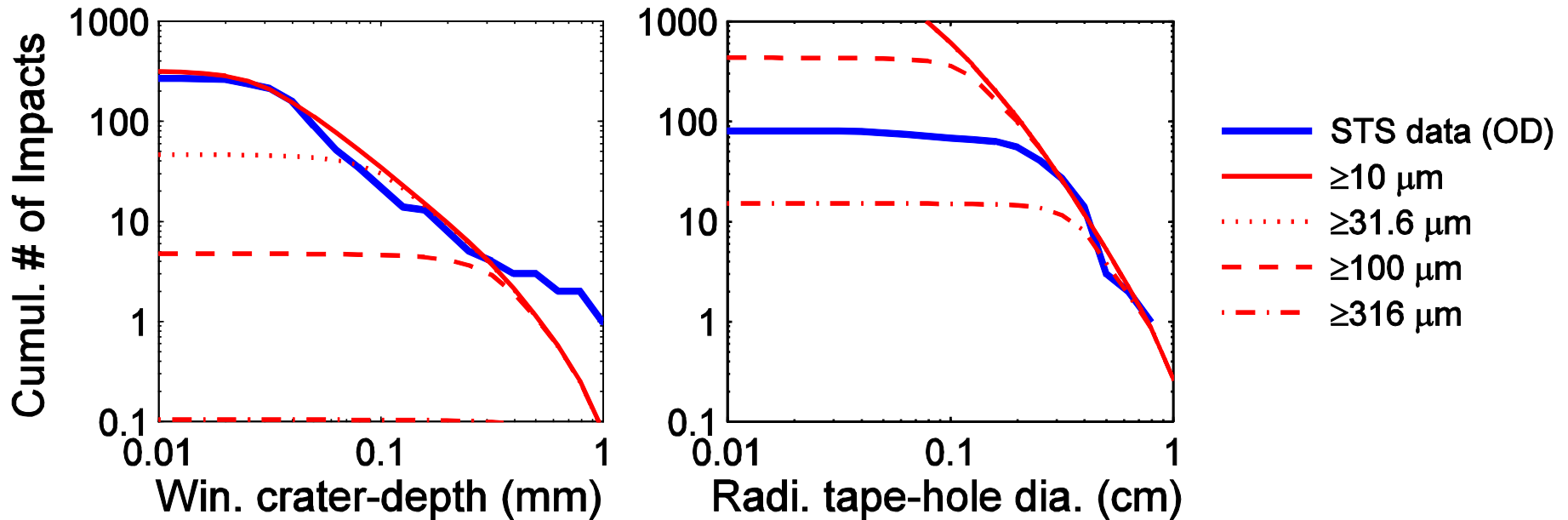


good data fitting \rightarrow bad results?

- Though the “*overemphasized*” data fitting (left) looks **good**, it generally causes the “dip” at $>31.6 \mu\text{m}$ and “hump” at $>316 \mu\text{m}$ cumulative fluxes (as shown in the above example) estimated from such derived model populations. See the next two slides for more discussions.



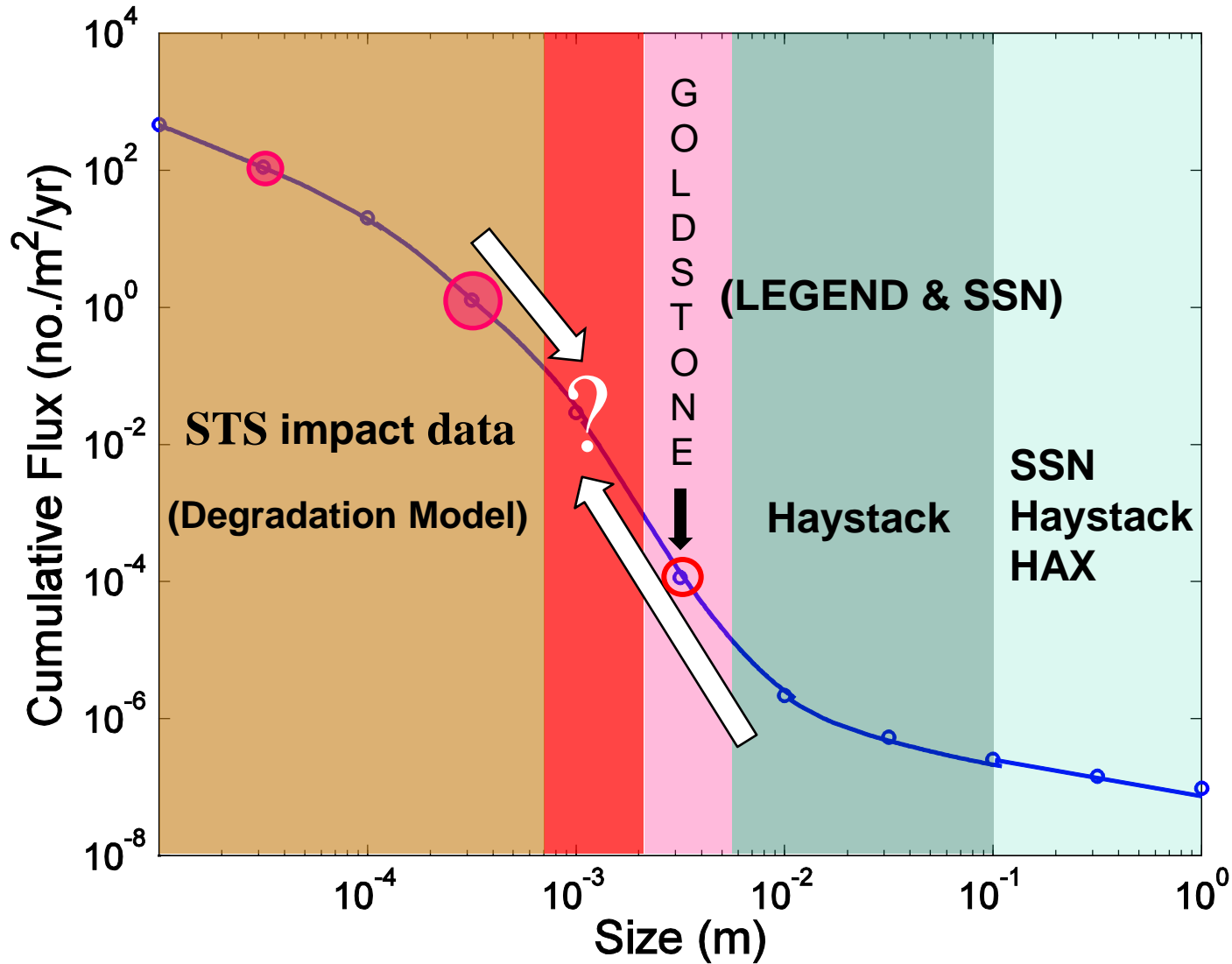
Final modeling results: MD+HD

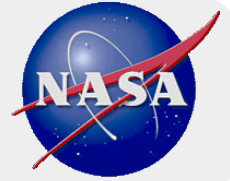


- Note the saddle-like shape and upward-turned tails of the window data curve (left panel)
- How is the data-matching in the final modeling results shown above compared with that shown in the last chart?



Derivation of ORDEM2010 model populations



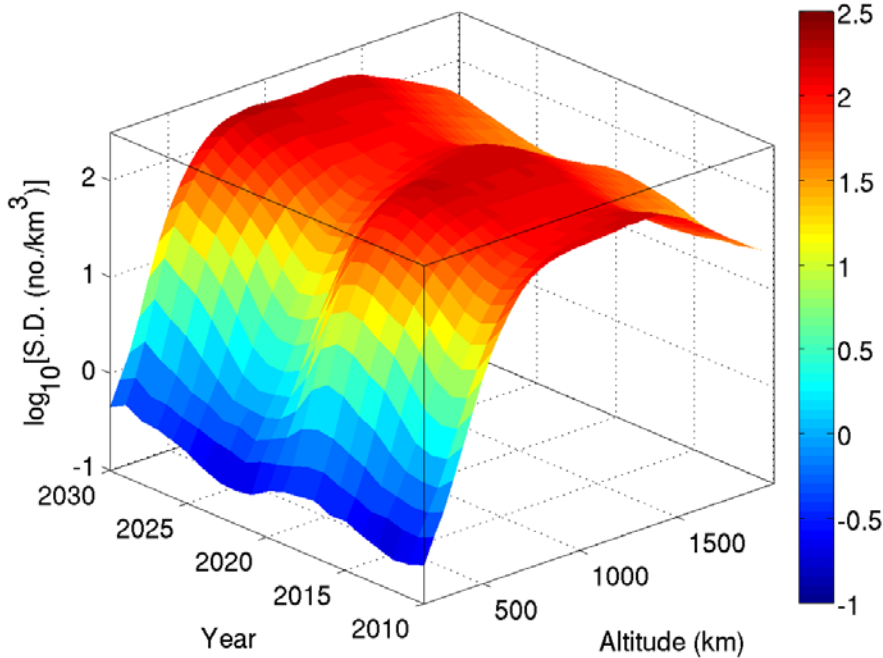


Spatial density distributions (≥ 10 and $\geq 100 \mu\text{m}$)

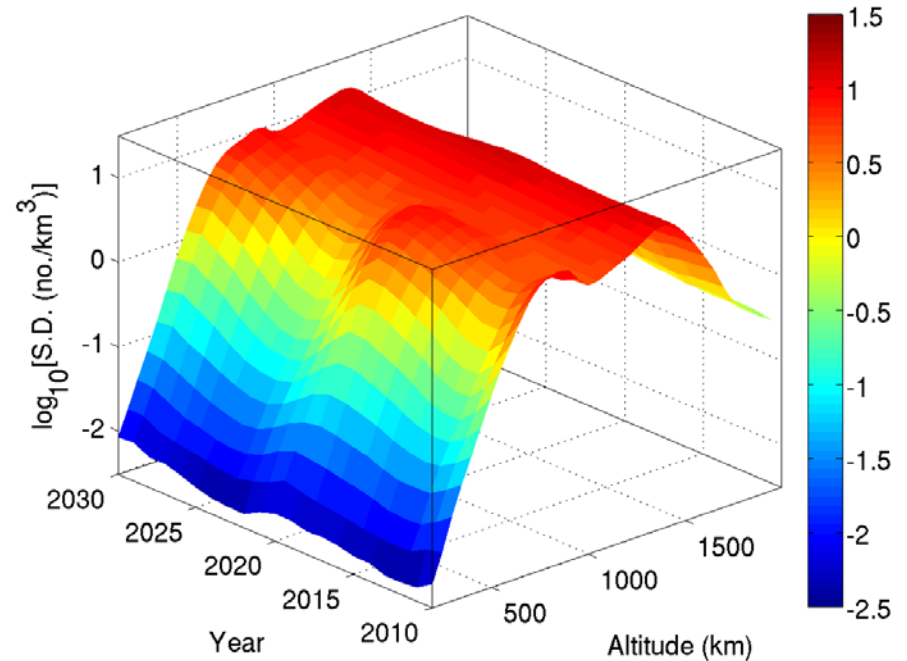
$\geq 10 \mu\text{m}$

$\geq 100 \mu\text{m}$

ORDEM2010, Spatial Density ($>10\mu\text{m}$)



ORDEM2010, Spatial Density ($>100\mu\text{m}$)





Summary

- **ORDEM2010 micro-debris populations are estimated from STS impact data.**
 - The principal data used in the modeling of the sub-millimeter debris populations are in-situ hypervelocity impact records, accumulated in post-flight damage surveys on the space-exposed surfaces of returned spacecrafts.
 - Besides data, the modeling process requires adequate prior information on the small-sized debris populations (i.e., reference populations from a source model).
 - The general statistical approach used in the population inference is stable and effective.
- **In spite of the very limited quantity of the available shuttle impact data, the population-derivation process is satisfactorily stable. Final modeling results obtained from shuttle window and radiator impact data are reasonably convergent and consistent, especially for the debris populations with object-size thresholds at 10 and 100 μm .**