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NASA Orbital Debris Engineering Model ORDEM 3.0 – Verification and Validation

Orbital Debris Program Office

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Acronyms

AP ..... argument of perigee
ASAT ..... anti-satellite weapon or test
Az..... azimuth

CCB ..... Configuration Control Board
CI ..... confidence interval
COTS ..... commercial off-the-shelf
cm ..... centimeter

DBS ..... data base, satellites
DOE ..... Department of Energy

ECC..... eccentricity
El..... elevation

FS..... (STS radiator) facesheet
FSH ..... (STS radiator) facesheet hole
FSdep ..... (STS radiator) facesheet crater depth

GEO ..... geosynchronous orbit
GTO ..... geosynchronous transfer orbit
GUI ..... graphical user interface

Ha..... height of apogee
HAX ..... Haystack Auxiliary Radar
HD ..... high density, OD mass density category
Hp ..... height of perigee
HVI ..... hypervelocity impact
HVIT ..... HVI Technology group; sister group of ODPO

IEEE ..... Institute of Electrical and Electronics Engineers
IN ..... "intact" (> 10 cm), OD mass density category set to that of aluminum
INC ..... inclination

JSC ..... Johnson Space Center

km ..... kilometer

LAT ..... latitude
Lc ..... characteristic length
LD ..... low density, OD mass density category
LEGEND ..... LEO to GEO Environment Debris model
LEO ..... low Earth orbit
LON ..... longitude
LRIR ..... Long Range Imaging Radar (*i.e.*, Haystack)
LVLH ..... local vertical / local horizontal

MD ..... medium density, OD mass density category

MEO ..... middle Earth orbit
MIT/LL ..... Massachusetts Institute of Technology / Lincoln Laboratory
MLE ..... maximum likelihood estimator
m ..... meter
mm ..... millimeter
MM ..... mean motion
MODEST ..... Michigan Orbital Debris Survey Telescope

N/A ..... not applicable
NASA ..... National Aeronautics and Space Administration
NOAA ..... National Atmospheric and Oceanic Administration

OD ..... orbital debris
ODPO ..... Orbital Debris Program Office (NASA)
ODRSO ..... Orbital Debris Research & Science Operations (Jacobs)
ORDEM ..... Orbital Debris Engineering Model

PCHIP ..... Piecewise Cubic Hermite Interpolation Polynomial
pdf ..... probability distribution function
PI ..... prediction interval
PRC ..... People's Republic of China

RAAN ..... right ascension of the ascending node
rcs ..... radar cross section [m^2]
RORSAT ..... Radar Ocean Reconnaissance SATellite

S/C ..... spacecraft
SEM ..... Size Estimation Model
SNR..... signal-to-noise ratio
SOCIT ..... Satellite Orbital Debris Characterization Impact Test
SSN ..... Space Surveillance Network
STS ..... Space Transportation System (specifically the US Space Shuttle)
SVVP ..... Software V&V Plan

TH ..... (STS radiator) thermal tape hole
TLE ..... two-line element set
TRD ..... technical requirements document

U ..... unknown (as it relates to impact features)

V&V ..... verification and validation

Symbols

χ^2 ..... chi-squared

° ..... degree

T_∞ ..... exospheric temperature

> ..... greater than

< ..... less than

μm ..... micrometer (micron)

§ ..... section

r ..... correlation coefficient

Ã ..... standard deviation

$\bar{\zeta}$ ..... unweighted average

$\check{\zeta}$ ..... weighted average

Glossary of Terms

Acquirer: the software customer, NASA's ODPO [*q.v.*]

Apparent magnitude: The brightness of an object (intact, debris) or, instrumental magnitude. It is the direct observable in orbital debris in the MODEST survey data.

Absolute magnitude: The brightness of an object (intact, debris) as it would appear at 36,000 km altitude and 0° phase angle. Since the MODEST rate box is set to view GEO objects, the apparent magnitude and absolute magnitude are similar.

Component: ORDEM subroutine or input data file.

Component testing: Testing conducted to verify the correct implementation of the design and compliance with program requirements for one software element (*e.g.*, unit, module) or a collection of software elements.

Design Phase: Jacobs software development project phase in which new or updated software is designed to meet all requirement specified in the drat execution plan, the execution plan is updated to contain the design and the verification and validation approach for the final software product, and the plan is finalized. This phase is traceable to IEEE §5.4 "Design Phase."

Development Phase: Jacobs software development project phase in which the software is coded to meet the requirements in the execution plan, and incremental, pre-beta, and beta testing of the software product occur. This phase is traceable to IEEE §5.5 "Implementation Phase."

Epoch: reference time of given satellite

Execution plan: A document that contains all necessary requirements, design information, and all elements of project management necessary to execute a software development or update project. This plan is traceable to both a Technical Requirements Document (TRD) and IEEE §5.1 "Management of V&V."

FY-1C: A People's Republic of China (PRC) LEO weather satellite; the target of a PRC ASAT test in January 2007.

Hazard analysis: A systematic qualitative or quantitative evaluation of software for undesirable outcomes resulting from the development or operation of a system. These outcomes may include injury, illness, death, mission failure, economic loss, property loss, environmental loss, or adverse social impact. This evaluation my include screening or analysis methods to categorize, eliminate, reduce, or mitigate hazards.

IDD: Interface Design Document; documentation that describes the architecture and design of interfaces between system and components. These descriptions include control algorithms, protocols, data contents and formats, and performance.

In situ: measured in place

Integration: the integrated ORDEM model (command line interface)

Integration testing: An orderly progression of testing of incremental pieces of the software program in which software elements, hardware elements, or both are combined and tested until the entire system has been integrated to show compliance with the program design, and capabilities and requirements of the system.

KESSLER: Refers to legacy software products for spacecraft and telescope cases. For spacecraft cases, the LEO_KESSLER_IGLOO and GEO_KESSLER_IGLOO program outputs are deemed "KESSLER" outputs. For telescope cases, this term applies to the LEO_KESSLER_TELE and GEO_KESSLER_TELE program outputs.

NaK: sodium-potassium liquid metal reactor coolant

ODRSO: (Jacobs) Orbital Debris Research & Science Operations

OL: ORDEM Lead (position, Jacobs team)

OTHR: ODPO category of anomalous debris from known and unknown sources ("OTHER")

Planning Phase: Jacobs software development project phase in which an initial draft of the execution plan is developed that contains a high-level discussion of the basic elements of the development project and a rough order magnitude estimate of cost and schedule. This phase is traceable to IEEE §5.2 "Concept Phase."

PM: Project Manager

Release Phase: Jacobs software development project phase in which the final validated software product is released per the delivery method specified in the execution plan. Final software documentation is released as specified in the execution plan. This phase is traceable to IEEE §5.7 "Installation and Checkout Phase."

Requirements Phase: Jacobs software development project phase in which new or updated requirements are collected and reviewed and the execution plan is updated to document the requirements for the software. This phase is traceable to IEEE §5.3 "Requirements Phase."

Supplier: the software supplier, Jacobs

SVVP: Software Verification and Validation Plan

System: the ORDEM model, including GUI

System Testing: The activities of testing an integrated hardware and software system to verify and validate whether the system meets its original objectives.

Validation: The process of evaluating software at the end of the software development process to ensure compliance to software requirements. "… validation assures that the correct product is built…" (Addy).

Verification: The process of determining whether or not products of a given phase of the software development process fulfill the requirements established during the previous phase. "Verification is intended to assure that the product is built correctly…" (Addy).

Verification and Validation Phase: Jacobs software development project phase in which a certification release of the software product is tested using the verification and validation plan contained within the execution plan and pass/fail criteria are evaluated and documented. This phase is traceable to IEEE §5.6 "Test Phase."

1.0 Introduction

The *NASA Orbital Debris Engineering Model ORDEM 3.0 - Verification and Validation* document accompanies the delivery of the latest Orbital Debris Engineering Model (ORDEM 3.0) and provides a detailed description of the verification and validation (V&V) process and results from the ORDEM 3.0 input populations.

1.1. MODEL VERIFICATION AND VALIDATION (V&V) PROCESS

The complete V&V process generally encompasses the entire software lifecycle, and is therefore a task from inception to retirement. The process for ORDEM 3.0 borrows from that formulated by the Institute of Electrical and Electronics Engineers (IEEE) in IEEE Std. 1012-1998. Table 1.1-1 highlights top-level V&V activities described in that document as they are interpreted to pertain to the ORDEM 3.0 program.

TABLE 1.1-1 – TOP-LEVEL ORDEM 3.0 V&V ACTIVITIES

Life Cycle Processes	ORDEM 3.0 Description
Acquisition	NASA decision to upgrade ORDEM 2.0 to ORDEM 3.0 and to enhance requirements
Supply	Inclusion by NASA of Jacobs as the developer of product
Development	Activities of Jacobs – analysis, design, coding, integration, installation, acceptance, verification, validation
Operation	Operation of ORDEM 3.0 and operational support to users
Maintenance	Future modifications, anomaly reporting, corrections and adaptations, and retirement of software

The first two processes, ***Acquisition*** and ***Supply***, are complete. The last two, ***Operation*** and ***Maintenance***, have not been initiated. This document reports on the latter portion of the third process, ***Development*** (Table 1.1-2).

TABLE 1.1-2 – DEVELOPMENT PHASE OF V&V

Development V&V Activities	ORDEM 3.0 V&V Tasks
Concept	Selection of system architecture, requirements, hardware, software, interfacing
Requirements	Define functional and performance requirements
Design	Detailed design of software components – databases, interfaces
Implementation	Develop coding, database structures, executables, testing
Test	Software and system testing and integration
Installation	Installation of software product in target environment
Checkout	NASA acceptance

All development V&V activities have been completed. The ***Design, Implementation, Test***, and ***Checkout*** activities are the subjects of this report.

1.2. PURPOSE

The purpose of this verification and validation document is to ensure that:

- all phases of the software (input file calls, igloo flux calculations, output file formats, GUI input operation) are compatible and consistent,
- population orbital element bins and spacecraft mode encounter igloo bins, and telescope/radar mode segmented bore-sight vectors are robust, and
- the populations themselves compare well against the appropriate measurement data.

This divides the process into its two named components – Verification (see Section 2.0) and Validation (see Section 3.0).

Elements of the IEEE V&V process are presented in tabular form in Appendix A. As Appendix A sometimes uses specialized terminology, relevant reference documents are provided in Section 4.0 as well as a glossary of terms on pages x and xi.

1.3. OTHER ORDEM 3.0 RELEASE PROCESSES

The formal V&V process described in this document guarantees the scientific and technical quality of the ORDEM tool. However, it is but one of several standards used to assess the model's quality and usability. Other release activities include §508 compliance via the Voluntary Product Accessibility Template, release authorization via the NASA JSC Application Control Board, delivery of the Software Release Request Authorization document and supporting documents, and delivery of the NASA Form 1679 "Disclosure of Invention and New Technology (Including Software)." While not discussed further in this document, these activities ensure that the general user community can operate ORDEM 3.0 effectively, safely, and securely.

1.4. REQUIREMENTS SUMMARY

Based on modeling data and techniques, NASA set a number of mandates for the new engineering model, ORDEM 3.0. The mandates for ORDEM 3.0 have expanded due to the singular events that occurred near the end of the last decade (*i.e.*, FY-1C anti-satellite test and Iridium/Cosmos collisions). Validation by analysis was performed for the ORDEM 3.0 requirements and specifications as defined by NASA. Details are shown in Table 1.4-1.

The results of the verification and validation activities were generated using all available data. These findings correctly and completely represent the ORDEM 3.0 model specifications and requirements defined by NASA.

TABLE 1.4-1 – ORDEM 3.0 REQUIREMENTS AND SPECIFICATIONS

Requirement	Result	Passed
Extend the model to GEO with the addition of (MODEST) data and modeling techniques to include GEO objects down to 10 cm	Complete; GEO component added to ORDEM	✓
Investigate and account for Molniya-type orbits with fixed arguments of perigee	Complete; Molniya and GTO orbit handling included	✓
Continue to include radar detections of debris (SSN, HAX, Haystack, and Goldstone) in the model and make use of these larger data sets to apply model fiducial points at half-decade sizes	Complete	✓
Use the NASA Hypervelocity Impact Technology (HVIT) group's STS microdebris impact database (STS 71-135 listing over 600 impacts), which includes crater dimension, chemical composition, and derived damage equations on STS aluminum radiator panels and windows	Complete; STS impact data incorporated to assess small particle (10 μm to ~ 3 mm) debris environment	✓
Assign small fragment (<10 cm) material density based on the SOCIT laboratory impact test results and on-orbit STS returned surface impactor analysis	Complete; low, medium and high density objects < 10 cm incorporated into ORDEM	✓
Model the Radar Ocean Reconnaissance SATellite (RORSAT) NaK coolant droplet population with radar measurements	Complete; NaK measurements incorporated into ORDEM	✓
Include specific, major debris-producing events that have been thoroughly observed (*i.e.*, the remnants of the FY-1C on 11 January 2007, and the accidental collision of Iridium 33 and Cosmos 2251 on 10 February 2009) and add to the general population	Complete; three major clouds modeled and incorporated into ORDEM populations	✓
Include long-term, debris-producing events that have been surmised from LEO high-altitude radar data (*i.e.*, SNAPSHOT, Transit, and 56° inclination-debris shedding activity) and add to the general population	Complete; all debris clouds modeled and incorporated into ORDEM populations	✓
Fully develop the Bayesian statistical model for population derivation	Complete	✓
Include debris population uncertainties	Complete; random and population uncertainties incorporated into ORDEM	✓
Provide "igloos" with equal-angle elements for full surrounding visualization of debris flux on spacecraft	Complete; two igloo configurations available	✓
Build the ORDEM 3.0 GUI to accommodate 4π steradian views of the large yearly input files.	Complete; full angle views incorporated via Mollweide projection	✓

2.0 Verification

Verification is the process of determining whether or not products of a given phase of the software development process fulfill the requirements established during the previous phase. Essentially, verification is intended to assure that the product is built correctly (Addy). The overall process determines whether or not the product fulfills requirements established by the program and verifies that it has done so correctly.

For ORDEM 3.0, verification includes comparisons between the generated debris populations and the binned versions that are used as direct input to ORDEM 3.0. It also includes comparisons between the outputs of the GUI for the tabulated sizes in both spacecraft and telescope/radar modes of operation, and other general sensitivity testing and code testing.

Traditional, though informal, verification methodologies used for software development by the Orbital Debris Program Office (ODPO) include, but are not necessarily limited to, the re-use of well-characterized legacy software, scientific and software engineering best practices, test case formulation and implementation, product versioning, and source code access control. For ORDEM 3.0 development and deployment, more formal methods were adopted.

2.1. LEGACY SOFTWARE

Because many of the algorithms used to compute fluxes in ORDEM 3.0 are unique, verifying them presented a special challenge. Several independent codes were created that use a different set of assumptions and algorithms to compute the same or similar flux values as the ORDEM software. These special codes are slower and can take many hours to run compared to the corresponding ORDEM codes. Therefore, only the MD60 (medium density, size = 1 m) test case was used for comparison.

The legacy ODPO programs – GEO_KESSLER_IGLOO and LEO_KESSLER_IGLOO – were modified to use the ORDEM populations to compute fluxes sorted by direction and velocity, specifically for spacecraft cases. The reason why a separate program is required for low Earth orbit (LEO) and geosynchronous orbit (GEO) is due to the differences in how the orbital elements of the populations are binned in the ORDEM model. These methods use an adaptation of the Kessler method (Kessler) to compute the spatial density of the debris, and “fly” the spacecraft through this environment. The Kessler spatial density formulation is based on the assumption of random ascending node and argument of perigee (AP), and therefore does not have the capability of simulating debris populations with fixed ascending nodes.

In order to compute fluxes for such cases independently from ORDEM, a Monte Carlo program was developed where each debris object is assigned an associated probability ellipsoid. The location of the debris object is randomly chosen, and the probability ellipsoid is treated as a spatial density with a fixed velocity vector that can now be compared against an asset orbit. This process is repeated many times in a Monte Carlo manner. In the case of the GEO_KESSLER_IGLOO and LEO_KESSLER_IGLOO programs, two alternate methods are used to integrate the populations – either a conventional Monte Carlo code, or by using a SOBOL quasi-random sequence. Alternatively, for telescope cases, the programs

LEO_KESSLER_TELE and GEO_KESSLER_TELE use the same spatial density subroutines to compute fluxes for the telescope cases. Finally, the algorithm GEO_LINE_DETECT uses this spatial density technique to compute the flux between any asset orbit – with fixed (or random) ascending node and fixed (or random) argument of perigee – against a debris population with a fixed ascending node.

In the remainder of this document (and Appendix C), the term "KESSLER" refers to the results of both the LEO and GEO runs. For spacecraft cases, the LEO_KESSLER_IGLOO and GEO_KESSLER_IGLOO program outputs are deemed "KESSLER" outputs. For telescope cases, this term applies to the LEO_KESSLER_TELE and GEO_KESSLER_TELE program outputs.

2.2. VERIFICATION METHODS

While the IEEE software V&V process defines top-level procedures, this section defines the methods that perform verification. Four methods are used to satisfy verification requirements: analysis, inspection, demonstration, and testing. The following sections depict these specific verification methods. Tables are included for each method that describe the success of the verification process. A green checkmark (✓) indicates a successful outcome, a red X (✗) indicates a failure. See Appendix C for figures and additional details in the case of verification by analysis, as well as accuracy and uncertainties of results. Inspection, demonstration, and testing are normally simple affirmation statements and are not included in any charts.

2.2.1. *Verification by Analysis*

The verification by analysis method uses techniques and tools such as computer simulations, input/output analysis, event trees, path analysis, and runtime analysis to confirm that requirements have been satisfied. In this case a researcher may develop specific criteria to answer very specific questions about a process. Analysis methods are used when testing and demonstration methods [*q.v.*] are not possible or feasible due to cost or schedule, or inspection is not adequate. For example, analysis is useful for statistical processes, including Monte Carlo simulations, or large scale simulation to verify a condition or expected outcome.

The spacecraft "utilization" component verifies that the same orbit can be computed from both a 10x10x1 igloo file and a 30x30x2 igloo file.

The spacecraft "risk of impact" component compares the number of impacts on a spacecraft, represented by a cube (1.0 m^2 on each side, in Local Vertical/Local Horizontal [LVLH] coordinate frame) in one year. The flux and binned distributions of pitch and yaw of the spacecraft are used in this comparison test.

In spacecraft mode, ORDEM 3.0 gives the user the option to enter an argument of perigee value or have ORDEM 3.0 generate a random argument of perigee. The purpose of spacecraft argument of perigee chi-squared (χ^2) comparison component compares two datasets – one with random argument of perigee selected and one without (*i.e.*, "fixed" AP.) See Appendix C for more details on how these two datasets were built.

The spacecraft mode component includes a χ^2 test between ORDEM 3.0 and KESSLER datasets generated with a random argument of perigee. The same is performed in the telescope/radar mode component. The IGLOO_ORBIT_SC and TELESCOPE_MODE components also perform a flux comparison between the same datasets as well as a goodness-of-fit test.

All comparisons between binned flux distributions are for medium density objects that are 1 m in size. Table 2.2.1-1 shows the analysis results of different components for this verification method. Angle brackets ("<" and ">") indicate the average of an ensemble of fixed AP cases.

TABLE 2.2.1-1 – ANALYSIS VERIFICATION

Component	Description	Specific Method	Result	Conclusion	Passed
Spacecraft igloo utilization	Igloo 10x10x1 vs. igloo 30x30x2	Identical orbits computed with different igloo files	Values of flux remained within expected parameters	Both 10x10x1 and 30x30x2 igloos produce valid results	✓
Spacecraft risk of impact	Computes the number of impacts in one year on a cube	Source model comparison	Results as expected	Software accepted	✓
Spacecraft argument of perigee χ^2 test	<Fixed AP> vs. Random AP	Random AP = <Fixed AP>	Results as expected	Software accepted	✓
Spacecraft mode χ^2 test	Modeled flux vs. debris size over various orbits and years	Inter-comparison of modeled flux, *e.g.*, symmetry	Results as expected	Spacecraft mode accepted	✓
IGLOO_ORBIT_SC	Flux processor for S/C Mode	Source model comparison	Agreement with source data	Software accepted	✓
Telescope / radar mode χ^2 test	Modeled flux using four radar/beam orientations	Inter-comparison of modeled flux, *e.g.*, symmetry	Results as expected	Telescope/ radar mode accepted	✓
TELESCOPE_MODE	Flux processor for T/R Mode	Source model comparison	Agreement with source data	Software accepted	✓

Two types of charts are used in the analysis verification. The first chart illustrates a normalized flux distribution between two datasets, supplemented with the results of a Ç^2 test. Figure 2.2.1-1 shows an example of a normalized flux distribution between ORDEM 3.0 flux values and KESSLER flux values. These charts show a binned dataset (usually relative velocity or yaw) versus normalized debris flux. Some charts show such a close match that it might be difficult to differentiate between the two datasets (*i.e.*, overlapping lines). The second chart is a linear correlation plot between two binned datasets of flux values. Figure 2.2.1-2 shows the sample data points taken from the ORDEM 3.0 and KESSLER binned flux distributions, as well as the best-fit line. In some cases, the 95% confidence interval (95% CI) and the 95% prediction interval (95% PI) are shown to better demonstrate the close correlation (*i.e.*, *r* H1.0) between two datasets.

All charts and detailed text on the analysis verification of spacecraft and telescope modes, as well as a quick reference of the different test satellites and sensors that were used, can be found in Appendix C. The tests performed during analysis verification correctly and completely represent the design specifications and requirements of the ORDEM 3.0 model.

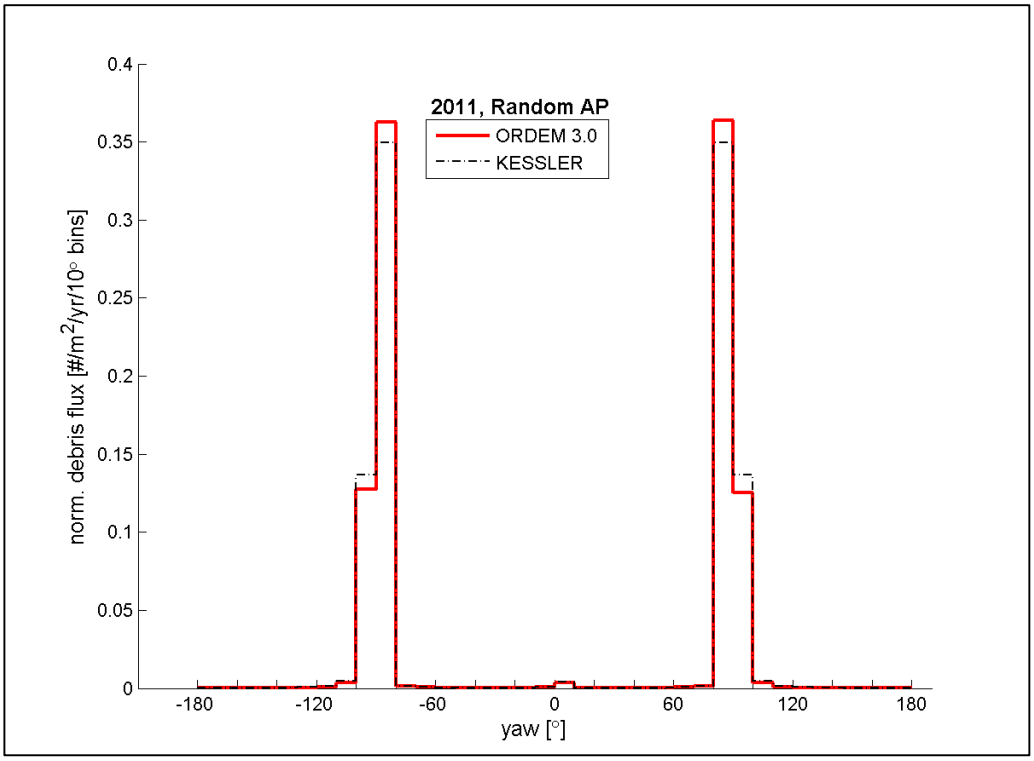

Figure 2.2.1-1. DIRECTV 12, yaw, 2011, Random AP.

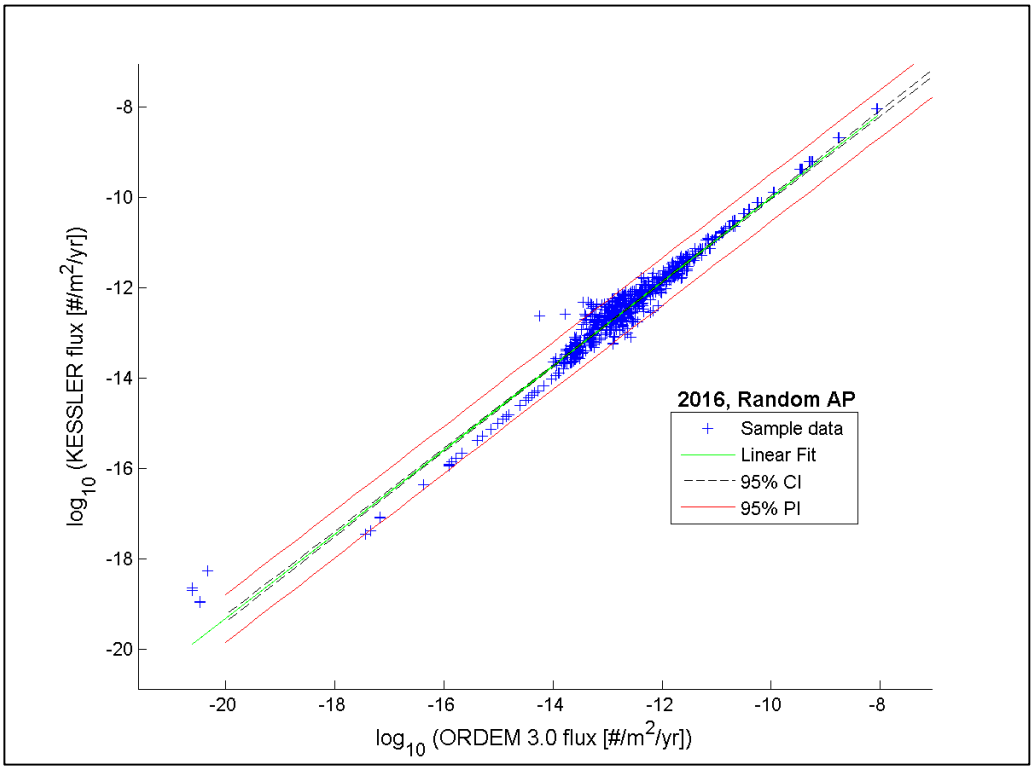

Figure 2.2.1-2. DIRECTV 12, flux, 2016.

2.2.2. *Verification by Inspection*

The verification by inspection method physically reviews or inspects software and its accompanying documentation to verify design feature and compliance with software requirements and coding standards. For example, legacy and newly-written software were inspected during integration into the standardized ORDEM 3.0 software structure; restructured code was compared against the original code to ensure identical results.

Verification by inspection entails simple manual reviews that are checked in Table 2.2.2-1. The development team considers these results acceptable and thus verified.

TABLE 2.2.2-1 – INSPECTION VERIFICATION

Component	Description	Specific Method	Result	Conclusion	Passed
OUTPUT_SC	Write file headers for Spacecraft Mode	Manual review of tabulated values	Header data valid	Software accepted	✓
OUTPUT_SC2	Write file data for Spacecraft Mode	Manual review of tabulated values	Tabulated data match plots	Software accepted	✓
OUTFILES	Write file headers for Telescope Mode	Manual review of tabulated values	Header data valid	Software accepted	✓
OUTFILE_TEL2	Write file data for Telescope Mode	Manual review of tabulated values	Tabulated data match plots	Software accepted	✓
PLOTDATA_SC	Write plotted flux data for spacecraft mode to file	Manual review of tabulated values	Plots match tabulated data	Software accepted	✓
PLOTDATA_TEL	Write plotted flux data for telescope mode to file	Manual review of tabulated values	Plots match tabulated data	Software accepted	✓
PCHIP_TLR	Tailors input data to a standard PCHIP input format	Confirmation of Documented Requirements	Delivered code met with established requirements	Software accepted	✓
PCHIP_FLUX_ALONE_SUBROUTINE	Controls PCHIP COTS suite	Confirmation of Documented Requirements	Delivered code met with established requirements	Software accepted	✓

2.2.3. *Verification by Demonstration*

The verification by demonstration method verifies qualitative requirements (such as performance, usability, and maintainability) by observing software operation or characteristics. Demonstration only requires reporting conformance of the software with design requirements rather than actual performance data. For example, demonstration was used by the professional staff to ensure consistent <TAB> key performance within the GUI for §508 compliance (*e.g.*, pressing the <TAB> key moved the computer cursor from GUI input box to input box in a predictable fashion).

Verification by demonstration entails the test cases in Table 2.2.3-1. The development team considers these results acceptable and thus verified.

TABLE 2.2.3-1 – DEMONSTRATION VERIFICATION

Component	Description	Specific Method	Result	Conclusion	Passed
SC_CALCS	Spacecraft-mode driver	User input of defined tests	Input direction resulted in expected output	Software accepted	✓
TELE_CALCS	Telescope-mode driver	User input of defined tests	Input direction resulted in expected output	Software accepted	✓
ERROR	Error handling routine	Fault injection	Artificial errors triggered expected results	Software accepted	✓

2.2.4. *Verification by Testing*

The goal of the verification by testing method is to ensure requirements are met by comparing software results with known results via input/output datasets. Testing is most relevant to cases proving an analytical result, or a non-statistical output. Testing normally implies a more organized study process than that of analysis, and testing provides program level metrics of merit. As an example, the calculation of relative velocities of ORDEM population members with respect to a target orbit is a well-defined mathematical process governed by the relative geometry of the target orbit plane and the population orbit parameters, resulting in 16 possible relative velocities per encounter. Given the ORDEM population and target orbit parameters, these may be verified by any available means, including by hand, using spreadsheets, or legacy code.

During verification by testing, each ORDEM 3.0 subroutine was examined using a specific technique to ensure that its output matches the expected result. Figure 2.2.4-1 shows the low-level (subroutine) dependencies of ORDEM 3.0. The desired result was produced in all test cases examined. The development team considers these results acceptable and thus verified.

TABLE 2.2.4-1 – TESTING VERIFICATION

Component	Description	Specific Method	Result	Conclusion	Passed
PCHIP-based cumulative spline fit function	Compared to previous spline fit code	Compared and determine cumulative nature of curve on multiple orbits and times	This new code is superior to the old code, no discontinuities, cumulative	PCHIP-based cumulative spline fit code is accepted	✓
GUI (see Appendix B)	GUI output flux vs independently-calculated flux	Flux as a function of size for nine test orbits	Identical, to machine precision	GUI code is accepted	✓
Testing platform verification	Windows PC vs. Linux workstation (RHEL5)	Comparison of identical tests between different platforms	Test results matched to within expected machine error regions	Tests acceptable on both developmental platforms	✓
LEO_FIXEDAP	Spacecraft mode flux computer for non-GEO population and fixed argument of perigee target orbit (use determined by target orbit input)	Targeted piecewise flux computation	Flux contributors matched expectations	Software accepted	✓
LEO_RANDAP_RANDRAAN	Spacecraft mode flux computer for non-GEO population and random argument of perigee and RAAN target orbit (use determined by target orbit input)	Targeted piecewise flux computation	Flux contributors matched expectations	Software accepted	✓
SC_GEO_AP_RAAN	Spacecraft mode flux computer for GEO population and target orbit (use determined by target orbit input)	Targeted piecewise flux computation	Flux contributors matched expectations	Software accepted	✓
NONZERO_IGLOO_ELEMENTS	Eliminates sparse igloo elements	Numerical pair test	Sparse input resulted in correctly reduced output	Software accepted	✓
SEEK_IGLOOCELL	Stores computed flux by directionality in LVLH target frame and relative velocity	Input known (pitch, yaw, relative velocity) triplets	Igloo cell ID# matched predicted value	Software accepted	✓
CHECK_IGFLUX	Ensure LEO flux is cumulative by size	Numerical pair test	Output matched expected	Software accepted	✓
CHECK_IGFLUX_GEO	Ensure GEO flux is cumulative by size	Numerical pair test	Output matched expected	Software accepted	✓
BIN_SEQUENCE_CHECK	Check population file integrity	Numerical pair test	Output matched expected	Software accepted	✓
TELE_LEO	Flux computer for non-GEO population for telescope mode (use determined by user input)	Targeted piecewise flux computation	Flux contributors matched expectations	Software accepted	✓
TELE_GEO	Telescope mode flux computer for GEO population (use determined by user input)	Targeted piecewise flux computation	Flux contributors matched expectations	Software accepted	✓
TELEPOINTING	Computes ground sensor pointing vector	Manual review	Manual review agreement	Software accepted	✓
ALT2RNG	Converts altitude to range along beam axis	Input altitude above spherical earth	Range calculation correct	Software accepted	✓
TRIGRANGE	Trigonometric boundary condition check	Unit	Boundary warnings given at expected threshold	Software accepted	✓
SAFEACOS	Trigonometric boundary condition check	Boundary testing	Values for acos exact match and within boundary conditions	Software accepted	✓
INTERPOLATED SUBROUTINE	Spline interpolation	Manual review of tabulated values	Values matched manual computation	Software accepted	✓
LATLON2MOLLWEIDE	Constructs data for Mollweide map projection	Manual review of tabulated values	Values matched manual computation	Software accepted	✓

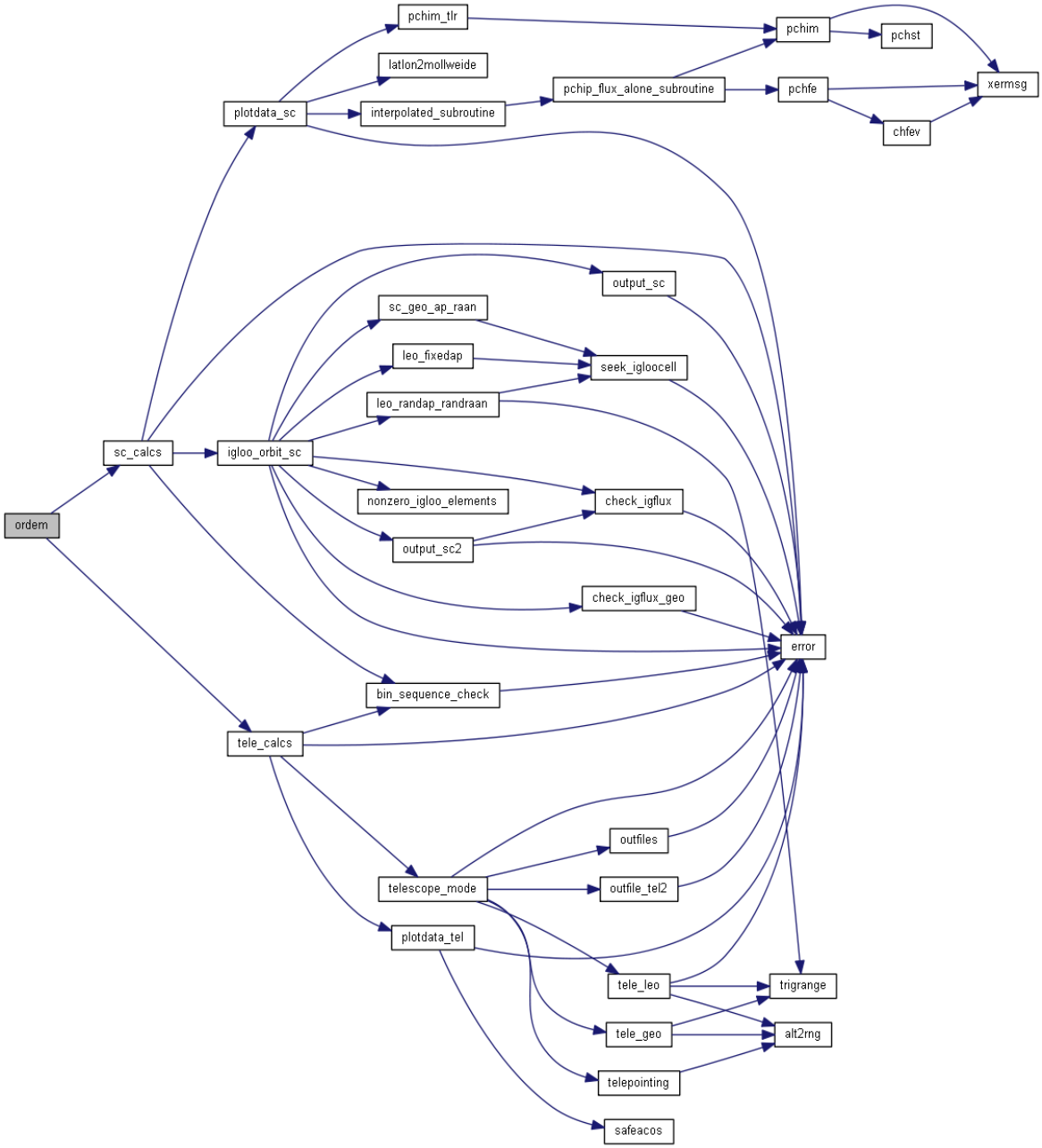

Figure 2.2.4-1. ORDEM 3.0 structural map.

2.3. ORDEM 3.0 SUPPORT SOFTWARE AND DATABASES

This section describes the support software used in the development of the ORDEM 3.0 software release. They may all be considered as legacy products in that they have been developed and tested over decades. The first three, LEGEND, DBS files, and solar activity tables are in-house ODPO products that are vetted through the ODPO Configuration Control Board (CCB) process. The last two, PCHIP and TeeChart, are off-the-shelf government and commercial products, respectively.

2.3.1. *LEGEND*

The LEO to GEO Environment Debris (LEGEND) three-dimensional, long-term environment model was used, during the development of ORDEM 3.0, to provide baseline orbital debris populations for sizes of 1 mm and larger. The baseline population is later scaled by matching model results to the observed environment. LEGEND is a CCB-managed software product maintained by NASA ODPO. LEGEND and LEGEND variant software were subject to continuing, informal V&V efforts during their development, including the extensive use of legacy software. However, the V&V of LEGEND and LEGEND variants are beyond the scope of this document.

2.3.2. *DBS files*

The DBS files consist of yearly (1957-2012) space launch traffic, maneuvers conducted in space (*e.g.*, re-orbit or deorbit maneuvers), and fragmentation events (collisions and explosions). The DBS files are used by LEGEND as historical inputs (1957-2007) and to serve as a basis for future space traffic. When used to model future space traffic over the period 2008-2035, the file set for 2000-2007 was repeated in a serial fashion.

While a formal V&V effort has not been conducted for the DBS files, the files are reviewed on a yearly basis during the construction of the latest year's input data. For example, orbital and physical data are regularly reviewed and corrected, augmented, and/or updated as necessary.

2.3.3. *Solar Activity*

Solar activity, as expressed by the Extreme Ultraviolet analogue of the 10.7 cm radio flux, is an important LEGEND input file. The radio flux governs the exospheric temperature, T_∞, and hence the atmospheric density as a function of altitude. Atmospheric drag is a function of atmospheric density. Therefore, the rate at which LEO debris is removed from orbit by atmospheric drag depends upon historical (1957-2009) and modeled (2010-2035) solar activity. Both historical and projected data sets are provided by the National Atmospheric and Oceanic Administration (NOAA). A formal V&V of the projected solar activity is beyond the scope of this document.

2.3.4. *PCHIP*

The Piecewise Cubic Hermite Interpolation Polynomial (PCHIP) computer software suite was used to provide interpolation while enforcing the cumulative (or monotone) nature of ORDEM 3.0 distributions, (*e.g.*, flux as a function of projectile size). The subroutines `pchim`, `pchfe`, `pchst`, `chfev`, and `xermsg` constitute the suite. PCHIP is a Department of Energy (DOE)-developed suite licensed for distribution with ORDEM 3.0 by the DOE Office of

Scientific and Technical Information's Energy Science and Technology Software Center. It is a commercial off-the-shelf (COTS) product and was not included in the ORDEM 3.0 V&V effort.

2.3.5. *TeeChart*

TeeChart .NET v3 is a standard graphical software product licensed from Steema Software (www.steema.com) for distribution with ORDEM 3.0. It is a COTS product and was not included in the ORDEM 3.0 V&V effort.

2.4. ORDEM 3.0 POPULATION

An ORDEM model population or environment consists of yearly files containing a large group of orbits with specified orbital elements (perigee altitude, eccentricity, and inclination for non-GEO populations) and the number of objects in each orbit (along with standard error), as well as size and material assignment for each object. GEO population orbital elements are mean motion, eccentricity, inclination, and right ascension of ascending node.

In general, data used in the model population derivations are random samplings collected from the debris environment under rather limited conditions. These data always are limited in quantity and scale and have limited accuracy as well. It is thus appropriate to apply the theory of probability to both orbital debris data interpretation and debris-population modeling. The general procedure for the statistical derivation of ORDEM 3.0 model populations based on measurement data takes the following key steps:

- selecting and analyzing data,
- constructing reference populations from supporting source models such as LEGEND and a degradation/ejecta model or from datasets,
- defining model parameters in terms of the reference model populations,
- linking model parameters with data,
- searching for best estimates of the model parameters based on measurement data through Maximum Likelihood Estimator (MLE) and Bayesian statistical approaches, and
- assessing of the modeling results and repeating relevant steps until satisfactory results are obtained.

This process is illustrated for small size populations, considered to be orbital debris sizes less than approximately 1 mm in characteristic length (Lc) in Figure 2.4-1 and for large size populations in Figure 2.4-2.

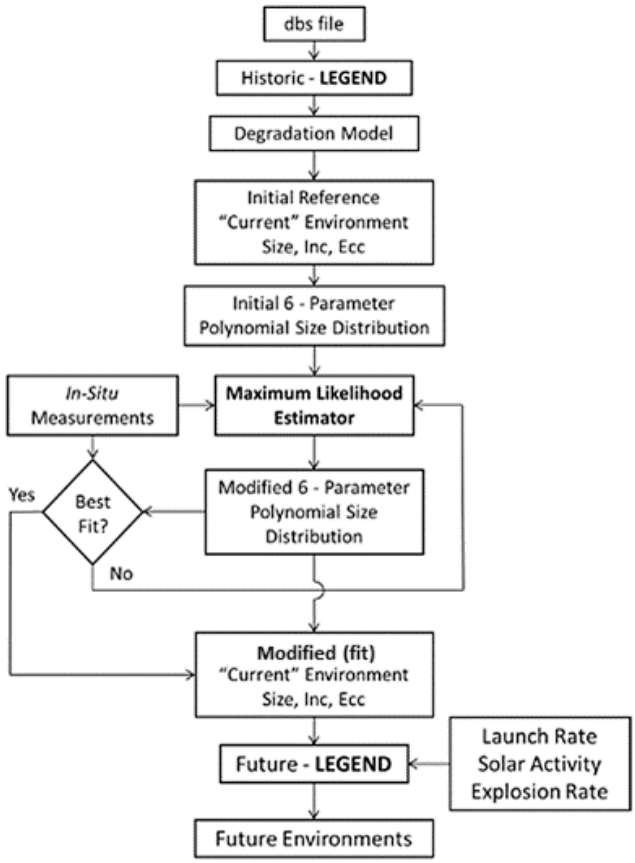

Figure 2.4-1. Small particle (d ~ 1 mm) estimation methodology.

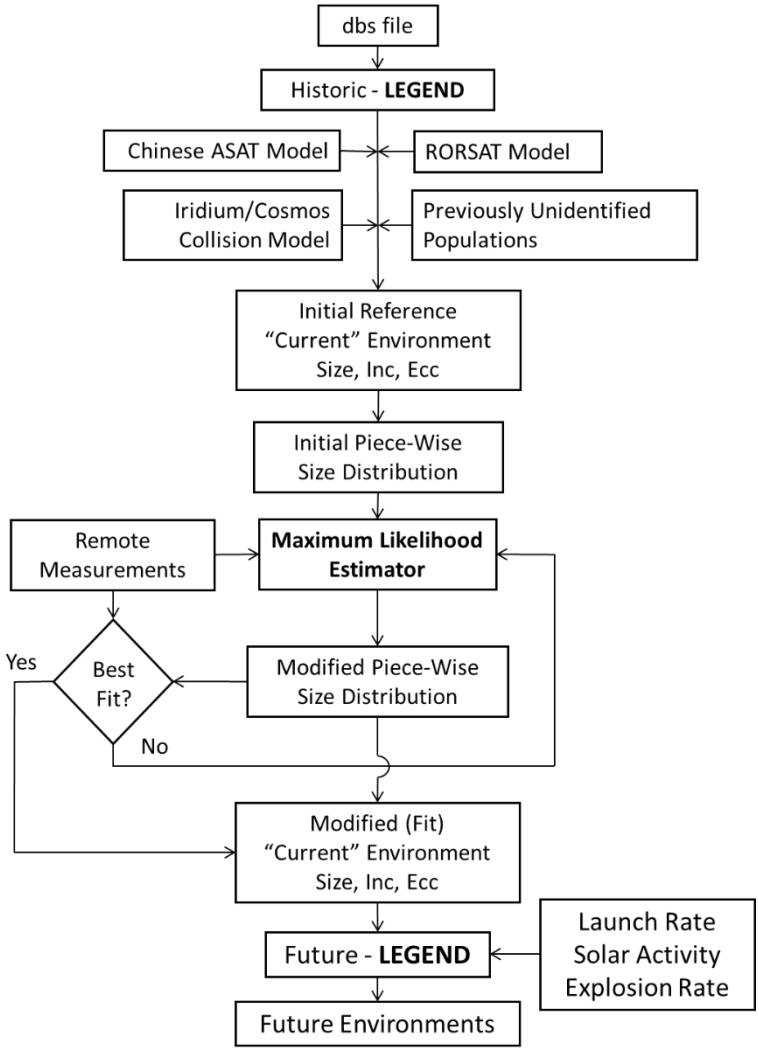

Figure 2.4-2. Large particle (> ~ 1 mm) estimation methodology.

While consistent with the method of MLE, Bayesian probability theory provides an elegant and rational approach to estimating orbital debris populations from data. A Bayesian inference process simply refines a reference debris population in terms of data. In Bayesian terminology, observed results change a prior distribution (given in the reference populations from source models and data) into a posterior distribution.

The orbital debris populations of the ORDEM 3.0 model are fit to data sets generated from either ground-based remote sensing or *in situ* data (see Table 2.4-1).

TABLE 2.4-1 – GENERATING THE ORDEM 3.0 ORBITAL DEBRIS POPULATIONS

Size Range	Processing Steps
1 μm to 1 mm	Modeled using the DBS files, then statistically filled to STS window and radiator data
< ~ 3 mm	Objects are selected so as to be statistically compatible with the total flux (micrometeoroids and orbital debris) estimated from the impact feature record observed on STS missions 71 through 133 (1995 through 2010)
~ 3 mm to ~ 8 mm	Inferred from data collected by the Goldstone radar.
> 1 cm	Inferred from radar data, mainly from the Long Range Imaging Radar (LRIR, also known as Haystack) and the Haystack Auxiliary (HAX) radars at the MIT Lincoln Laboratory, which are operated in a staring mode for debris observations
> ~10cm	Derived from the Space Surveillance Network (SSN) catalog and associated characterization and modeling data resident in the LEGEND DBS input files

ORDEM 3.0's populations are divided into LEO and GEO population components. For the purposes of ORDEM, the GEO population is defined by two criteria (Van Der Ha):

- eccentricity < 0.1,
- 40821 km radius < semi-major axis < 43638 km (*i.e.*, 1.05 day > period > 0.95 day).

The LEO population component contains GEO Transfer Orbits (GTO) and as such, might be more properly considered the "non-GEO" population component. LEO's GTO component provides flux down to 10 μm in the GEO region, while the GEO population is itself limited to 10 cm and larger sizes.

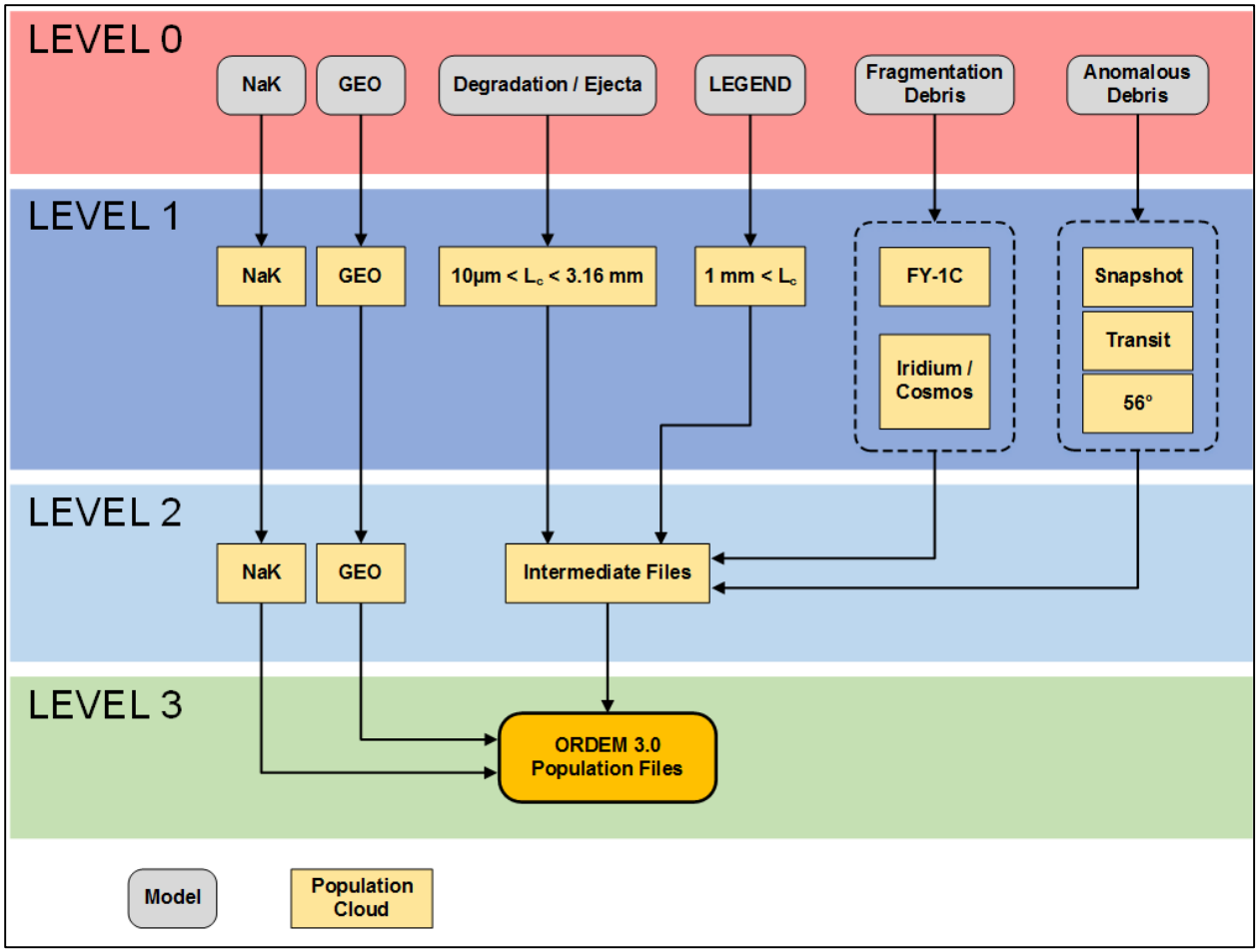

Figure 2.4-3. ORDEM 3.0 input population tree.

The process by which yearly ORDEM 3.0 population sets are generated by various baseline source models and subsequent analysis is displayed in Figure 2.4-3. Note that L_C is used to represent an object's size. The individual populations are labeled not by size but by source model. In Figure 2.4-3, note that OTHR ("Other") refers to anomalous debris from known and unknown sources. Population data levels are defined by:

- LEVEL 0 – ODPO computer models used to generate the initial populations
- LEVEL 1 – Populations by individual orbits, weighted according to predetermined requirements ascertained from comparison of measurements (using MLE and Bayesian statistics)
- LEVEL 2 – Individual orbits from LEVEL 1 are binned according to an established classification scheme of orbital elements
- LEVEL 3 – Final ORDEM 3.0 input populations, combined LEVEL 2 populations and output in the ORDEM proprietary binary file format.

To ensure that all populations are correctly incorporated into the yearly ORDEM 3.0 population files, a verification plan was instituted. Table 2.4-2 describes population verification activities.

TABLE 2.4-2 – POPULATION VERIFICATION

Component	Description	Specific Method	Result	Conclusion	Passed
General populations	LEVEL2 (itemized) vs. LEVEL3 (tabulated)	Independent population comparison with tabulated ORDEM form	Populations matched within expected boundaries	Originating population matches tabulated population	✓
FY-1C contributing population	Normal (total) population vs. FY-1C-free population	Removal of FY-1C population	FY-1C population resides in expected zones of the ORDEM environment	FY-1C population exists in ORDEM total populations	✓
Iridium/Cosmos contributing population	Normal population vs. Iridium/Cosmos collision cloud-free population	Removal of Iridium/Cosmos collision cloud population	Population resides in expected zones of the ORDEM environment	Iridium/Cosmos collision cloud population exists in ORDEM total populations	✓
Special populations: Transit-related, SNAPSHOT, 56°	Normal population vs. special population-free population	Removal of special population clouds	Special population clouds reside in expected zones of the ORDEM environment	Special populations exist in ORDEM total populations	✓
Sodium Potassium (NaK)	Normal population vs. NaK-free population	Removal of NaK population	NaK population resides in well-defined, expected zone of the ORDEM environment	NaK population exists in ORDEM total populations	✓
Microdebris contributing population	Normal population vs. micron-sized-free population	Removal of population less than 1 mm in size	Population resides in expected zones of the ORDEM environment	Micron-sized population exists in ORDEM total populations	✓
General 1mm contributing population	Normal population vs. general 1 mm population	Removal of general 1 mm population	Population resides in expected zones of the ORDEM environment	General 1 mm population exists in ORDEM total populations	✓
GEO	Normal population vs. GEO-free population	Removal of GEO population	GEO population resides in expected zones of the ORDEM environment	GEO population exists in ORDEM total populations	✓

3.0 Validation

Validation is the process of evaluating software at the end of the software development process to ensure compliance of software requirements for comparisons of the final modeled environment with measurements of that environment. It is vital to the development process and assures that the correct product was built (Addy).

Validation is provided through the systematic comparison of model populations and environmental *in situ* and remotely-sensed measurements. The validation of the ORDEM 3.0 modeled debris populations in terms of the original NASA measurements has been a high-priority effort for several years during the development of the program. It has culminated in techniques and sets of metrics that were chosen by the developers to corroborate the precision of the model.

Simply put, a study matrix that includes the parameters of debris size, altitude, and year, the measured environments of available sensors (Goldstone, Haystack, HAX, the SSN), and in-situ measurements are compared to the ORDEM 3.0 modeled environments. Of course, comparisons of this kind are limited to those regions of space and time where measurements have been performed and analyzed.

The model populations cover the very large range in orbital region (LEO through GEO) and size (10 μm through 1 m for LEO/GTO and 10 cm through 1 m for GEO). Radar measurements are used to cover the LEO region (Haystack, HAX, and Goldstone, sizes ~ 3 mm to 10 cm) and LEO-to-GEO (SSN, sizes larger than ~ 10 cm in LEO and ~ 1 m in GEO). Optical assets also provide coverage and population assessment in GEO for objects larger than approximately 1 m down to 30 cm. The LEO small particle (10 μm to ~ 1 mm) measurements are provided by the inspection of Space Transportation System (STS) and other returned surfaces.

3.1. VALIDATION METHODS

Two methods of validation – analysis and testing – are applied in this document. The following sections depict these specific validation methods. Tables are included for each method that describe the success of the validation process. A green checkmark (✓) indicates a successful outcome, whereas a red X (✗) indicates a failure. See Appendix D for figures and additional details in the case of validation by testing.

3.1.1. *Validation by Analysis*

The goal of the validation by analysis method is to ensure that each software requirement has been thoroughly tested with its own test plan.

3.1.2. *Validation by Testing, LEO Region (10 μm to ~2 mm)*

The LEO (including MEO, GTO, Molniya, and other elliptical orbits) orbital debris environment as modeled in ORDEM 3.0 consists of seven populations, distinguished by size, source, and measurement technique. The populations are enumerated in the table below.

TABLE 3.1.2-1 – LEO SOURCE MODELS & VALIDATING MEASUREMENTS

Population	Description	Model or Data	Measurement
10 μm to ~2 mm	Baseline population	Degradation/ejecta model	STS window and radiator surfaces
1 mm and larger	Baseline population	Modified LEGEND three density model	Goldstone, Haystack, HAX, and SSN radars
NaK	NaK nuclear reactor coolant baseline population	NaK data	Haystack
Iridium 33 cloud	Collision debris cloud	Modified LEGEND three-density model	Haystack/HAX/SSN
Cosmos 2251 cloud	Collision debris cloud	Modified LEGEND three-density model	Haystack/HAX/SSN
FY-1C cloud	Collision debris cloud	Modified LEGEND three-density model	Haystack/HAX/SSN
OTHR clouds	Anomalous debris clouds associated with the SNAPSHOT, Transit constellation, and a 56° inclination unknown source	Modified LEGEND three-density model	Haystack

In ORDEM 3.0, the > 1 mm LEGEND, FY-1C, Iridium/Cosmos, and OTHR populations are combined into the general background populations (the NaK droplets population remaining distinct). Separate datasets and metrics for the validation of micro-debris are presented in this section.

The tests performed during testing validation of the LEO section correctly and completely represent the design specifications and requirements of the ORDEM 3.0 model.

3.1.2.1. *In situ STS Window and Radiator Impacts*

Impact data derived from the STS missions (1995-2010) used in the development of ORDEM 3.0 are tabulated in the NASA Hypervelocity Impact Technology (HVIT) group's STS impact databases (Feb 2012). Over 600 craters are tagged with location, feature sizes, predicted particle size, and chemical analysis. Each STS mission has a small number of impacts. Chemical analysis of impactor material allows identification of high-density orbital debris (HD), medium-density orbital debris (MD), micrometeoroids, and unknowns. Radiator impacts are categorized by damage of three types: thermal-tape hole (TH), facesheet hole (FSH), and facesheet crater depth (FSdep). Separate HVIT damage equations for projectile size are available for each damage type. Radiator FSH and FSdep data are mutually exclusive.

To make the number of impacts statistically significant, the entire database is treated as a Poisson sample of the complete, time-varying population. Table 3.1.2.1-1 summarizes the HVIT database coverage of STS mission exposure to the environment and the accompanying sample size range.

TABLE 3.1.2.1-1 –IN-SITU DATASETS

In-situ Sources (Surface)	Total Area	Total Exposure Time	Approx. Region/ Detection Size Limit
STS windows, STS-71 through STS-133, excluding cargo bay windows	3.6 m^2	1.942 years	LEO/~10 μm < ~200 μm
STS radiators STS-71 through STS-133, excluding STS-75 and STS-100	117 m^2	1.866 years	LEO/~150 μm << ~2 mm

Because the radiator data analyzed consisted of integer data values, it is relatively straightforward to compute the Poisson P-value for the data (see Appendix D for details on the Poisson P-value calculation). However, trying to calculate an objective measure of the quality of the fit to the window data is more problematic because a large number of the impact features are of unknown source ("*U*" features). Unlike the radiator data, many of these *U* features have a certain probability of being assigned as "MD," "HD," or micrometeoroids. The model fits were computed by randomly assigning the type of the *U* impactors based on the fraction of each material type among the "known" impactors in that feature size regime. However, this was done in a Monte Carlo manner, where for each Monte Carlo draw, a different set of assignments was created. The model fit was made to the mean of the Monte Carlo data realizations.

Throughout the Shuttle *in situ* analysis for ORDEM, *U* features were statistically assigned a material type (MD, HD, or micrometeoroid) based on the ratios of these populations among the features that were identified, using a Monte Carlo technique (note that the LD population was excluded). Based on the ratios seen in the window data, all the *U* FSH features above ~1 mm in diameter could be assigned with high confidence to the MD population. This results in the FSH data set having integer number of features at each feature size (*i.e.*, the window data, where the mean curve consists of "fractional" numbers of craters of a given type). Integer data allows the use of more conventional statistical tools to determine the quality of fit.

The data preserved in the Shuttle database is feature size – either the depth of a crater or the width of a crater or hole. Ideally, one would like to extract the size of the impacting particle from the feature size, but in addition to the impactor size and material density, the feature size is a function of the impact speed and angle. Because the Shuttle surfaces were exposed to a flux from a variety of speeds and directions, extracting particle size carries with it some uncertainty.

A more direct technique is to make use of the model flux in terms of particle size, density, direction, and speed to make a prediction of the size distribution of cratering features using the empirically-derived damage equations.

The largest set of features from the Shuttle database is the holes in the radiators. These represent a unique insight into the millimeter debris flux. However, one of the problems with the radiator damage is that the radiators themselves are made of aluminum; therefore, it is often difficult to identify the chemical residue of aluminum particles on the aluminum radiator surface.

The red curve in Figure 3.1.2.1-1 is the cumulative number of facesheet hole features created from MD particles as a function of hole diameter. The black curve is the ORDEM model prediction. The dotted black lines represent the upper and lower 1-sigma range possible from the predicted curve based on Poisson statistics alone. See Appendix D for remaining charts.

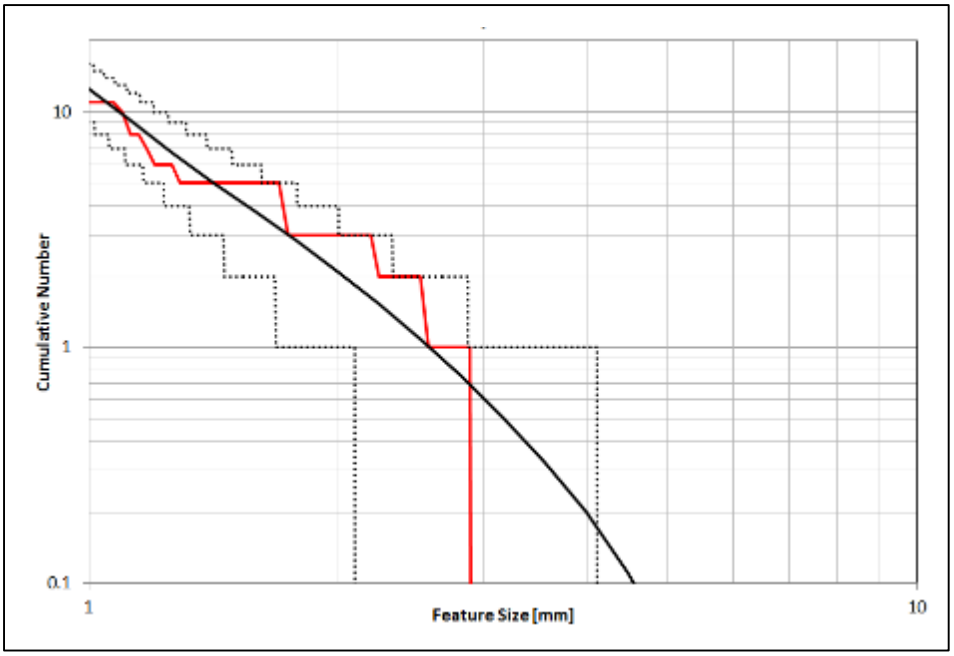

Figure 3.1.2.1-1. Example chart, Shuttle radiator facesheet hole (MD population).

The largest single impact assigned to the HD population hit in a section of the radiators where an extra aluminum layer known as a "doubler" had been added to thicken and protect the radiator. As a result, there is added uncertainty about the best feature size to use for this analysis – the diameter of the hole in the outer doubler, the diameter of the hole in the actual facesheet behind the doubler, or an "equivalent" diameter hole in a single facesheet determined from empirical tests. Hypervelocity tests indicate that for perforations of the facesheet, the presence of the doubler makes the facesheet hole larger than would otherwise be expected from a single facesheet. Therefore the "equivalent" diameter hole is computed to be smaller than the sizes of the hole actually observed. This also means that the largest possible value – that of the facesheet hole – is probably an extreme upper limit.

With the exception of the largest possible feature size option for the HD population (the diameter of the hole in the actual facesheet behind the doubler), all the data curves fall within the 1-sigma Poisson values.

The development team considers these results acceptable and thus validated.

3.1.2.2. *In situ Estimated Impactor Size*

The computation of impactor size is a much more difficult task than simply comparing model prediction to feature size data. This is because a feature of a given size could have been made by a large particle travelling slowly, or a smaller particle travelling more quickly. For these

calculations, the mean values of the impact velocity and direction have been computed using the ORDEM model, but for each impact, there is still a residual uncertainty in the derived size.

Figure 3.1.2.2-1 shows the calculated impactor size for the HD radiator facesheet hole distribution based on the assumption that each impactor has the HD density of 7900 kg/m^3. Each point represents a single impact, with vertical error bars giving the 1-sigma Poisson uncertainties. The horizontal error bars represent an estimate of the 1-sigma range in possible impactor sizes. Note that the largest impact has extended horizontal error bars due to the uncertainty in the exact impact feature size to be used in computing the particle size (see above for details). The dotted lines above and below the model distribution represent the computed uncertainties in the model. The link between the magnitudes of these uncertainties in the calculated particle size can be easily seen.

The distribution of estimated impactor sizes is compared to the model prediction for the HD population. The relationship between vertical (due to Poisson sampling error) and horizontal (due to uncertainties in the particle size estimate) error bars of the data and the model uncertainties (shown as dotted lines) can be clearly seen.

Figure 3.1.2.2-2 shows the same information, but in this case for the MD data. Because the *U* impacts in the radiators in this size range are assigned to MD (under the assumption that these are predominantly aluminum impactors on the aluminum radiators, and thus are indiscernible to the electron microscopes used to identify material type), the features that were originally identified as *U* are shown in this chart as hollow squares, while those identified as MD are shown as filled squares. As with Figure 3.1.2.2-1, the MD calculated sizes match the data well, and the link between the measurement uncertainties and model uncertainties are evident.

The distribution of estimated impactor sizes is compared to the model prediction for the MD population. Features with unknown impactors that were assumed to be MD impactors are shown as hollow squares. The relationship between vertical (due to Poisson sampling error) and horizontal (due to uncertainties in the particle size estimate) error bars of the data and the model uncertainties (shown as dotted lines) can be clearly seen.

The development team considers these results acceptable and thus validated.

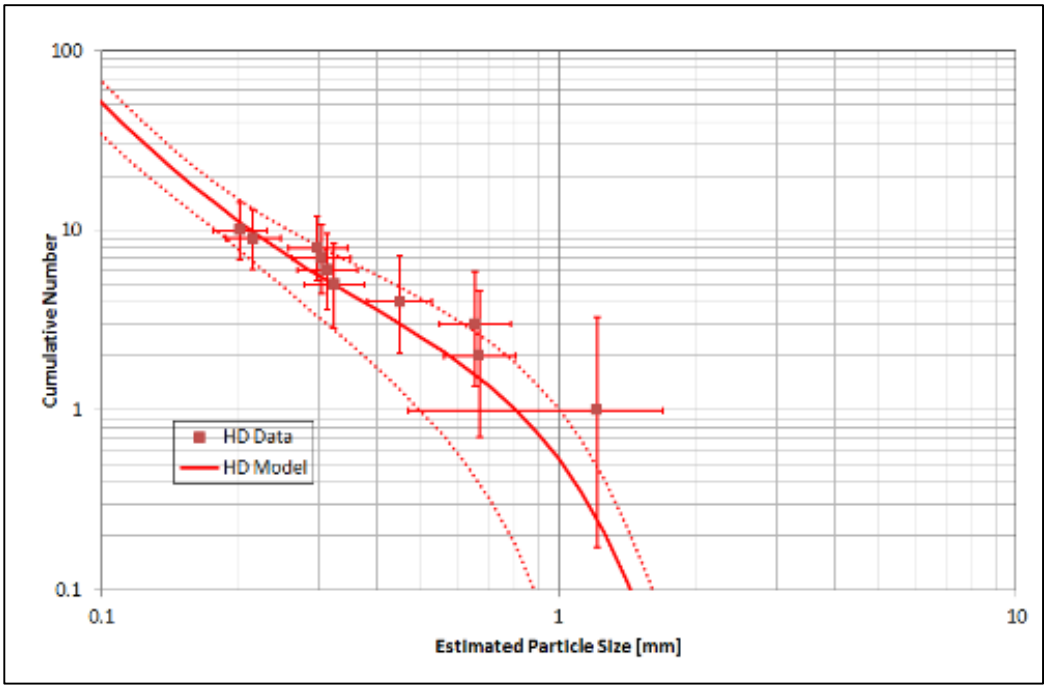

Figure 3.1.2.2-1. Calculated impactor size, shuttle radiator hole data, HD population.

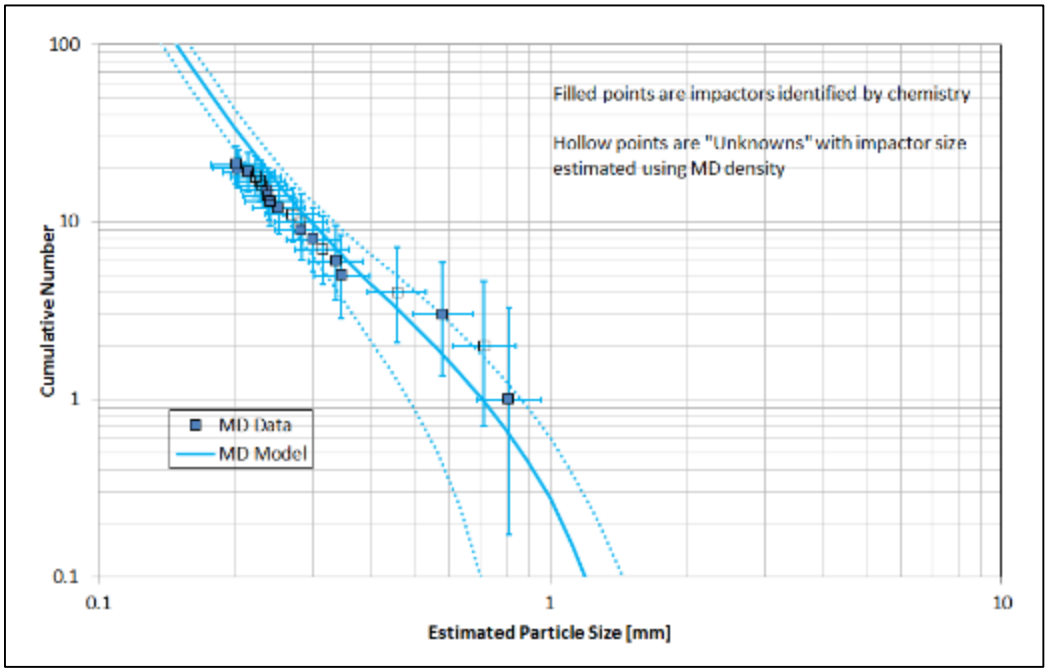

Figure 3.1.2.2-2. Calculated impactor size, shuttle radiator hole data, MD population.

3.1.3. *Validation by Testing, LEO Region (> 3 mm)*

Table 3.1.2-1 conveys the importance of radar data in validating the seven populations that are a part of ORDEM's LEO/GTO environment model. ODPO-sponsored radar campaigns collect approximately one thousand hours per year of radar data. These data characterize the environment in a statistical manner. In statistical sampling, no effort is made to track or catalog individual detections; rather, the radar beams are fixed in azimuth/elevation for extended periods. Objects penetrate the surface of the beam and are detected in a manner sufficient to estimate their altitude, inclination, and size. Haystack/HAX calibration is provided by observing on-orbit calibration spheres and the NaK population. At larger sizes, the SSN catalogs (TLEs, satellite catalogs, and RCS catalogs) provide a basis for characterizing the 10 cm environment from LEO to GEO.

Figure 3.1.3-1 depicts the approximate coverage of altitude and debris size by the radars used in the ORDEM study. The SSN data is available over the span 1995-date, while the Haystack/ HAX data covers 1995-2003. Goldstone data were provided intermittently from 1996 through 2006.

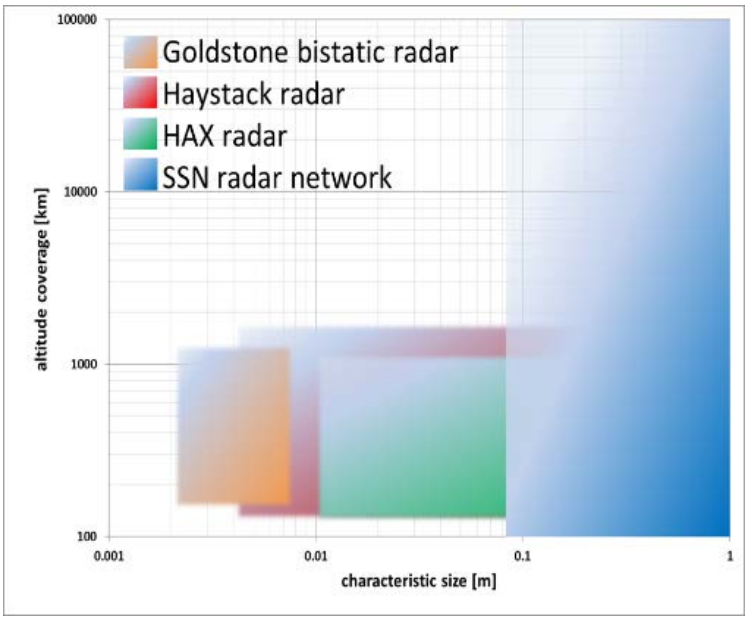

Figure 3.1.3-1. Approximate radar coverage in altitude and debris size.

Table 3.1.3-1 shows information on radar data for the ORDEM 3.0 development and V&V. See Appendix D for more Haystack, HAX, and Goldstone radar sensor information concerning specific observation times, range windows, and pointing directions.

TABLE 3.1.3-1 – IN-SITU DATASETS, RADAR DATA

Radar System	Years Accessed	Location (Lat, Lon)& Pointing (El/Az)	Region/Detection Size Limit
SSN	1995-2011	Multiple Detectors	LEO > 10 cm, GEO > 1 m
Haystack	1999-2003, 2007-2009	42.6°NLat, 71.5°WLon&75° E, 20°S	LEO > 5.5 mm
HAX	1999-2003, 2007-2009	42.6°NLat, 71.5°WLon&75° E	LEO > 3 cm
Goldstone	2001, 2005-2007, 2009	35.4°NLat, 116.8°WLon&90° elevation	2 mm < LEO < 8 mm

Motions of debris orbits in LEO and methods of remote observation have been coupled over the years, such that sets of standard measurements have been developed to concisely give the viewer an intuitive understanding of the environment's evolution. These metrics (scaled flux deviations vs. altitude, surface area flux vs. altitude, surface area flux vs. size, and cross-sectional area flux vs. size) are described and presented in this section.

3.1.3.1. *Scaled Flux Deviations vs. Altitude*

The >3.16 cm and >1 cm model populations currently used in ORDEM 3.0 are statistically estimated from available Haystack/HAX staring-mode data, using LEGEND source models as benchmarks. The population estimation is based on observed and predicted radar detection probability distributions in the two-dimensional space of radar-range and range-rate. Due to the statistical nature of the limited radar samplings, the model populations are obtained as an average over all the detailed aspects such as altitudes, year, different radar viewing geometries, etc. Table 3.1.3.1-1 shows the best-estimated model parameters for objects > 1 cm, with an inclination 40° and perigee < 1350 km. The weighted average model parameter is a weighted average over different data sets (*i.e.*, of different year and with different radar viewing geometry) based on the variances that include the dispersion parameter, which is a measure of the deviation of data from the assumption of pure Poisson statistics. In this regard, the observed OD fluxes are supposed to be randomly distributed around model predicted mean values. This has been tested, specifically for the deviations of radar-observed OD fluxes from ORDEM model predictions.

TABLE 3.1.3.1-1 – BEST-ESTIMATED MODEL PARAMETERS FOR HAYSTACK, > 1 CM

Year	Haystack Radar data (El, Az), wave form code	Observable Hours	Best-estimated Model Parameter	Dispersion Parameter
1999	75°E,WFC7	210.2	0.896 ± 6.25%	1.201
2000	75°E,WFC7	264.9	0.837 ± 5.78%	1.460
2001	75°E,WFC7	250.6	0.816 ± 6.12%	1.635
2002, near	75°E,WFC7	175.5	1.298 ± 8.02%	1.716
2002, far	75°E,WFC7	171.3	0.801 ± 7.65%	1.299
2003	75°E,WFC4	633.3	1.220 ± 2.70%	1.861
1999	20°S,WFC7	89.7	0.753 ± 8.36%	2.196
2000	20°S,WFC7	114.6	0.721 ± 7.57%	2.686
2001	20°S,WFC7	105.8	0.630 ± 8.61%	2.251
2002	20°S,WFC5	225.7	1.092 ± 10.4%	8.741
Weighted average model parameter:			**1.000 ± 9.77%**	

The radar data used in the model population estimations are with NaK droplets excluded, because the special NaK populations are modeled separately, mainly due to their particular spherical shape. In addition, there are some small specific families of populations (*i.e.*, OTHR from Section 2.4), which are not included in the LEGEND source populations and also modeled separately with a special approach. It is not surprising that when the ORDEM-predicted fluxes include contributions from the special NaK and OTHR populations, the averages become a bit worse. The obvious reason for this is that the special populations are not included in the statistical derivation process. Therefore, to ensure proper comparison of radar data to ORDEM 3.0 data, the fluxes that are included in validation testing have NaK contributions removed.

ORDEM 3.0 predicted OD fluxes are computed for 50-km altitude bins. Corresponding radar observed fluxes are calculated from the number of detections in the same altitude bins. For each 50-km bin (denoted by the subscript "*i*") per year of observation, let m_i be the integer number of radar detections, f_i the radar-observed flux, μ_i the ORDEM-predicted OD flux, and σ_{μ_i} the ORDEM 3.0 uncertainty calculated for that flux. The expected (mean) value x_i and standard deviation σ_{x_i} based on ORDEM 3.0 is

$$x_i = \mu_i \cdot \left(\frac{m_i}{f_i}\right), \qquad \sigma_{x_i} = \sigma_{\mu_i} \cdot \left(\frac{m_i}{f_i}\right)$$

Thus, for each 50-km altitude bin, the scaled data-to-ORDEM deviation ζ_i ("*zeta*") is

$$\zeta_i = \frac{(m_i + ½) - x_i}{\sqrt{x_i + \sigma_{x_i}^2}}$$

Note that the formula above uses a "continuity correction" of ½ to remove the statistical bias that arises when converting Poisson integer values to real values. See Appendix D for more information on this concept.

For an individual yearly based data set, the weighted averaging over all 50-km altitudes (each one denoted by the subscript "*j*") is based on the number of OD objects the radar actually detected. Let *N* stand for the total data points per year of observation. Thus, for a single data set, the unweighted average $\bar{\zeta}$ and weighted average $\check{\zeta}$ are:

$$\bar{\zeta} = \frac{\sum_{j=1}^{N} \zeta_j}{N}, \qquad \check{\zeta} = \frac{\sum_{j=1}^{N} m_j \zeta_j}{\sum_{j=1}^{N} m_j}$$

Each validation test includes two charts a scaled flux deviation ζ vs. altitude chart, a probability distribution function (pdf) histogram supplemented with a normal curve fit – $N(\nu, \sigma)$ using a fitted mean ν, and a pdf histogram supplemented with a normal curve fit of 1-sigma $N(\bar{\zeta}, 1)$. The first two charts are shown below as examples. Figure 3.1.3.1-1 shows the ζ vs. altitude for Haystack 75°E pointing direction for years 1999 to 2003 for particles > 1 cm. The blue, red, and/or black dots represent observational data points. The unweighted average $\bar{\zeta}$ and weighted average $\check{\zeta}$ are included and shown as a solid black line and a dashed red line, respectively. Figure 3.1.3.1-2 shows the probability distribution histogram of ζ (solid black line) for Haystack 75°E pointing direction, 1999-2003, > 1 cm. This distribution is overlapped by a normal curve

fit – $N(\nu, \sigma)$ (solid blue line). Notice the fitted mean ν is very close to $\bar{\zeta}$. The unweighted average $\bar{\zeta}$ is represented as a dashed red line. The remaining chart includes the same pdf histogram as before, but with a different curve fit – $N(\bar{\zeta}, 1)$. See Appendix D for all the ζ distribution charts.

For completeness, two comparison tests – a Kolmogorov-Smirnov test and a Log-Likelihood test – were performed on both the radar data and the ORDEM 3.0 model (see Appendix D). The development team considers these results acceptable and thus validated.

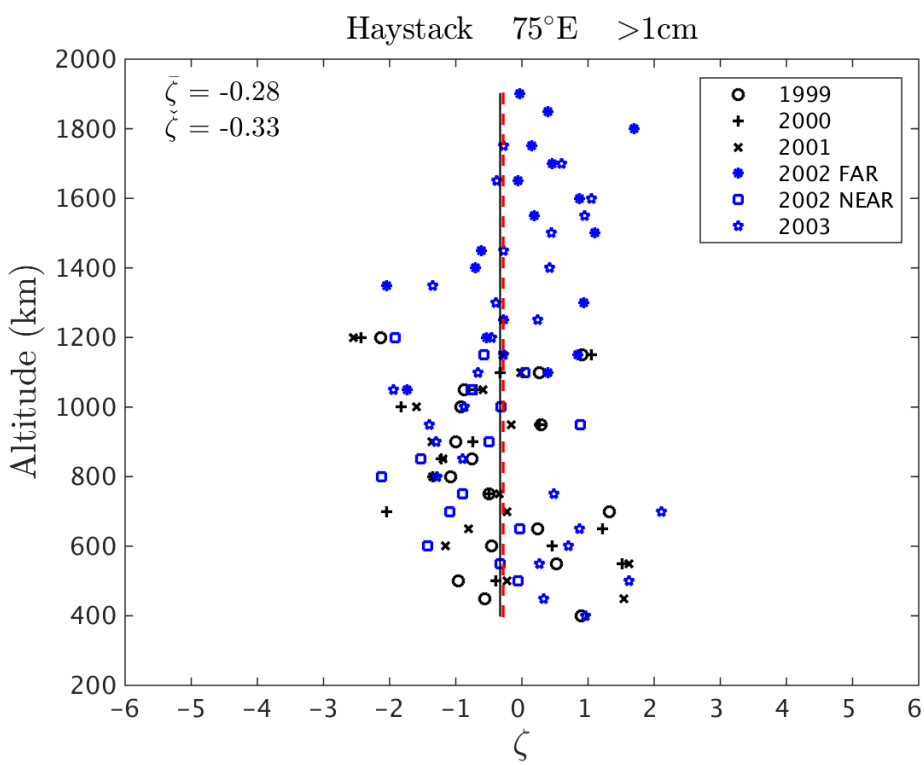

Figure 3.1.3.1-1. Sample chart, Haystack 75°E, >1 cm.

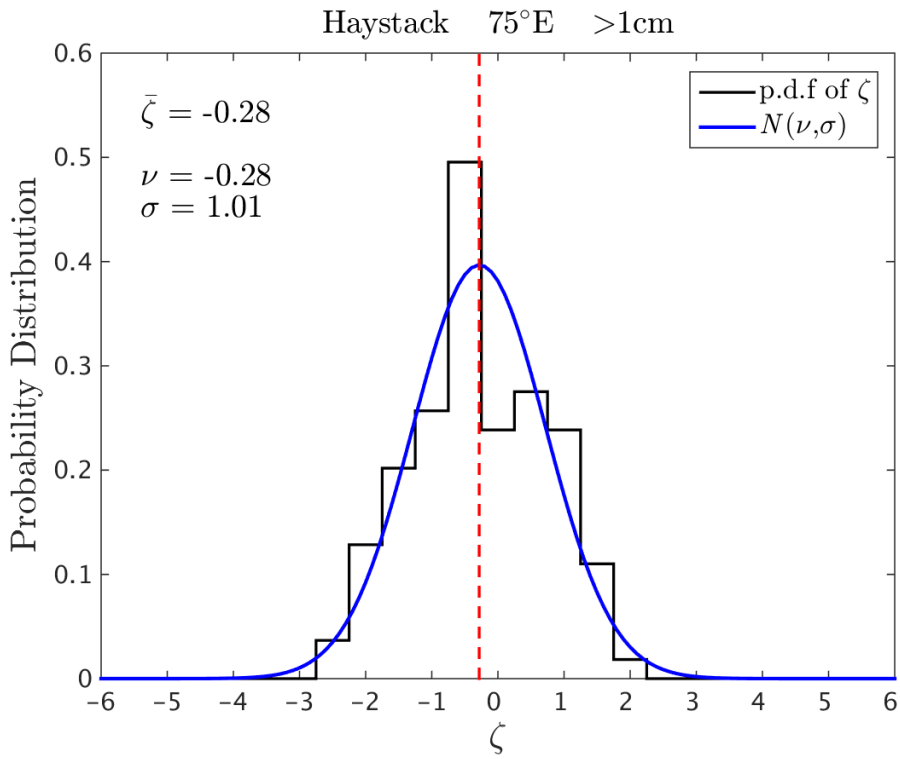

Figure 3.1.3.1-2. Sample Chart, Haystack 75°E, >1 cm, fitted.

3.1.3.2. *Surface Area Flux vs. Altitude*

The ORDEM 3.0 telescope/radar mode is used to estimate the surface area flux to be observed by a ground-based sensor. Here, telescope/radar encompasses any generic conical beam sensor, such as a pencil beam emitted by a mechanically-steered dish radar. ORDEM's model sensor is placed at the latitude of Haystack/HAX, with an azimuth of 90°, and an elevation of 75°; this mimics the most common 75°E mode employed by the Haystack/HAX radars. For comparisons with the Goldstone bi-static radar transmitter/receiver, the azimuth is set to 89.9° and elevation at 89.7°. The radar fluxes are derived from direct counts with Poisson confidence limits in the datasets and using the NASA SEM (Size Estimation Model).

Comparisons between observed and modeled surface area flux as a function of altitude are made on a yearly basis. The comparison includes Poisson sampling errors (radar data) and random and population errors of 1-sigma. Comparisons are made from 1999-2003 for Haystack/HAX and 2001, 2005, 2006, 2007 for Goldstone. The radar data include Poisson confidence limits. Radar data at higher altitudes (> 1200 km for Haystack/HAX and >1000 km for Goldstone) become sparse and less reliable, and are therefore not displayed. Sets of charts by year and debris size are presented in Appendix D.

Figure 3.1.3.2-1 is a sample chart that compares ORDEM 3.0 and Haystack/HAX and SSN observations as a function of altitude vs. flux of particles > 1 m, using 1999 Haystack/HAX (75°E) radar (observation hours 210.2/579.2, number of detections 10/49). Additional Haystack/HAX charts, as well as Goldstone observations, are also included in Appendix D. The development team considers these results acceptable and thus validated.

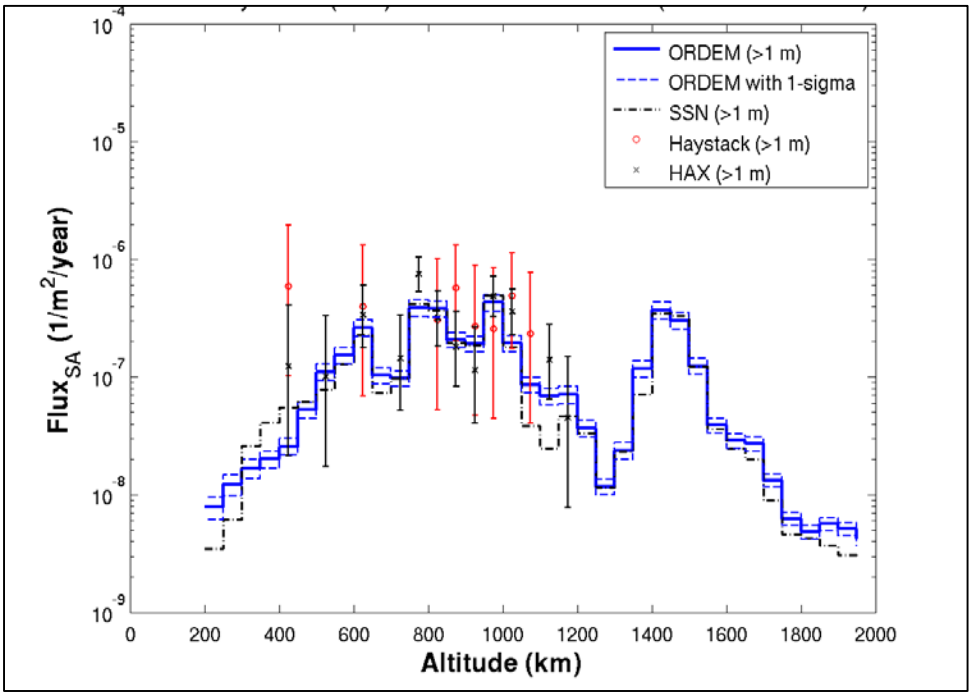

Figure 3.1.3.2-1. Sample chart, 1999 Haystack/HAX (75°E), > 1 m.

3.1.3.3. *Surface Area Flux vs. Size*

Radar data are used to compute a surface area flux as a function of size over the range (1 mm to 1 m). The ORDEM 3.0 telescope/radar mode is used to produce similar plots over this size range, and the results are validated by the radar data down to a limiting estimated size of approximately 3 mm from 1995-2003.

Figure 3.1.3.3-1 is a sample chart that compares ORDEM 3.0 and Haystack/HAX and SSN observations. The figure plots cumulative size in half decade $\log_{10}$ bins versus orbital debris flux. The ORDEM 3.0 population includes Poisson lower and upper confidence limits of 1-sigma bars. The radar data uses the Poisson single-sided confidence level of 84.13. Additional Haystack/HAX charts, as well as Goldstone observations, are also included in Appendix D. The development team considers these results acceptable and thus validated.

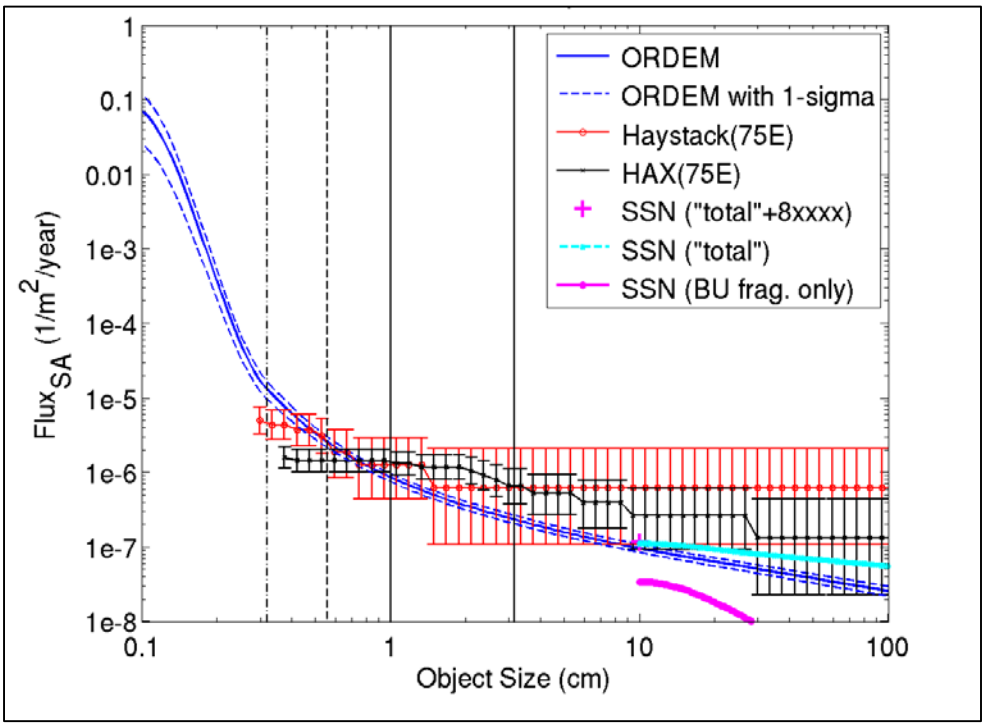

Figure 3.1.3.3-1. Sample chart, 1999 altitudes: 400-450 km Haystack/HAX counts: 8/12.

3.1.3.4. *Cross-Sectional Area Flux vs. Size*

The ORDEM 3.0 spacecraft mode output mimics the surface area flux observed by a spacecraft-encompassing spherical igloo. The igloo is oriented around the spacecraft through its orbit, with poles at zenith and nadir respectively. The default gradation of the igloo is 10x10x1 (degree by degree by km/sec).

Figure 3.1.3.4-1 is a sample chart that compares ORDEM 3.0 with radar sensor data (Haystack/ HAX, Goldstone) and SSN data observations for cumulative size in half decade $\log_{10}$ bins versus orbital debris flux. The ORDEM 3.0 population includes Poisson lower and upper confidence limits of 1-sigma bars. The radar data uses the Poisson single-sided confidence level of 84.13. Additional Haystack/HAX/Goldstone charts are also included in Appendix D. The development team considers these results acceptable and thus validated.

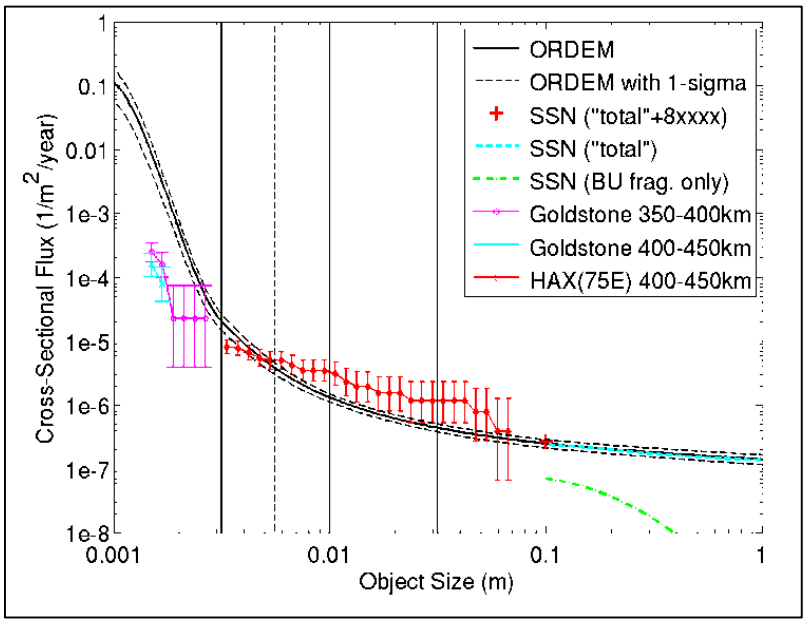

Figure 3.1.3.4-1. Sample chart, 2001 ISS (Hp=Ha=400 km, inc=51.5°.

3.1.4. *Validation by Testing, GEO Region*

The GEO populations (10 cm and larger) in ORDEM 3.0 have been derived separately from those of the non-GEO regions. The timeline below illustrates the process of combining a standard LEGEND run from 1957 to 2035 (with objects > 10 cm) with the available Michigan Orbital Debris Survey Telescope (MODEST) uncataloged data for the years 2004 to 2006 (with objects > 30 cm). That data is extended to the ODPO-mandated 10-cm size limit and propagated to 2035.

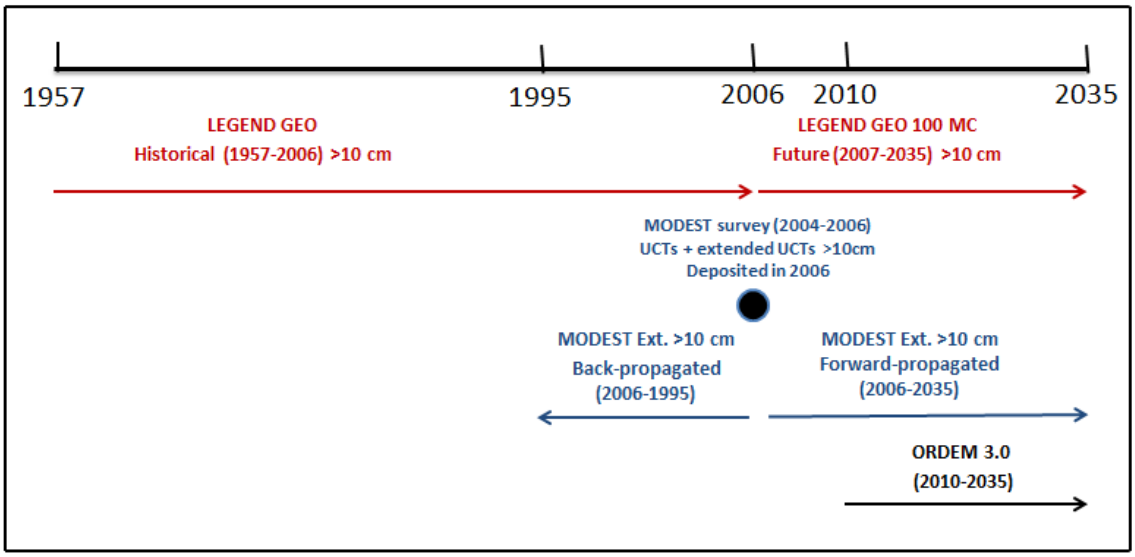

Figure 3.1.4-1. ORDEM 3.0 GEO population timeline.

In the GEO region the SSN catalog is generally considered reliable to objects ~ 1 m or larger in size. MODEST extends these measurements down to ~ 30 cm. The dataset specifically addresses the evidence that the historical period has experienced a number of unobserved explosive breakups in GEO other than the acknowledged two cases in the SSN catalog (Titan 3-C Transtage [SSN #3432] and Ekran 2 [SSN #10365]). For the purposes of ORDEM 3.0 GEO development, the ODPO considers the MODEST survey to be complete down to 30 cm. The MODEST dataset, which contains ~235 objects larger than ~30 cm, appears to follow the power law in $\log_{10}$ (cumulative number) vs. $\log_{10}$ (size) that is similar to that which governs well-observed LEO explosive fragmentation debris. Figure 3.1.4-2 displays the power law curve, derived from the SSN data (Johnson), as represented by a black bolded line, with an average slope of the debris population curve of -1.6. This breakup model predicts that ~40 fragments larger than ~30 cm will be generated in a single explosive breakup and it indicates that there have been ~6 explosive breakups in GEO as of 2006.

Note: No attempt has been made to identify the origin of any fragments in the MODEST database. It was discovered after the ORDEM 3.0 software release that the Titan 3-C Transtage (SSN #3432) fragments were counted twice, once without identification in the MODEST and extended MODEST database and again in the LEGEND fragmentation deposit. This results in a 10% population error that will be rectified in the next ORDEM release.

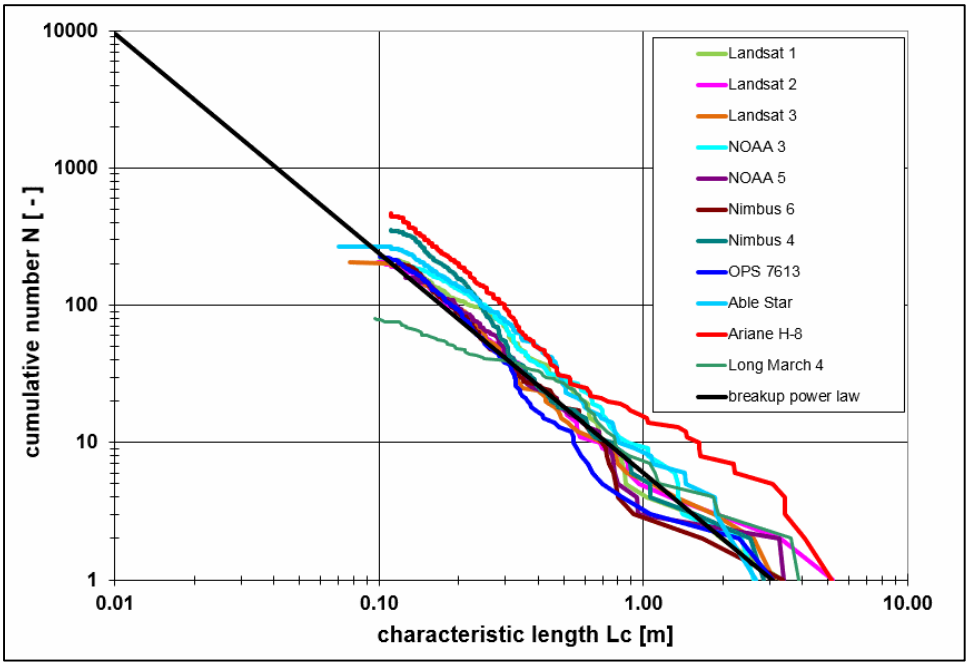

Figure 3.1.4-2. Sample debris size distributions, 11 accidental LEO upper stage breakups.

The histograms in Figures 3.1.4-3 and 3.1.4-4 display the ORDEM 3.0 GEO population at the end of 2006 in terms of number vs. absolute magnitude and number vs. size, respectively. The individual curves represent source components. The cataloged objects (in red) are pulled from the LEGEND output. These satellites include the complete set of cataloged objects in GEO. MODEST data does include fortuitous surveyed observations of cataloged objects, but the survey is intended to be statistical, where multiple observations are handled by estimating and correcting for the observation biases. For these reasons the MODEST cataloged data is excluded from the ORDEM 3.0 GEO objects, using instead the more complete catalog and DBS data.

Uncataloged objects in green are also derived from LEGEND. These are the fragments (> 10 cm) that are distributed from statistical breakup events in the LEGEND process. The number of these objects continues to increase with decreasing size, as shown in Figure 3.1.4-4. Uncataloged objects in blue are MODEST observations (> 30 cm). For the construction of the ORDEM 3.0 populations, these objects are weighted by their observation probability. The drop-off in detections beginning at around 17th absolute magnitude (~ 6 cm) is due to known limitations of the MODEST system as object size decreases. Uncataloged objects in magenta represent an extension (30 cm to 10 cm) of the MODEST observation data based on the NASA breakup model.

The absolute magnitude is the calibrated and corrected magnitude normalized (in GEO) to a distance of 36,000 km and a 0° phase angle). The ODPO converts absolute magnitude to size by assuming that each object is a Lambertian sphere with an albedo of 0.13. The process is inverted to derive absolute magnitude from size for the LEGEND objects. Absolute magnitude and size are inversely related. Bright/large objects have low magnitudes, while dim/small objects have larger magnitudes. The cut off of 20th absolute magnitude corresponds to 10 cm in size.

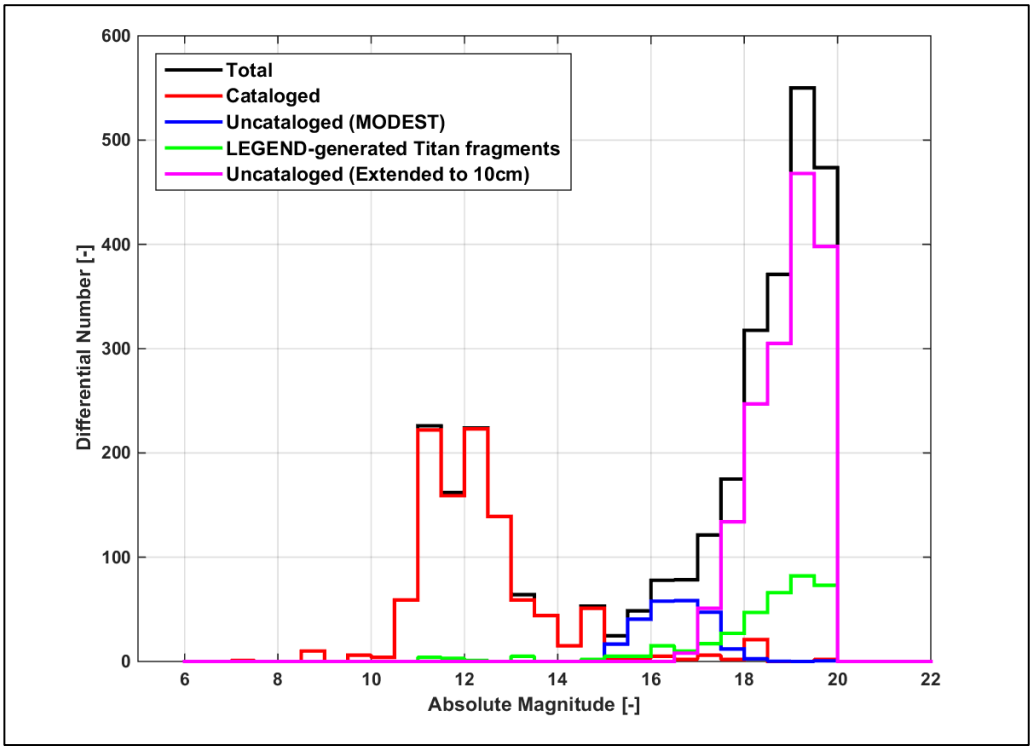

Figure 3.1.4-3. ORDEM 3.0 GEO file for 2006, absolute magnitude (bins = 0.5).

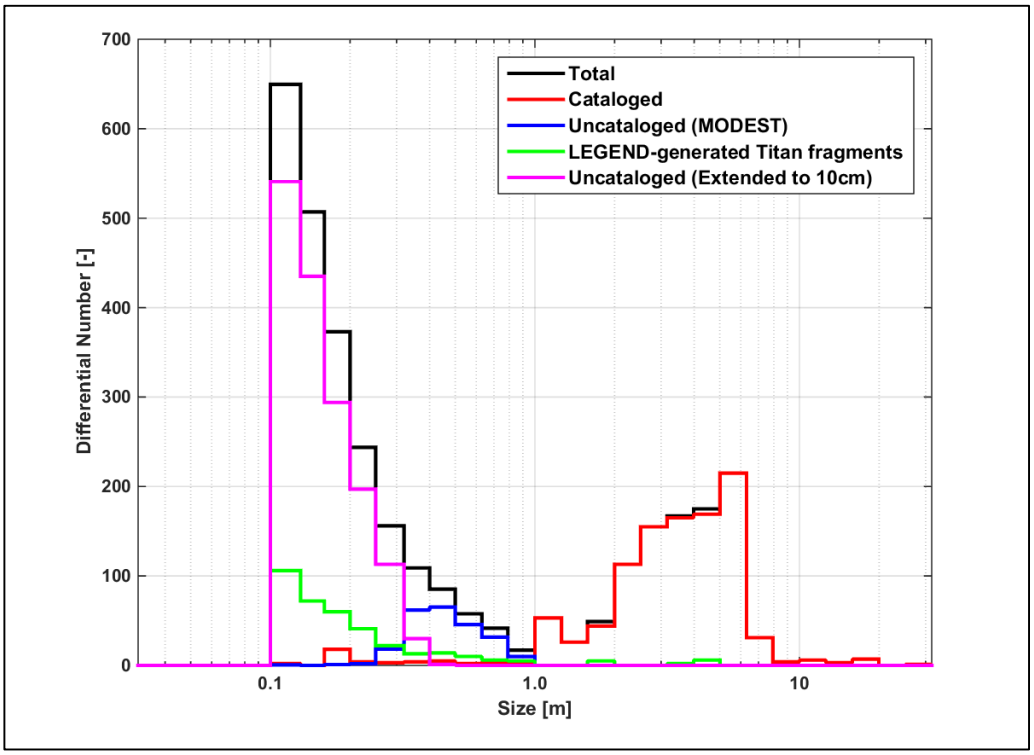

Figure 3.1.4-4. ORDEM 3.0 GEO file for 2006, log10 size (bins = 0.1).

Validation in GEO depends almost exclusively on the cataloged objects ~ > 1 m. Figure 3.1.4-5 below displays the frequency vs. inclination of those satellites at the end of 2006. The GEO TLEs are compared to the companion ORDEM 3.0 GEO population (green vs. red). The black curve in the figure below represents the ORDEM 3.0 GEO smaller satellites that cannot be validated by the SSN catalog.

Qualitative comparisons between ESA 1-m telescope and NASA MODEST survey data are included in Appendix D, as well as all orbital element and spatial density validations.

The tests performed during testing validation of the GEO section correctly and completely represent the design specifications and requirements of the ORDEM 3.0 model.

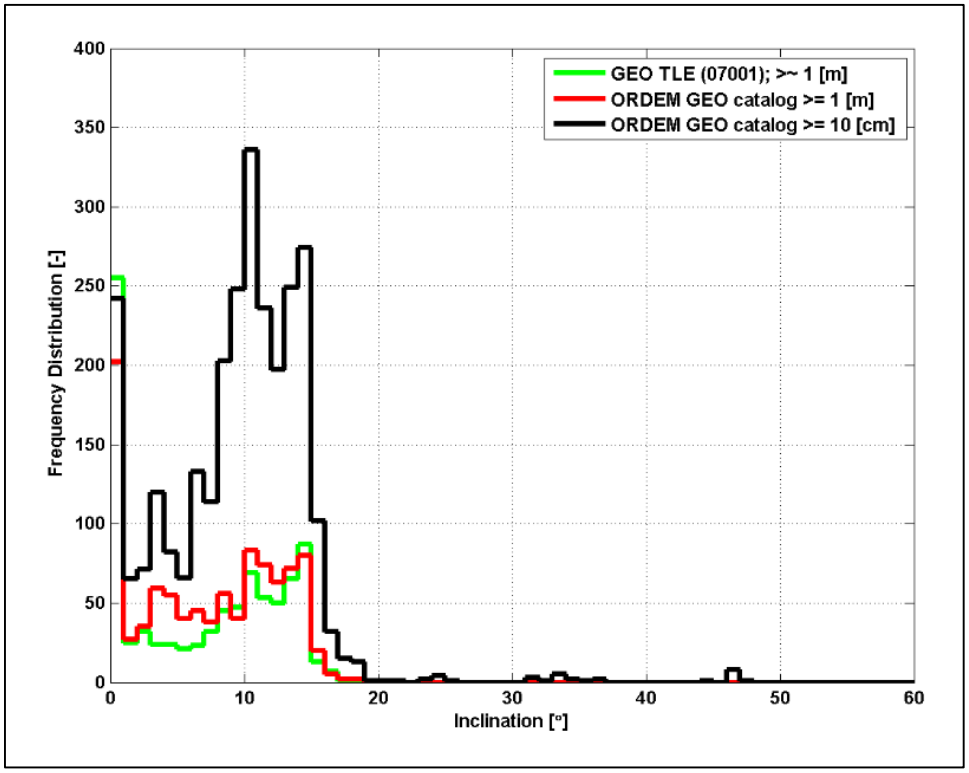

Figure 3.1.4-5. Frequency vs. Inclination at the end of 2006.

4.0 References

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Appendix A: SVVP Compliance Matrix

This Appendix includes the Software Verification and Validation Plan (SVVP) compliance matrix.

TABLE A.1-1 – SVVP COMPLIANCE MATRIX

Task	Life Cycle Processes	V&V Activities	V&V Tasks	V&V Subtasks	IEEE Summary Description	Jacobs Fulfillment	Description or Descriptive Element	V&V Independence	V&V Status
1	**Acquisition**								
	1.1	*Acquisition Support V&V Activities*							
		1.1.1	Management of V&V						
			1.1.1.1	(b) interface with organizational supporting processes	Coordinate the V&V effort with organizational (*e.g.,* management) and supporting processes (*e.g.,* quality assurance, joint review). Identify the V&V data to be exchanged with these processes. Document the data exchange requirements in the SVVP.	no formal analysis conducted			
			1.1.1.2	(d) management review of V&V	Review and summarize the V&V effort to define changes to V&V tasks or to redirect the V&V effort. Recommend whether to proceed to the next set of V&V and development life cycle activities, and provide task reports, anomaly reports, and V&V Activity Summary Reports to the organizations identified in the SVVP. Verify that all V&V tasks comply with task requirements defined in the SVVP. Verify that V&V task results have a basis of evidence supporting the results. Assess V&V results and provide recommendations for program acceptance and certification as input to the V&V Final Report.	no formal analysis conducted			

Task	Life Cycle Processes	V&V Activities	V&V Tasks	V&V Subtasks	IEEE Summary Description	Jacobs Fulfillment	Description or Descriptive Element	V&V Independence	V&V Status
		1.1.2	Planning the interface between the V&V effort & supplier		Plan the V&V schedule for each V&V task. Identify the preliminary list of development processes and products to be evaluated for the V&V process. Describe V&V access rights to proprietary and classified information. Coordinate plan with acquirer (customer: NASA). Incorporate the project software integrity scheme into the planning process.	no formal analysis conducted			
		1.1.3	Scoping the V&V effort		Define the project V&V software criticality (*e.g.,* safety, security, mission critical, technical complexity). Assign a software integrity level to the system and the software. Establish the degree of independence required for the V&V. Provide an estimate of the V&V budget, including test facilities and tools as required. To scope the V&V effort, the following steps shall be performed: (i) adopt the system integrity scheme assigned to the project; if no system integrity level scheme exists, then select one, (ii) determine the minimum V&V tasks for the software integrity level using this scheme and IEEE Table 2, (iii) augment the minimum V&V tasks with optional V&V tasks, as necessary, (iv) establish the scope of the V&V from the description of V&V tasks, inputs, and outputs defined in IEEE Table 1.	no formal analysis conducted			

Task	Life Cycle Processes	V&V Activities	V&V Tasks	V&V Subtasks	IEEE Summary Description	Jacobs Fulfillment	Description or Descriptive Element	V&V Independence	V&V Status
		1.1.4	System Requirements Review		Review system requirements to (i) verify the consistency of requirement to user needs, (ii) validate whether the requirements can be satisfied by the defined technologies, methods, and algorithms defined for the project (feasibility), and (iii) verify whether objective information that can be demonstrated by testing is provided in the requirements (testability). Review other requirements such as deliverable definitions, listing of appropriate compliance standards and regulations, user needs, etc. for completeness, correctness, and accuracy.	no formal analysis conducted			
2	**Supply**								
	2.1	*Planning V&V Activity*							
		2.1.1	Management of V&V						
			2.1.1.1	(b) interface with organizational supporting processes	Coordinate the V&V effort with organizational (*e.g.,* management) and supporting processes (*e.g.,* quality assurance, joint review). Identify the V&V data to be exchanged with these processes. Document the data exchange requirements in the SVVP.	no formal analysis conducted			

Task	Life Cycle Processes	V&V Activities	V&V Tasks	V&V Subtasks	IEEE Summary Description	Jacobs Fulfillment	Description or Descriptive Element	V&V Independence	V&V Status
			2.1.1.2	(d) management review of V&V	Review and summarize the V&V effort to define changes to V&V tasks or to redirect the V&V effort. Recommend whether to proceed to the next set of V&V and development life cycle activities, and provide task reports, anomaly reports, and V&V Activity Summary Reports to the organizations identified in the SVVP. Verify that all V&V tasks comply with task requirements defined in the SVVP. Verify that V&V task results have a basis of evidence supporting the results. Assess V&V results and provide recommendations for program acceptance and certification as input to the V&V Final Report.	no formal analysis conducted			
		2.1.2	Planning the interface between the V&V effort & supplier		Review the supplier (Jacobs) development plans and schedules to coordinate the V&V effort with development activities. Establish procedures to exchange V&V data and results with the development effort. Coordinate with the acquirer (NASA). Incorporate the project software integrity level scheme into the planning process.	no formal analysis conducted			
3	**Development**								
	3.1	*Concept V&V Activity*							

Task	Life Cycle Processes	V&V Activities	V&V Tasks	V&V Subtasks	IEEE Summary Description	Jacobs Fulfillment	Description or Descriptive Element	V&V Independence	V&V Status
		3.1.1	Concept documentation evaluation		Verify that the concept documentation satisfies user needs and is consistent with acquisition needs. Validate constraints of interfacing systems and constraints or limitations on proposed approach. Analyze system requirements and validate that the following satisfy user needs: (i) system functions, (ii) end-to-end system performance, (iii) feasibility and testability of the functional requirements, (iv) system architecture design, (v) operation and maintenance requirements, and (vi) migration requirements from any existing systems.	no formal analysis conducted			
		3.1.2	Criticality Analysis		Determine whether software integrity levels are established for requirements, detailed functions, software modules, subsystem, or other software partitions. Verify that the assigned software integrity levels are correct. Document the software integrity level assigned to individual software components. For V&V planning purposes, the most critical software integrity level assigned to individual elements shall be the integrity level assigned to the entire software. Verify whether any software component can influence individual software components assigned a higher software integrity level, and if such conditions exist, then assign that software component the same higher software integrity level.	no formal analysis conducted			
		3.1.3	Hazard Analysis		Analyze the potential hazards to and from the conceptual system. The analysis shall (i) identify the potential system hazards, (ii) assess the severity of each hazard, (iii) assess the probability of each hazard, and (iv) identify mitigation strategies for each hazard.	no formal analysis conducted			

Task	Life Cycle Processes	V&V Activities	V&V Tasks	V&V Subtasks	IEEE Summary Description	Jacobs Fulfillment	Description or Descriptive Element	V&V Independence	V&V Status
		3.1.4	Management of V&V						
			3.1.4.1	(b) interface with organizational supporting processes	Coordinate the V&V effort with organizational (*e.g.,* management) and supporting processes (*e.g.,* quality assurance, joint review). Identify the V&V data to be exchanged with these processes. Document the data exchange requirements in the SVVP.	no formal analysis conducted			
			3.1.4.2	(c) management and technical review support	Support project management reviews and technical reviews (*e.g.,* PDR, CDR) by assessing the review materials, attending the reviews, and providing task reports and anomaly reports. Verify the timely delivery according to the approved schedule of all software products and documents.	no formal analysis conducted			
			3.1.4.3	(d) management review of V&V	Review and summarize the V&V effort to define changes to V&V tasks or to redirect the V&V effort. Recommend whether to proceed to the next set of V&V and development life cycle activities, and provide task reports, anomaly reports, and V&V Activity Summary Reports to the organizations identified in the SVVP. Verify that all V&V tasks comply with task requirements defined in the SVVP. Verify that V&V task results have a basis of evidence supporting the results. Assess V&V results and provide recommendations for program acceptance and certification as input to the V&V Final Report.	no formal analysis conducted			
			3.1.4.4	(e) software V&V plan (SVVP) generation	Generate an SVVP for all life cycle processes. The SVVP may require updating throughout the life cycle. Establish a baseline SVVP prior to the Requirements V&V activities. Identify project milestones in the SVVP. Schedule V&V tasks to support project management reviews and technical reviews.	no formal analysis conducted			

Task	Life Cycle Processes	V&V Activities	V&V Tasks	V&V Subtasks	IEEE Summary Description	Jacobs Fulfillment	Description or Descriptive Element	V&V Independence	V&V Status
		3.1.5	Operation Procedure evaluation		Verify that the operating procedures are consistent with the user documentation and conform to the system requirements.	no formal analysis conducted			
		3.1.6	Risk Analysis		Identify the technical and management risks. Provide recommendations to eliminate, reduce, or mitigate the risks.	no formal analysis conducted			
		3.1.7	Traceability Analysis		Identify all system requirements that will be implemented completely or partially by software. Verify that these system requirements are traceable to customer (NASA) needs. Start the software requirements traceability analysis with system requirements.	no formal analysis conducted			
	3.2	*Require-ments V&V Activity*							
		3.2.1	Algorithm analysis		Verify the correct implementation of algorithms, equations, mathematical formulations, or expressions. Re-derive any significant algorithms, and equations from basic principles and theories. Compare against established references or proven past historical data. Validate the algorithms, equations, mathematical formulations, or expressions with respect to the system and software requirements. Ensure that the algorithms and equations are appropriate for the problem solution. Validate the correctness of any constraints or limitations such as rounding, truncation, expression simplifications, best fit estimations, and/or non-linear solutions imposed by the algorithms and equations.	no formal analysis conducted			

Task	Life Cycle Processes	V&V Activities	V&V Tasks	V&V Subtasks	IEEE Summary Description	Jacobs Fulfillment	Description or Descriptive Element	V&V Independence	V&V Status
		3.2.2	Acceptance V&V test plan generation and verification		Plan acceptance V&V testing to validate that software correctly implements system and software requirements in an operational environment. The task criteria are (i) compliance with acceptance requirements in the operational environment, and (ii) adequacy of user documentation. Plan tracing of acceptance test requirements to test design, cases, procedures, and execution results. Plan documentation of test tasks and results. Validate that the acceptance Test Plan satisfies the following criteria: (i) test coverage of system requirements, (ii) conformance to expected results, and (iii) feasibility of operation and maintenance (*e.g.,* capability to be operated and maintained in accordance with user needs).	no formal analysis conducted			
		3.2.3	Configuration management assessment		Verify that the configuration management process is complete and adequate. See IEEE Table 1 5.4.2 (7) for criteria description.	no formal analysis conducted			
		3.2.4	Criticality Analysis		Verify that no inconsistent or undesired software integrity consequences are introduced by reviewing the revised software integrity levels.	no formal analysis conducted			
		3.2.5	Hazard Analysis		Determine software contributions to system hazards. The hazard analysis shall (i) identify the software requirements that contribute to each system hazard, and (ii) validate that the software addresses, controls, or mitigates each hazard.	no formal analysis conducted			
		3.2.6	Interface Analysis		Verify and validate that the requirements for software interfaces with hardware, user, operator, and other systems are correct, consistent, complete, accurate, and testable. See IEEE Table 1 5.4.2 (3) for task criteria.	no formal analysis conducted			
		3.2.7	Management of V&V						

Task	Life Cycle Processes	V&V Activities	V&V Tasks	V&V Subtasks	IEEE Summary Description	Jacobs Fulfillment	Description or Descriptive Element	V&V Independence	V&V Status
			3.2.7.1	(a) baseline change assessment	Evaluate proposed software changes (*e.g.,* anomaly corrections and requirement changes) for effects on previously completed V&V tasks. Plan iteration of affected tasks or initiate new tasks to address software baseline changes or iterative development processes. Verify and validate that the change is consistent with system requirements and does not adversely affect requirements directly or indirectly. An adverse effect is a change that could create new system hazards and risks or impact previously resolved hazards and risks.	no formal analysis conducted			
			3.2.7.2	(b) interface with organizational supporting processes	Coordinate the V&V effort with organizational (*e.g.,* management) and supporting processes (*e.g.,* quality assurance, joint review). Identify the V&V data to be exchanged with these processes. Document the data exchange requirements in the SVVP.	no formal analysis conducted			
			3.2.7.3	(c) management and technical review support	Support project management reviews and technical reviews (*e.g.,* PDR, CDR) by assessing the review materials, attending the reviews, and providing task reports and anomaly reports. Verify the timely delivery according to the approved schedule of all software products and documents.	no formal analysis conducted			

Task	Life Cycle Processes	V&V Activities	V&V Tasks	V&V Subtasks	IEEE Summary Description	Jacobs Fulfillment	Description or Descriptive Element	V&V Independence	V&V Status
			3.2.7.4	(d) management review of V&V	Review and summarize the V&V effort to define changes to V&V tasks or to redirect the V&V effort. Recommend whether to proceed to the next set of V&V and development life cycle activities, and provide task reports, anomaly reports, and V&V Activity Summary Reports to the organizations identified in the SVVP. Verify that all V&V tasks comply with task requirements defined in the SVVP. Verify that V&V task results have a basis of evidence supporting the results. Assess V&V results and provide recommendations for program acceptance and certification as input to the V&V Final Report.	no formal analysis conducted			
		3.2.8	Risk Analysis		Review and update risk analysis using prior task reports. Provide recommendations to eliminate, reduce, or mitigate the risks.	no formal analysis conducted			
		3.2.9	Software requirements evaluation		Evaluate the requirements (*e.g.,* functional, capability, interface, qualification, safety, security, human factors, data definitions, user documentation, installation and acceptance, user operation, and user maintenance) for correctness, consistency, completeness, accuracy, readability, and testability. Task criteria are described in IEEE Table 1 5.4.2 (2).	no formal analysis conducted			

Task	Life Cycle Processes	V&V Activities	V&V Tasks	V&V Subtasks	IEEE Summary Description	Jacobs Fulfillment	Description or Descriptive Element	V&V Independence	V&V Status
		3.2.10	System V&V test plan generation and verification		Plan system V&V testing to validate software requirements. Plan tracing of system requirements to test designs, cases, procedures, and results. Plan document of test designs, cases, procedures, and results. The SVVP shall address the following (i) compliance with all system requirements, (ii) adequacy of user documentation, and (iii) performance at boundaries and under stress conditions. Verify that the System V&V Test Plan conforms to project-defined test document's purpose, format, and content. Validate that the System Test Plan satisfies the following criteria: (i) test coverage of system requirements, (ii) appropriateness of test methods and standards used, (iii) conformance to expected results, (iv) feasibility of system qualification testing, and (v) feasibility and testability of operation and maintenance requirements.	no formal analysis conducted			
		3.2.11	Traceability Analysis		Trace the software requirements to system requirements, and system requirements to the software requirements. Analyze identified relationships for correctness, consistency, completeness, and accuracy. See IEEE Table 1 5.4.2 (1) for description of these four attributes.	no formal analysis conducted			
	3.3	*Design V&V*							

Task	Life Cycle Processes	V&V Activities	V&V Tasks	V&V Subtasks	IEEE Summary Description	Jacobs Fulfillment	Description or Descriptive Element	V&V Independence	V&V Status
		3.3.1	Algorithm analysis		Verify the correct implementation of algorithms, equations, mathematical formulations, or expressions. Re-derive any significant algorithms, and equations from basic principles and theories. Compare against established references or proven past historical data. Validate the algorithms, equations, mathematical formulations, or expressions with respect to the system and software requirements. Ensure that the algorithms and equations are appropriate for the problem solution. Validate the correctness of any constraints or limitations such as rounding, truncation, expression simplifications, best fit estimations, and/or non-linear solutions imposed by the algorithms and equations.	no formal analysis conducted			

Task	Life Cycle Processes	V&V Activities	V&V Tasks	V&V Subtasks	IEEE Summary Description	Jacobs Fulfillment	Description or Descriptive Element	V&V Independence	V&V Status
		3.3.2	Component V&V test plan & verification		Plan component V&V testing to validate that the software components (*e.g.,* units, source code modules) correctly implement component requirements. The task criteria are (i) compliance with design requirements, (ii) assessment of timing, sizing, and accuracy, (iii) performance at boundaries and interfaces and under stress and error conditions, and (iv) measure of requirement's test coverage and software reliability and maintainability. Plan tracing of design requirements to test design, cases, procedures, and results. Plan documentation of test tasks and results. Verify that the Component V&V Test Plan complies with project-defined test document purpose, format, and content. Validate that the Component V&V Test Plan satisfies the following criteria: (i) traceable to the software requirements and design, (ii) external consistency with the software requirements and design, (iii) internal consistency between unit requirements, (iv) test coverage of requirements in each unit, (v) feasibility of software integration and testing, and (vi) feasibility of operation and maintenance (*e.g.,* capability to be operated and maintained in accordance with user needs).	no formal analysis conducted			

Task	Life Cycle Processes	V&V Activities	V&V Tasks	V&V Subtasks	IEEE Summary Description	Jacobs Fulfillment	Description or Descriptive Element	V&V Independence	V&V Status
		3.3.3	Criticality Analysis		Review and update the existing criticality analysis results from the prior Criticality Task Report. Implementation methods and interfacing technologies may cause previously assigned software integrity levels to be raised or lowered for a given software element (i.e., requirement, module, function, subsystem, other software partition). Verify that no inconsistent or undesired software integrity consequences are introduced by reviewing the revised software integrity levels.	no formal analysis conducted			
		3.3.4	Hazard Analysis		Verify that logic design and associated data elements correctly implement the critical requirements and introduce no new hazards. Update the hazard analysis.	no formal analysis conducted			
		3.3.5	Interface Analysis		Verify and validate that the software design interfaces with hardware, user, operator, software, and other systems for correctness, consistency, completeness, accuracy, and testability. The task criteria are described in IEEE 5.4.3 (3).	no formal analysis conducted			
		3.3.6	Management of V&V						
			3.3.6.1	(a) baseline change assessment	Evaluate proposed software changes (*e.g.,* anomaly corrections and requirement changes) for effects on previously completed V&V tasks. Plan iteration of affected tasks or initiate new tasks to address software baseline changes or iterative development processes. Verify and validate that the change is consistent with system requirements and does not adversely affect requirements directly or indirectly. An adverse effect is a change that could create new system hazards and risks or impact previously resolved hazards and risks.	no formal analysis conducted			

Task	Life Cycle Processes	V&V Activities	V&V Tasks	V&V Subtasks	IEEE Summary Description	Jacobs Fulfillment	Description or Descriptive Element	V&V Independence	V&V Status
			3.3.6.2	(b) interface with organizational supporting processes	Coordinate the V&V effort with organizational (*e.g.,* management) and supporting processes (*e.g.,* quality assurance, joint review). Identify the V&V data to be exchanged with these processes. Document the data exchange requirements in the SVVP.	no formal analysis conducted			
			3.3.6.3	(c) management and technical review support	Support project management reviews and technical reviews (*e.g.,* PDR, CDR) by assessing the review materials, attending the reviews, and providing task reports and anomaly reports. Verify the timely delivery according to the approved schedule of all software products and documents.	no formal analysis conducted			
			3.3.6.4	(d) management review of V&V	Review and summarize the V&V effort to define changes to V&V tasks or to redirect the V&V effort. Recommend whether to proceed to the next set of V&V and development life cycle activities, and provide task reports, anomaly reports, and V&V Activity Summary Reports to the organizations identified in the SVVP. Verify that all V&V tasks comply with task requirements defined in the SVVP. Verify that V&V task results have a basis of evidence supporting the results. Assess V&V results and provide recommendations for program acceptance and certification as input to the V&V Final Report.	no formal analysis conducted			
		3.3.7	Risk Analysis		Review and update risk analysis using prior task reports. Provide recommendations to eliminate, reduce, or mitigate the risks.	no formal analysis conducted			
		3.3.8	Software Design Evaluation		Evaluate the design elements for correctness, consistency, completeness, accuracy, readability, and testability.	no formal analysis conducted			

Task	Life Cycle Processes	V&V Activities	V&V Tasks	V&V Subtasks	IEEE Summary Description	Jacobs Fulfillment	Description or Descriptive Element	V&V Independence	V&V Status
			3.3.8.1	correctness	Verify and validate that the source code component satisfies the software design; verify that the source code components comply with standards, references, regulations, policies, physical laws, and business rules; validate the source code component sequences of states and state changes using logic and data flows coupled with domain expertise, prototyping results, engineering principles, or other basis; validate that the flow of data and control satisfy functionality and performance requirements; validate data usage and format; and assess the appropriateness of coding methods and standards.	no formal analysis conducted			
			3.3.8.2	consistency	Verify that all terms and code concepts are documented consistently; verify that there is internal consistency between the source code components.	no formal analysis conducted			
			3.3.8.3	completeness	Verify that the following elements are in the software design description (SDD), within the assumptions and constraints of the system: (i) functionality (*e.g.,* algorithms, state/mode definitions, input/output validation, exception handling, reporting and logging), (ii) process definition and scheduling, (iii) hardware, software, and user interface descriptions, (iv) performance criteria (*e.g.,* timing, sizing, speed, capacity, accuracy, precision, safety, and security), (v) critical configuration data, and (vi) system, device, and software control (*e.g.,* initialization, transaction and state monitoring, and self-testing); verify that the SDD and Interface Design Document (IDD) satisfy specified configuration management procedures.	no formal analysis conducted			

Task	Life Cycle Processes	V&V Activities	V&V Tasks	V&V Subtasks	IEEE Summary Description	Jacobs Fulfillment	Description or Descriptive Element	V&V Independence	V&V Status
			3.3.8.4	accuracy	Validate that the logic, computational and interface precision (*e.g.,* truncation and rounding) satisfy the requirements in the system environment; validate that the modeled physical phenomena conform to system accuracy requirements and physical laws.	no formal analysis conducted			
			3.3.8.5	readability	Verify that the documentation is legible, understandable, and unambiguous to the intended audience; verify that the documentation defines all acronyms, mnemonics, abbreviations, terms, symbols, and design language, if any.	no formal analysis conducted			
			3.3.8.6	testability	Verify that there are objective acceptance criteria for validating each software design element and the system design; verify that each software design element is testable to objective acceptance criteria.	no formal analysis conducted			
		3.3.9	Traceability Analysis		Trace design elements to requirements and requirements to design elements. Analyze relationships for correctness, consistency, and completeness. See IEEE 5.4.3 (1) for task criteria explanation.	no formal analysis conducted			
		3.3.10	V&V test design generation and verification		Design tests for (i) component testing, (ii) integration testing, (iii) system testing, and (iv) acceptance testing. Continue tracing required by the V&V Test Plan. Verify that the V&V Test Design complies with project-defined test document's purpose, format, and content. Validate that the V&V Test Design satisfies the criteria in IEEE 5.4.3 (7).	no formal analysis conducted			
			3.3.10.1	(a) component	(Jacobs): ORDEM subroutine-level				
			3.3.10.2	(b) integration	(Jacobs): ORDEM executable				
			3.3.10.3	(c) system	(Jacobs): ORDEM GUI-level				
			3.3.10.4	(d) acceptance	(Jacobs): ORDEM 3.0 deliverable				

Task	Life Cycle Processes	V&V Activities	V&V Tasks	V&V Subtasks	IEEE Summary Description	Jacobs Fulfillment	Description or Descriptive Element	V&V Independence	V&V Status
	3.4	*Implemen-tation V&V*							
		3.4.1	Algorithm Analysis		Verify the correct implementation of algorithms, equations, mathematical formulations, or expressions. Re-derive any significant algorithms, and equations from basic principles and theories. Compare against established references or proven past historical data. Validate the algorithms, equations, mathematical formulations, or expressions with respect to the system and software requirements. Ensure that the algorithms and equations are appropriate for the problem solution. Validate the correctness of any constraints or limitations such as rounding, truncation, expression simplifications, best fit estimations, and/or non-linear solutions imposed by the algorithms and equations.	Algorithms developed independently by supplier or in concert with acquirer. Programming best practices used.	Extensive use of legacy software from other projects, *e.g.,* LEGEND.	internal	pass
		3.4.2	Component V&V test plan & verification		Perform V&V component testing. Analyze test results to validate that software correctly implements the design. Validate that the test results trace to test criteria established by the test traceability in the test planning documents. Document the results as required by the Component V&V Test Plan. Use the V&V component test results to validate that the software satisfies the V&V test acceptance criteria. Document discrepancies between actual and expected test results.	No formal test plan. Component V&V conducted using best practices for ORDEM spacecraft and telescope modes.	Programming best practices used.	internal	pass

Task	Life Cycle Processes	V&V Activities	V&V Tasks	V&V Subtasks	IEEE Summary Description	Jacobs Fulfillment	Description or Descriptive Element	V&V Independence	V&V Status
		3.4.3	Criticality Analysis		Review and update the existing criticality analysis results from the prior Criticality Task Report using the source code. Implementation methods and interfacing technologies may cause previously assigned software integrity levels to be raised or lowered for a given software element (*i.e.,* requirement, module, function, subsystem, or other software partition). Verify that no inconsistent or undesired software integrity consequences are introduced by reviewing the revised software integrity levels.	Criticality (3) determined by PM using IEEE Std. 1012-1998, Annex B, September 2011.	An error to a function or system feature that causes catastrophic consequences with occasional or infrequent likelihood.	internal	n/a
		3.4.4	Hazard Analysis		Verify that the implementation and associated data elements correctly implement the critical requirements and introduce no new hazards. Update the hazard analysis.	no formal analysis conducted			
		3.4.5	Interface Analysis		Verify and validate that the software source code interfaces with hardware, user, operator, software, and other systems for correctness, consistency, completeness, accuracy, and testability. The task criteria are described further in IEEE 5.4.4 (3).	GUI testing only	GUI tested for correctness, consistency, completeness, and accuracy. Limitations due to TeeChart bug; bug fixed by using hardwired values for vertical (flux) axes.	internal and embedded	conditional pass (non dynamic axes)
		3.4.6	Management of V&V						

Task	Life Cycle Processes	V&V Activities	V&V Tasks	V&V Subtasks	IEEE Summary Description	Jacobs Fulfillment	Description or Descriptive Element	V&V Independence	V&V Status
			3.4.6.1	(a) baseline change assessment	Evaluate proposed software changes (*e.g.,* anomaly corrections and requirement changes) for effects on previously completed V&V tasks. Plan iteration of affected tasks or initiate new tasks to address software baseline changes or iterative development processes. Verify and validate that the change is consistent with system requirements and does not adversely affect requirements directly or indirectly. An adverse effect is a change that could create new system hazards and risks or impact previously resolved hazards and risks.	Conducted as required by model and/or population(s) revision	Results reported upon in internal/external meetings & conferences.	internal	completed
			3.4.6.2	(b) interface with organizational supporting processes	Coordinate the V&V effort with organizational (*e.g.,* management) and supporting processes (*e.g.,* quality assurance, joint review). Identify the V&V data to be exchanged with these processes. Document the data exchange requirements in the SVVP.	Jacobs and/or Jacobs/NASA joint review meetings, '05-date. Jacobs matrixed personnel for GUI and TeeChart programming.	Results reported upon in internal/external meetings & conferences.	internal	completed
			3.4.6.3	(c) management and technical review support	Support project management reviews and technical reviews (*e.g.,* PDR, CDR) by assessing the review materials, attending the reviews, and providing task reports and anomaly reports. Verify the timely delivery according to the approved schedule of all software products and documents.	Jacobs and/or Jacobs/NASA joint review meetings, '05-date. Software beta release and review conducted 3 April '09 - Summer '10.	Results reported upon in internal/external meetings & conferences.	internal; beta release: technical, managerial, and financial indepencence	n/a

Task	Life Cycle Processes	V&V Activities	V&V Tasks	V&V Subtasks	IEEE Summary Description	Jacobs Fulfillment	Description or Descriptive Element	V&V Independence	V&V Status
			3.4.6.4	(d) management review of V&V	Review and summarize the V&V effort to define changes to V&V tasks or to redirect the V&V effort. Recommend whether to proceed to the next set of V&V and development life cycle activities, and provide task reports, anomaly reports, and V&V Activity Summary Reports to the organizations identified in the SVVP. Verify that all V&V tasks comply with task requirements defined in the SVVP. Verify that V&V task results have a basis of evidence supporting the results. Assess V&V results and provide recommendations for program acceptance and certification as input to the V&V Final Report.	NASA lead/Jacobs PM KA meeting, 22 July 2011. ML/PM prerogatives and initiatives.	Direction received from KA. Internal review at project level.	internal	completed
		3.4.7	Risk Analysis		Review and update risk analysis using prior task reports. Provide recommendations to eliminate, reduce, or mitigate the risks.	no formal analysis conducted			
		3.4.8	Source code and source code documentation evaluation		Evaluate the source code components (Source Code Documentation) for correctness, consistency, completeness, accuracy, readability, and testability. The task criteria are defined further in IEEE 5.4.4 (2).	no formal analysis conducted			
		3.4.9	Traceability Analysis		Trace the source code components to corresponding design specification(s), and design specification(s) to source code components. Analyze identified relationships for correctness, consistency, and completeness. The task criteria are defined further in IEEE 5.4.4 (1).	no formal analysis conducted			
		3.4.10	V&V test case generation and verification		Develop V&V Test Cases for (i) component testing, (ii) integration testing, (iii) system testing and (iv) acceptance testing. Continue tracing required by the V&V Test Plans. Verify that the V&V Test Cases comply with project-defined test document's purpose, format, and content.				

Task	Life Cycle Processes	V&V Activities	V&V Tasks	V&V Subtasks	IEEE Summary Description	Jacobs Fulfillment	Description or Descriptive Element	V&V Independence	V&V Status
			3.4.10.1	(a) component	(Jacobs): ORDEM subroutine-level	Subroutine- and input data file-level testing	LINUX testing	internal	completed
			3.4.10.2	(b) integration	(Jacobs): ORDEM executable	ORDEM executable-level testing	LINUX/PC testing	internal	completed
			3.4.10.3	(c) system	(Jacobs): ORDEM GUI-level	ORDEM GUI-level testing	ORDEM spacecraft mode: typical/high interest orbits including ISS, HST, GEO, GTO, and sun-sync orbits. Integration vs. system-level testing to ensure that GUI outputs are identical to executable outputs.	internal	completed
			3.4.10.4	(d) acceptance	(Jacobs): ORDEM 3.0 deliverable	ORDEM spacecraft mode: test orbits determined by Jacobs and/or NASA. ORDEM telescope mode: test scenarios determined by Jacobs.	ORDEM spacecraft mode: typical/high interest orbits including ISS, HST, GEO, GTO, and sun-sync orbits; ORDEM telescope mode: beam orientation matrix check for symmetry/ asymmetries, etc. See SVVP.	internal	completed
		3.4.11	V&V test procedure generation and verification		Develop V&V Test Procedures for (i) component testing, (ii) integration testing, and (iii) system testing. Continue tracing required by the V&V Test Plans. Verify that the V&V Test Procedures comply with project-defined test document's purpose, format, and content.	Developed unique test software	As described in V&V report Sect. 2	internal	completed
			3.4.11.1	(a) component	(Jacobs): ORDEM subroutine-level				
			3.4.11.2	(b) integration	(Jacobs): ORDEM executable				
			3.4.11.3	(c)system	(Jacobs): ORDEM GUI-level				
	3.5	Test V&V Activity							

Task	Life Cycle Processes	V&V Activities	V&V Tasks	V&V Subtasks	IEEE Summary Description	Jacobs Fulfillment	Description or Descriptive Element	V&V Independence	V&V Status
		3.5.1	Acceptance V&V test execution and verification		Develop Acceptance Test V&V Procedures. Continue the tracing required by the Acceptance V&V Test Plan. Verify that the V&V Test Procedures comply with project-defined test document purpose, format, and content. Validate that the Acceptance V&V Test Procedures satisfy the criteria in V&V task IEEE 5.4.2 (6).	ML/PM/Jacobs statistician assessment of quantitative validation methods including, but not limited to, *z*-score and pairwise tests of ORDEM model vs. measurements.	Pairwise statistical tests of differences and/or *z*-scores used in formal clustering and/or confidence (hypothesis testing) analysis	internal; embedded	completed
		3.5.2	Acceptance V&V test procedure generation and verification		Perform acceptance V&V testing. Analyze test results to validate that the software satisfies the system requirements. Validate that the test results trace to test criteria established by the test traceability in the test planning documents. Document the results as required by the Acceptance V&V Test Plan. Use the acceptance V&V test results to validate that the software satisfies the V&V test acceptance criteria. Document discrepancies between actual and expected test results.	Quantitative testing of ORDEM model (mean, st. dev.) vs. measurements.	ORDEM spacecraft mode: comparison vs. returned surfaces (LEO) and independently-derived flux (LEO/GEO); ORDEM telescope mode: comparison vs. radar (Haystack/HAX/ Goldstone) measurements. See SVVP for altitude/size/time matrix.	internal	completed
		3.5.3	Hazard Analysis		Verify that the test instrumentation does not introduce new hazards. Update the hazard analysis.	no formal analysis conducted			
		3.5.4	Integration V&V test execution and verification		Perform V&V integration testing. Analyze test results to verify that the software components are integrated correctly. Validate that the test results trace to test criteria established by the test traceability in the test planning documents. Document the results as required by the Integration V&V Test Plan. Use the V&V integration test results to validate that the software satisfies the V&V test acceptance criteria. Document discrepancies between actual and expected test results.	Jacobs testing of ORDEM executable	Testing conducted on LINUX & PC hardware; tests yield identical results	internal	completed
		3.5.5	Management of V&V						

Task	Life Cycle Processes	V&V Activities	V&V Tasks	V&V Subtasks	IEEE Summary Description	Jacobs Fulfillment	Description or Descriptive Element	V&V Independence	V&V Status
			3.5.5.1	(a) baseline change assessment	Evaluate proposed software changes (*e.g.,* anomaly corrections and requirement changes) for effects on previously completed V&V tasks. Plan iteration of affected tasks or initiate new tasks to address software baseline changes or iterative development processes. Verify and validate that the change is consistent with system requirements and does not adversely affect requirements directly or indirectly. An adverse effect is a change that could create new system hazards and risks or impact previously resolved hazards and risks.	no formal analysis conducted			
			3.5.5.2	(b) interface with organizational supporting processes	Coordinate the V&V effort with organizational (*e.g.,* management) and supporting processes (*e.g.,* quality assurance, joint review). Identify the V&V data to be exchanged with these processes. Document the data exchange requirements in the SVVP.	Jacobs matrixed personnel for statistical analysis services (Jacobs Statistician)	Dr. Darwin Poritz	embedded	n/a
			3.5.5.3	(c) management and technical review support	Support project management reviews and technical reviews (*e.g.,* PDR, CDR) by assessing the review materials, attending the reviews, and providing task reports and anomaly reports. Verify the timely delivery according to the approved schedule of all software products and documents.	Planned 1-2 Technical Interchange Meeting (TIM) with Jacobs/NASA ODPO & KA staff	see SVVP Master Schedule	n/a	n/a

Task	Life Cycle Processes	V&V Activities	V&V Tasks	V&V Subtasks	IEEE Summary Description	Jacobs Fulfillment	Description or Descriptive Element	V&V Independence	V&V Status
			3.5.5.4	(d) management review of V&V	Review and summarize the V&V effort to define changes to V&V tasks or to redirect the V&V effort. Recommend whether to proceed to the next set of V&V and development life cycle activities, and provide task reports, anomaly reports, and V&V Activity Summary Reports to the organizations identified in the SVVP. Verify that all V&V tasks comply with task requirements defined in the SVVP. Verify that V&V task results have a basis of evidence supporting the results. Assess V&V results and provide recommendations for program acceptance and certification as input to the V&V Final Report.	no formal analysis conducted			
		3.5.6	Risk Analysis		Review and update risk analysis using prior task reports. Provide recommendations to eliminate, reduce, or mitigate the risks.	no formal analysis conducted			
		3.5.7	System V&V test execution and verification		Perform V&V system testing. Analyze test results to validate that the software satisfies the system requirements. Validate that the test results trace to test criteria established by the test traceability in the test planning documents. Document the results are required by the System V&V Test Plan. Use the V&V system test results to validate that the software satisfies the V&V test acceptance criteria. Document discrepancies between actual and expected test results.	Comparisons executed between integration (ORDEM executable) and system (ORDEM GUI) levels for test case orbits (ORDEM spacecraft mode).	ORDEM output (flux vs. size) served as basis of comparison.	internal	completed
		3.5.8	Traceability Analysis		Analyze relationships in the V&V Test Plans, Design, Cases, and Procedures for correctness and completeness. For correctness, verify that there is a valid relationship between the V&V Test Plans, Designs, Cases, and Procedures. For completeness, verify that all V&V Test Procedures are traceable to the V&V Test Plans.	no formal analysis conducted			

Task	Life Cycle Processes	V&V Activities	V&V Tasks	V&V Subtasks	IEEE Summary Description	Jacobs Fulfillment	Description or Descriptive Element	V&V Independence	V&V Status
	3.6	*Installation /checkout V&V Activity*							
		3.6.1	Hazard Analysis		Verify that the installation procedures and installation environment doesn't introduce new hazards. Update the hazard analysis.	implicit	no hazards identified	internal	completed
		3.6.2	Installation checkout		Conduct analyses or tests to verify that the installed software corresponds to the software subjected to V&V. Verify that the software code and databases initialize, execute, and terminate as specified. In the transition from one version of software to the next, the V&V effort shall validate that the software can be removed from the system without affecting the functionality of the remaining system components. The V&V effort shall verify the requirements for continuous operation and service during transition, including user notification.	Implicit; some actionable items identified by beta release	All actionable items identified and corrected	internal; beta release: technical, managerial, and financial indepencence	completed
		3.6.3	Installation configuration audit		Verify that all software products required to correctly install and operate the software are present in the installation package. Validate that all site-dependent parameters or conditions to verify supplied values are correct.	Implicit; some actionable items identified by beta release	All actionable items identified and corrected	internal; beta release: technical, managerial, and financial indepencence	completed
		3.6.4	Management of V&V						

Task	Life Cycle Processes	V&V Activities	V&V Tasks	V&V Subtasks	IEEE Summary Description	Jacobs Fulfillment	Description or Descriptive Element	V&V Independence	V&V Status
			3.6.4.1	(a) baseline change assessment	Evaluate proposed software changes (*e.g.,* anomaly corrections and requirement changes) for effects on previously completed V&V tasks. Plan iteration of affected tasks or initiate new tasks to address software baseline changes or iterative development processes. Verify and validate that the change is consistent with system requirements and does not adversely affect requirements directly or indirectly. An adverse effect is a change that could create new system hazards and risks or impact previously resolved hazards and risks.	OL/project team/PM review	professional/best practices	internal	completed
			3.6.4.2	(b) interface with organizational supporting processes	Coordinate the V&V effort with organizational (*e.g.,* management) and supporting processes (*e.g.,* quality assurance, joint review). Identify the V&V data to be exchanged with these processes. Document the data exchange requirements in the SVVP.	OL/project team/PM review	professional/best practices	internal	completed
			3.6.4.3	(c) management and technical review support	Support project management reviews and technical reviews (*e.g.,* PDR, CDR) by assessing the review materials, attending the reviews, and providing task reports and anomaly reports. Verify the timely delivery according to the approved schedule of all software products and documents.	OL/project team/PM review	professional/best practices	internal	completed

Task	Life Cycle Processes	V&V Activities	V&V Tasks	V&V Subtasks	IEEE Summary Description	Jacobs Fulfillment	Description or Descriptive Element	V&V Independence	V&V Status
			3.6.4.4	(d) management review of V&V	Review and summarize the V&V effort to define changes to V&V tasks or to redirect the V&V effort. Recommend whether to proceed to the next set of V&V and development life cycle activities, and provide task reports, anomaly reports, and V&V Activity Summary Reports to the organizations identified in the SVVP. Verify that all V&V tasks comply with task requirements defined in the SVVP. Verify that V&V task results have a basis of evidence supporting the results. Assess V&V results and provide recommendations for program acceptance and certification as input to the V&V Final Report.	OL/project team/PM review	professional/best practices	internal	completed
		3.6.5	Risk Analysis		Review and update risk analysis using prior task reports. Provide recommendations to eliminate, reduce, or mitigate the risks.	no formal analysis conducted			
		3.6.6	V&V Final Report generation		Summarize in the V&V final report the V&V activities, tasks and results, including status and disposition of anomalies. Provide an assessment of the overall software quality and provide recommendations.	V&V Final Report written	V&V Final Report delivered; see Master Schedule in SVVP.	internal	completed
	4.1	*Operation V&V Activity*							
		4.1.1	Evaluation of new constraints		Evaluate new constraints (*e.g.,* operational requirements, platform characteristics, operating environment) on the system or software requirements to verify the applicability of the SVVP. Software changes are maintenance activities. See IEEE 5.6.1.	**TBD**			
		4.1.2	Hazard Analysis		Verify that the operating procedures and operational environment does not introduce new hazards. Update the hazard analysis.	**TBD**			
		4.1.3	Management of V&V						

Task	Life Cycle Processes	V&V Activities	V&V Tasks	V&V Subtasks	IEEE Summary Description	Jacobs Fulfillment	Description or Descriptive Element	V&V Independence	V&V Status
			4.1.3.1	(a) baseline change assessment	Evaluate proposed software changes (*e.g.,* anomaly corrections and requirement changes) for effects on previously completed V&V tasks. Plan iteration of affected tasks or initiate new tasks to address software baseline changes or iterative development processes. Verify and validate that the change is consistent with system requirements and does not adversely affect requirements directly or indirectly. An adverse effect is a change that could create new system hazards and risks or impact previously resolved hazards and risks.	**TBD**			
			4.1.3.2	(b) interface with organizational supporting processes	Coordinate the V&V effort with organizational (*e.g.,* management) and supporting processes (*e.g.,* quality assurance, joint review). Identify the V&V data to be exchanged with these processes. Document the data exchange requirements in the SVVP.	**TBD**			
			4.1.3.3	(c) management and technical review support	Support project management reviews and technical reviews (*e.g.,* PDR, CDR) by assessing the review materials, attending the reviews, and providing task reports and anomaly reports. Verify the timely delivery according to the approved schedule of all software products and documents.	**TBD**			

Task	Life Cycle Processes	V&V Activities	V&V Tasks	V&V Subtasks	IEEE Summary Description	Jacobs Fulfillment	Description or Descriptive Element	V&V Independence	V&V Status
			4.1.3.4	(d) management review of V&V	Review and summarize the V&V effort to define changes to V&V tasks or to redirect the V&V effort. Recommend whether to proceed to the next set of V&V and development life cycle activities, and provide task reports, anomaly reports, and V&V Activity Summary Reports to the organizations identified in the SVVP. Verify that all V&V tasks comply with task requirements defined in the SVVP. Verify that V&V task results have a basis of evidence supporting the results. Assess V&V results and provide recommendations for program acceptance and certification as input to the V&V Final Report.	**TBD**			
		4.1.4	Operating procedures evaluation		Verify that the operating procedures are consistent with the user documentation and conform to the system requirements.	**TBD**			
		4.1.5	Proposed change assessment		Assess proposed changes (*e.g.,* modifications, enhancements, or additions) to determine the effect of the changes on the system. Determine the extent to which V&V tasks would be iterated.	**TBD**			
		4.1.6	Risk Analysis		Review and update risk analysis using prior task reports. Provide recommendations to eliminate, reduce, or mitigate the risks.	**TBD**			
5	**Maintenance**								
	5.1	*Maintenance V&V Activity*							

Task	Life Cycle Processes	V&V Activities	V&V Tasks	V&V Subtasks	IEEE Summary Description	Jacobs Fulfillment	Description or Descriptive Element	V&V Independence	V&V Status
		5.1.1	Algorithm analysis		Verify the correct implementation of algorithms, equations, mathematical formulations, or expressions. Re-derive any significant algorithms, and equations from basic principles and theories. Compare against established references or proven past historical data. Validate the algorithms, equations, mathematical formulations, or expressions with respect to the system and software requirements. Ensure that the algorithms and equations are appropriate for the problem solution. Validate the correctness of any constraints or limitations such as rounding, truncation, expression simplifications, best fit estimations, and/or non-linear solutions imposed by the algorithms and equations.	**TBD**			
		5.1.2	Anomaly evaluation		Evaluate the effect of software operation anomalies.	**TBD**			
		5.1.3	Criticality Analysis		Determine the software integrity levels for proposed modifications. Validate the integrity levels provided by the maintainer. For V&V planning purposes, the highest software integrity level assigned to the software shall be the software system integrity level.	**TBD**			
		5.1.4	Hazard Analysis		Verify that software modifications correctly implement the critical requirements and introduce no new hazards. Update the hazard analysis.	**TBD**			
		5.1.5	Management of V&V						

Task	Life Cycle Processes	V&V Activities	V&V Tasks	V&V Subtasks	IEEE Summary Description	Jacobs Fulfillment	Description or Descriptive Element	V&V Independence	V&V Status
			5.1.5.1	(a) baseline change assessment	Evaluate proposed software changes (*e.g.,* anomaly corrections and requirement changes) for effects on previously completed V&V tasks. Plan iteration of affected tasks or initiate new tasks to address software baseline changes or iterative development processes. Verify and validate that the change is consistent with system requirements and does not adversely affect requirements directly or indirectly. An adverse effect is a change that could create new system hazards and risks or impact previously resolved hazards and risks.	**TBD**			
			5.1.5.2	(b) interface with organizational supporting processes	Coordinate the V&V effort with organizational (*e.g.,* management) and supporting processes (*e.g.,* quality assurance, joint review). Identify the V&V data to be exchanged with these processes. Document the data exchange requirements in the SVVP.	**TBD**			
			5.1.5.3	(c) management and technical review support	Support project management reviews and technical reviews (*e.g.,* PDR, CDR) by assessing the review materials, attending the reviews, and providing task reports and anomaly reports. Verify the timely delivery according to the approved schedule of all software products and documents.	**TBD**			

Task	Life Cycle Processes	V&V Activities	V&V Tasks	V&V Subtasks	IEEE Summary Description	Jacobs Fulfillment	Description or Descriptive Element	V&V Independence	V&V Status
			5.1.5.4	(d) management review of V&V	Review and summarize the V&V effort to define changes to V&V tasks or to redirect the V&V effort. Recommend whether to proceed to the next set of V&V and development life cycle activities, and provide task reports, anomaly reports, and V&V Activity Summary Reports to the organizations identified in the SVVP. Verify that all V&V tasks comply with task requirements defined in the SVVP. Verify that V&V task results have a basis of evidence supporting the results. Assess V&V results and provide recommendations for program acceptance and certification as input to the V&V Final Report.	**TBD**			
			5.1.5.5	(e) software V&V plan (SVVP) generation	Generate an SVVP for all life cycle processes. The SVVP may require updating throughout the life cycle. Establish a baseline SVVP prior to the Requirements V&V activities. Identify project milestones in the SVVP. Schedule V&V tasks to support project management reviews and technical reviews.	**TBD**			
		5.1.6	Migration assessment		Assess whether the software requirements and implementation address (i) specific migration requirements, (ii) migration tools, (iii) conversion of software products and data, (iv) software archiving, (v) support for the prior environment, and (vi) user notification.	**TBD**			
		5.1.7	Proposed change assessment		Assess proposed changes (i.e., modifications, enhancements, or additions) to determine the effect of the changes on the system. Determine the extent to which V&V tasks would be iterated.	**TBD**			
		5.1.8	Risk Analysis		Review and update risk analysis using prior task reports. Provide recommendations to eliminate, reduce, or mitigate the risks.	**TBD**			

Task	Life Cycle Processes	V&V Activities	V&V Tasks	V&V Subtasks	IEEE Summary Description	Jacobs Fulfillment	Description or Descriptive Element	V&V Independence	V&V Status
		5.1.9	Retirement assessment		For software retirement, assess whether the installation package addresses: (i) software support, (ii) impact on existing systems and databases, (iii) software archiving, (iv) transition to a new software product, and (v) user notification.	**TBD**			
		5.1.10	SVVP revision		Revise the SVVP to comply with approved changes. When the development documentation required by this standard is not available, generate a new SVVP and consider the methods in IEEE Annex D (V&V of reusable software) for deriving the required development documentation.	**TBD**			
		5.1.11	Task iteration		Perform V&V tasks, as needed, to ensure that (i) planned changes are implemented correctly, (ii) documentation is complete and current, and (iii) changes do not cause unacceptable or unintended system behaviors.	**TBD**			

Appendix B: ORDEM 3.0 GUI Input Verification Process

This Appendix defines the GUI input verification process and its results for the ORDEM 3.0 V&V activity.

1.0 Setup

The ORDEM 3.0 GUI was put through a series of tests to verify that the numeric inputs entered by the user were effectively communicated to the underlying ORDEM 3.0 processing software and that the GUI system operated as expected.

Under normal operations, the ORDEM 3.0 processor takes inputs and initiates the processing sequence. Because this can be quite lengthy, a dummy version of the ORDEM 3.0 executable was produced that returns a printout to the screen of the inputs received and simply exits upon completing the printout. The test user compared the input values of the GUI to the printed values from the dummy ORDEM 3.0 processor, and made note of any discrepancies.

Three separate groups of tests were performed: Spacecraft Mode using the Perigee/Apogee altitude input option (see Table B.2.0-1), Spacecraft Mode using the Semi-major Axis/Eccentricity option (see Table B.2.0-2), and Telescope/radar Mode (see Table B.2.0-3).

2.0 Results

TABLE B.2.0-1 – SPACECRAFT MODE, PERIGEE & APOGEE ALTITUDES

Test	Year	Perigee	Apogee	Inclination	Arg of Perigee	RAAN	Passed
1	2010	200.00	200.00	0.01	Random	127.22	✓
2	2011	357.31	357.31	7.44	112.94	270.65	✓
3	2012	514.63	514.63	14.87	284.30	341.33	✓
4	2013	671.94	671.94	22.30	210.26	Random	✓
5	2014	829.26	829.26	29.72	111.78	348.66	✓
6	2015	986.57	986.57	37.15	214.21	294.21	✓
7	2016	1143.89	1143.89	44.58	Random	Random	✓
8	2017	1301.20	1301.20	52.01	280.92	211.87	✓
9	2018	1458.52	1458.52	59.44	234.98	98.19	✓
10	2019	1615.83	1615.83	66.86	104.70	20.88	✓
11	2020	1773.15	1773.15	74.29	89.22	2.06	✓
12	2021	1930.46	1930.46	81.72	91.39	8.43	✓
13	2022	2087.77	2087.77	89.15	Random	58.80	✓
14	2023	25012.39	25012.39	96.58	69.11	53.89	✓
15	2024	44015.38	44015.38	104.00	358.07	22.25	✓
16	2025	669.19	669.19	111.43	224.61	Random	✓
17	2026	826.51	826.51	118.86	242.74	1.78	✓
18	2027	983.82	983.82	126.29	134.81	191.95	✓
19	2028	1141.14	1141.14	133.72	Random	Random	✓
20	2029	1298.45	1298.45	141.14	277.34	250.86	✓
21	2030	1455.77	1455.77	148.57	276.22	242.39	✓
22	2031	1613.08	1613.08	156.00	Random	138.01	✓
23	2032	15824.50	15824.50	163.43	331.77	305.51	✓
24	2033	18969.66	18969.66	170.86	272.27	292.67	✓
25	2034	22114.82	22114.82	178.28	34.61	Random	✓
26	2035	25259.98	25259.98	180.00	159.54	254.17	✓

TABLE B.2.0-2 – SPACECRAFT MODE, SEMI-MAJOR AXIS & ECCENTRICITY

Test	Year	Semi-major Axis	Eccentricity	Inclination	Arg Perigee	RAAN	Passed
1	2010	49173.16	0.01	0.01	Random	81.48	✓
2	2011	18882.22	0.89	7.44	152.18	262.19	✓
3	2012	22135.15	0.54	14.87	60.91	329.26	✓
4	2013	51179.37	0.05	22.30	342.32	Random	✓
5	2014	38066.52	0.99	29.72	96.37	111.03	✓
6	2015	20777.04	0.58	37.15	322.57	119.24	✓
7	2016	29963.71	0.39	44.58	Random	Random	✓
8	2017	33388.55	0.81	52.01	72.76	251.57	✓
9	2018	21541.77	0.86	59.44	296.70	298.13	✓
10	2019	42978.81	0.39	66.86	105.63	220.58	✓
11	2020	48588.85	0.94	74.29	235.78	299.55	✓
12	2021	31880.17	0.58	81.72	108.33	256.00	✓
13	2022	6601.94	0.41	89.15	Random	265.03	✓
14	2023	14286.36	0.39	96.58	141.13	93.99	✓
15	2024	34305.60	0.27	104.00	9.69	283.36	✓
16	2025	27713.80	0.39	111.43	110.93	Random	✓
17	2026	49365.51	0.01	118.86	260.28	112.67	✓
18	2027	11798.04	0.19	126.29	282.38	207.21	✓
19	2028	40609.68	0.58	133.72	Random	Random	✓
20	2029	34760.57	0.87	141.14	353.82	278.99	✓
21	2030	13266.90	0.24	148.57	27.92	7.30	✓
22	2031	6903.89	0.17	156.00	Random	48.12	✓
23	2032	24798.96	0.66	163.43	289.84	278.93	✓
24	2033	8555.81	0.82	170.86	217.29	109.38	✓
25	2034	38150.57	0.01	178.28	94.02	Random	✓
26	2035	11349.09	0.95	180.00	99.53	98.46	✓

TABLE B.2.0-3 – TELESCOPE/RADAR MODE

Test	Year	Sensor Latitude	Sensor Azimuth	Sensor Elevation	Passed
1	2010	90.00	3.14	1.16	✓
2	2011	84.88	16.57	4.30	✓
3	2012	79.75	87.36	7.45	✓
4	2013	74.63	102.49	10.59	✓
5	2014	69.50	117.61	13.73	✓
6	2015	64.38	132.74	16.87	✓
7	2016	59.25	147.86	20.01	✓
8	2017	54.13	162.99	23.16	✓
9	2018	49.00	178.11	26.30	✓
10	2019	43.88	193.24	29.44	✓
11	2020	38.75	208.36	32.58	✓
12	2021	33.63	223.49	35.72	✓
13	2022	28.50	238.61	38.87	✓
14	2023	23.38	253.74	42.01	✓
15	2024	18.25	268.86	45.15	✓
16	2025	13.13	283.99	48.29	✓
17	2026	8.00	299.11	51.43	✓
18	2027	2.88	314.24	54.58	✓
19	2028	-2.25	329.36	57.72	✓
20	2029	-7.38	344.49	60.86	✓
21	2030	-12.50	359.61	64.00	✓
22	2031	-17.63	3.14	67.14	✓
23	2032	-22.75	16.57	70.29	✓
24	2033	-27.88	87.36	73.43	✓
25	2034	-33.00	102.49	76.57	✓
26	2035	-38.13	117.61	79.71	✓

3.0 Figures

Each of the tests performed passed the numeric input comparison. The appropriate warning and error dialog boxes were displayed when user inputs were not correct (see Table B.3.0-1). These figures are displayed below (see Figure B.3.0-1 through Figure B.3.0-14).

TABLE B.3.0-1 – ORDEM 3.0 GUI INPUT VERIFICATION RESULTS

Test #	Description	Expected Behavior	Figure	Passed
1	Perigee less than 100 km	Error Message	1.2-1	✓
2	Perigee greater than 40,000 km	Warning Message	1.2-2	✓
3	Apogee less than 100 km	Error Message	1.2-3	✓
4	Apogee greater than 40,000 km	Warning Message	1.2-4	✓
5	Perigee greater than Apogee	Error Message	1.2-5	✓
6	Semi-Major axis less than (6378.135 km + 100 km)	Error Message	1.2-6	✓
7	Eccentricity less than 0 or greater than 1	Error Message	1.2-7	✓
8	Inclination less than 0 or greater than 180	Error Message	1.2-8	✓
9	Argument of Perigee less than 0 or greater than 360	Error Message	1.2-9	✓
10	RAAN less than 0 or greater than 360	Error Message	1.2-10	✓
11	Latitude less than -90 or greater than 90	Error Message	1.2-11	✓
12	Azimuth less than 0 or greater than 360	Error Message	1.2-12	✓
13	Elevation less than 0 or greater than 90	Error Message	1.2-13	✓
14	Size less than 10^-5	Error Message	1.2-14	✓

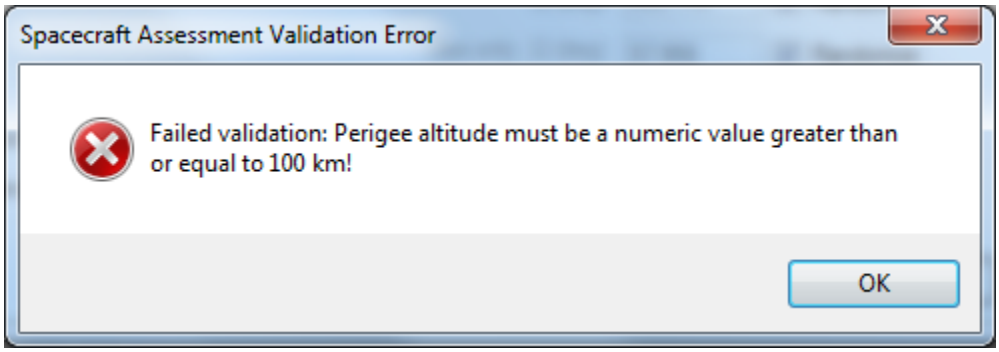

Figure B.3.0-1. Low perigee error.

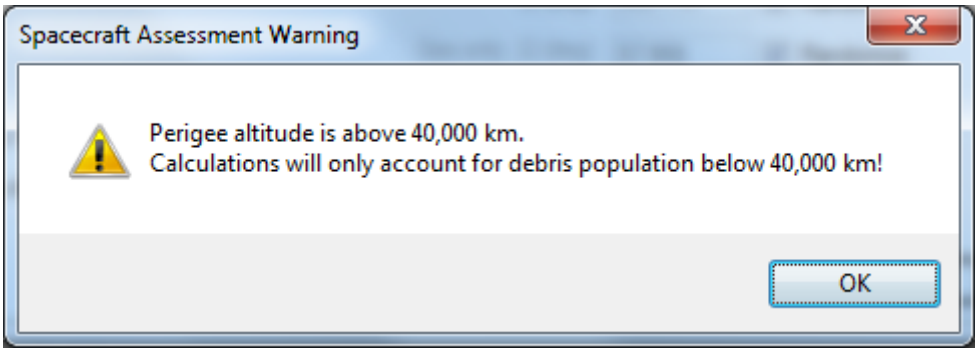

Figure B.3.0-2. High perigee warning.

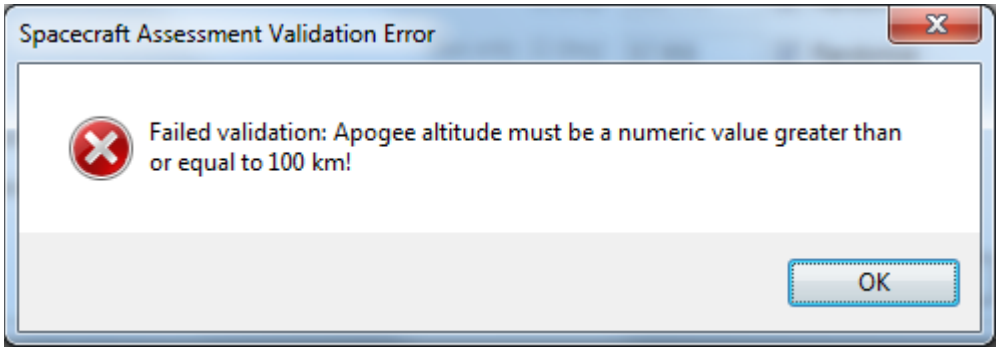

Figure B.3.0-3. Low apogee error.

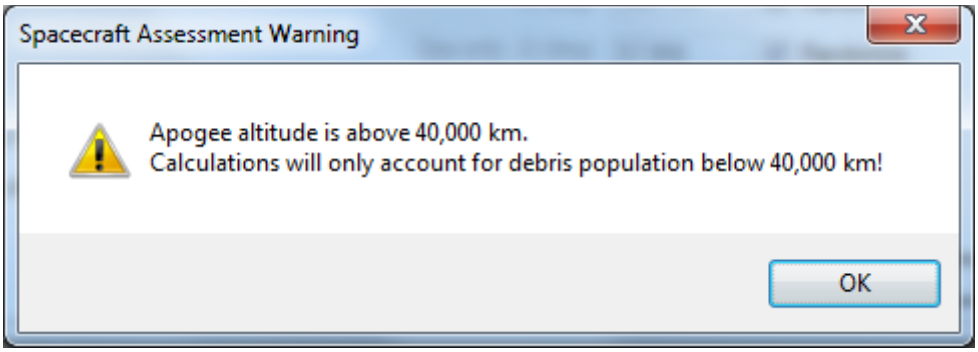

Figure B.3.0-4. High apogee warning.

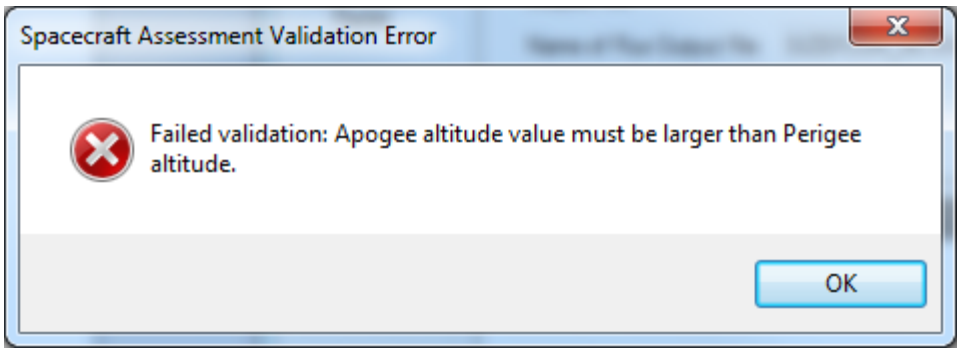

Figure B.3.0-5. Switched apogee and perigee warning.

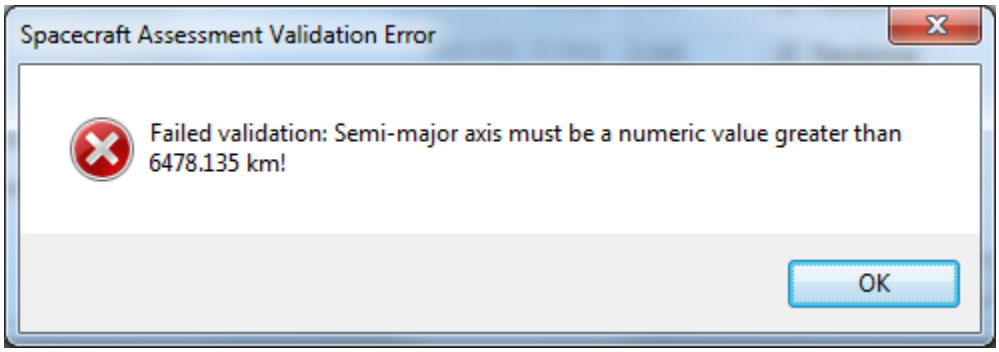

Figure B.3.0-6. Low semi-major axis error.

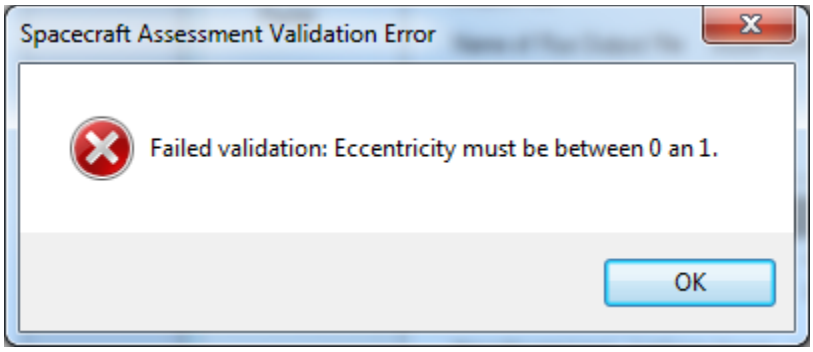

Figure B.3.0-7. Out-of-range eccentricity error.

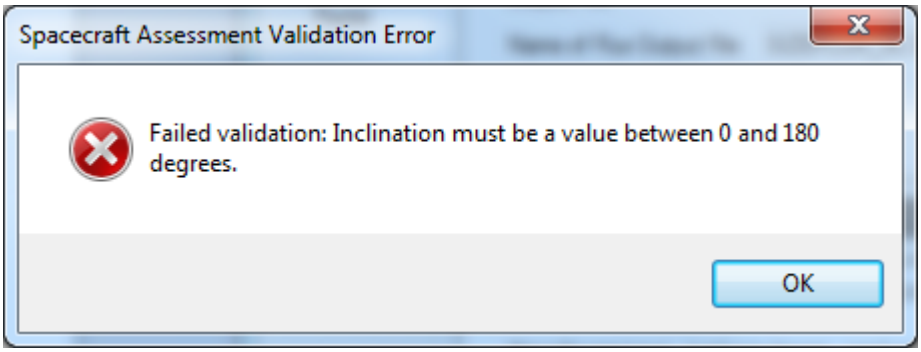

Figure B.3.0-8. Out-of-range inclination error.

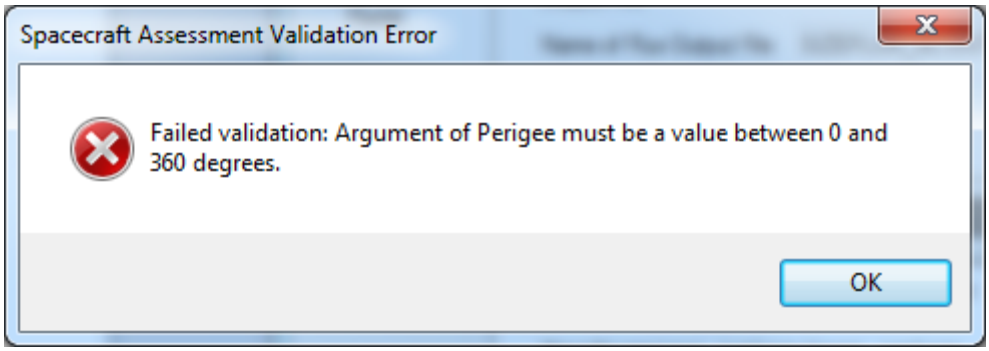

Figure B.3.0-9. Out-of-range argument of perigee error.

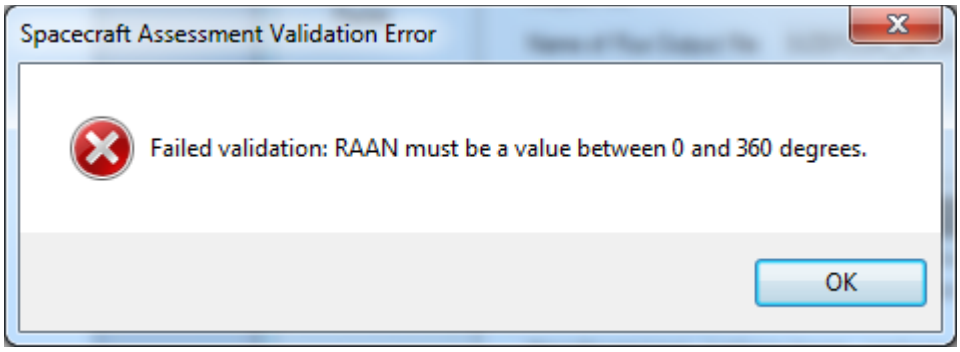

Figure B.3.0-10. Out-of-range right ascension of ascending node error.

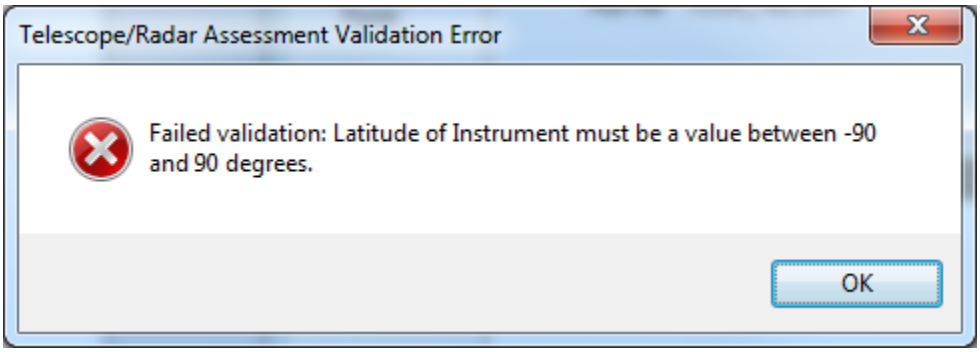

Figure B.3.0-11. Out-of-range latitude error.

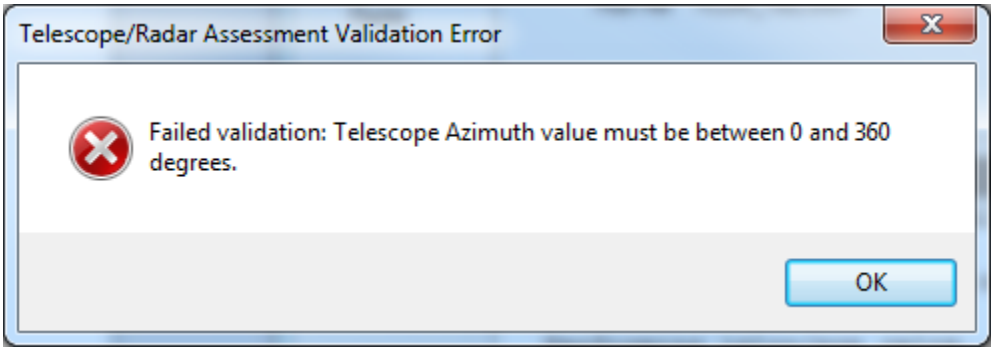

Figure B.3.0-12. Out-of-range azimuth error.

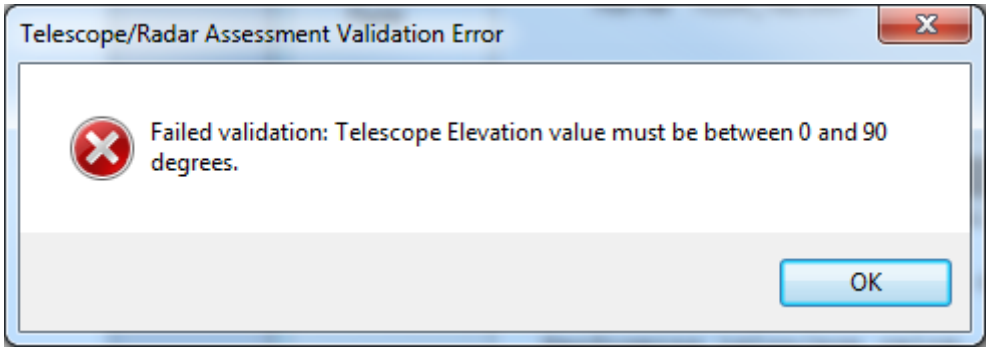

Figure B.3.0-13. Out-of-range elevation error.

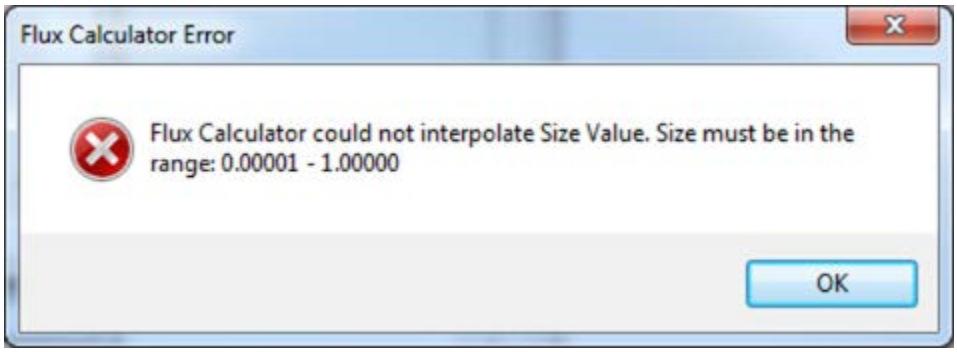

Figure B.3.0-14. Out-of-range flux calculator error.

Appendix C: Analysis Verification

This appendix provides a detailed description of the analysis verification tests and results from the ORDEM 3.0 V&V process. Section 2.0 describes the verification steps for spacecraft mode and section 3.0 describes the steps in telescope mode.

1.0 Accuracy and Uncertainties

This section provides a detailed description of any discrepancies between actual and expected results during analysis verification testing.

1.1. MOLNIYA ORBITS

A spacecraft in a Molniya-type orbit is defined to have an eccentricity above 0.7, an argument of perigee near 270°, and an inclination of 63.4°. Molniya orbits offer a wide coverage for land areas at high latitudes. The user must take into account the argument of perigee of 270° when comparing a spacecraft in a Molniya orbit with one in a similar LEO orbit.

For these calculations, a special case of a Molniya-type orbit was considered that had a random argument of perigee. While this orbit would not be expected in the real world, it was a good test for the interaction of elliptical orbits with the GEO population. For this particular spacecraft orbit, analysis verification results show a small difference in the goodness-of-fit test between the ORDEM 3.0 fluxes (model data) and the KESSLER fluxes (“actual data”). This deviation is apparent in any of the spacecraft verification charts in this appendix (*e.g.*, relative velocity/yaw vs. normalized debris flux) for a spacecraft in Molniya-type orbit with a random argument of perigee. This deviation occurred because the release version of ORDEM 3.0, when computing flux for certain orbits with highly-elliptical orbits at high inclination, under-samples the minimum number of Monte Carlo integration calls, and thus under-predicts the flux by a few percent. This discrepancy only showed up when the test KESSLER legacy software was run with a very large number of numerical integration steps. The χ^2 values generated when comparing these two datasets (for this particular orbit type) are well above the threshold of what is considered a good fit, and all tests concerning the Molniya-type orbit with a random argument of perigee were successful. This issue only occurs for the largest size debris fluxes, and the next update of ORDEM 3.0 will correct it.

1.2. COLUMN DESCRIPTIONS

Table C.1.2-1 describes the table columns that are shown in the spacecraft and telescope verification sections.

TABLE C.1.2-1 – COLUMNS FOR RELATIVE VELOCITY, YAW, AND ALTITUDE CORRELATION TABLES

Column Name	Description
Sat No.	Integer flag (1-6)
Satellite Name	Abbreviated satellite name
Year	Run year
χ^2 parameter	Chi-squared parameter
Passed	Passed – green check; Failed – red x

The 95% prediction and confidence intervals are shown in each flux linear correlation figure in sections 2.3.3 and 3.2.2 as well as the spacecraft impact assessment in section 2.2. Table C.1.2-2 describes the parameters needed to calculate these intervals.

TABLE C.1.2-2 – COLUMN FOR FLUX CORRELATION TABLES

Column Name	Description
Satellite Name	Abbreviated satellite name
Year	Run year
Std Error Of Mean	A measure of dispersion of observed values, *i.e.*, how inaccurate the estimate might be
Slope	Slope value of the best-fit line
Y-int	Y-intercept value of the best-fit line
Coef. of Corr.	Coefficient of Correlation - a measure of strength between two independent variables
Coef. of Det.	Coefficient of Determination – proportion of variance of one variable predicted by the other variable, *i.e.*, (corr. coef.)^2
Std. Covar.	A measure of how much two independent variables change together
Non-Zero Pairs	(ORDEM3.0, KESSLER) pairs that were used in analysis figures.
Single Pairs	(ORDEM3.0, KESSLER) pairs, where only one value was zero (not used in analysis figures)
Zero Pairs	(ORDEM3.0, KESSLER) pairs, each value was zero (not used in analysis figures)
# outside of P.I.	Number of correlation points outside of prediction interval
Passed	Passed – green check; Failed – red x

2.0 Spacecraft Mode Verification

This section outlines the verification steps taken to ensure the output of ORDEM 3.0 is valid in spacecraft mode. These tests were run with argument of perigee in fixed and random mode.

2.1. SETUP

Table C.2.1-1 shows the three tests that were run to verify ORDEM 3.0 output in spacecraft mode.

TABLE C.2.1-1 – SUMMARY OF S/C MODE TESTS

Section	Section/Test Name	Size	Chart Type
2.2	Igloo verification	All	N/A
2.3	ORDEM 3.0 vs KESSLER, Impacts	Medium Density, 1 m	Linear correlation of flux
2.4	ORDEM 3.0, Fixed AP vs. Random AP	Medium Density, 1 m	Relative velocity, yaw
2.5	ORDEM 3.0 vs KESSLER, Random AP	Medium Density, 1 m	Relative velocity, yaw, linear correlation of flux

Table C.2.1-2 describes the satellites that were used during the analysis verification of the spacecraft mode. Note that these satellites are spread out through six different regions – LEO (low), LEO (high), MEO, Molniya, GTO, and GEO. Table C.2.1-3 shows the yearly output files that were used in the analysis. The same set of satellites were used in both S/C tests. However, satellite #6, CZ-3A DEB (GTO orbit), was used only in the second (ORDEM 3.0 vs KESSLER, Impacts) and fourth test (ORDEM 3.0 vs. Kessler, Random AP).

TABLE C.2.1-2 – SATELLITES USED IN ANALYSIS VERIFICATION, S/C MODE

#	Int. Designator	SSN #	Name	Orbit type	Start year	TLE epoch	Ha [km]	Hp [km]	INC [°]	RAAN [°]	AP [°]
1	1986-003C	16483	SATCOM K1 R/B (PAM-D2)	GTO	2010	10001.41392	33774.277	353.095	27.2269	38.5592	100.218
2	1992-030E	21980	COSMOS 2191	LEO (hi)	2011	11001.77944	1503.504	1473.873	74.0039	332.4734	226.6512
3	1992-089A	22275	NAVSTAR 29 (USA 87)	MEO	2012	12001.09744	21439.850	21216.659	56.2616	310.4942	352.0576
4	1997-074A	25063	TRMM	LEO (lo)	2013	13001.22005	397.642	397.011	34.9609	59.1713	247.0172
5	2009-075A	36131	DIRECTV 12	GEO	2014	14001.42237	35786.885	35785.772	0.0306	216.3227	85.4424
6	2007-003K	35551	CZ-3A DEB	GTO	2015	15001.51857	37332.00	645.00	24.7377	151.9145	337.0494
7	2004-005A	28163	MOLNIYA 1-93	Molniya	2010	11001.15607	38591.13	1764.275	64.8345	221.6592	267.1067

TABLE C.2.1-3 – SATELLITES USED IN VERIFICATION, GIVEN YEARS

Satellite Name	Years
COSMOS 2191	2010, 2015, 2020, 2025, 2030, 2035
DIRECTV 12	2011, 2016, 2021, 2026, 2031
NAVSTAR 29	2012, 2017, 2022, 2027, 2032
SATCOM K1	2013, 2018, 2023, 2028, 2033
TRMM	2014, 2019, 2024, 2029, 2034
CZ-3A DEB	2015
MOLNIYA1-93	2010, 2015, 2020, 2025, 2030, 2035

2.2. IGLOO UTILIZATION

For the spacecraft igloo utilization component, the nomenclature refers to bin widths in (Pitch/Yaw/relative velocity space) centered on the spacecraft and defined by the spacecraft velocity vector (+X axis) and the local horizontal plane (X-Y plane). Units are degrees (°) and kilometers per second (km/s). Table C.2.2-1 shows the two test objectives that were completed in this section.

TABLE C.2.2-1 – S/C IGLOO UTILIZATION TESTS

Objective	Passed
S/C Igloo 10 x 10 x 1 utilization	✓
S/C Igloo 30 x 30 x 2 utilization	✓

2.3. ORDEM 3.0 VS. KESSLER, IMPACTS

The objective of spacecraft risk for impact verification is to project the number of impacts on a spacecraft in one year. Each spacecraft is represented by a cube (oriented in an LVLH coordinate frame) of unit area on each face. Igloo files are used as input and the total number of impacts on each face – port, ram, starboard, wake, zenith, and nadir – and the total number of impacts on the cube are outputs.

2.3.1. *Flux*

Linear correlation analysis shows that the outputs for ORDEM 3.0 and KESSLER are a very close match (*i.e.*, r H1.0). Notice that the MOLNIYA1-93 satellite has a better fit when the argument of perigee = 270°. This behavior is expected due to its uniquely oriented, fixed-AP orbit. See section 1.1 for accuracy and uncertainties during analysis verification.

Table C.2.3.1-1 shows the test objectives that were completed in this section.

TABLE C.2.3.1-1 – S/C RISK OF IMPACT

Objective	Passed
Use test satellites, each with various years	✓
Successfully read in igloo files, MD60 flux	✓
Run comparison when AP=270° on Molniya orbit	✓
Linear correlation analysis	✓

TABLE C.2.3.1-2 – S/C RISK OF IMPACT ASSESSMENT, ORDEM 3.0 VS. KESSLER

Satellite Name	Year	Slope	Y-int	Coef. of Corr.	Coef. of Det.	Std. Covar.	Passed
COSMOS_2191	2010	1.000164E+00	2.419713E-12	1.000000E+00	1.000000E+00	1.439877E-15	✓
COSMOS_2191	2015	1.000084E+00	2.050818E-12	1.000000E+00	1.000000E+00	1.574708E-15	✓
COSMOS_2191	2020	1.000159E+00	1.525165E-12	1.000000E+00	1.000000E+00	2.048839E-15	✓
COSMOS_2191	2025	1.000017E+00	1.856118E-12	1.000000E+00	1.000000E+00	2.062536E-15	✓
COSMOS_2191	2030	1.000026E+00	9.695323E-13	1.000000E+00	1.000000E+00	2.425329E-15	✓
COSMOS_2191	2035	1.000037E+00	1.303308E-12	1.000000E+00	1.000000E+00	2.479256E-15	✓
DIRECTV_12	2011	1.080080E+00	4.006247E-11	9.999606E-01	9.999212E-01	1.312177E-16	✓
DIRECTV_12	2016	1.078382E+00	3.987192E-11	9.999587E-01	9.999175E-01	1.262312E-16	✓
DIRECTV_12	2021	1.068209E+00	4.313231E-11	9.999651E-01	9.999303E-01	1.763984E-16	✓
DIRECTV_12	2026	1.079667E+00	4.966738E-11	9.999588E-01	9.999175E-01	1.983113E-16	✓
DIRECTV_12	2031	1.070442E+00	5.273001E-11	9.999637E-01	9.999273E-01	2.529997E-16	✓
NAVSTAR_29	2012	1.002543E+00	7.318764E-17	9.999997E-01	9.999994E-01	2.459193E-22	✓
NAVSTAR_29	2017	1.006647E+00	6.667860E-16	9.999999E-01	9.999999E-01	7.337342E-22	✓
NAVSTAR_29	2022	1.004192E+00	3.816278E-15	9.999998E-01	9.999997E-01	1.669425E-21	✓
NAVSTAR_29	2027	1.006290E+00	1.150320E-15	1.000000E+00	9.999999E-01	2.424658E-21	✓
NAVSTAR_29	2032	1.006613E+00	1.068957E-15	9.999999E-01	9.999997E-01	3.065699E-21	✓
SATCOM_K1	2013	1.003267E+00	1.080675E-13	9.999997E-01	9.999994E-01	2.486672E-18	✓
SATCOM_K1	2018	1.000886E+00	3.431259E-15	1.000000E+00	9.999999E-01	7.178327E-18	✓
SATCOM_K1	2023	1.000459E+00	8.406777E-14	1.000000E+00	1.000000E+00	1.200913E-17	✓
SATCOM_K1	2028	1.001231E+00	7.956461E-14	1.000000E+00	9.999999E-01	1.720859E-17	✓
SATCOM_K1	2033	1.000061E+00	3.073812E-14	1.000000E+00	1.000000E+00	2.432665E-17	✓
TRMM	2014	1.000508E+00	1.172590E-12	9.999999E-01	9.999999E-01	2.710688E-16	✓
TRMM	2019	1.000396E+00	1.345383E-12	1.000000E+00	1.000000E+00	1.858366E-15	✓
TRMM	2024	1.000561E+00	2.680778E-12	9.999998E-01	9.999997E-01	1.864228E-15	✓
TRMM	2029	1.000158E+00	1.577660E-12	9.999998E-01	9.999996E-01	4.160548E-15	✓
TRMM	2034	1.000420E+00	2.886721E-12	1.000000E+00	1.000000E+00	6.342705E-15	✓
CZ-3A DEB	2015	0.937857E+00	-0.527044E+00	0.994788E+00	0.998958E+00	0.385147E-17	✓
MOLNIYA1-93	2010	1.087770E+00	1.351977E-12	9.976245E-01	9.952546E-01	4.822095E-20	✓
MOLNIYA1-93	2015	1.034475E+00	5.396483E-13	9.991492E-01	9.982992E-01	6.400148E-20	✓
MOLNIYA1-93	2020	1.034530E+00	8.766113E-13	9.993780E-01	9.987565E-01	1.026602E-19	✓
MOLNIYA1-93	2025	1.039443E+00	1.265571E-12	9.993087E-01	9.986179E-01	1.463134E-19	✓
MOLNIYA1-93	2030	1.022642E+00	8.796398E-13	9.994995E-01	9.989992E-01	1.771334E-19	✓
MOLNIYA1-93	2035	1.016915E+00	9.832083E-13	9.996301E-01	9.992604E-01	2.370832E-19	✓
fixed AP (É =270°)							
MOLNIYA1-93	2010	9.997173E-01	-2.905849E-14	9.999992E-01	9.999990E-01	3.688383E-20	✓
MOLNIYA1-93	2015	9.992461E-01	-3.198375E-14	9.999991E-01	9.999987E-01	4.916502E-20	✓
MOLNIYA1-93	2020	9.984141E-01	-2.054696E-14	9.999995E-01	9.999991E-01	8.634347E-20	✓
MOLNIYA1-93	2025	9.980917E-01	7.349500E-15	9.999997E-01	9.999994E-01	1.226245E-19	✓
MOLNIYA1-93	2030	9.980821E-01	1.525719E-14	9.999998E-01	9.999995E-01	1.575181E-19	✓
MOLNIYA1-93	2035	9.983022E-01	4.743269E-14	9.999996E-01	9.999992E-01	2.170771E-19	✓

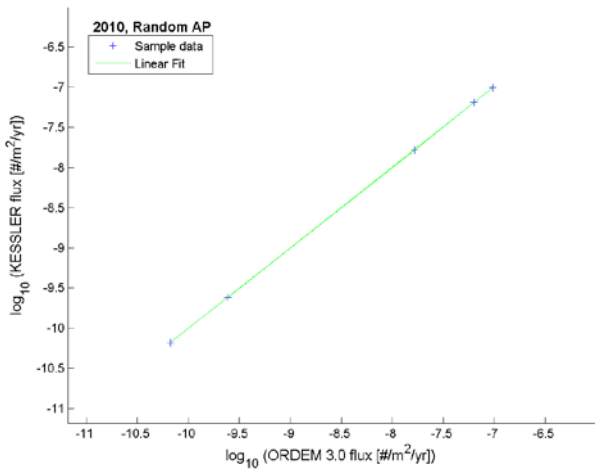

Figure C.2.3.1-1. Impacts, COSMOS 2191, flux, 2010.

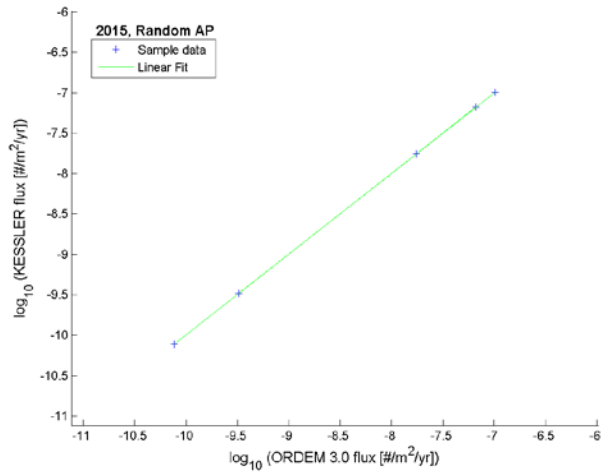

Figure C.2.3.1-2. Impacts, COSMOS 2191, flux, 2015.

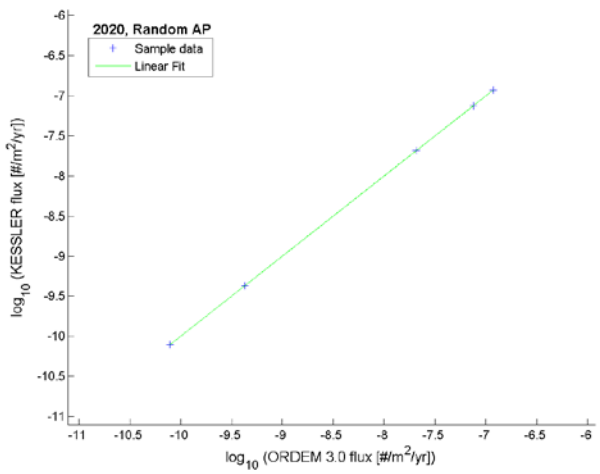

Figure C.2.3.1-3. Impacts, COSMOS 2191, flux, 2020.

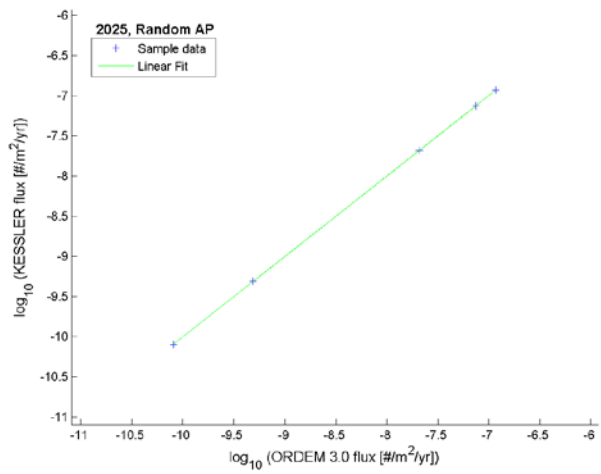

Figure C.2.3.1-4. Impacts, COSMOS 2191, flux, 2025.

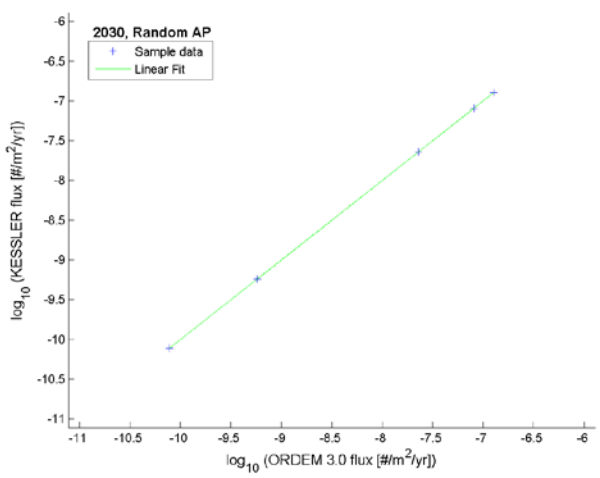

Figure C.2.3.1-5. Impacts, COSMOS 2191, flux, 2030.

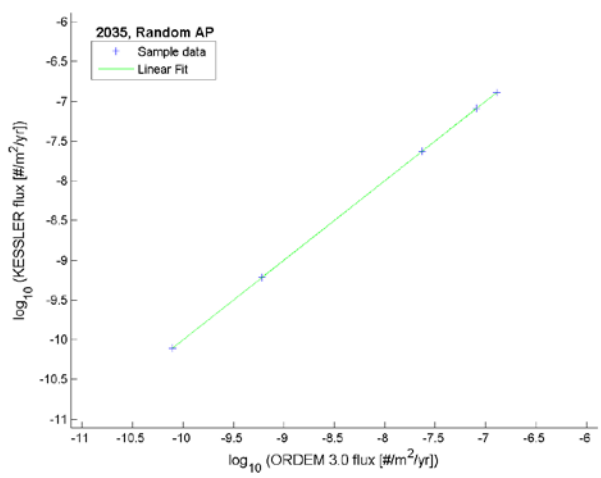

Figure C.2.3.1-6. Impacts, COSMOS 2191, flux, 2035.

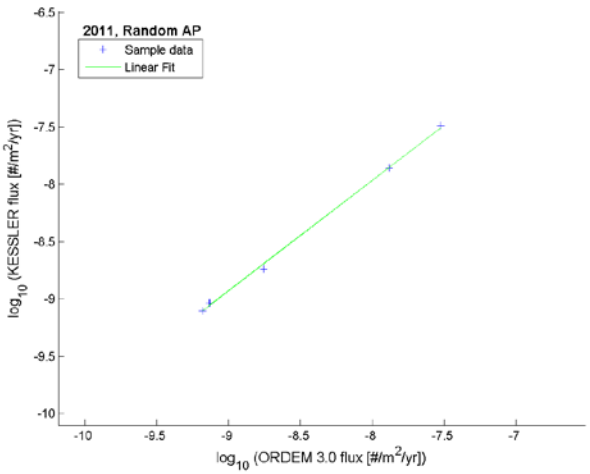

Figure C.2.3.1-7. Impacts, DIRECTV 12, flux, 2011.

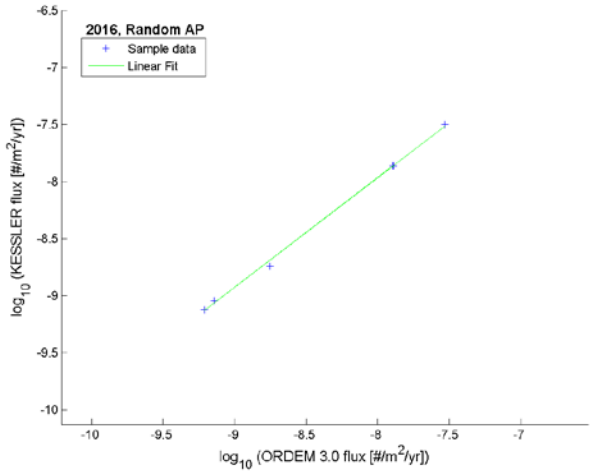

Figure C.2.3.1-8. Impacts, DIRECTV 12, flux, 2016.

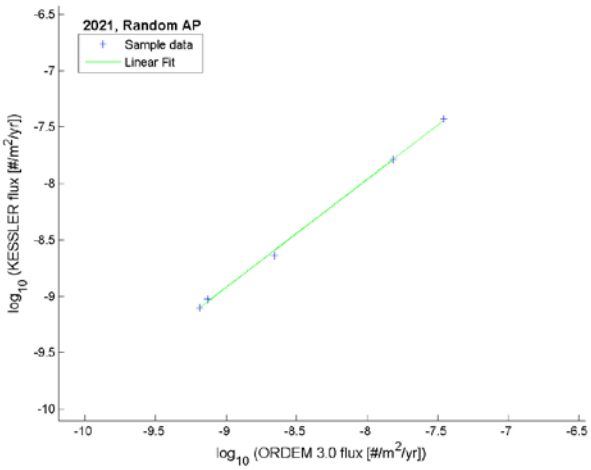

Figure C.2.3.1-9. Impacts, DIRECTV 12, flux, 2021.

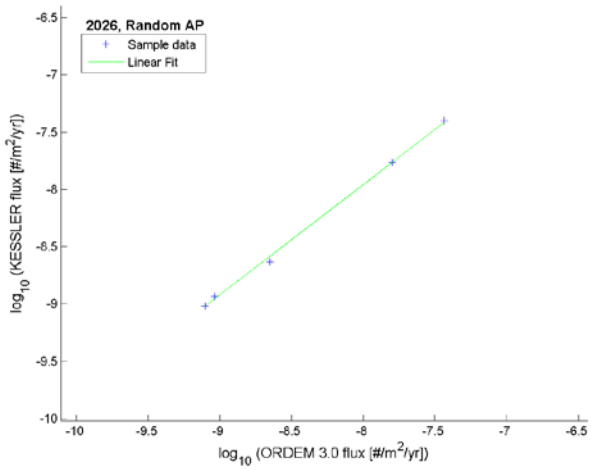

Figure C.2.3.1-10. Impacts, DIRECTV 12, flux, 2026.

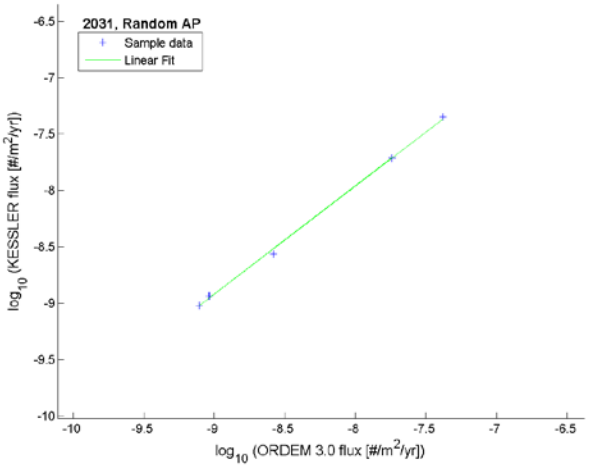

Figure C.2.3.1-11. Impacts, DIRECTV 12, flux, 2031.

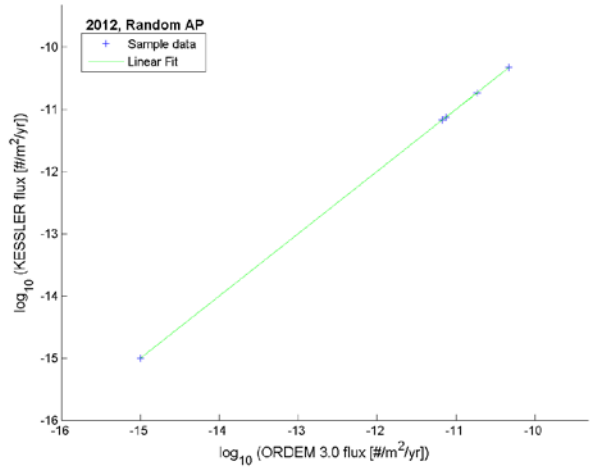

Figure C.2.3.1-12. Impacts, NAVSTAR 29, flux, 2012.

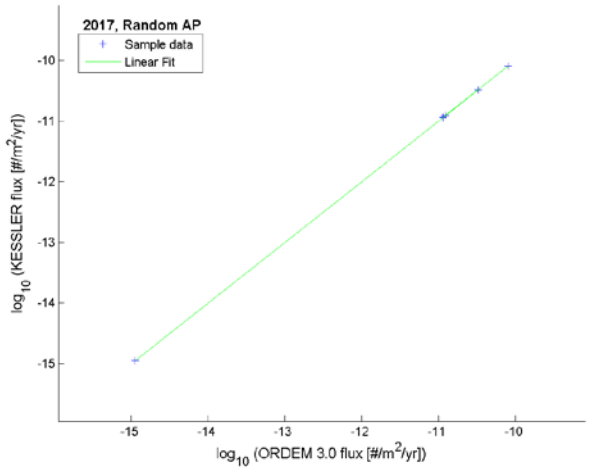

Figure C.2.3.1-13. Impacts, NAVSTAR 29, flux, 2017.

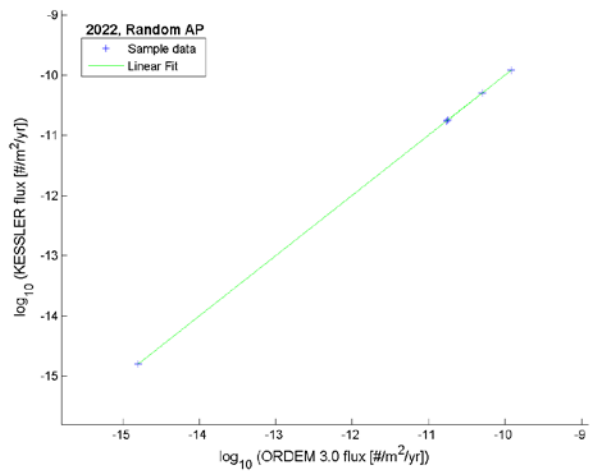

Figure C.2.3.1-14. Impacts, NAVSTAR 29, flux, 2022.

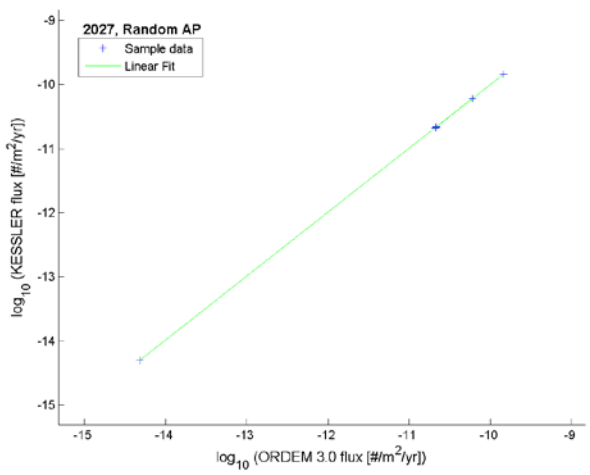

Figure C.2.3.1-15. Impacts, NAVSTAR 29, flux, 2027.

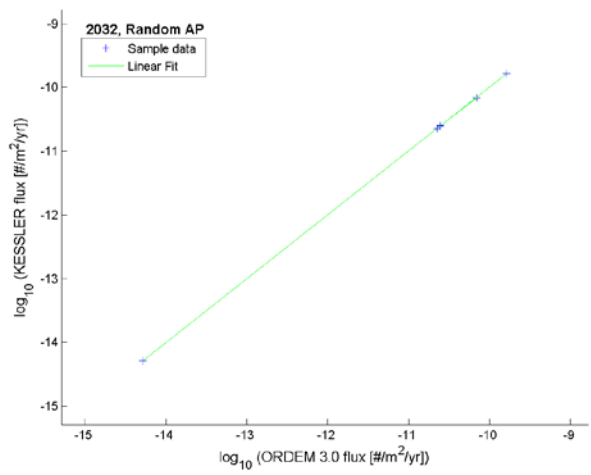

Figure C.2.3.1-16. Impacts, NAVSTAR 29, flux, 2032.

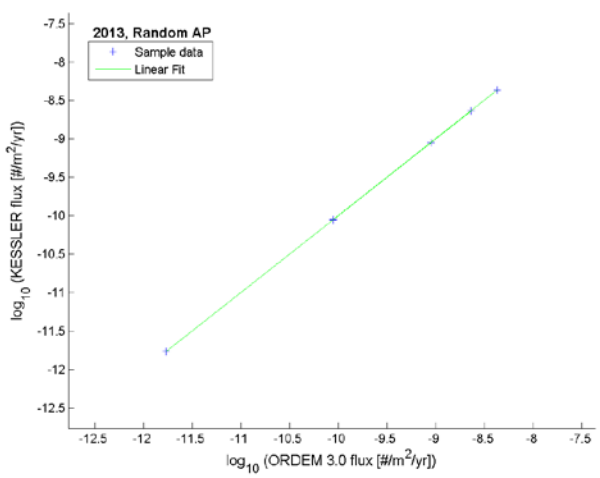

Figure C.2.3.1-17. Impacts, SATCOM K1, flux, 2013.

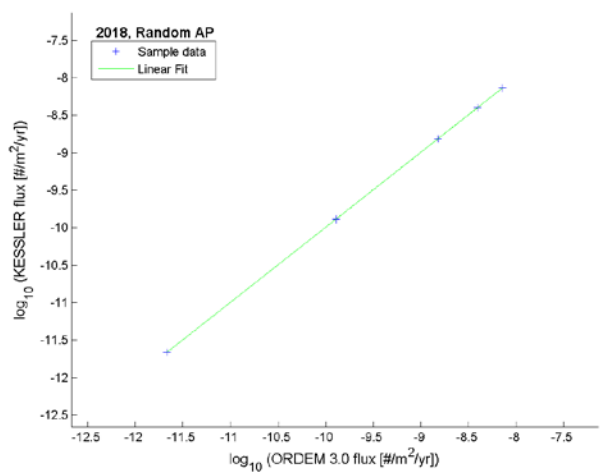

Figure C.2.3.1-18. Impacts, SATCOM K1, flux, 2018.

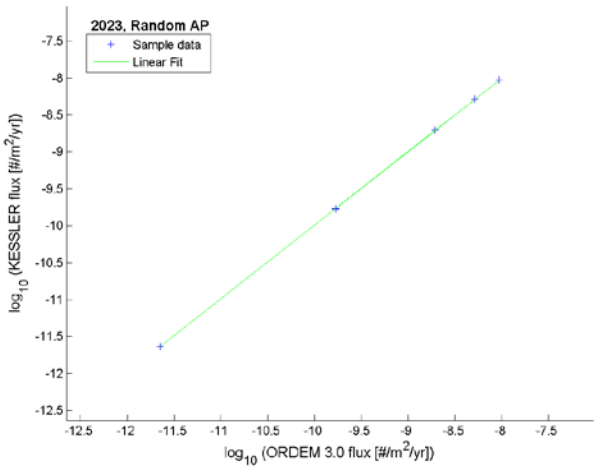

Figure C.2.3.1-19. Impacts, SATCOM K1, flux, 2023.

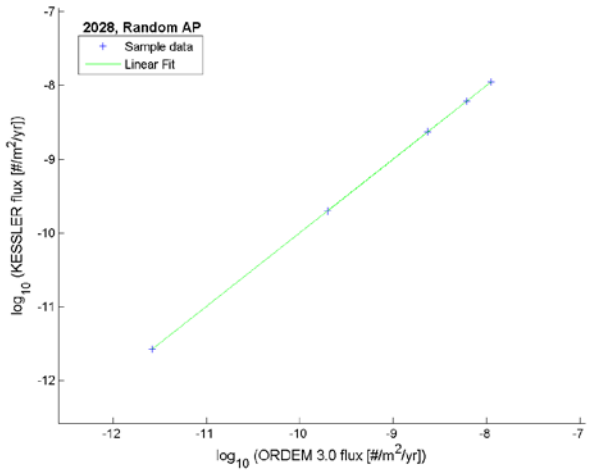

Figure C.2.3.1-20. Impacts, SATCOM K1, flux, 2028.

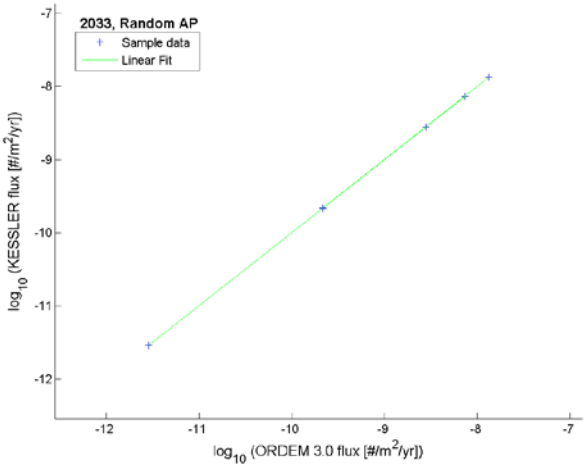

Figure C.2.3.1-21. Impacts, SATCOM K1, flux, 2033.

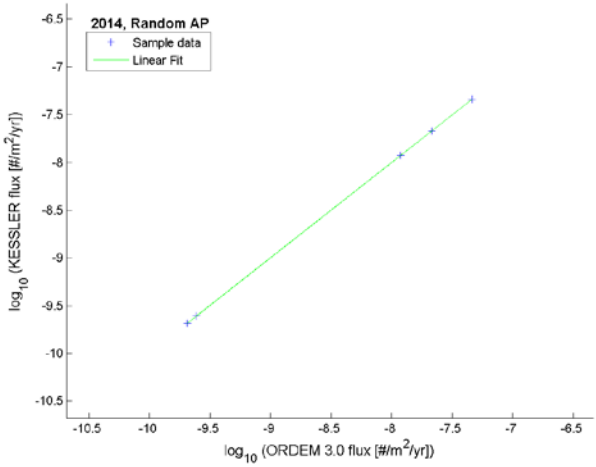

Figure C.2.3.1-22. Impacts, TRMM, flux, 2014.

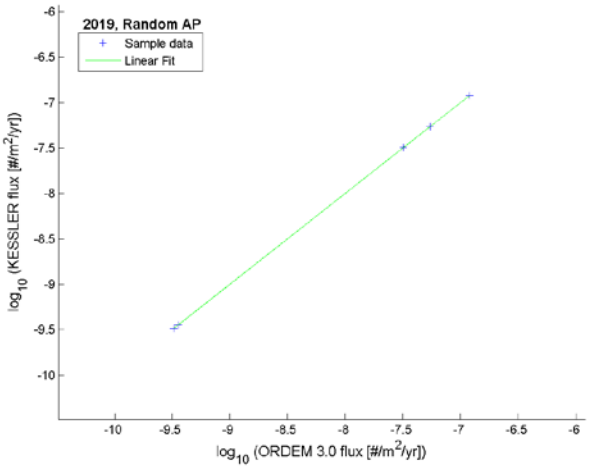

Figure C.2.3.1-23. Impacts, TRMM, flux, 2019.

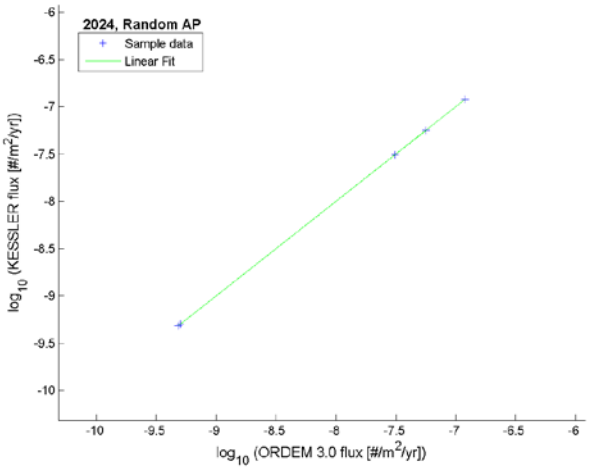

Figure C.2.3.1-24. Impacts, TRMM, flux, 2024.

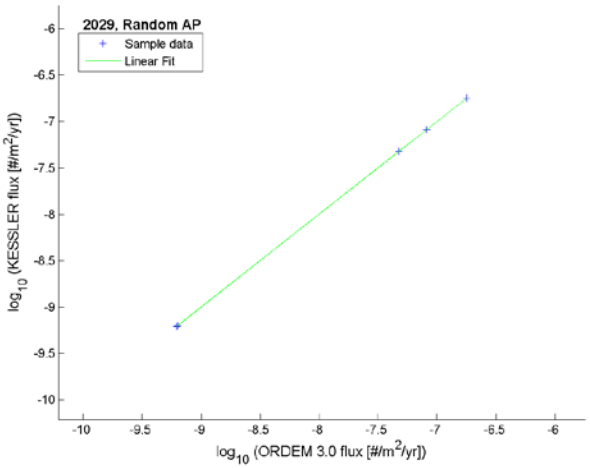

Figure C.2.3.1-25. Impacts, TRMM, flux, 2029.

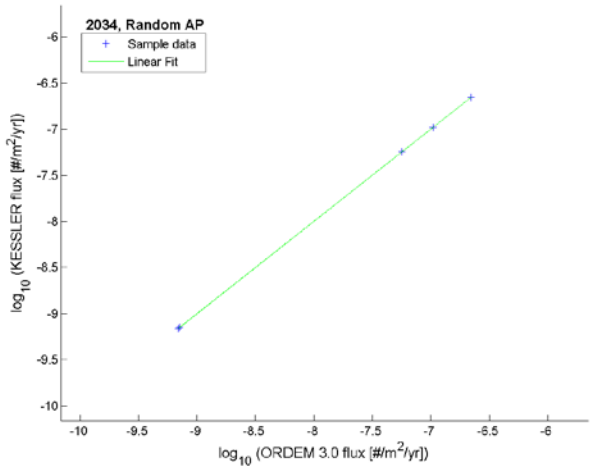

Figure C.2.3.1-26. Impacts, TRMM, flux, 2034.

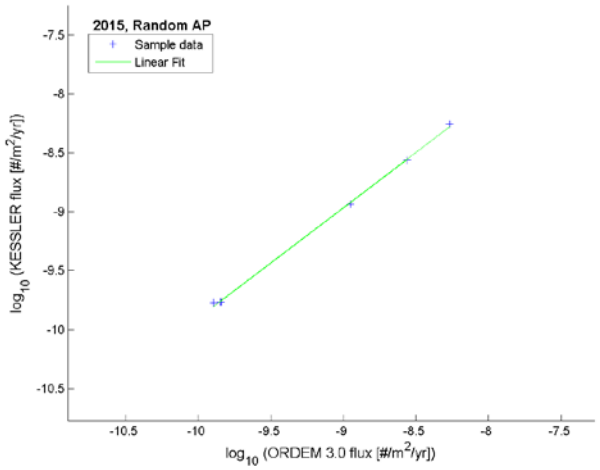

Figure C.2.3.1-27. Impacts, CZ-3A DEB, flux, 2015.

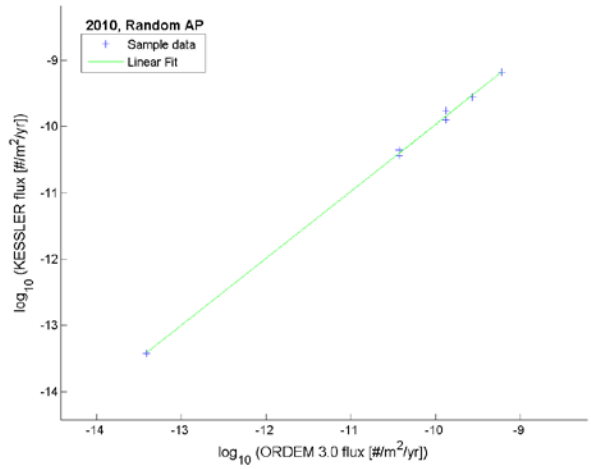

Figure C.2.3.1-28. Impacts, MOLNIYA1-93, flux, 2010.

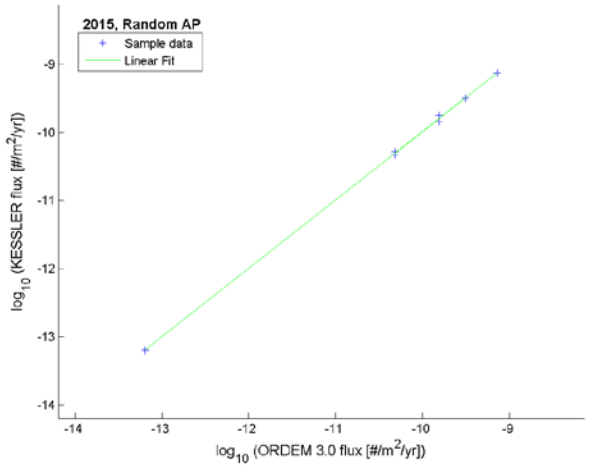

Figure C.2.3.1-29. Impacts, MOLNIYA1-93, flux, 2015.

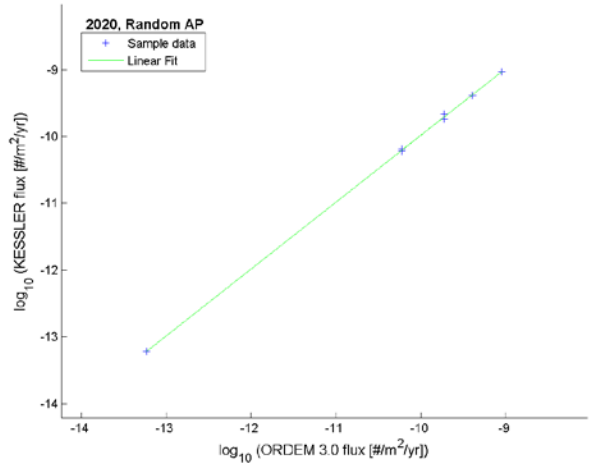

Figure C.2.3.1-30. Impacts, MOLNIYA1-93, flux, 2020.

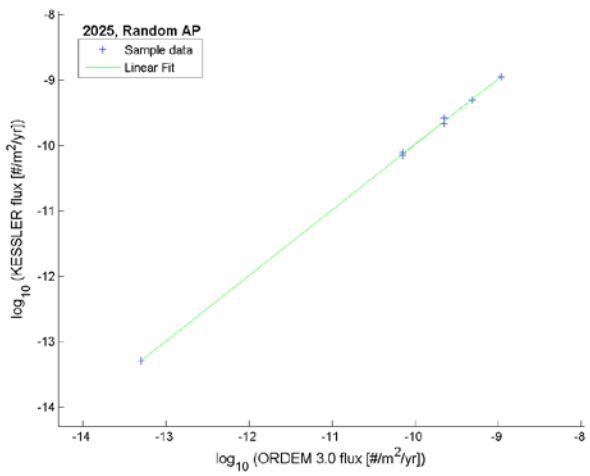

Figure C.2.3.1-31. Impacts, MOLNIYA1-93, flux, 2025.

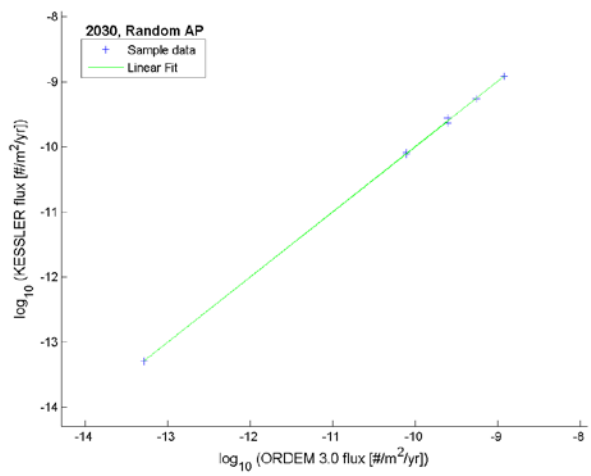

Figure C.2.3.1-32. Impacts, MOLNIYA1-93, flux, 2030.

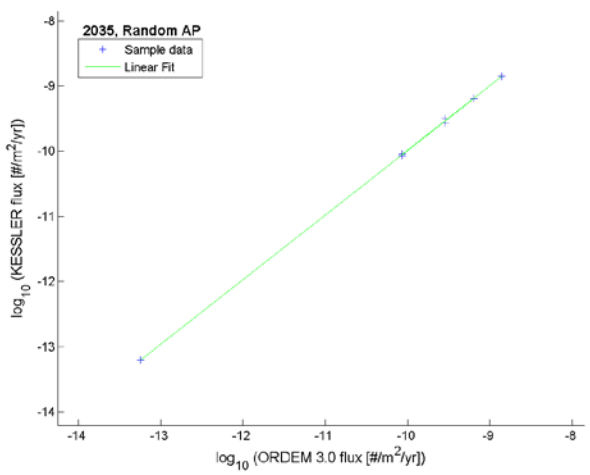

Figure C.2.3.1-33. Impacts, MOLNIYA1-93, flux, 2035.

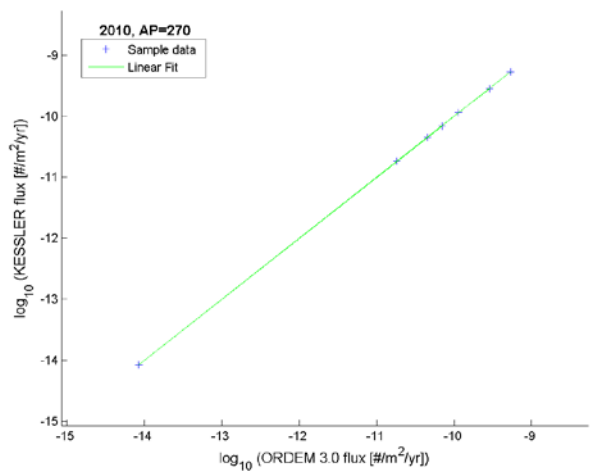

Figure C.2.3.1-34. Impacts, MOLNIYA1-93, flux, 2010, AP=270°.

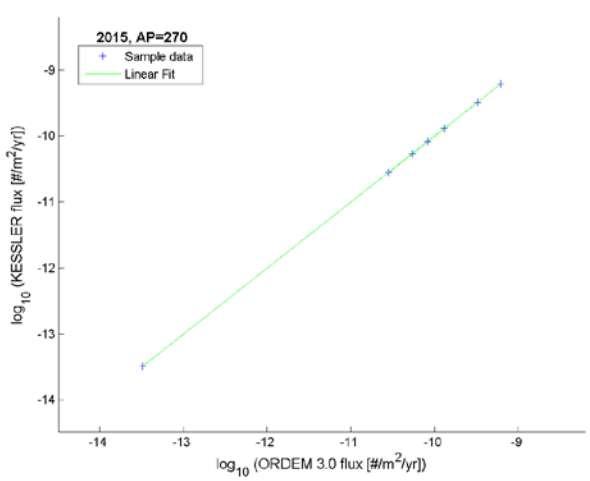

Figure C.2.3.1-35. Impacts, MOLNIYA1-93, flux, 2015, AP=270°.

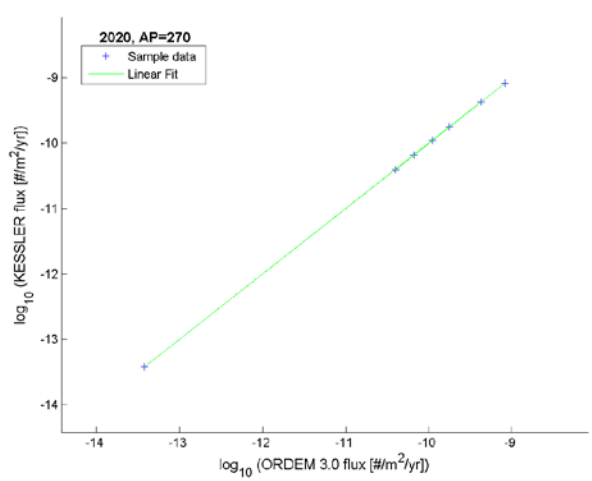

Figure C.2.3.1-36. Impacts, MOLNIYA1-93, flux, 2020, AP=270°.

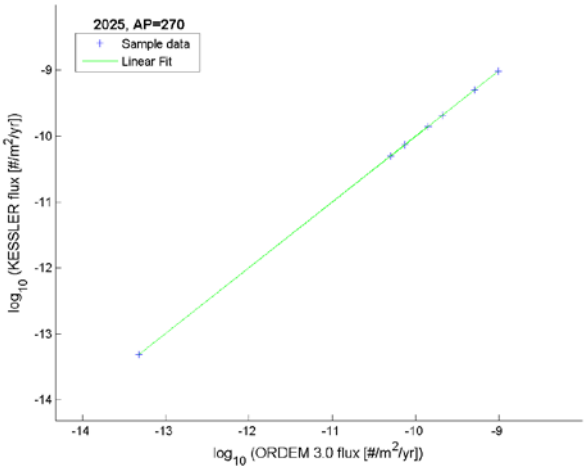

Figure C.2.3.1-37. Impacts, MOLNIYA1-93, flux, 2025, AP=270°.

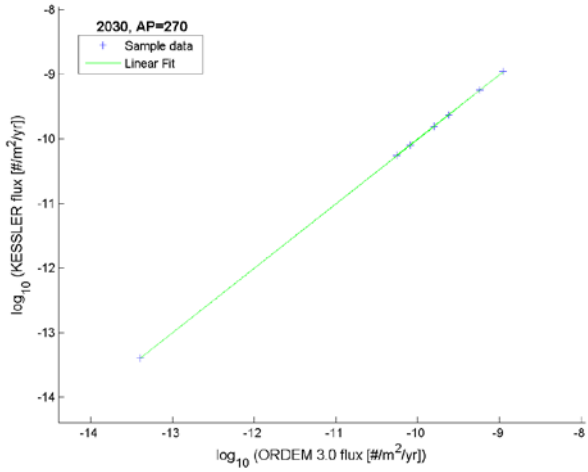

Figure C.2.3.1-38. Impacts, MOLNIYA1-93, flux, 2030, AP=270°.

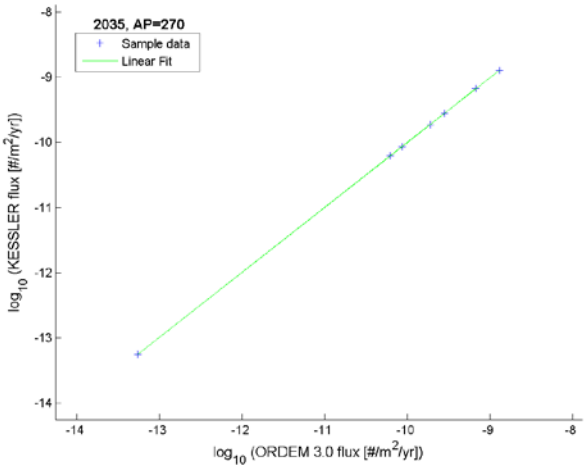

Figure C.2.3.1-39. Impacts, MOLNIYA1-93, flux, 2035, AP=270°.

2.4. ORDEM 3.0, FIXED AP VS. RANDOM AP

This analysis requires a comparison of two data sets – data stored in IGLOOFLUX_SC.OUT (from several ORDEM 3.0 run sessions) given a fixed argument of perigee and data stored in IGLOOFLUX_SC.OUT given a random argument of perigee.

The first data set is built as follows. A sub-set of 20 runs is executed, each with a different argument of perigee ranging from 0° to 360°, incremented by 18°. This process is repeated for each test satellite, given the test satellite's year. The second data set is similar to the first data set, except that a single run is executed with a random argument of perigee for each test satellite, given the test satellite's year (see Tables E.2.1-2 and E.2.1-3).

The relative velocity and yaw distributions were chosen for this comparison analysis. The yaw was calculated by reading in the *az_low* and *az_high* columns stored in the IGLOOFLUX_SC.OUT output file. The relative velocity was calculated by simply reading in the *vel_low* and *vel_high* columns of IGLOOFLUX_SC.OUT.

For a given satellite during a given year, the average relative velocity and yaw distributions of the sub-set of runs with a fixed AP should be equal to the relative velocity and yaw distributions given a random AP. Symbolically,

$$< Fixed\ AP > = \ Random\ AP$$

A Ç^2 test was used to compare the binned distributions (relative velocity, yaw) of the fixed AP and random AP runs.

Table C.2.4-1 shows the test objectives that were completed in this section.

TABLE C.2.4-1 – SPACECRAFT ARGUMENT OF PERIGEE

Objective	Passed
Use test satellites, each with various years	✓
χ^2 test between binned distributions, ORDEM 3.0 and KESSLER	✓
Relative velocity, yaw comparisons	✓
Random AP = <Fixed AP>	✓
Generate figures for comparison	✓

2.4.1. *Relative Velocity*

Table C.2.4.1-1 shows the test satellites used in the statistical comparison of relative velocity distributions between fixed AP and random AP runs. The following figures in this section pair the binned relative velocity distribution between fixed AP and random AP runs. Notice that the MOLNIYA1-93 satellite has a better fit when the argument of perigee = 270°. This behavior is expected due to its uniquely oriented, fixed-AP orbit. See section 1.1 for accuracy and uncertainties during analysis verification.

TABLE C.2.4.1-1 – ORDEM 3.0, FIXED AP VS. RANDOM AP, RELATIVE VELOCITY

Sat No.	Satellite Name	Year	χ^2 parameter	Passed
1	COSMOS_2191	2010	1.27E-05	✓
1	COSMOS_2191	2015	1.28E-05	✓
1	COSMOS_2191	2020	1.13E-05	✓
1	COSMOS_2191	2025	1.06E-05	✓
1	COSMOS_2191	2030	1.08E-05	✓
1	COSMOS_2191	2035	1.08E-05	✓
2	DIRECTV_12	2011	4.16E-09	✓
2	DIRECTV_12	2016	6.64E-09	✓
2	DIRECTV_12	2021	4.87E-07	✓
2	DIRECTV_12	2026	7.38E-09	✓
2	DIRECTV_12	2031	1.54E-08	✓
3	NAVSTAR_29	2012	2.49E-07	✓
3	NAVSTAR_29	2017	1.39E-07	✓
3	NAVSTAR_29	2022	7.49E-08	✓
3	NAVSTAR_29	2027	2.33E-07	✓
3	NAVSTAR_29	2032	4.09E-08	✓
4	SATCOM_K1	2013	2.97E-04	✓
4	SATCOM_K1	2018	2.45E-04	✓
4	SATCOM_K1	2023	3.37E-04	✓
4	SATCOM_K1	2028	3.42E-04	✓
4	SATCOM_K1	2033	3.34E-04	✓
5	TRMM	2014	5.33E-06	✓
5	TRMM	2019	7.05E-06	✓
5	TRMM	2024	7.82E-06	✓
5	TRMM	2029	1.52E-06	✓
5	TRMM	2034	1.86E-06	✓
6	MOLNIYA1-93	2010	2.81E-03	☐
6	MOLNIYA1-93	2015	1.58E-03	☐
6	MOLNIYA1-93	2020	1.92E-03	☐
6	MOLNIYA1-93	2025	1.94E-03	☐
6	MOLNIYA1-93	2030	1.68E-03	☐
6	MOLNIYA1-93	2035	3.29E-03	☐

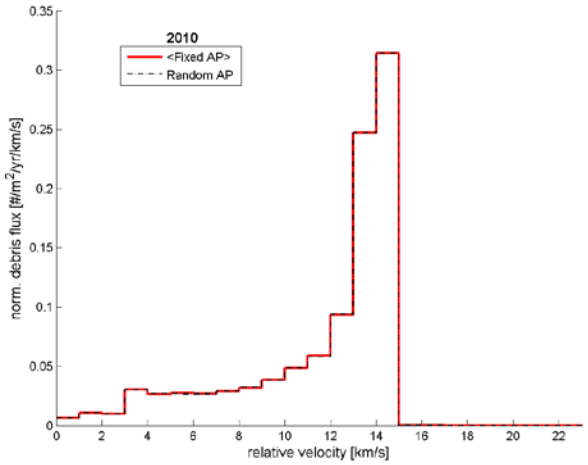

Figure C.2.4.1-1. COSMOS 2191, rel v, 2010.

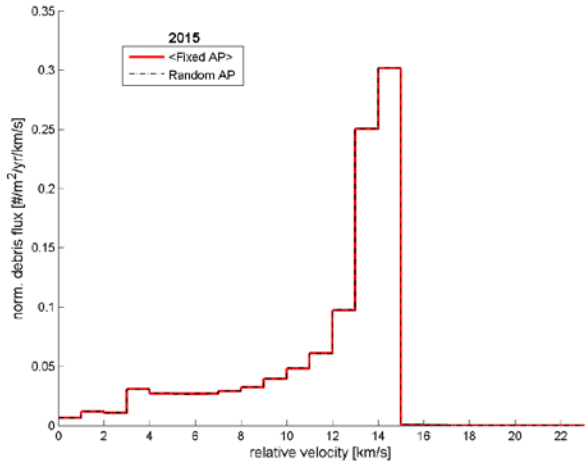

Figure C.2.4.1-2. COSMOS 2191, rel v, 2015.

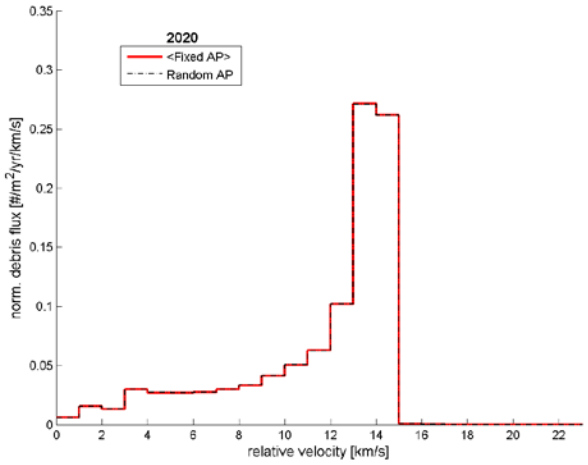

Figure C.2.4.1-3. COSMOS 2191, rel v, 2020.

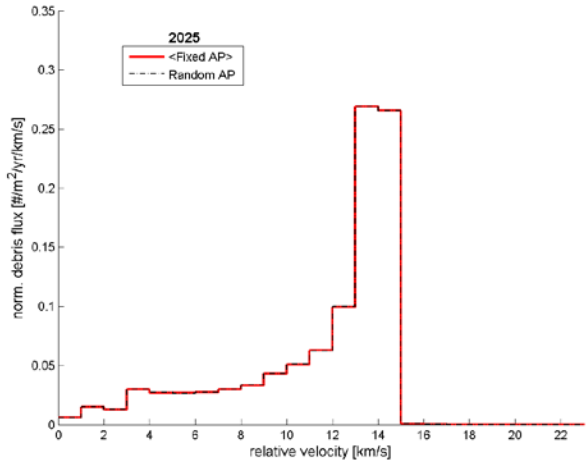

Figure C.2.4.1-4. COSMOS 2191, rel v, 2025.

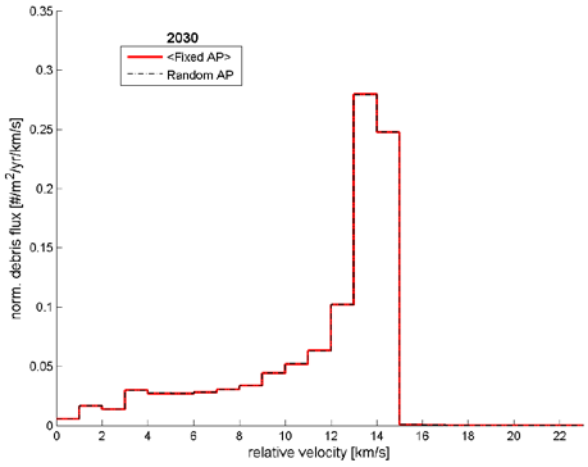

Figure C.2.4.1-5. COSMOS 2191, rel v, 2030.

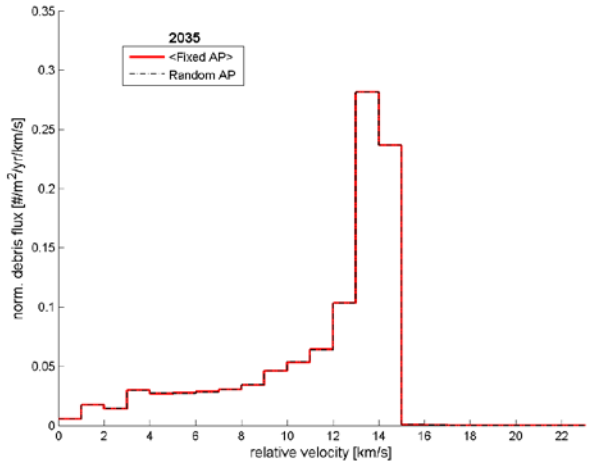

Figure C.2.4.1-6. COSMOS 2191, rel v, 2035.

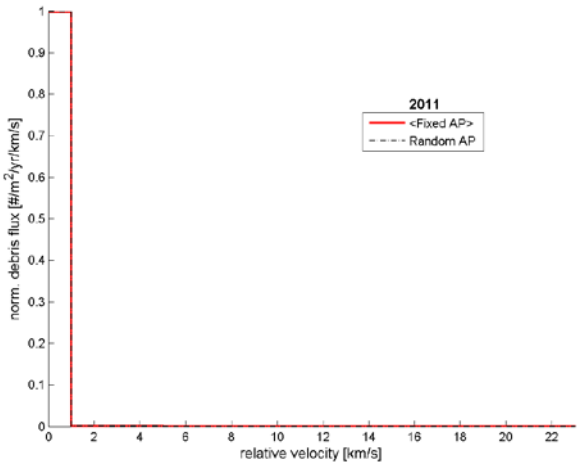

Figure C.2.4.1-7. DIRECTV 12, rel v, 2011.

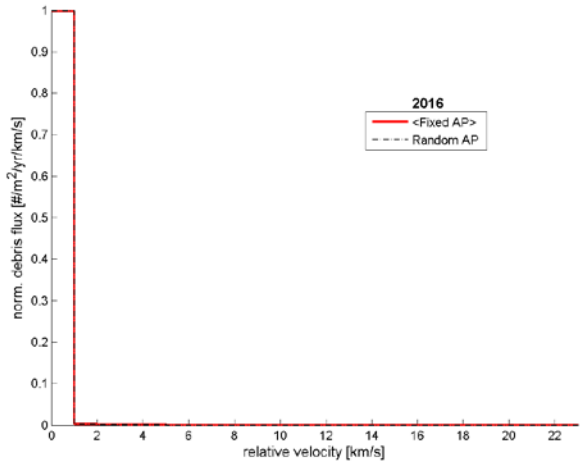

Figure C.2.4.1-8. DIRECTV 12, rel v, 2016.

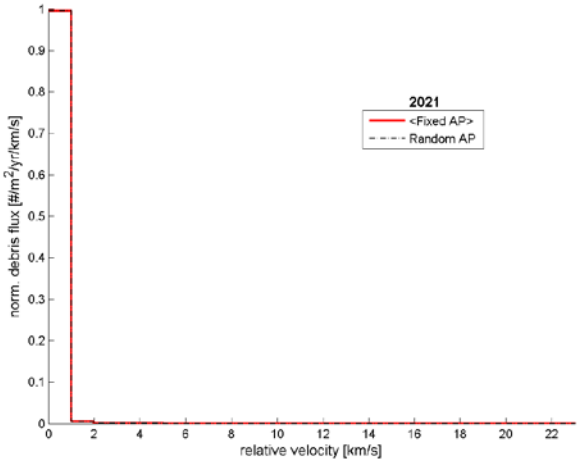

Figure C.2.4.1-9. DIRECTV 12, rel v, 2021.

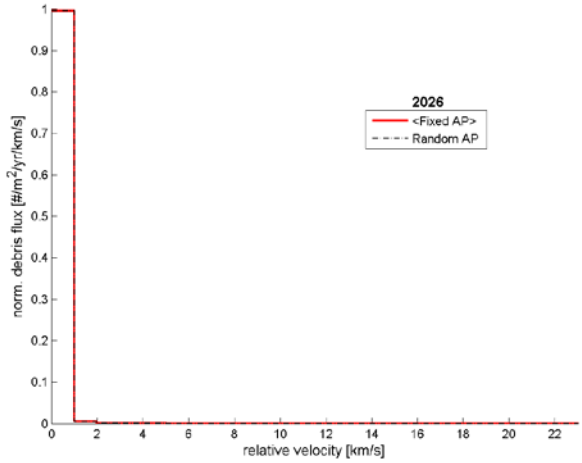

Figure C.2.4.1-10. DIRECTV 12, rel v, 2026.

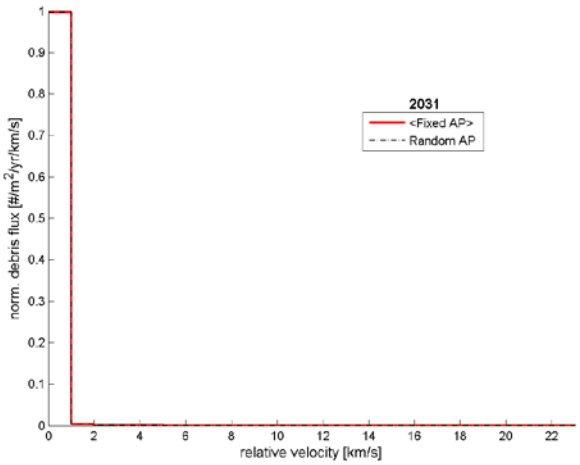

Figure C.2.4.1-11. DIRECTV 12, rel v, 2031.

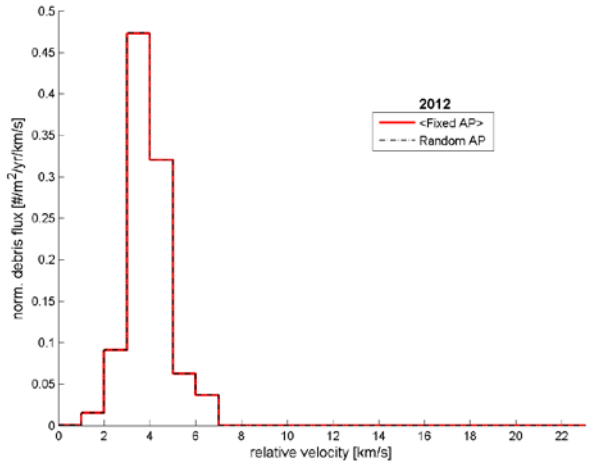

Figure C.2.4.1-12. NAVSTAR 29, rel v, 2012.

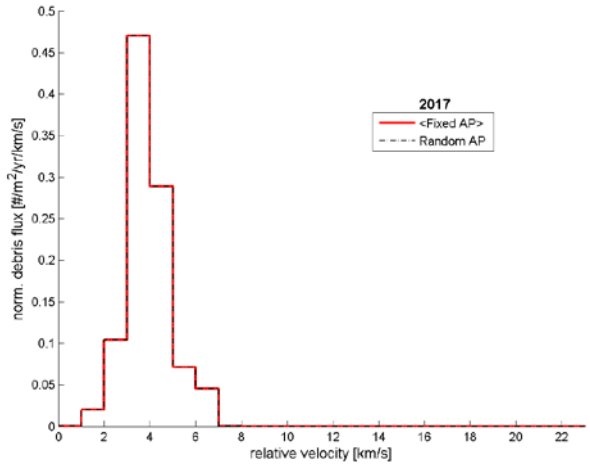

Figure C.2.4.1-13. NAVSTAR 29, rel v, 2017.

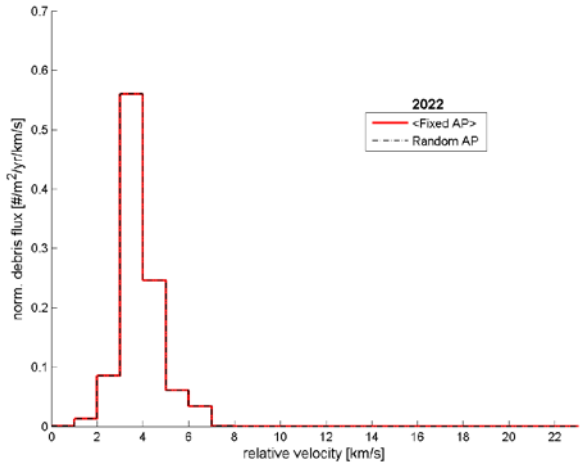

Figure C.2.4.1-14. NAVSTAR 29, rel v, 2022.

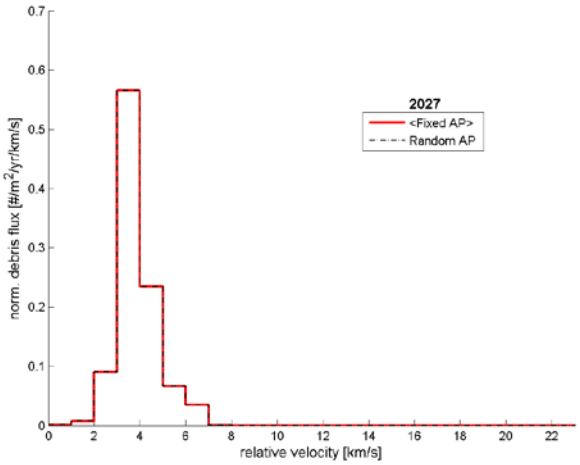

Figure C.2.4.1-15. NAVSTAR 29, rel v, 2027.

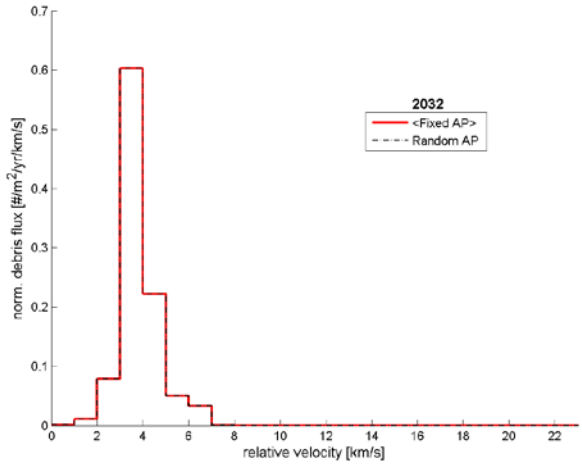

Figure C.2.4.1-16. NAVSTAR 29, rel v, 2032.

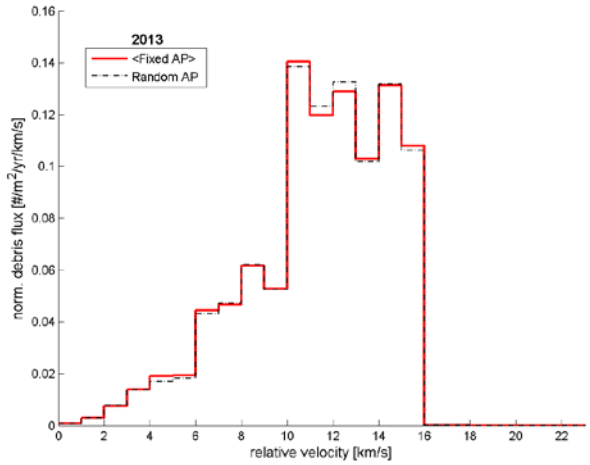

Figure C.2.4.1-17. SATCOM K1, rel v, 2013.

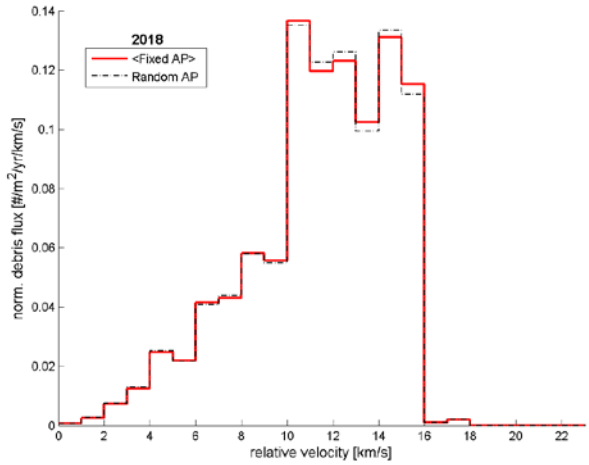

Figure C.2.4.1-18. SATCOM K1, rel v, 2018.

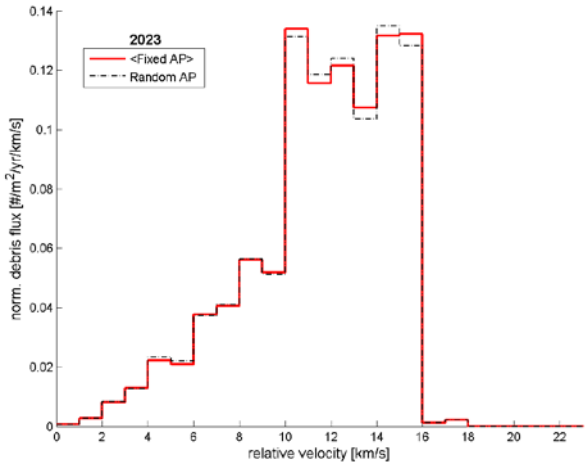

Figure C.2.4.1-19. SATCOM K1, rel v, 2023.

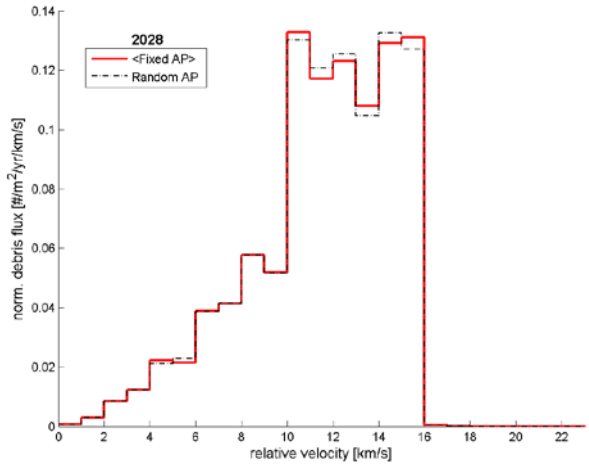

Figure C.2.4.1-20. SATCOM K1, rel v, 2028.

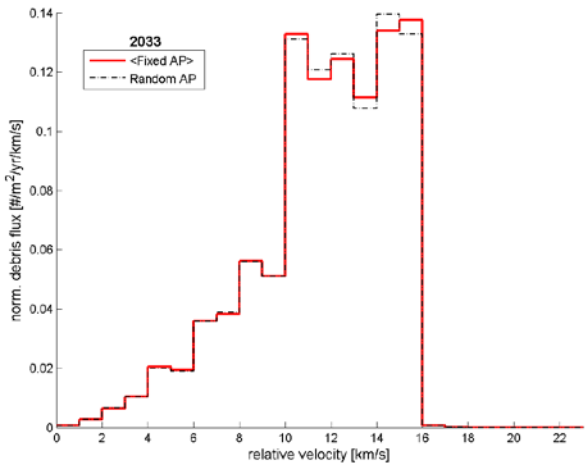

Figure C.2.4.1-21. SATCOM K1, rel v, 2033.

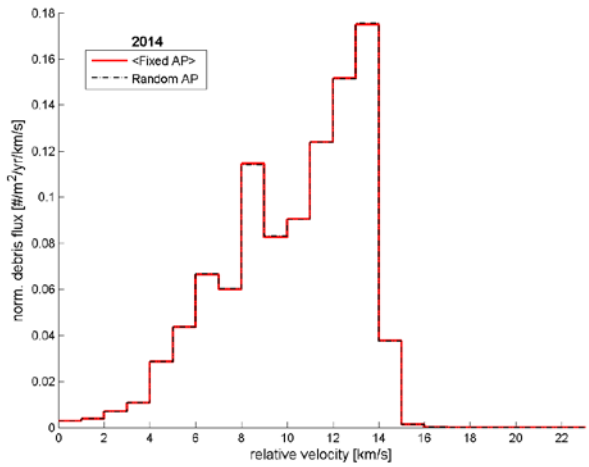

Figure C.2.4.1-22. TRMM, rel v, 2014.

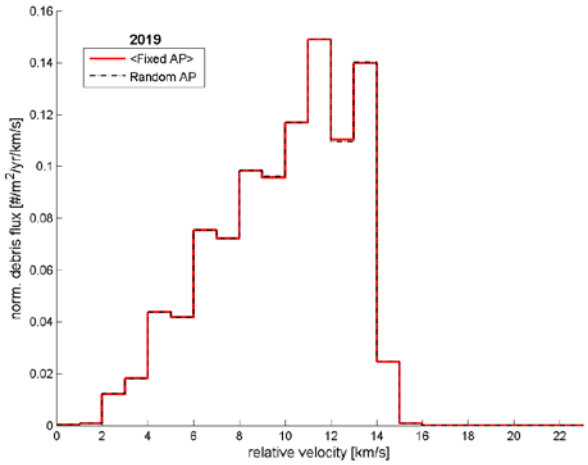

Figure C.2.4.1-23. TRMM, rel v, 2019.

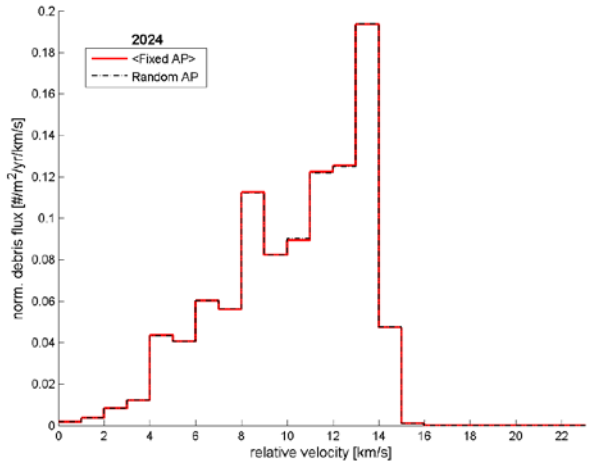

Figure C.2.4.1-24. TRMM, rel v, 2024.

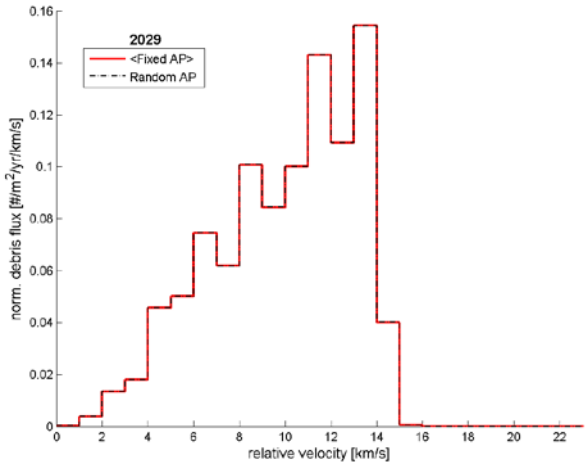

Figure C.2.4.1-25. TRMM, rel v, 2029.

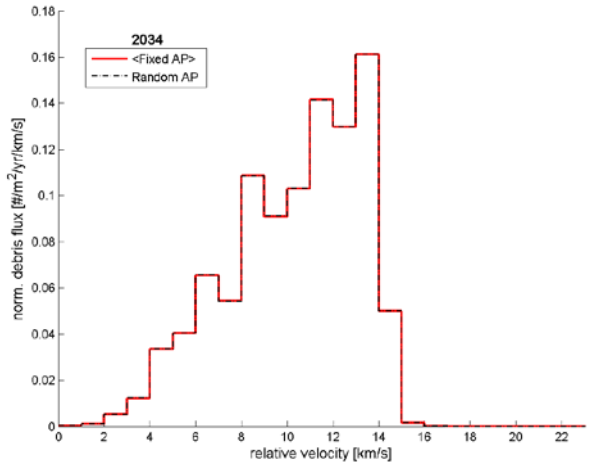

Figure C.2.4.1-26. TRMM, rel v, 2034.

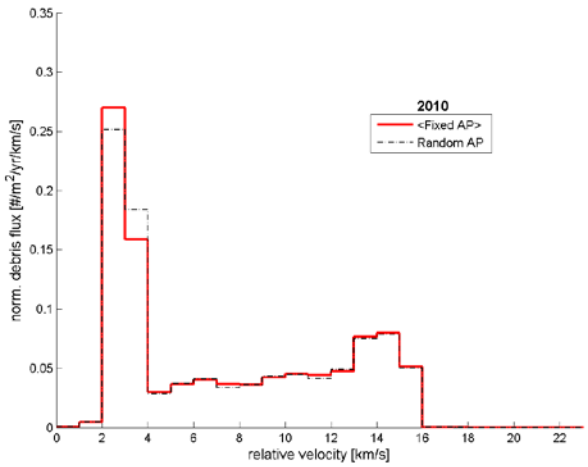

Figure C.2.4.1-27. MOLNIYA1-93, rel v, 2010.

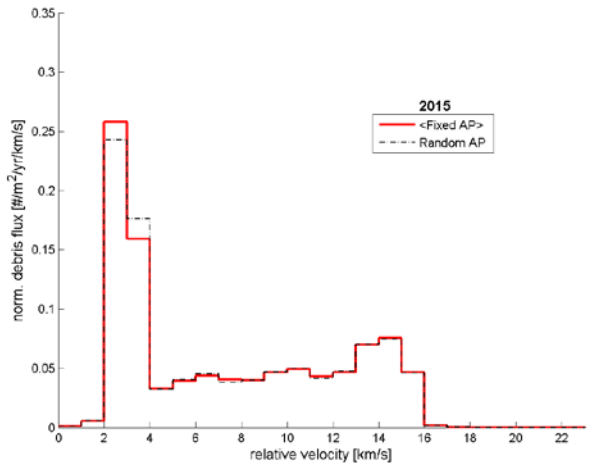

Figure C.2.4.1-28. MOLNIYA1-93, rel v, 2015.

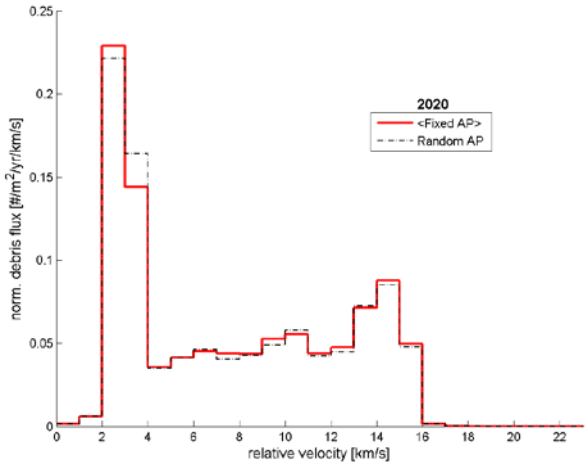

Figure C.2.4.1-29 . MOLNIYA1-93, rel v, 2020.

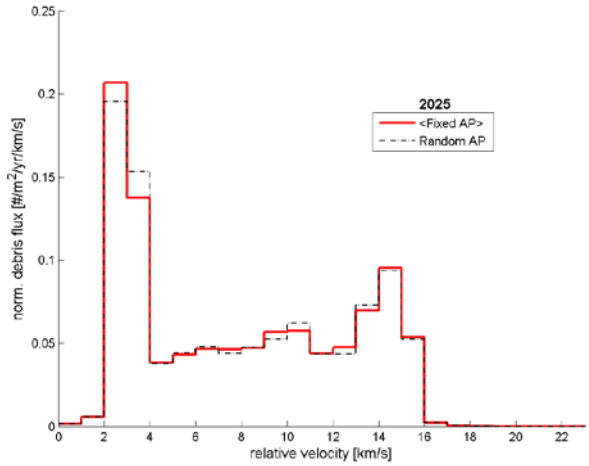

Figure C.2.4.1-30. MOLNIYA1-93, rel v, 2025.

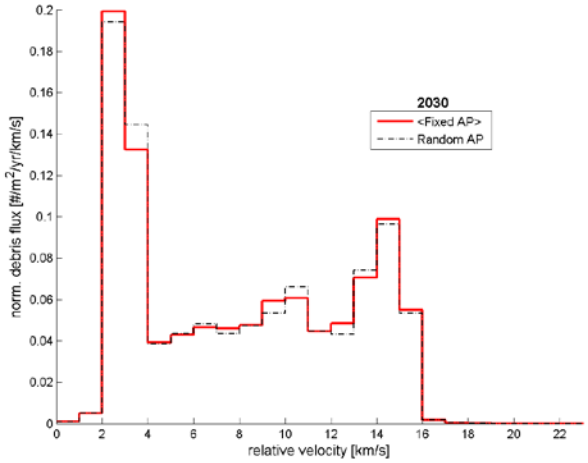

Figure C.2.4.1-31. MOLNIYA1-93, rel v, 2030.

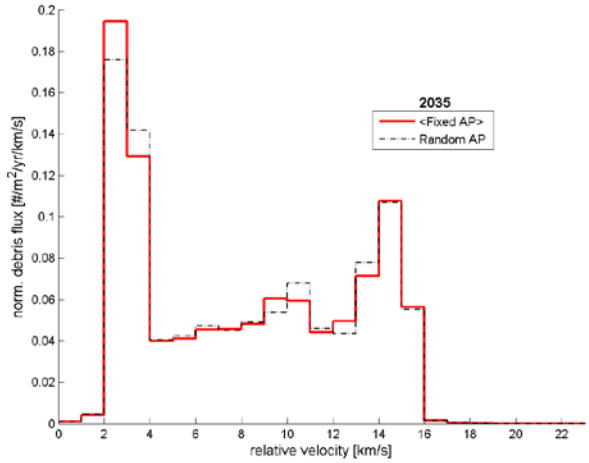

Figure C.2.4.1-32. MOLNIYA1-93, rel v, 2035.

2.4.2. *Yaw*

Table C.2.4.2-1 shows the test satellites used in the statistical comparison of yaw distributions between fixed AP and random AP runs. The following figures in this section pair the binned yaw distribution between fixed AP and random AP runs. Notice that the MOLNIYA1-93 satellite has a better fit when the argument of perigee = 270°. This behavior is expected due to its uniquely oriented, fixed-AP orbit. See section 1.1 for accuracy and uncertainties during analysis verification.

TABLE C.2.4.2-1 – ORDEM 3.0, FIXED AP VS. RANDOM AP, YAW

Sat No.	Satellite Name	Year	χ^2 parameter	Passed
1	COSMOS_2191	2010	1.40E-12	✓
1	COSMOS_2191	2015	1.34E-12	✓
1	COSMOS_2191	2020	1.31E-12	✓
1	COSMOS_2191	2025	1.34E-12	✓
1	COSMOS_2191	2030	1.31E-12	✓
1	COSMOS_2191	2035	1.39E-12	✓
2	DIRECTV_12	2011	3.42E-13	✓
2	DIRECTV_12	2016	3.11E-13	✓
2	DIRECTV_12	2021	2.10E-11	✓
2	DIRECTV_12	2026	4.31E-11	✓
2	DIRECTV_12	2031	4.91E-11	✓
3	NAVSTAR_29	2012	2.41E-17	✓
3	NAVSTAR_29	2017	4.71E-17	✓
3	NAVSTAR_29	2022	1.04E-16	✓
3	NAVSTAR_29	2027	7.54E-17	✓
3	NAVSTAR_29	2032	1.26E-16	✓
4	SATCOM_K1	2013	1.40E-13	✓
4	SATCOM_K1	2018	2.85E-14	✓
4	SATCOM_K1	2023	1.35E-13	✓
4	SATCOM_K1	2028	8.34E-14	✓
4	SATCOM_K1	2033	3.07E-14	✓
5	TRMM	2014	1.49E-13	✓
5	TRMM	2019	2.83E-13	✓
5	TRMM	2024	4.34E-13	✓
5	TRMM	2029	2.97E-13	✓
5	TRMM	2034	2.69E-13	✓
6	MOLNIYA1-93	2010	7.86E-13	✓
6	MOLNIYA1-93	2015	1.50E-12	✓
6	MOLNIYA1-93	2020	7.43E-13	✓
6	MOLNIYA1-93	2025	5.85E-13	✓
6	MOLNIYA1-93	2030	2.83E-13	✓
6	MOLNIYA1-93	2035	6.22E-13	✓

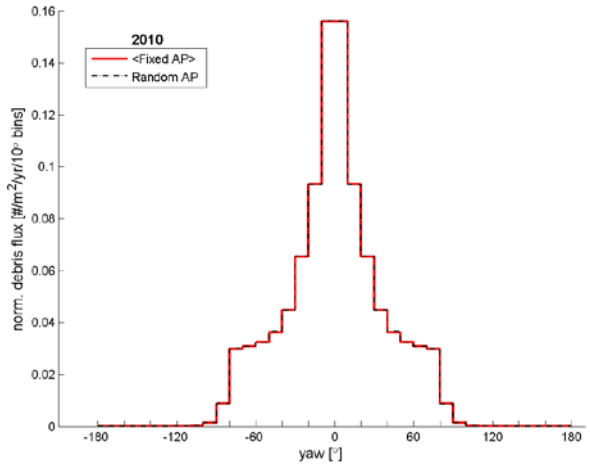

Figure C.2.4.2-1. COSMOS 2191, yaw, 2010.

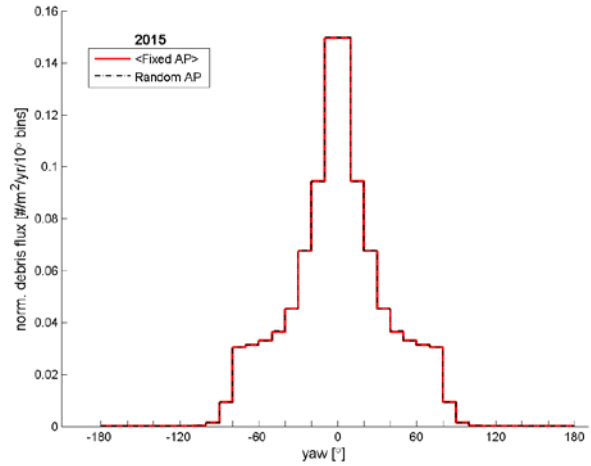

Figure C.2.4.2-2. COSMOS 2191, yaw, 2015.

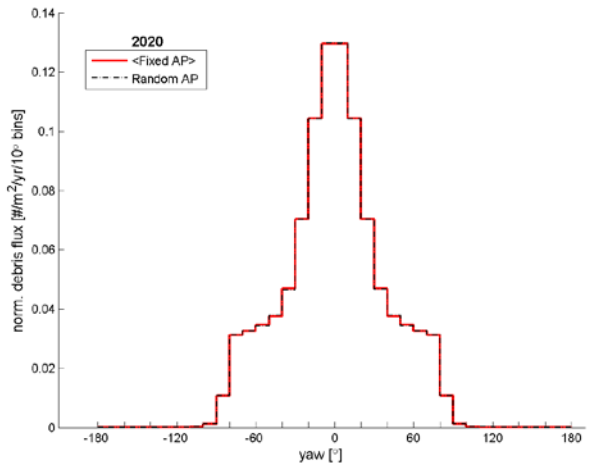

Figure C.2.4.2-3. COSMOS 2191, yaw, 2020.

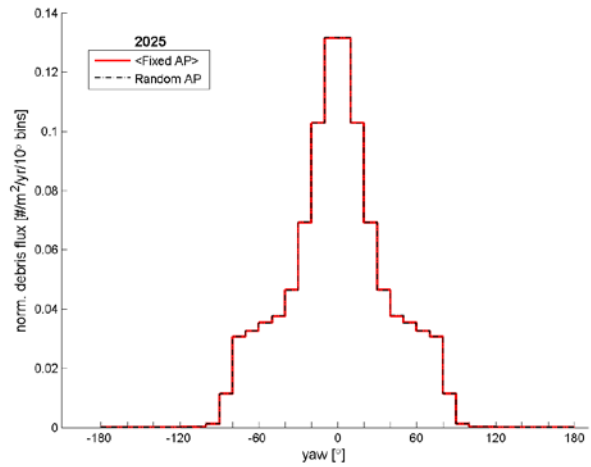

Figure C.2.4.2-4. COSMOS 2191, yaw, 2025.

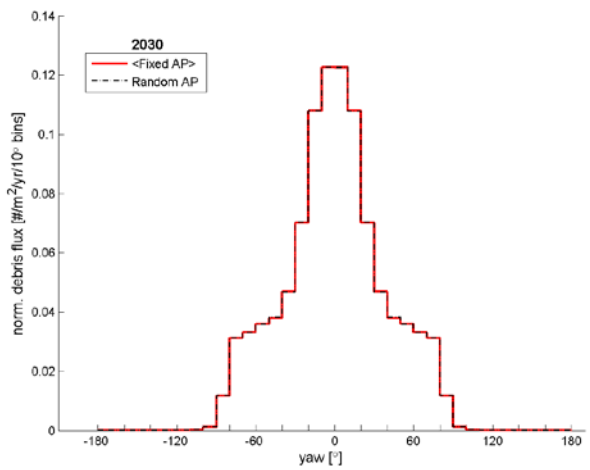

Figure C.2.4.2-5. COSMOS 2191, yaw, 2030.

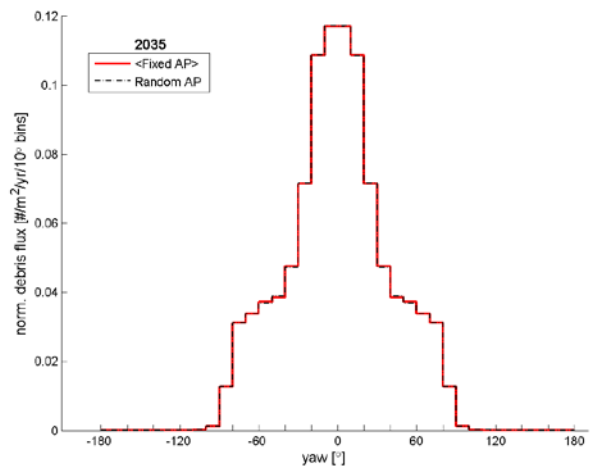

Figure C.2.4.2-6. COSMOS 2191, yaw, 2035.

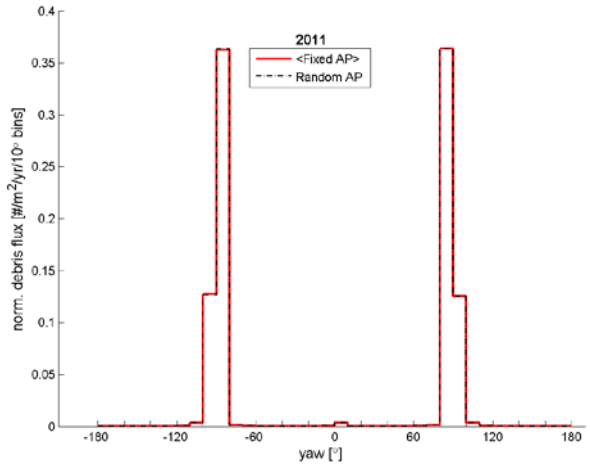

Figure C.2.4.2-7. DIRECTV 12, yaw, 2011.

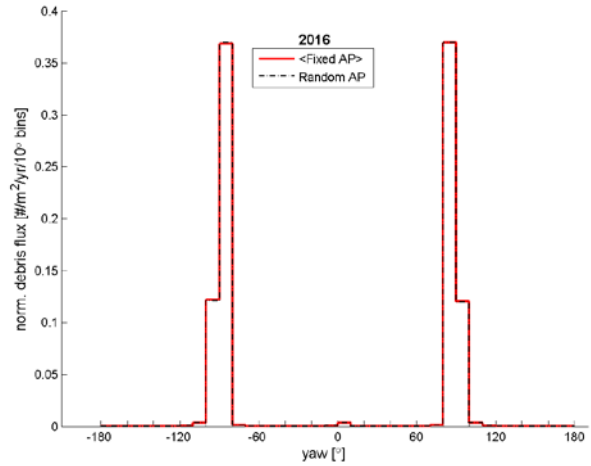

Figure C.2.4.2-8. DIRECTV 12, yaw, 2016.

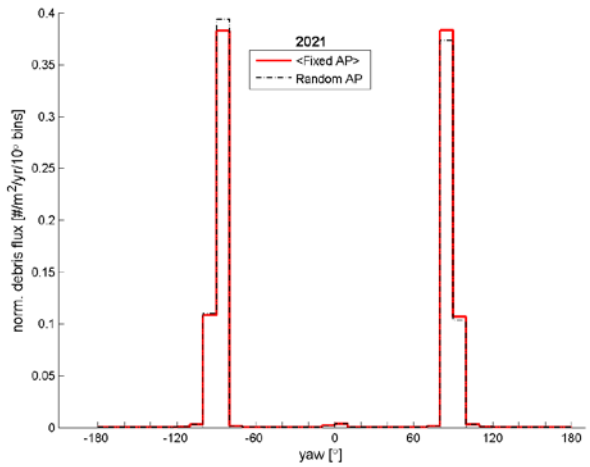

Figure C.2.4.2-9. DIRECTV 12, yaw, 2021.

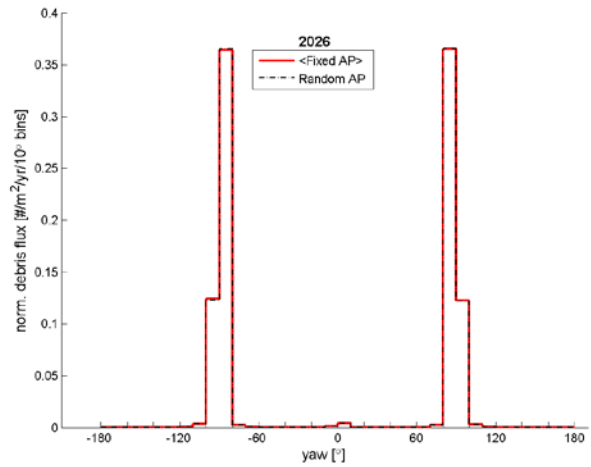

Figure C.2.4.2-10. DIRECTV 12, yaw, 2026.

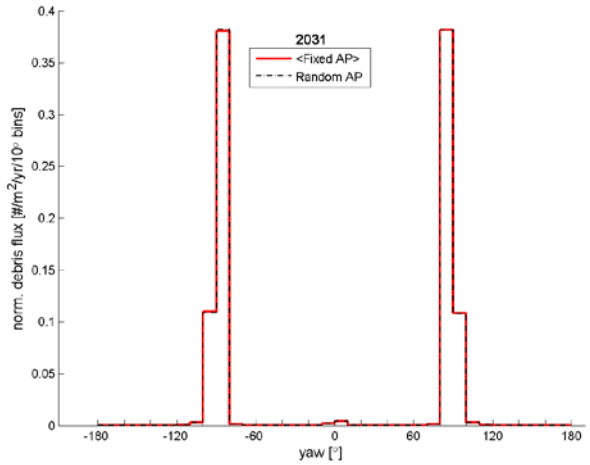

Figure C.2.4.2-11. DIRECTV 12, yaw, 2031.

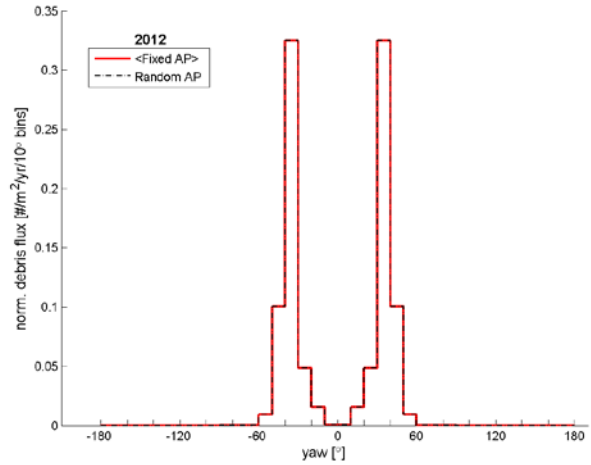

Figure C.2.4.2-12. NAVSTAR 29, yaw, 2012.

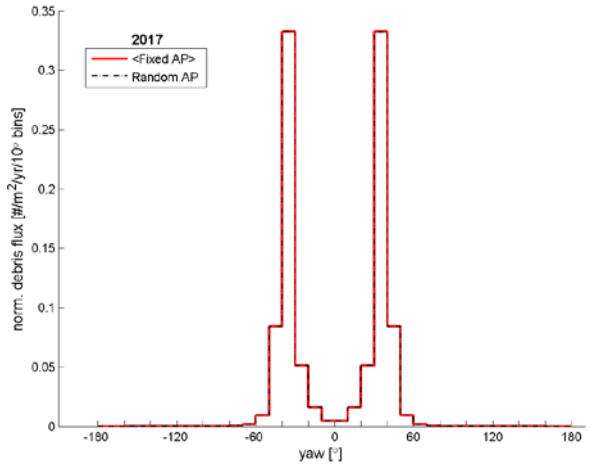

Figure C.2.4.2-13. NAVSTAR 29, yaw, 2017.

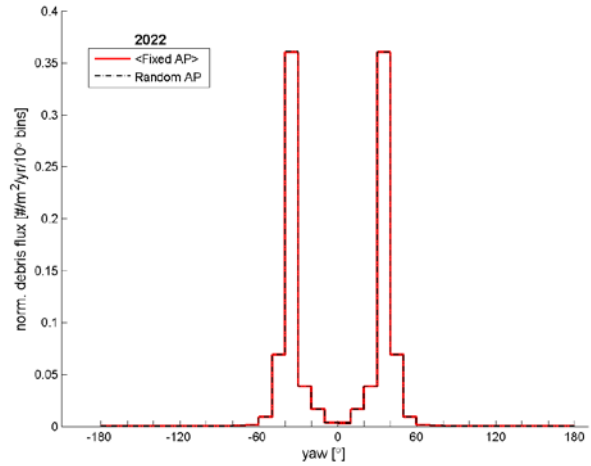

Figure C.2.4.2-14. NAVSTAR 29, yaw, 2022.

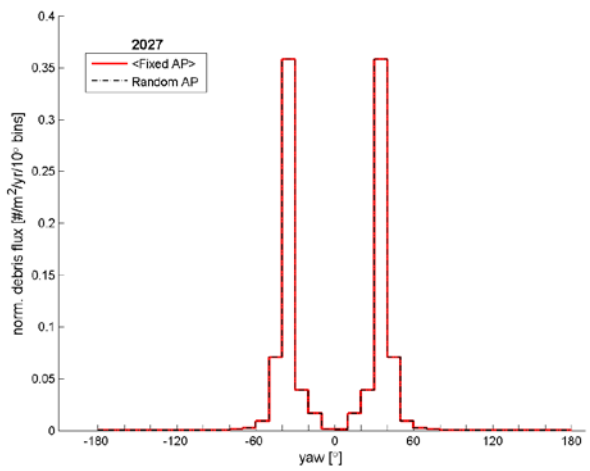

Figure C.2.4.2-15. NAVSTAR 29, yaw, 2027.

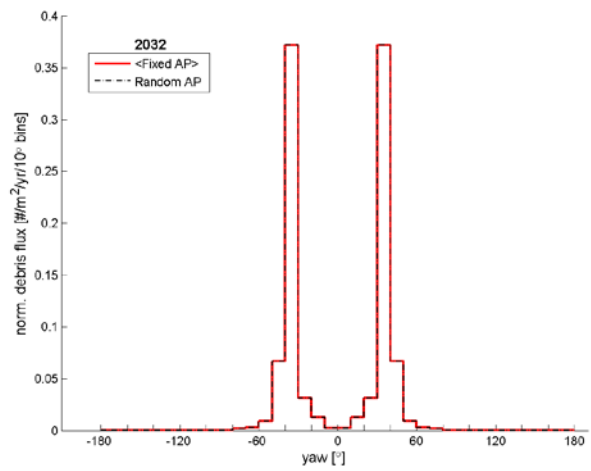

Figure C.2.4.2-16. NAVSTAR 29, yaw, 2032.

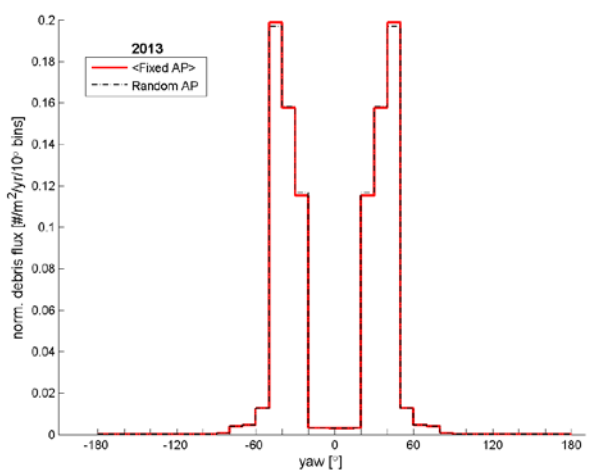

Figure C.2.4.2-17. SATCOM K1, yaw, 2013.

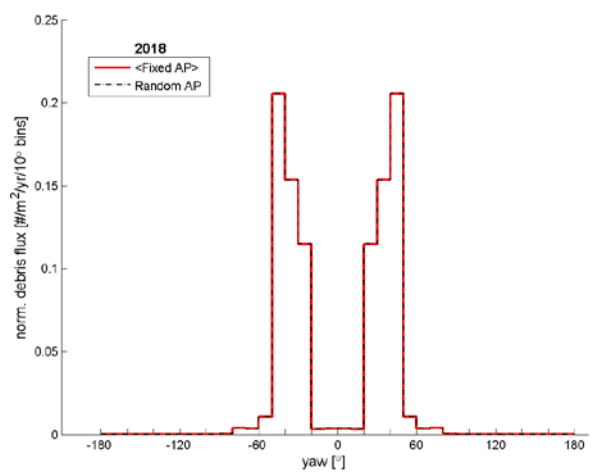

Figure C.2.4.2-18. SATCOM K1, yaw, 2018.

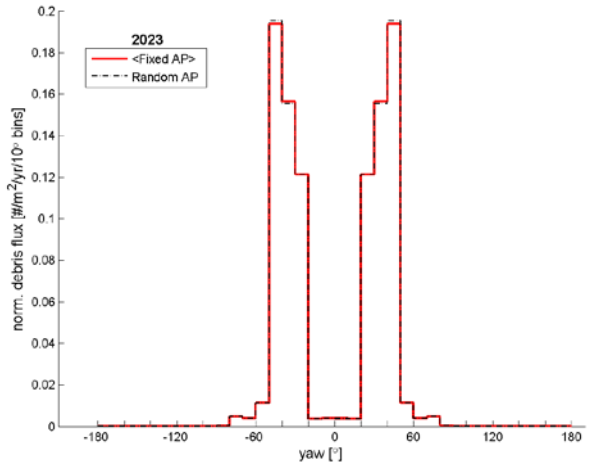

Figure C.2.4.2-19. SATCOM K1, yaw, 2023.

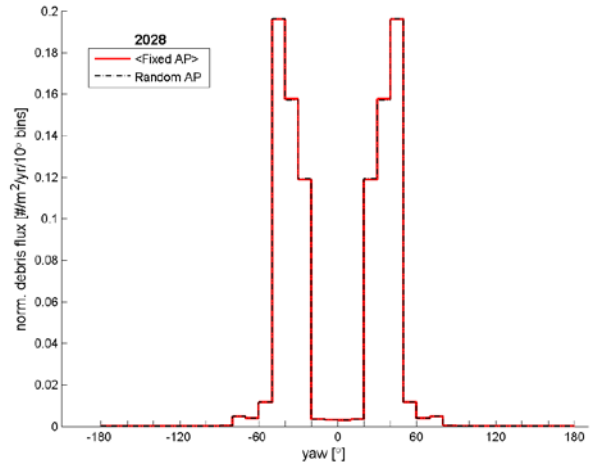

Figure C.2.4.2-20. SATCOM K1, yaw, 2028.

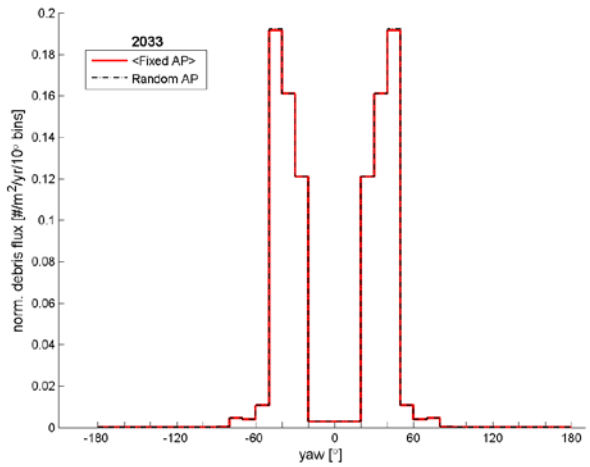

Figure C.2.4.2-21. SATCOM K1, yaw, 2033.

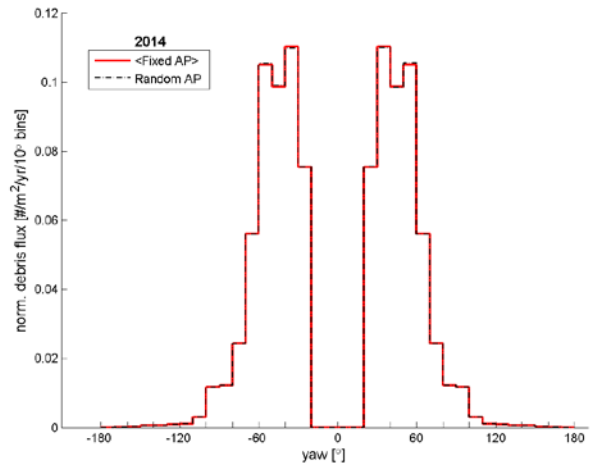

Figure C.2.4.2-22. TRMM, yaw, 2014.

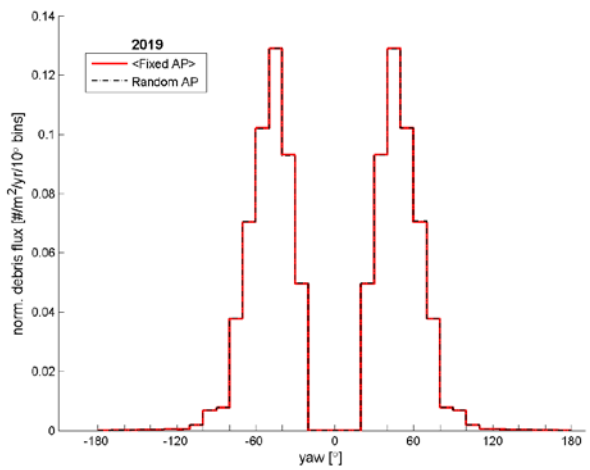

Figure C.2.4.2-23. TRMM, yaw, 2019.

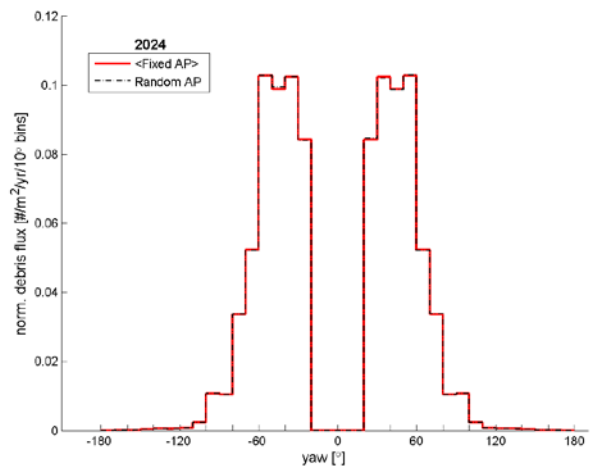

Figure C.2.4.2-24. TRMM, yaw, 2024.

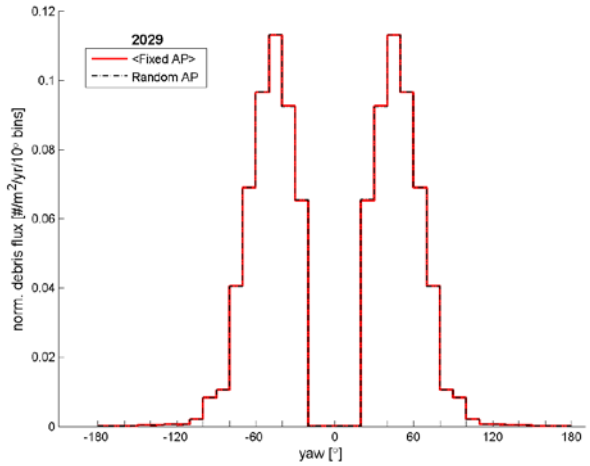

Figure C.2.4.2-25. TRMM, yaw, 2029.

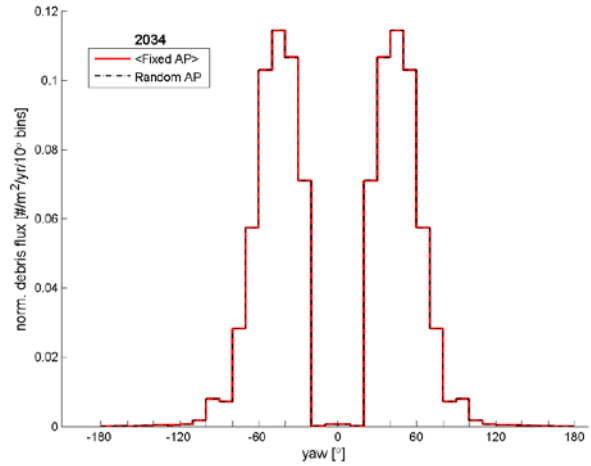

Figure C.2.4.2-26. TRMM, yaw, 2034.

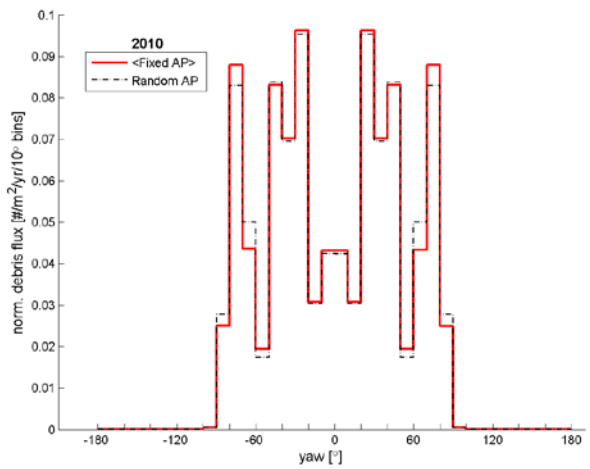

Figure C.2.4.2-27. MOLNIYA1-93, yaw, 2010.

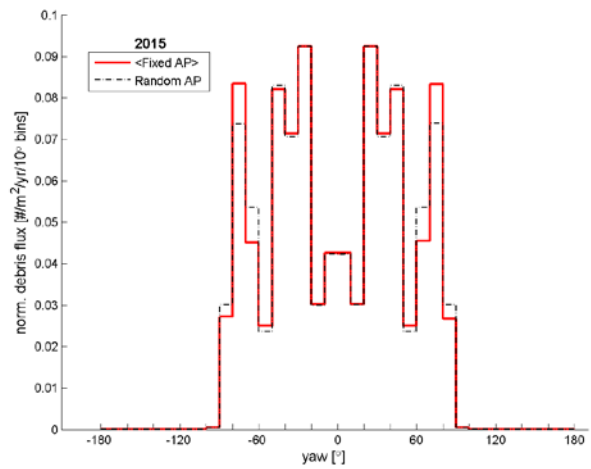

Figure C.2.4.2-28. MOLNIYA1-93, yaw, 2015.

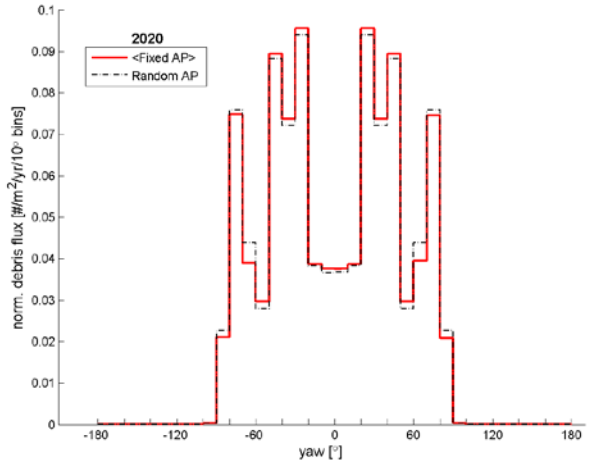

Figure C.2.4.2-29. MOLNIYA1-93, yaw, 2020.

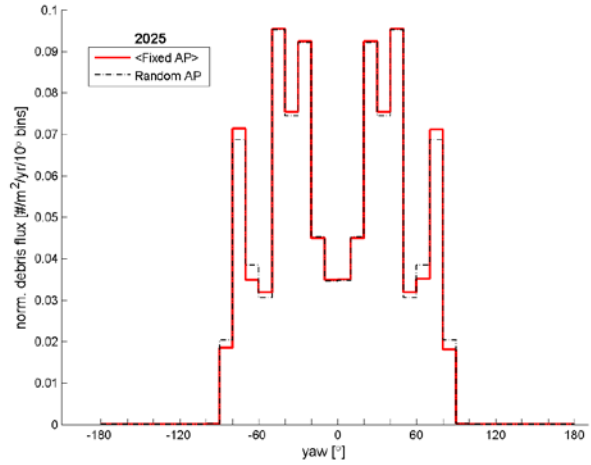

Figure C.2.4.2-30. MOLNIYA1-93, yaw, 2025.

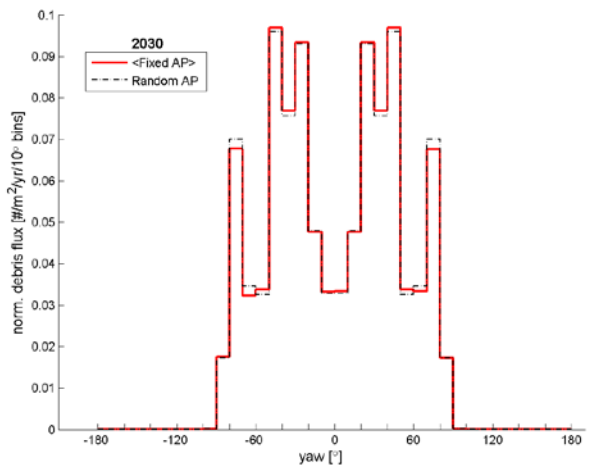

Figure C.2.4.2-31. MOLNIYA1-93, yaw, 2030.

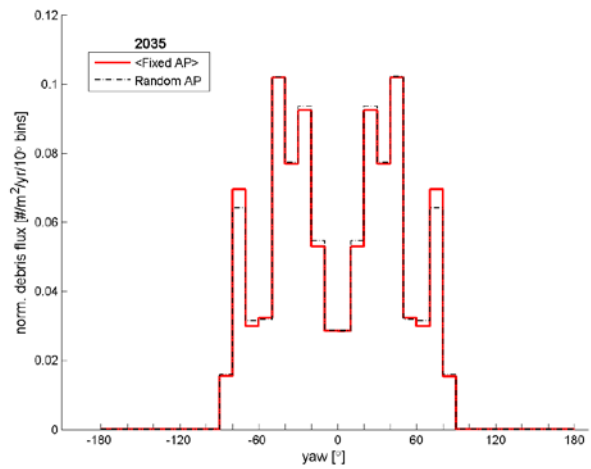

Figure C.2.4.2-32. MOLNIYA1-93, yaw, 2035.

2.5. ORDEM 3.0 VS. KESSLER, RANDOM AP

This analysis requires a comparison of two data sets – a data set of ORDEM 3.0 run sessions given a random AP and a data set of KESSLER run sessions given a random AP. Each data set consists of output files for each test satellite, given the test satellite's year (see Tables C.2.1-2 and C.2.1-3).

The relative velocity and yaw distributions were chosen for this comparison analysis. For the ORDEM 3.0 files, the yaw was calculated by reading in the *az_low* and *az_high* columns stored in the IGLOOFLUX_SC.OUT output file. The relative velocity was calculated by reading in the *vel_low* and *vel_high* columns of IGLOOFLUX_SC.OUT. For the KESSLER runs, the process, the appropriate columns in the output files of the LEO_KESSLER_IGLOO, and GEO_KESSLER_IGLOO programs were averaged and the result was used in this comparison. A Ç^2 test was used to compare the binned distributions (relative velocity, yaw) of the fixed AP and random AP runs.

An additional comparison was made between the actual flux values (Flux MD60) produced by ORDEM 3.0 and KESSLER to ensure a close match. The results of this comparison are in section 2.5.3.

Table C.2.5-1 shows the test objectives that were completed in this section.

TABLE C.2.5-1 – SPACECRAFT MODE χ^2 TEST

Objective	Passed
Use test satellites, each with various years	✓
χ^2 test between binned distributions, ORDEM 3.0 and KESSLER	✓
Relative velocity, yaw comparisons	✓
Run comparison when AP=270° on Molniya orbit	✓
Demonstrate symmetry between two models	✓
Generate figures for comparison	✓

2.5.1. *Relative Velocity*

Table C.2.5.1-1 shows the test satellites used in the statistical comparison of relative velocity distributions between fixed AP and random AP runs. The following figures in this section pair the binned relative velocity distribution between fixed AP and random AP runs. Notice that the MOLNIYA1-93 satellite has a better fit when the argument of perigee = 270°. This behavior is expected due to its uniquely oriented, fixed-AP orbit. See section 1.1 for accuracy and uncertainties during analysis verification.

TABLE C.2.5.1-1 – ORDEM 3.0 VS. KESSLER, RANDOM AP, RELATIVE VELOCITY

Sat No.	Satellite Name	Year	χ^2 parameter	Passed
1	COSMOS_2191	2010	2.08E-05	✓
1	COSMOS_2191	2015	1.86E-05	✓
1	COSMOS_2191	2020	1.39E-05	✓
1	COSMOS_2191	2025	1.41E-05	✓
1	COSMOS_2191	2030	1.24E-05	✓
1	COSMOS_2191	2035	1.37E-05	✓
2	DIRECTV_12	2011	4.07E-06	✓
2	DIRECTV_12	2016	5.93E-06	✓
2	DIRECTV_12	2021	1.20E-05	✓
2	DIRECTV_12	2026	1.46E-05	✓
2	DIRECTV_12	2031	8.91E-06	✓
3	NAVSTAR_29	2012	1.67E-06	✓
3	NAVSTAR_29	2017	9.06E-06	✓
3	NAVSTAR_29	2022	1.21E-06	✓
3	NAVSTAR_29	2027	9.13E-06	✓
3	NAVSTAR_29	2032	7.52E-06	✓
4	SATCOM_K1	2013	4.70E-05	✓
4	SATCOM_K1	2018	6.08E-06	✓
4	SATCOM_K1	2023	8.55E-06	✓
4	SATCOM_K1	2028	8.72E-06	✓
4	SATCOM_K1	2033	7.36E-06	✓
5	TRMM	2014	5.44E-06	✓
5	TRMM	2019	1.61E-06	✓
5	TRMM	2024	5.49E-06	✓
5	TRMM	2029	9.45E-06	✓
5	TRMM	2034	1.58E-06	✓
6	CZ-3A DEB	2015	2.92E-03	✓
7	MOLNIYA1-93	2010	6.46E-03	✓
7	MOLNIYA1-93	2015	3.45E-03	✓
7	MOLNIYA1-93	2020	4.87E-03	✓
7	MOLNIYA1-93	2025	4.50E-03	✓
7	MOLNIYA1-93	2030	4.44E-03	✓
7	MOLNIYA1-93	2035	3.98E-03	✓
fixed AP (É =270°)				
7	MOLNIYA1-93	2010	2.21E-05	✓
7	MOLNIYA1-93	2015	1.74E-05	✓
7	MOLNIYA1-93	2020	2.22E-05	✓
7	MOLNIYA1-93	2025	3.80E-05	✓
7	MOLNIYA1-93	2030	5.13E-05	✓
7	MOLNIYA1-93	2035	7.22E-05	✓

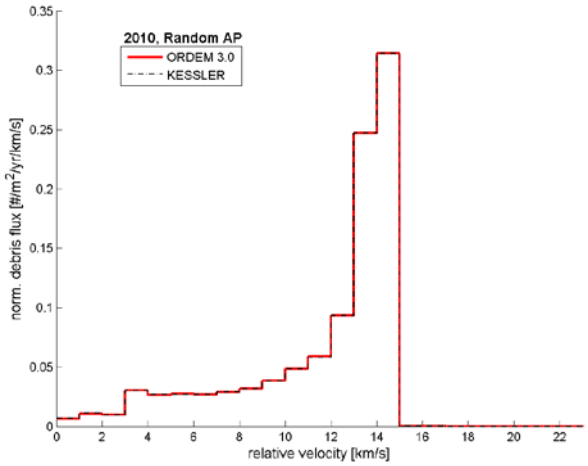

Figure C.2.5.1-1. COSMOS 2191, rel v, 2010.

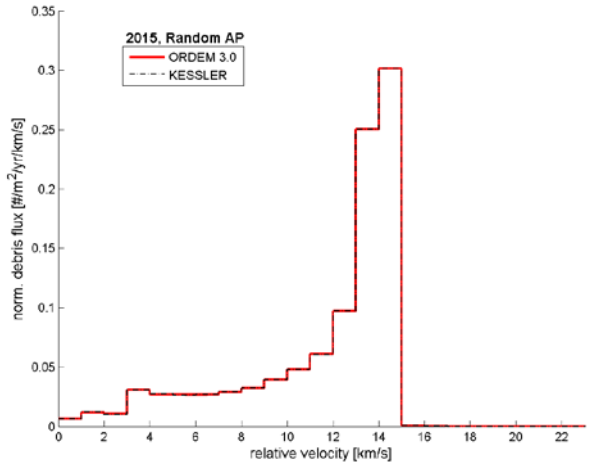

Figure C.2.5.1-2. COSMOS 2191, rel v, 2015.

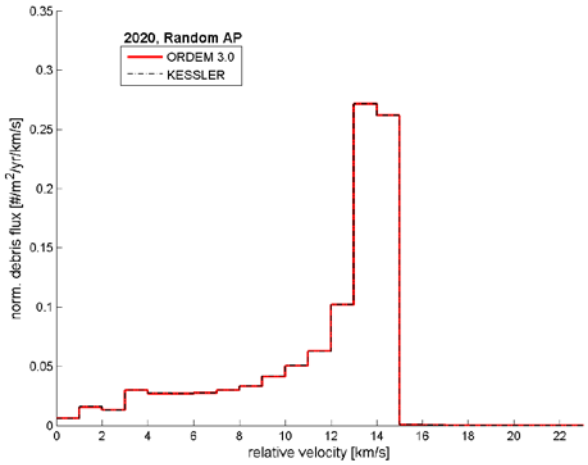

Figure C.2.5.1-3. COSMOS 2191, rel v, 2020.

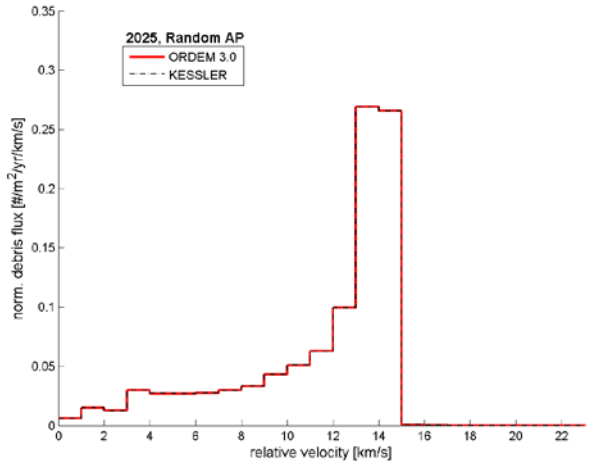

Figure C.2.5.1-4. COSMOS 2191, rel v, 2025.

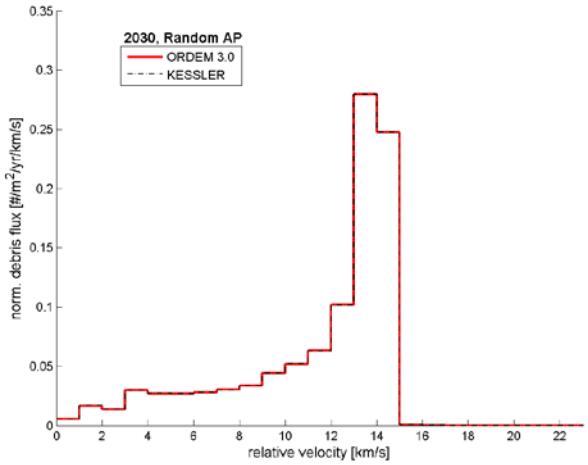

Figure C.2.5.1-5. COSMOS 2191, rel v, 2030.

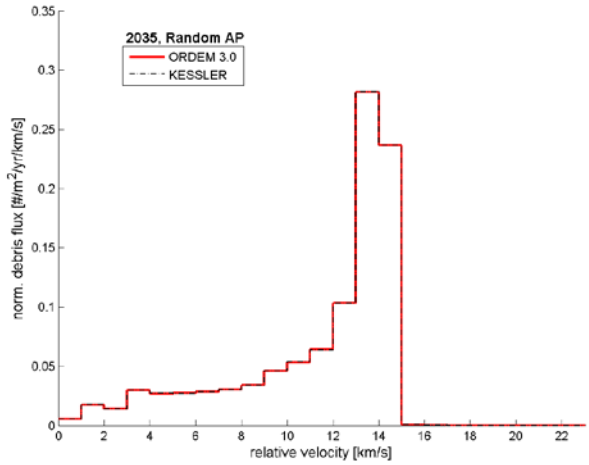

Figure C.2.5.1-6. COSMOS 2191, rel v, 2035.

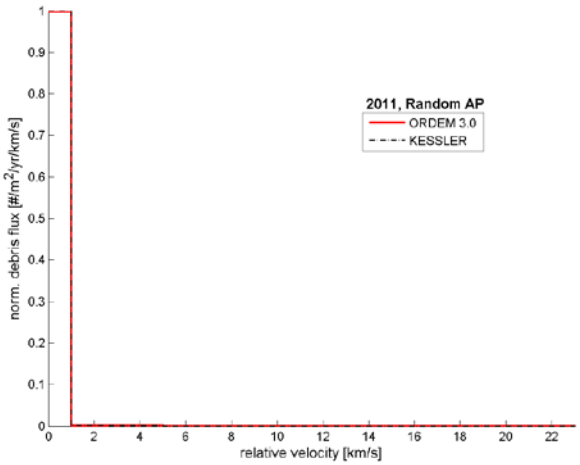

Figure C.2.5.1-7. DIRECTV 12, rel v, 2011.

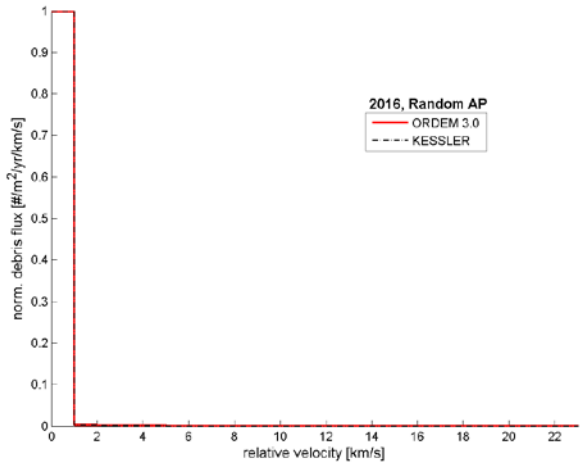

Figure C.2.5.1-8. DIRECTV 12, rel v, 2016.

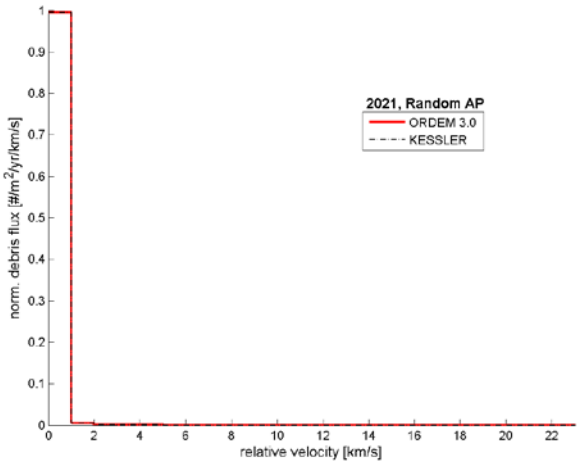

Figure C.2.5.1-9. DIRECTV 12, rel v, 2021.

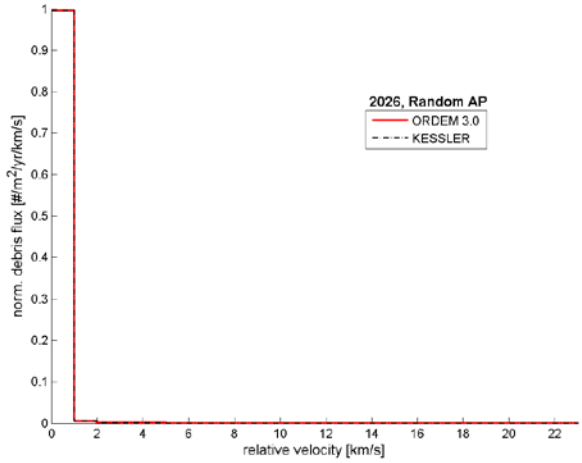

Figure C.2.5.1-10. DIRECTV 12, rel v, 2026.

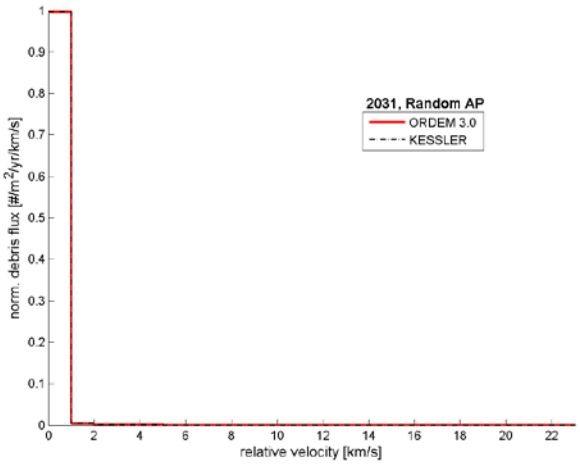

Figure C.2.5.1-11. DIRECTV 12, rel v, 2031.

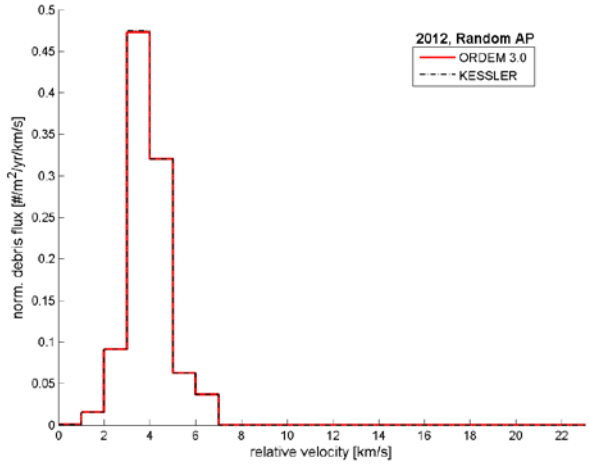

Figure C.2.5.1-12. NAVSTAR 29, rel v, 2012.

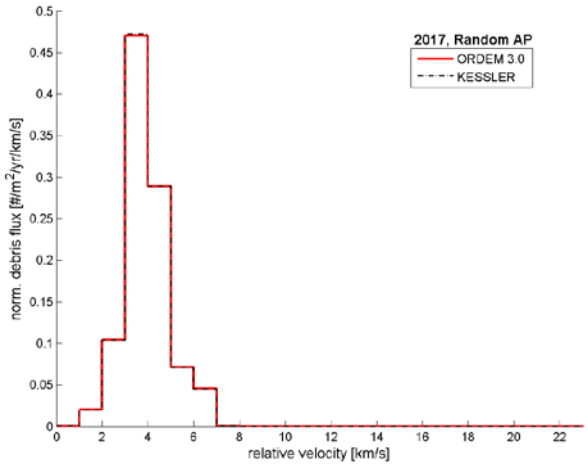

Figure C.2.5.1-13. NAVSTAR 29, rel v, 2017.

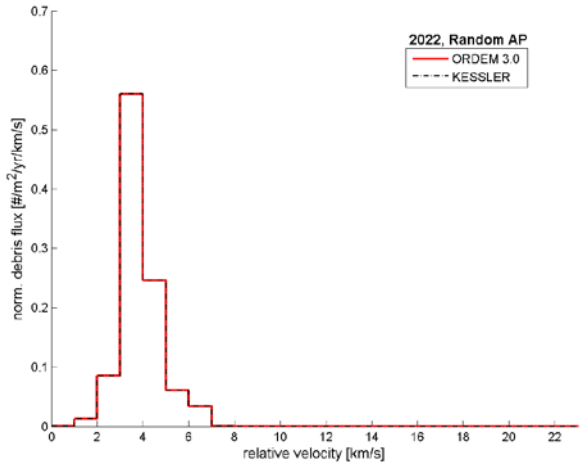

Figure C.2.5.1-14. NAVSTAR 29, rel v, 2022.

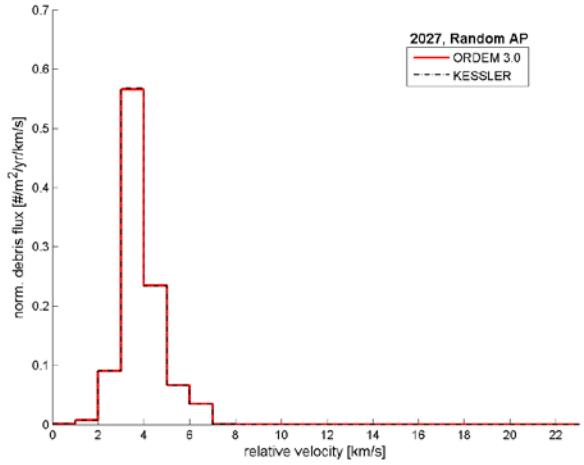

Figure C.2.5.1-15. NAVSTAR 29, rel v, 2027.

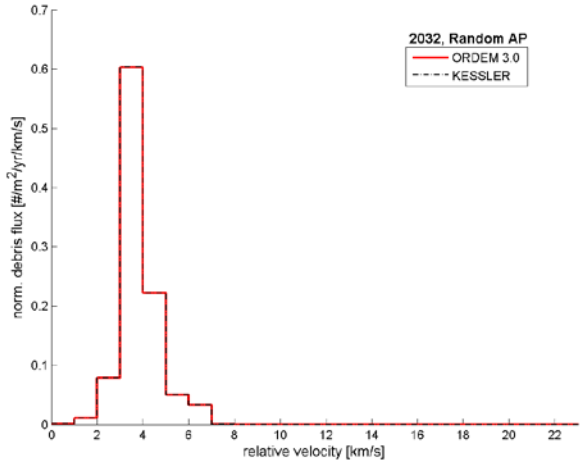

Figure C.2.5.1-16. NAVSTAR 29, rel v, 2032.

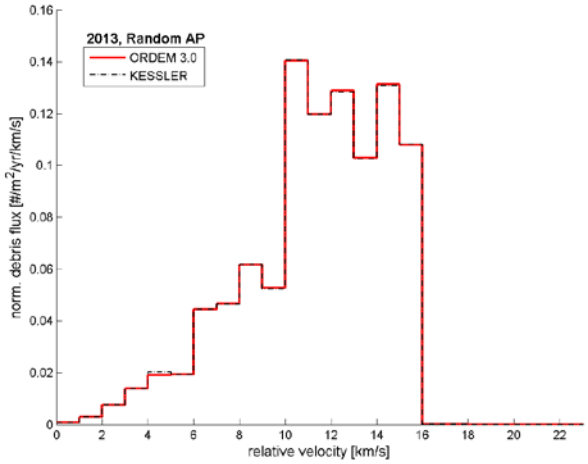

Figure C.2.5.1-17. SATCOM K1, rel v, 2013.

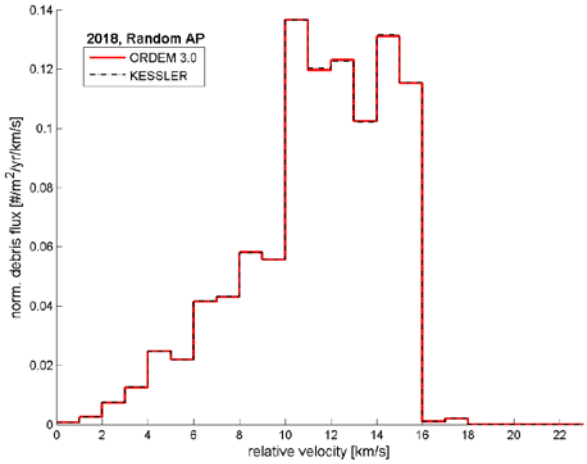

Figure C.2.5.1-18. SATCOM K1, rel v, 2018.

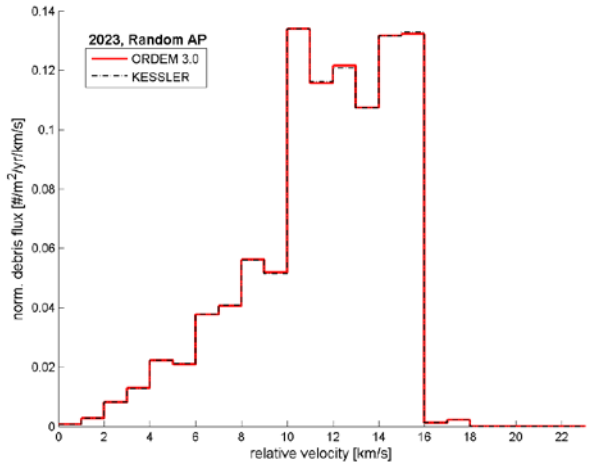

Figure C.2.5.1-19. SATCOM K1, rel v, 2023.

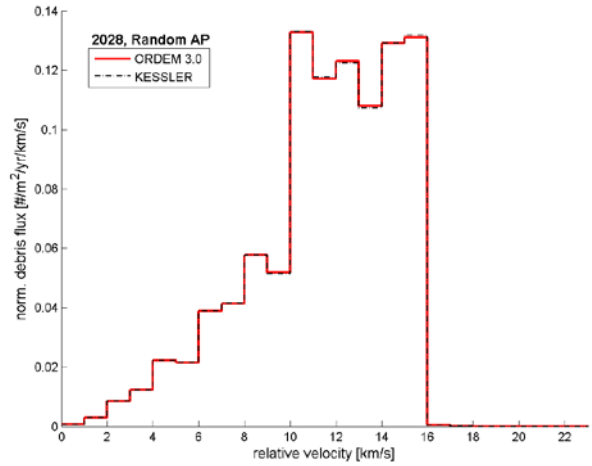

Figure C.2.5.1-20. SATCOM K1, rel v, 2028.

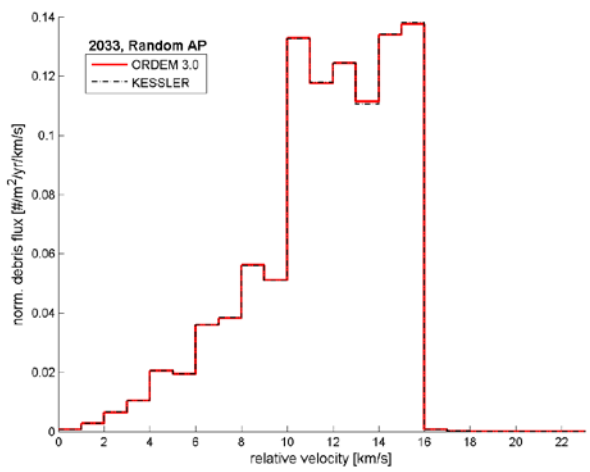

Figure C.2.5.1-21. SATCOM K1, rel v, 2033.

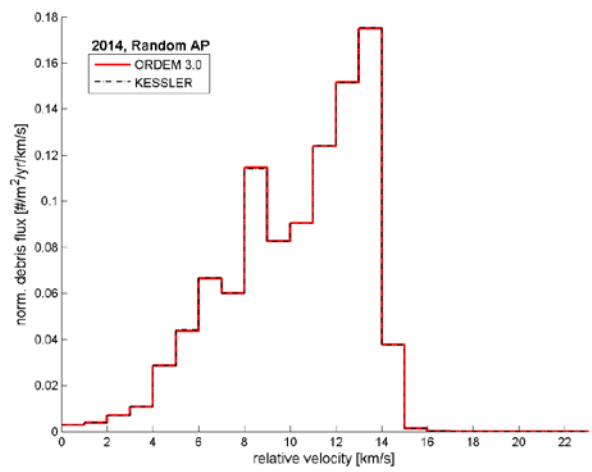

Figure C.2.5.1-22. TRMM, rel v, 2014.

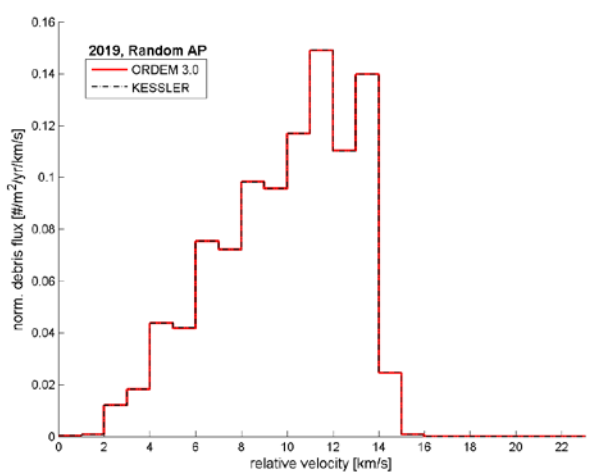

Figure C.2.5.1-23. TRMM, rel v, 2019.

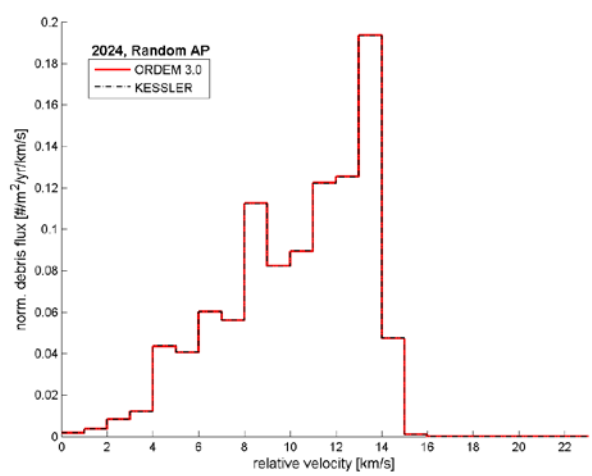

Figure C.2.5.1-24. TRMM, rel v, 2024.

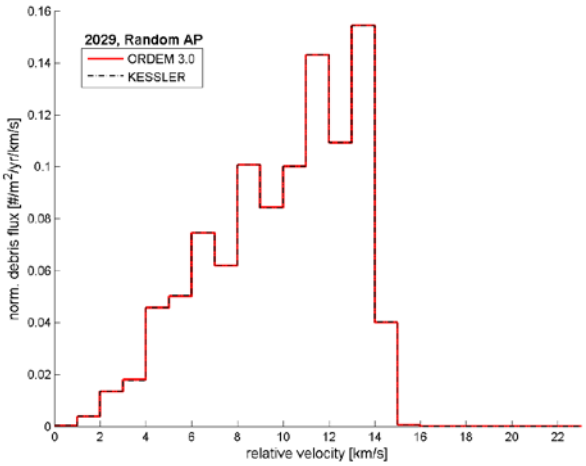

Figure C.2.5.1-25. TRMM, rel v, 2029.

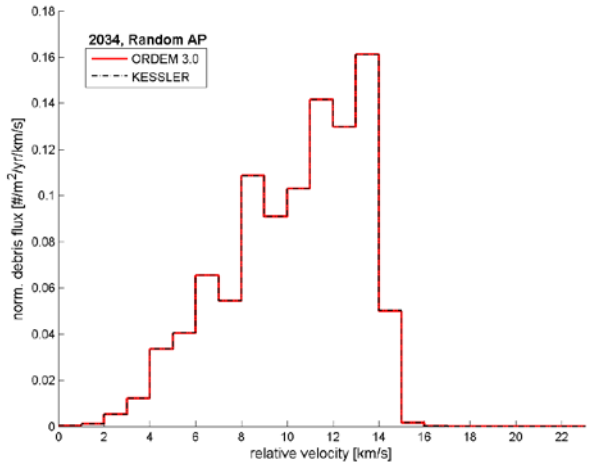

Figure C.2.5.1-26. TRMM, rel v, 2034.

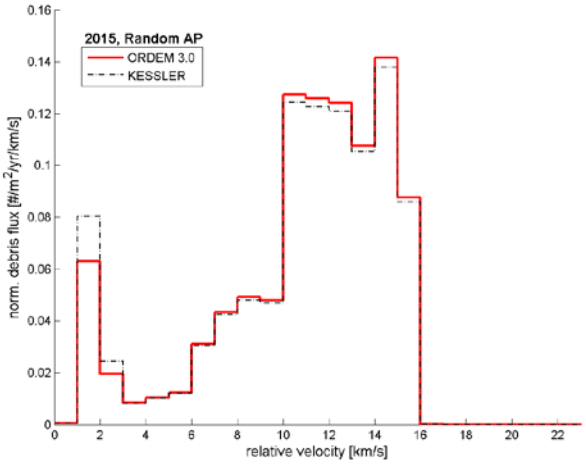

Figure C.2.5.1-27. CZ-3A DEB, rel v, 2015.

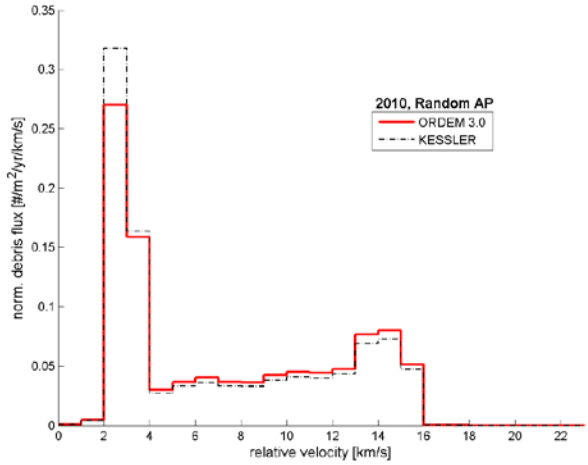

Figure C.2.5.1-28. MOLNIYA1-93, rel v, 2010

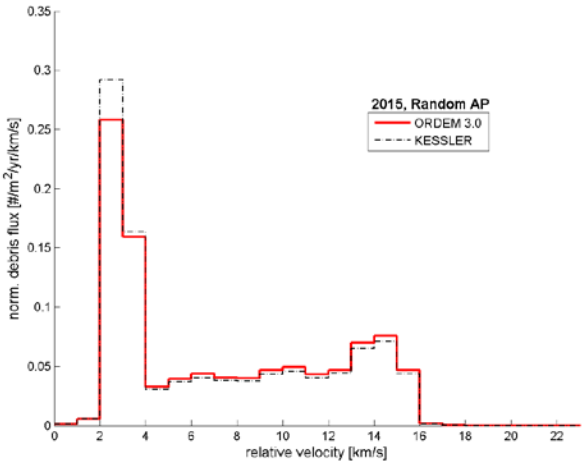

Figure C.2.5.1-29. MOLNIYA1-93, rel v, 2015.

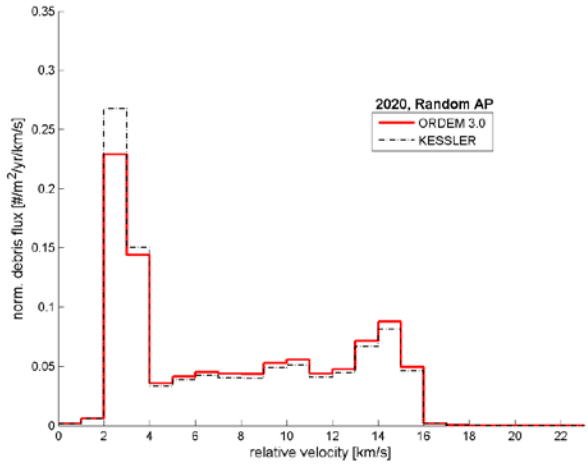

Figure C.2.5.1-30. MOLNIYA1-93, rel v, 2020.

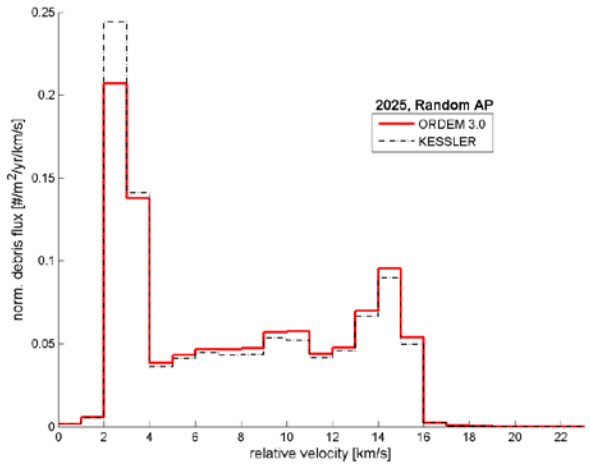

Figure C.2.5.1-31. MOLNIYA1-93, rel v, 2025.

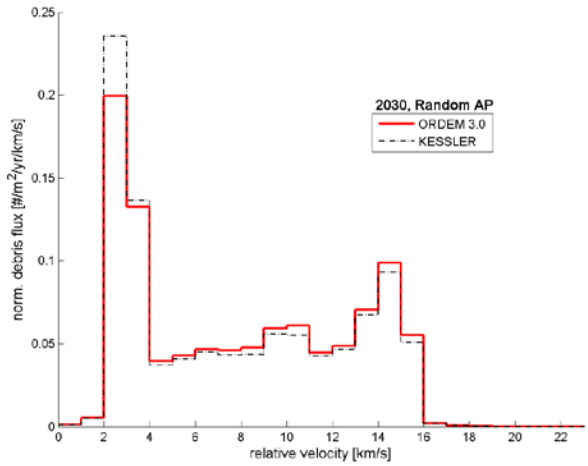

Figure C.2.5.1-32. MOLNIYA1-93, rel v, 2030.

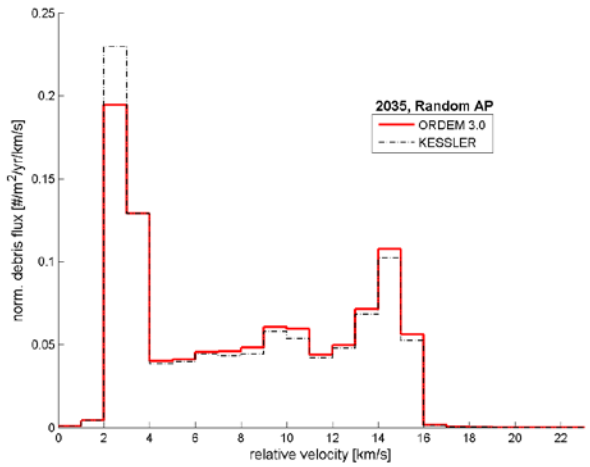

Figure C.2.5.1-33. MOLNIYA1-93, rel v, 2035.

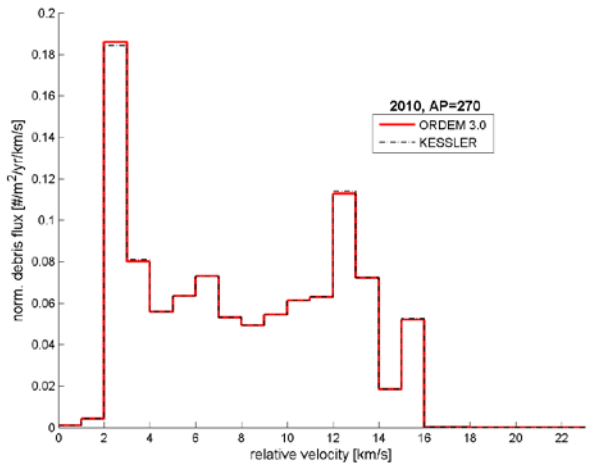

Figure C.2.5.1-34. MOLNIYA1-93, rel v, 2010, AP=270°.

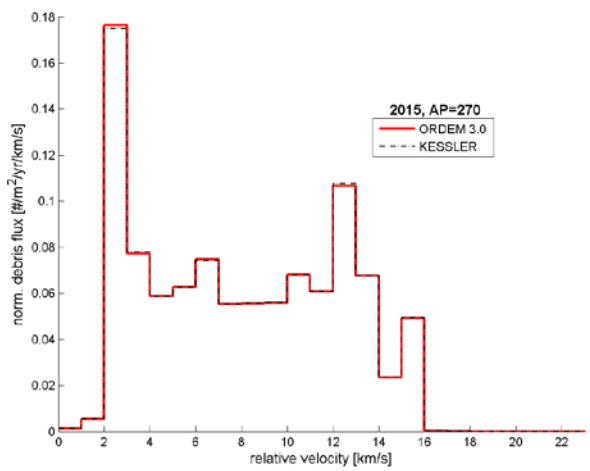

Figure C.2.5.1-35. MOLNIYA1-93, rel v, 2015, AP=270°.

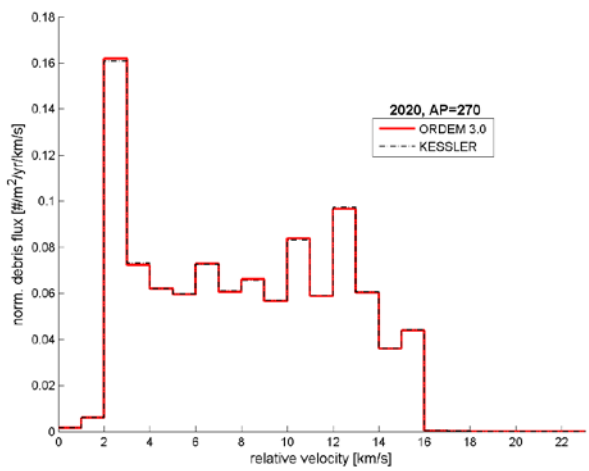

Figure C.2.5.1-36. MOLNIYA1-93, rel v, 2020, AP=270°.

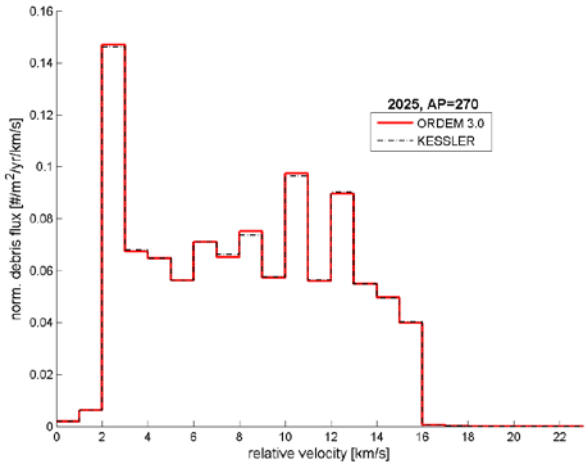

Figure C.2.5.1-37. MOLNIYA1-93, rel v, 2025, AP=270°.

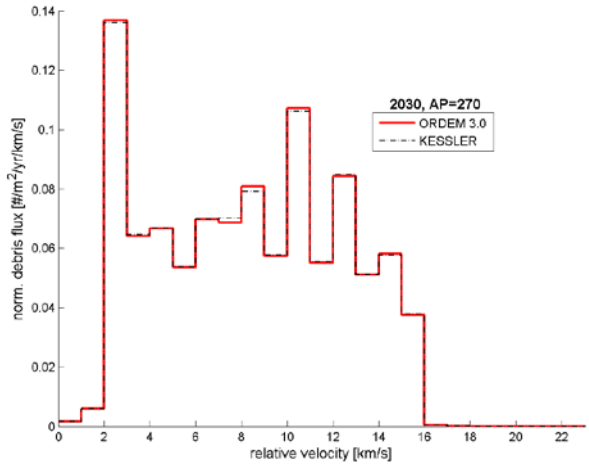

Figure C.2.5.1-38. MOLNIYA1-93, rel v, 2030, AP=270°.

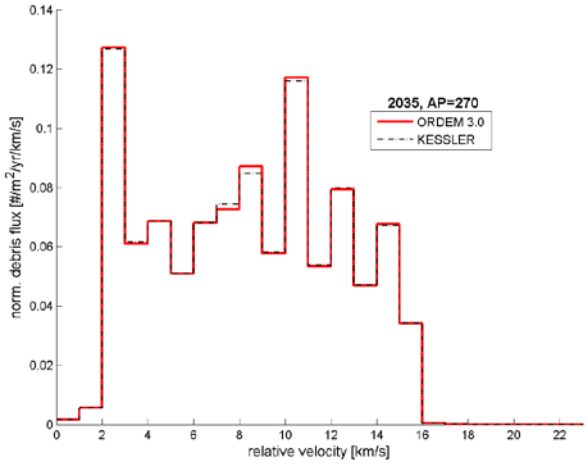

Figure C.2.5.1-39. MOLNIYA1-93, rel v, 2035, AP=270°.

2.5.2. *Yaw*

Table C.2.5.2-1 shows the test satellites used in the statistical comparison of yaw distributions between fixed AP and random AP runs. The following figures in this section pair the binned yaw distribution between fixed AP and random AP runs. Notice that the MOLNIYA1-93 satellite has a better fit when the argument of perigee = 270°. This behavior is expected due to its uniquely oriented, fixed-AP orbit. See section 1.1 for accuracy and uncertainties during analysis verification.

TABLE C.2.5.2-1 – ORDEM 3.0 VS. KESSLER, RANDOM AP, YAW

Sat No.	Satellite Name	Year	χ^2 parameter	Passed
1	COSMOS_2191	2010	1.37E-12	✓
1	COSMOS_2191	2015	1.04E-12	✓
1	COSMOS_2191	2020	8.97E-13	✓
1	COSMOS_2191	2025	1.01E-12	✓
1	COSMOS_2191	2030	8.39E-13	✓
1	COSMOS_2191	2035	9.15E-13	✓
2	DIRECTV_12	2011	1.49E-10	✓
2	DIRECTV_12	2016	1.49E-10	✓
2	DIRECTV_12	2021	1.49E-10	✓
2	DIRECTV_12	2026	1.85E-10	✓
2	DIRECTV_12	2031	1.86E-10	✓
3	NAVSTAR_29	2012	3.06E-16	✓
3	NAVSTAR_29	2017	1.40E-15	✓
3	NAVSTAR_29	2022	6.93E-16	✓
3	NAVSTAR_29	2027	2.26E-15	✓
3	NAVSTAR_29	2032	3.27E-15	✓
4	SATCOM_K1	2013	6.17E-14	✓
4	SATCOM_K1	2018	4.95E-14	✓
4	SATCOM_K1	2023	6.63E-14	✓
4	SATCOM_K1	2028	1.11E-13	✓
4	SATCOM_K1	2033	9.09E-14	✓
5	TRMM	2014	2.34E-13	✓
5	TRMM	2019	3.68E-13	✓
5	TRMM	2024	7.50E-13	✓
5	TRMM	2029	1.34E-12	✓
5	TRMM	2034	5.50E-13	✓
6	CZ-3A DEB	2015	1.43E-11	✓
7	MOLNIYA1-93	2010	7.16E-12	✓
7	MOLNIYA1-93	2015	4.38E-12	✓
7	MOLNIYA1-93	2020	6.93E-12	✓
7	MOLNIYA1-93	2025	6.68E-12	✓
7	MOLNIYA1-93	2030	7.47E-12	✓
7	MOLNIYA1-93	2035	6.84E-12	✓
fixed AP (É =270°)				
7	MOLNIYA1-93	2010	2.00E-14	✓
7	MOLNIYA1-93	2015	3.63E-14	✓
7	MOLNIYA1-93	2020	5.13E-14	✓
7	MOLNIYA1-93	2025	7.35E-14	✓
7	MOLNIYA1-93	2030	1.01E-13	✓
7	MOLNIYA1-93	2035	1.55E-13	✓

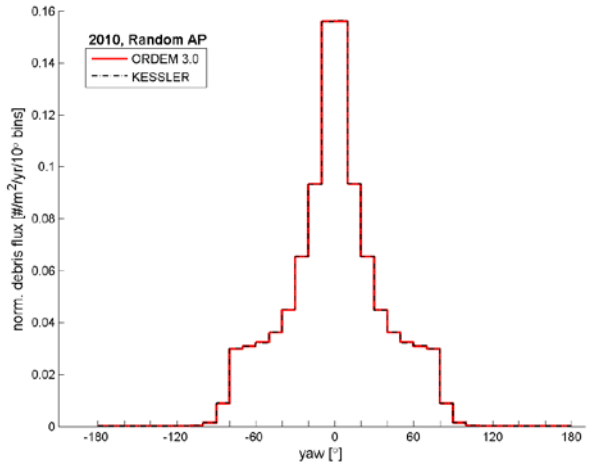

Figure C.2.5.2-1. COSMOS 2191, yaw, 2010.

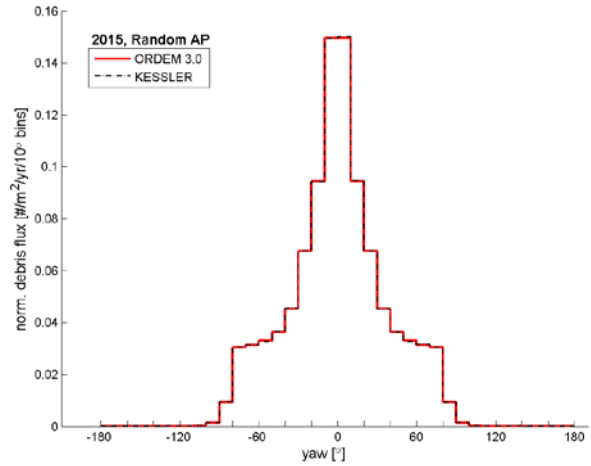

Figure C.2.5.2-2. COSMOS 2191, yaw, 2015.

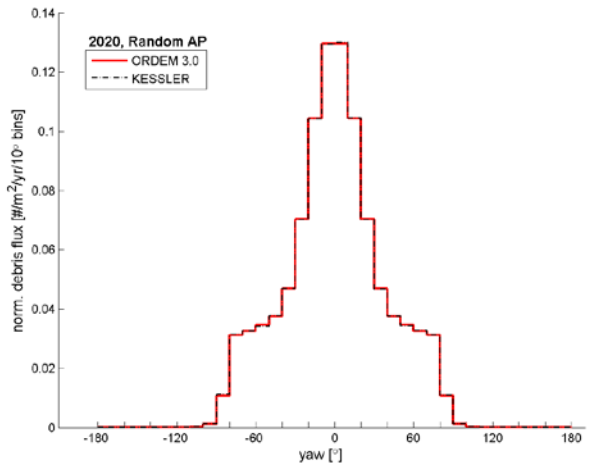

Figure C.2.5.2-3. COSMOS 2191, yaw, 2020.

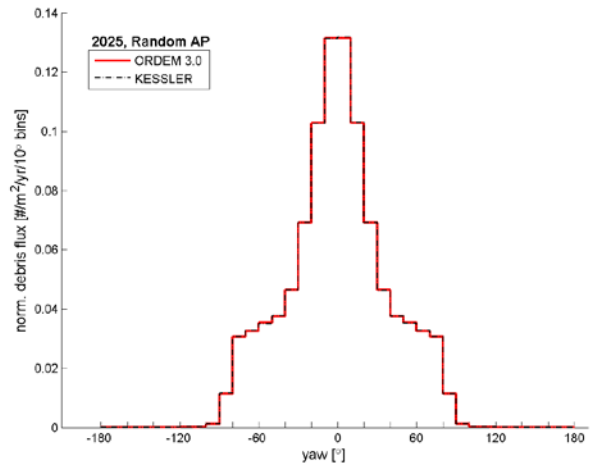

Figure C.2.5.2-4. COSMOS 2191, yaw, 2025.

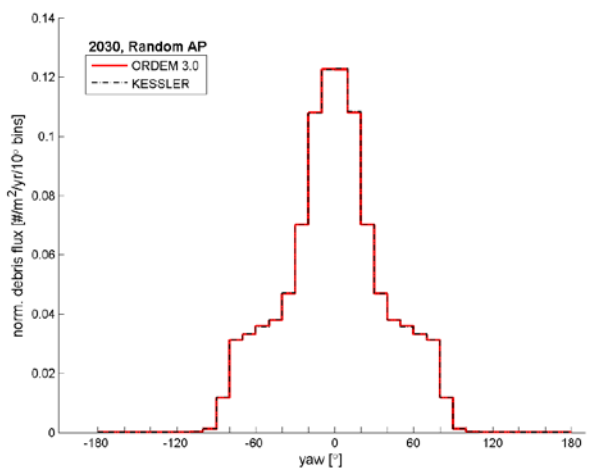

Figure C.2.5.2-5. COSMOS 2191, yaw, 2030.

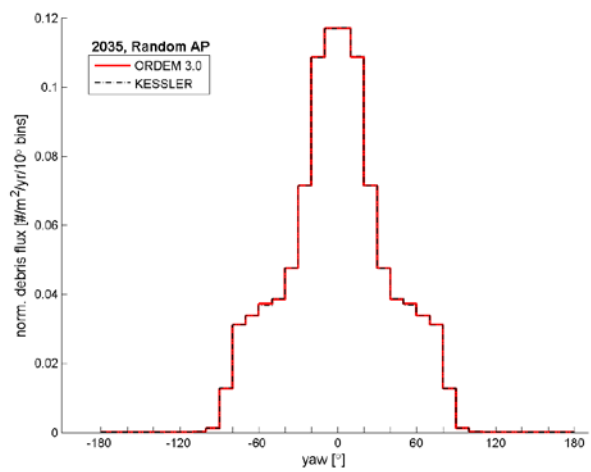

Figure C.2.5.2-6. COSMOS 2191, yaw, 2035.

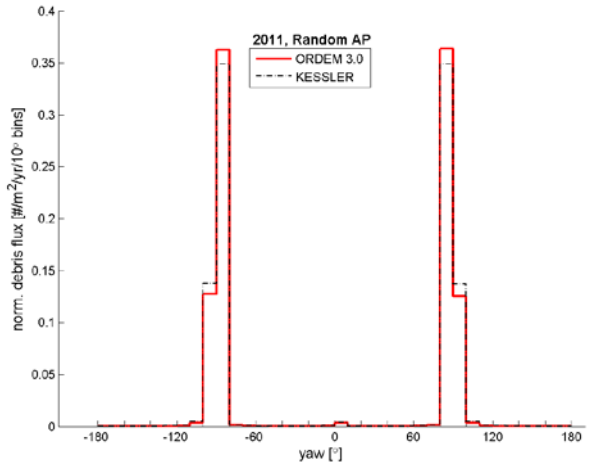

Figure C.2.5.2-7. DIRECTV 12, yaw, 2011.

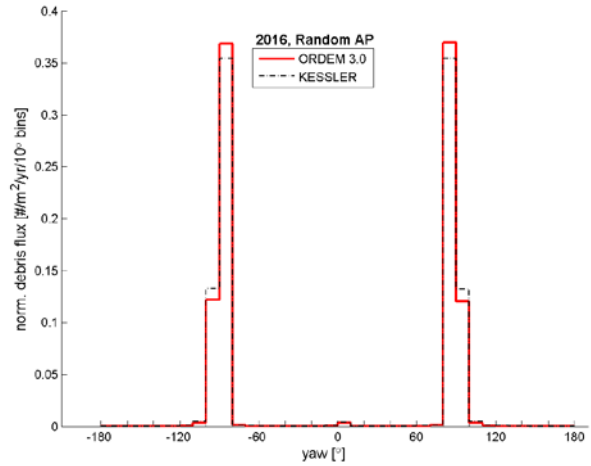

Figure C.2.5.2-8. DIRECTV 12, yaw, 2016.

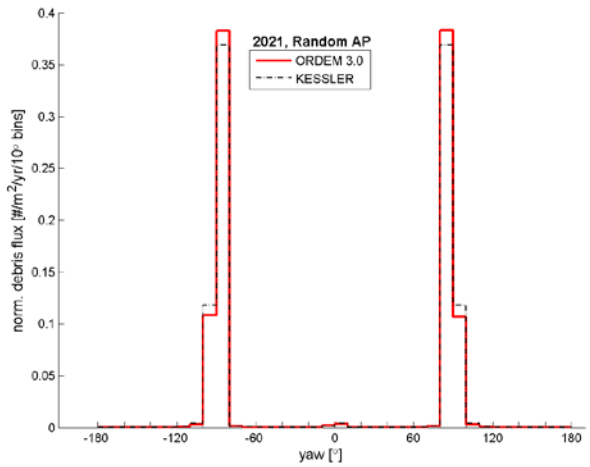

Figure C.2.5.2-9. DIRECTV 12, yaw, 2021.

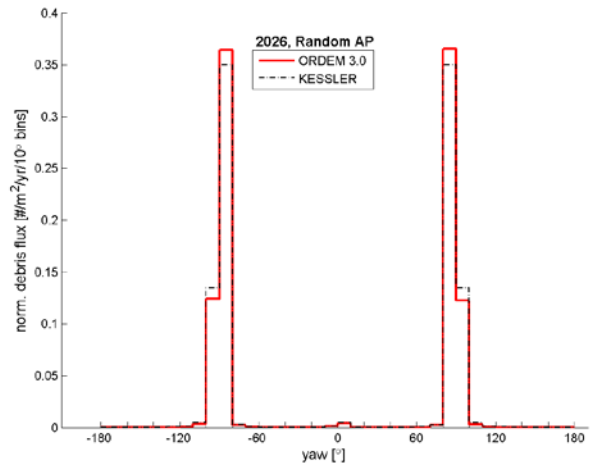

Figure C.2.5.2-10. DIRECTV 12, yaw, 2026.

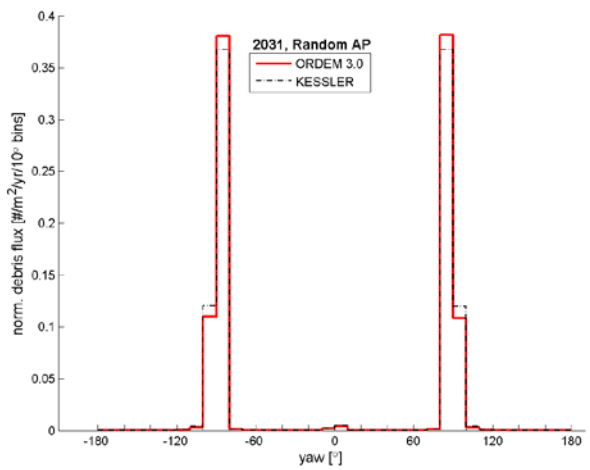

Figure C.2.5.2-11. DIRECTV 12, yaw, 2031.

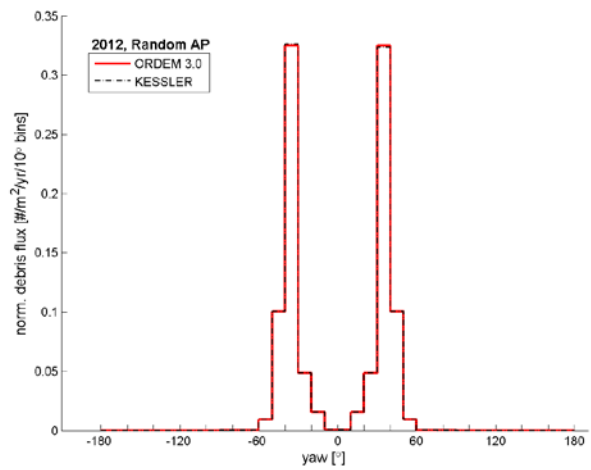

Figure C.2.5.2-12. NAVSTAR 29, yaw, 2012.

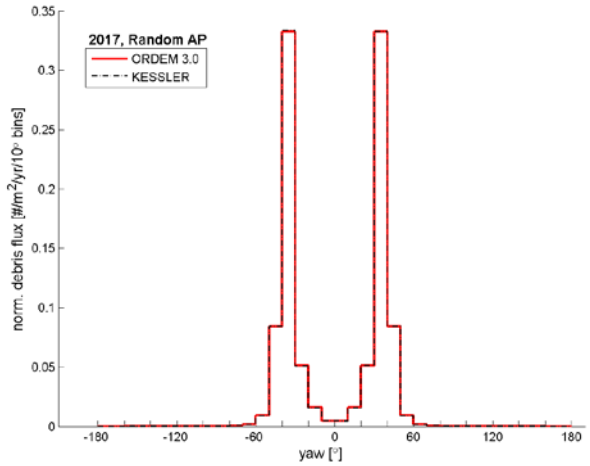

Figure C.2.5.2-13. NAVSTAR 29, yaw, 2017.

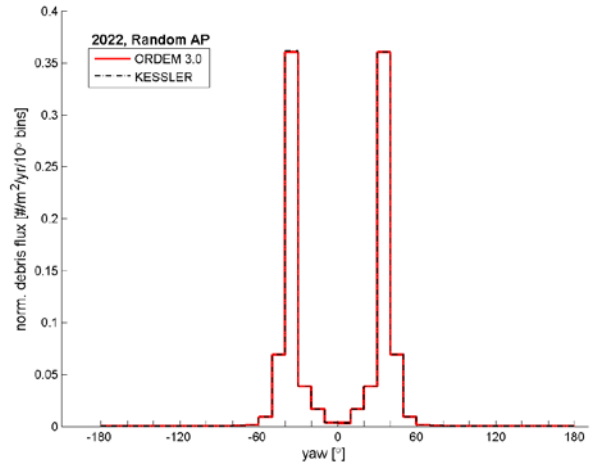

Figure C.2.5.2-14. NAVSTAR 29, yaw, 2022.

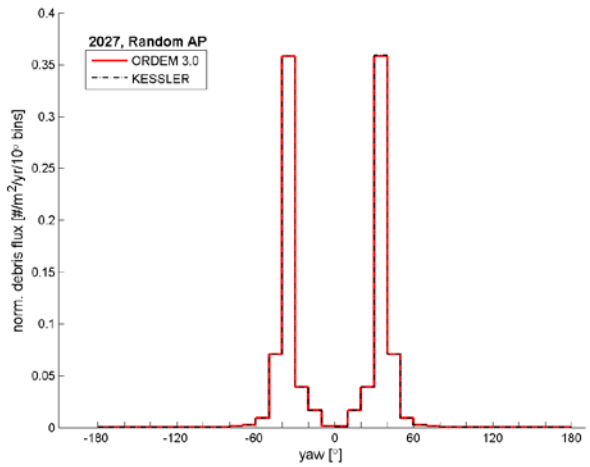

Figure C.2.5.2-15. NAVSTAR 29, yaw, 2027.

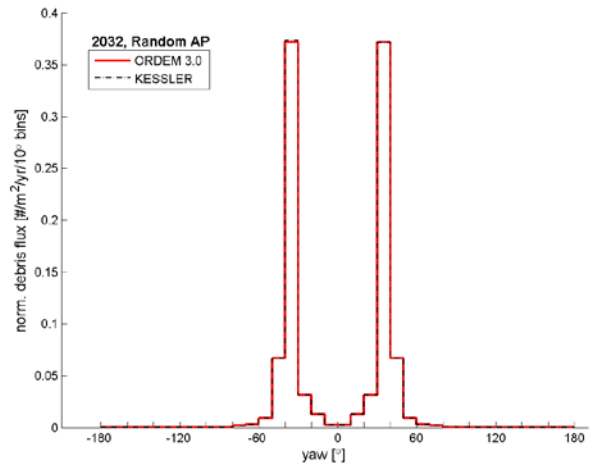

Figure C.2.5.2-16. NAVSTAR 29, yaw, 2032.

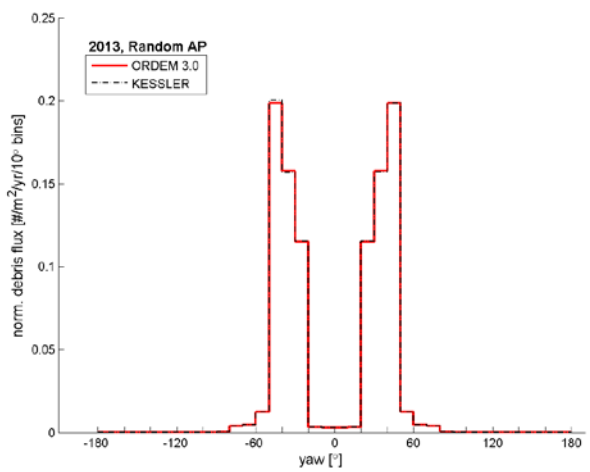

Figure C.2.5.2-17. SATCOM K1, yaw, 2013.

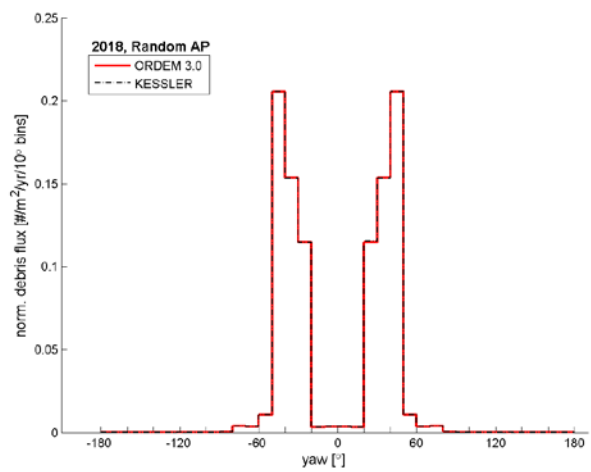

Figure C.2.5.2-18. SATCOM K1, yaw, 2018.

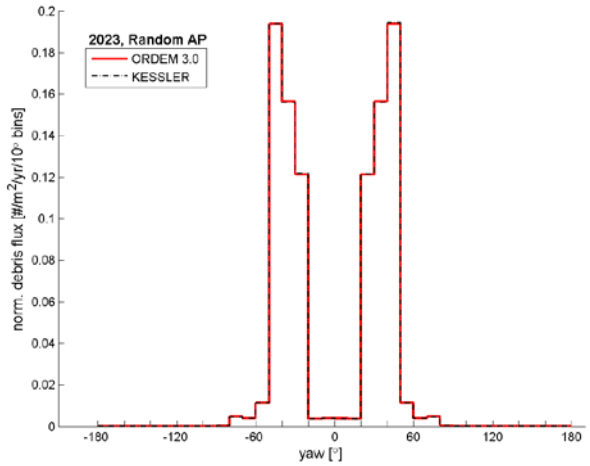

Figure C.2.5.2-19. SATCOM K1, yaw, 2023.

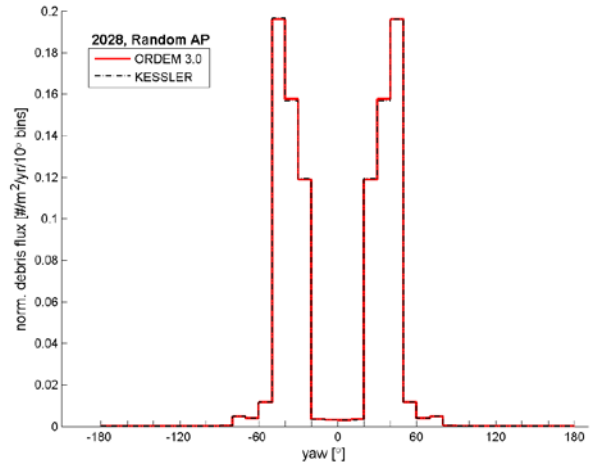

Figure C.2.5.2-20. SATCOM K1, yaw, 2028.

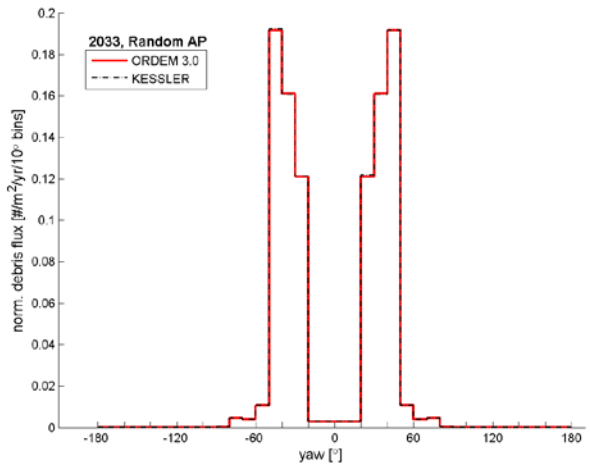

Figure C.2.5.2-21. SATCOM K1, yaw, 2033.

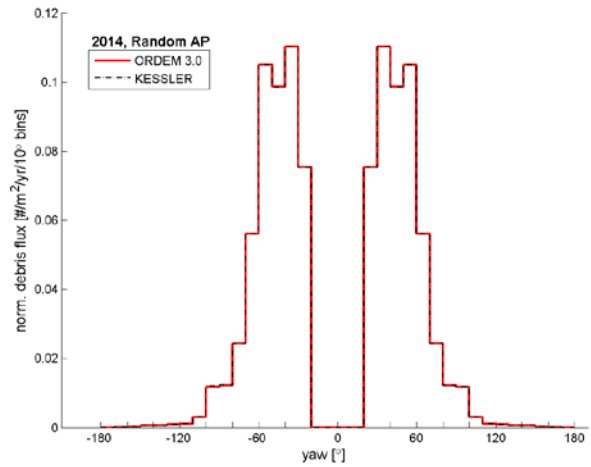

Figure C.2.5.2-22. TRMM, yaw, 2014.

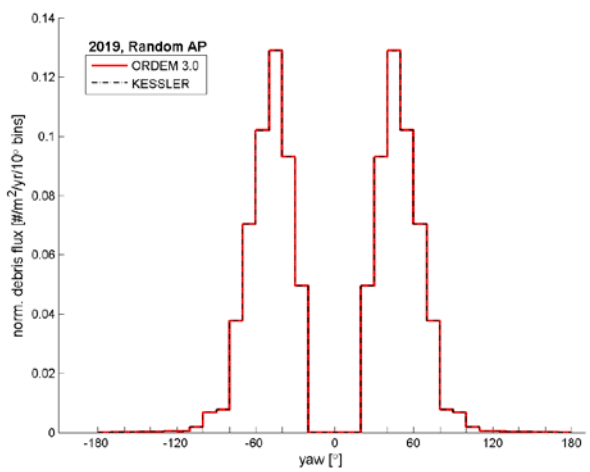

Figure C.2.5.2-23. TRMM, yaw, 2019.

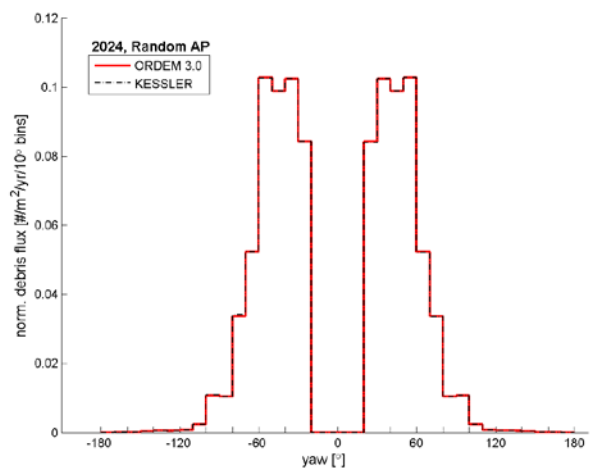

Figure C.2.5.2-24. TRMM, yaw, 2024.

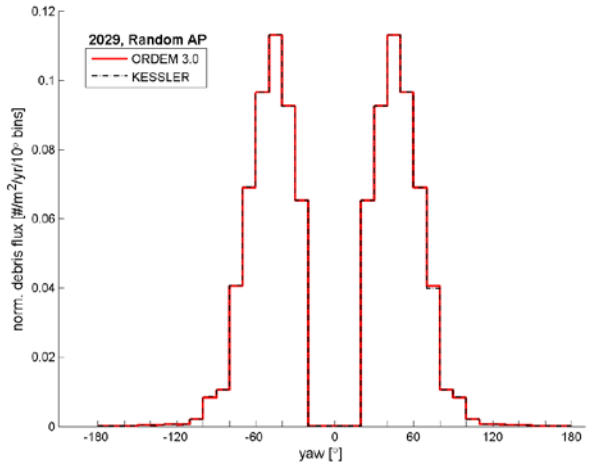

Figure C.2.5.2-25. TRMM, yaw, 2029.

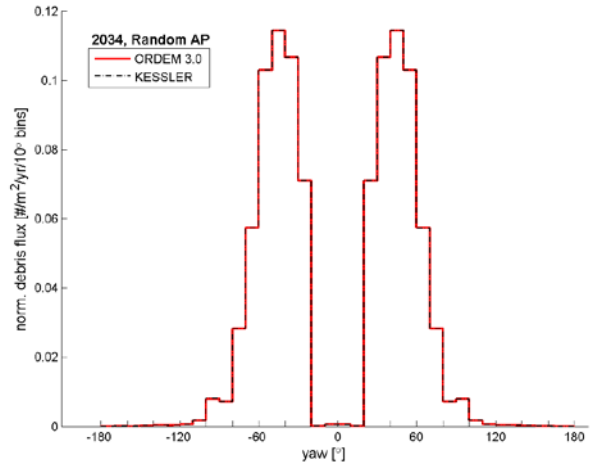

Figure C.2.5.2-26. TRMM, yaw, 2034.

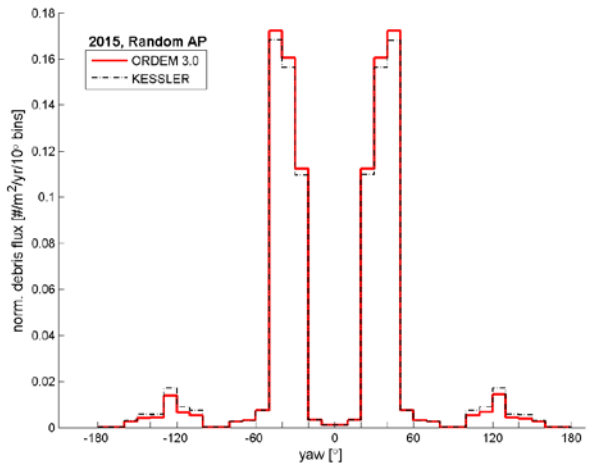

Figure C.2.5.2-27. CZ-3A DEB, yaw, 2015.

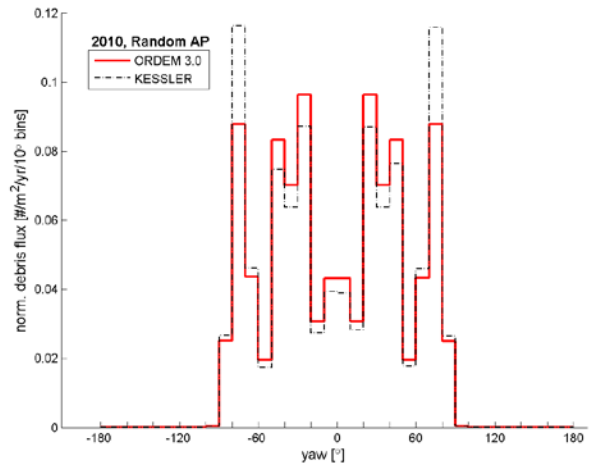

Figure C.2.5.2-28. MOLNIYA1-93, yaw, 2010.

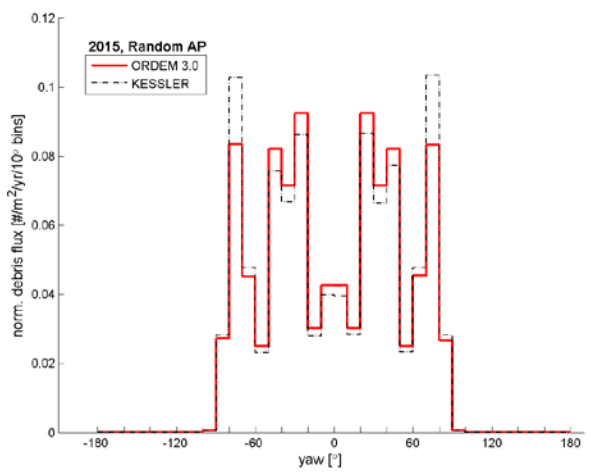

Figure C.2.5.2-29. MOLNIYA1-93, yaw, 2015.

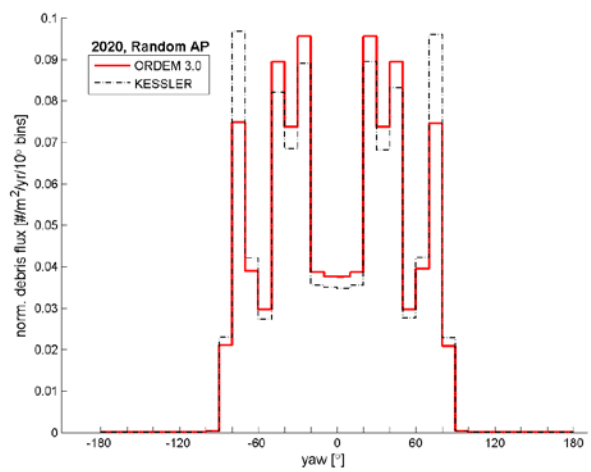

Figure C.2.5.2-30. MOLNIYA1-93, yaw, 2020.

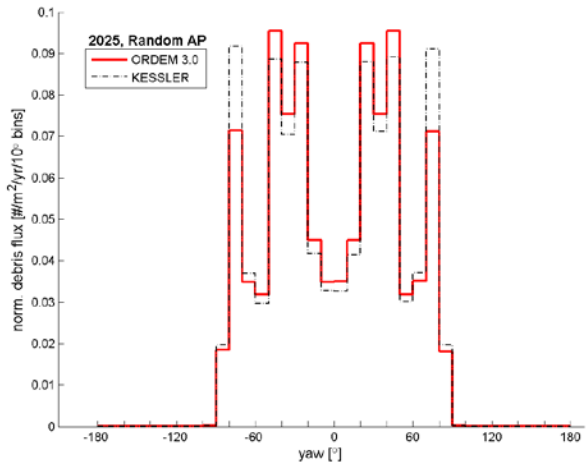

Figure C.2.5.2-31. MOLNIYA1-93, yaw, 2025.

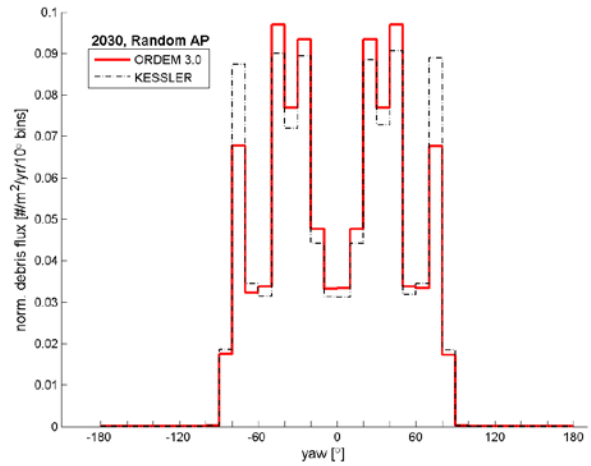

Figure C.2.5.2-32. MOLNIYA1-93, yaw, 2030.

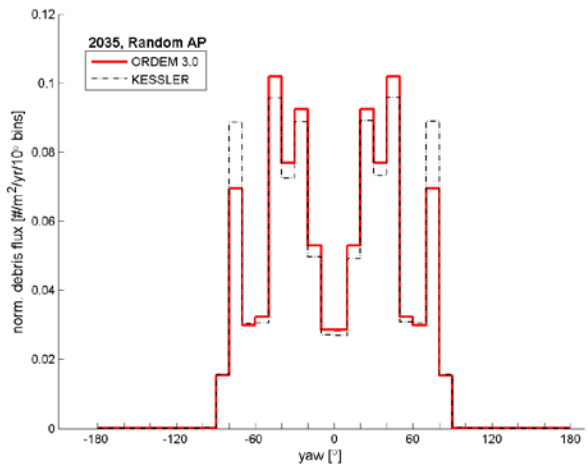

Figure C.2.5.2-33. MOLNIYA1-93, yaw, 2035.

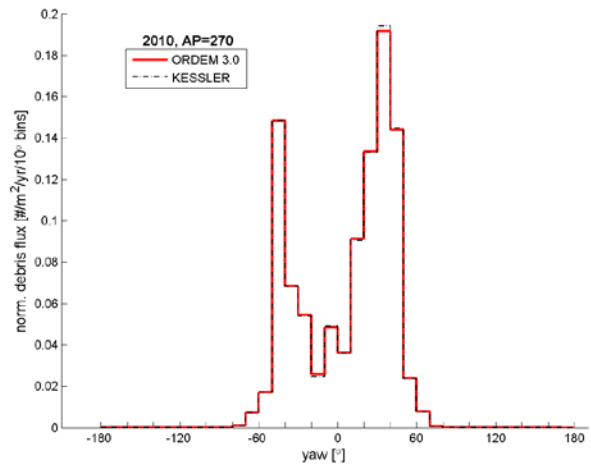

Figure C.2.5.2-34. MOLNIYA1-93, yaw, 2010, AP=270°.

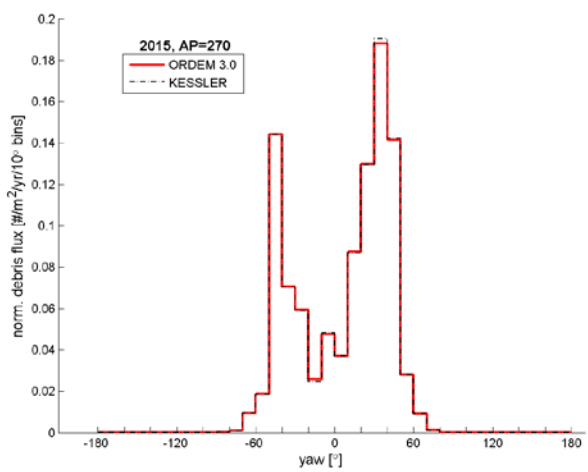

Figure C.2.5.2-35. MOLNIYA1-93, yaw, 2015, AP=270°.

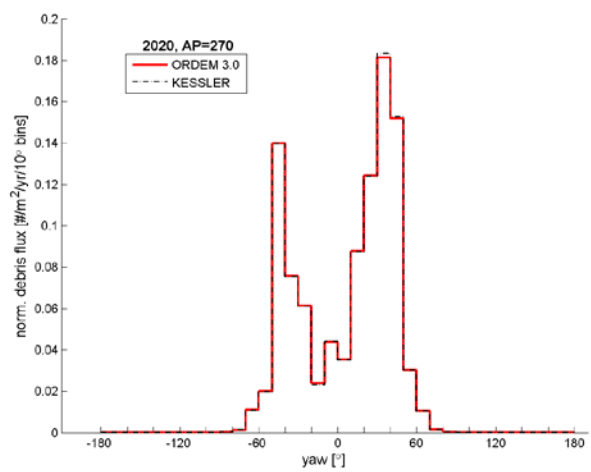

Figure C.2.5.2-36. MOLNIYA1-93, yaw, 2020, AP=270°.

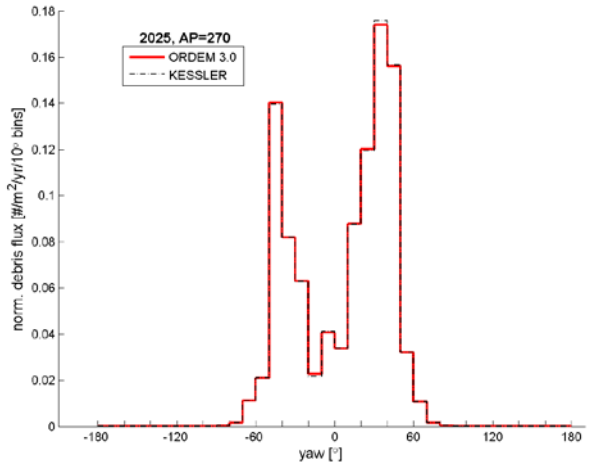

Figure C.2.5.2-37. MOLNIYA1-93, yaw, 2025, AP=270°.

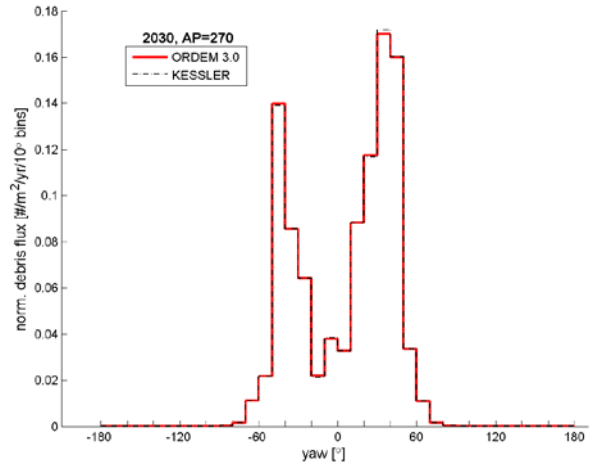

Figure C.2.5.2-38. MOLNIYA1-93, yaw, 2030, AP=270°.

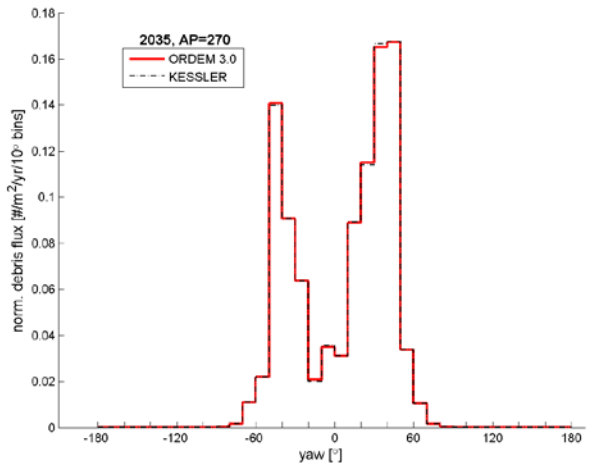

Figure C.2.5.2-39. MOLNIYA1-93, yaw, 2035, AP=270°.

2.5.3. *Flux*

Table C.2.5.3-1 shows the test satellites used in the statistical comparison of flux distributions between ORDEM 3.0 and KESSLER runs, given a random AP. The following figures in this section pair the flux distribution between ORDEM 3.0 and KESSLER runs, given a random AP. Notice that the MOLNIYA1-93 satellite has a better fit when the argument of perigee = 270°. This behavior is expected due to its uniquely oriented, fixed-AP orbit. See section 1.1 for accuracy and uncertainties during analysis verification.

Table C.2.5.3-1 shows the test objectives that were completed in this section.

TABLE C.2.5.3-1 – IGLOO_ORBIT_SC

Objective	Passed
Use test satellites, each with various years	✓
Compare MD60 flux values	✓
Compute linear correlation values (coefficient of correlation, covariance, etc.)	✓
Run comparison when AP=270° on Molniya orbit	✓
Generate figures for comparison	✓

TABLE C.2.5.3-2 – ORDEM 3.0 VS. KESSLER, RANDOM AP, FLUX

Satellite Name	Year	Std Error of Mean	Slope	Y-Int	Coef. of Corr.	Coef. of Det.	Std. Covar.	Non-Zero Pairs	Single Pairs	Zero Pairs	# Outside of P.I.	Passed
COSMOS_2191	2010	0.0798	1.00072	0.01092	0.99859	0.99719	20.0099	1227	60	12835	49	✓
COSMOS_2191	2015	0.07683	0.99628	-0.04527	0.99905	0.9981	28.43876	1522	7	12593	80	✓
COSMOS_2191	2020	0.10049	0.99908	-0.01087	0.9984	0.9968	30.96103	1555	13	12554	61	✓
COSMOS_2191	2025	0.07164	0.99656	-0.03931	0.99918	0.99836	30.13391	1596	14	12512	83	✓
COSMOS_2191	2030	0.09079	1.00356	0.04636	0.99843	0.99686	20.67997	1594	17	12511	37	✓
COSMOS_2191	2035	0.09075	1.00347	0.04521	0.9986	0.99721	27.7095	1636	14	12472	54	✓
DIRECTV_12	2011	0.18956	1.00664	0.24038	0.98909	0.9783	15.73615	816	2	13304	43	✓
DIRECTV_12	2016	0.26714	0.93124	-0.69878	0.98316	0.9666	41.38856	846	0	13276	31	✓
DIRECTV_12	2021	0.19643	1.01415	0.33888	0.98938	0.97887	14.61106	852	4	13266	48	✓
DIRECTV_12	2026	0.18887	1.02717	0.4953	0.99205	0.98417	23.1899	896	4	13222	57	✓
DIRECTV_12	2031	0.21136	1.01882	0.40386	0.99021	0.98051	21.66021	900	12	13210	50	✓
NAVSTAR_29	2012	0.05524	1.01279	0.17665	0.99941	0.99882	23.38561	506	4	13612	28	✓
NAVSTAR_29	2017	0.0868	0.9989	-0.01476	0.9988	0.9976	19.0924	926	30	13166	43	✓
NAVSTAR_29	2022	0.1029	1.00032	0.00501	0.99832	0.99664	20.37022	1118	22	12982	30	✓
NAVSTAR_29	2027	0.09804	0.99876	-0.01667	0.99846	0.99691	21.5433	1357	37	12728	53	✓
NAVSTAR_29	2032	0.06185	0.99842	-0.02438	0.99931	0.99862	18.04672	1348	22	12752	56	✓
SATCOM_K1	2013	0.08574	0.99967	-0.00618	0.99807	0.99614	16.01375	3307	27	10788	107	✓
SATCOM_K1	2018	0.10188	0.99645	-0.05153	0.99675	0.99352	9.75217	3386	11	10725	93	✓
SATCOM_K1	2023	0.10708	0.99217	-0.10786	0.99665	0.99332	11.54981	3369	24	10729	98	✓
SATCOM_K1	2028	0.11756	0.9838	-0.2166	0.99617	0.99236	14.53716	3380	14	10728	77	✓
SATCOM_K1	2033	0.07981	0.9954	-0.06339	0.99814	0.99629	10.80151	3392	12	10718	96	✓
TRMM	2014	0.03182	0.99663	-0.03886	0.99974	0.99949	11.81665	718	4	13400	34	✓
TRMM	2019	0.04574	0.99586	-0.04789	0.99959	0.99917	19.61225	804	18	13300	33	✓
TRMM	2024	0.08346	1.00438	0.04949	0.99863	0.99726	18.63434	882	6	13234	24	✓
TRMM	2029	0.04972	0.99448	-0.06377	0.99948	0.99895	16.49782	978	19	13125	24	✓
TRMM	2034	0.04079	0.99248	-0.08531	0.99964	0.99928	17.37266	792	10	13320	24	✓
CZ-3A DEB	2015	0.10238	0.99636	-0.04514	0.99717	0.99434	12.04300	3243	18	10861	111	✓
MOLNIYA1-93	2010	0.09573	0.99390	-0.08539	0.99770	0.99540	11.14195	3056	52	11014	111	✓
MOLNIYA1-93	2015	0.10810	0.99208	-0.10990	0.99762	0.99524	21.73700	3250	42	10830	102	✓
MOLNIYA1-93	2020	0.10714	1.00046	0.00631	0.99758	0.99516	19.81719	3283	39	10800	75	✓
MOLNIYA1-93	2025	0.08902	0.99108	-0.12212	0.99824	0.99648	14.82882	3472	43	10607	104	✓
MOLNIYA1-93	2030	0.08435	0.99964	-0.00438	0.99847	0.99694	15.37636	3505	61	10556	119	✓
MOLNIYA1-93	2035	0.08580	1.00120	0.01634	0.99836	0.99671	14.23585	3548	31	10543	115	✓
fixed AP (É =270°)												
MOLNIYA1-93	2010	0.10948	0.99746	-0.03665	0.99706	0.99413	12.81479	2477	55	11590	85	✓
MOLNIYA1-93	2015	0.12257	0.99627	-0.05368	0.996	0.99201	10.86079	2749	39	11334	57	✓
MOLNIYA1-93	2020	0.0813	0.99996	-0.00247	0.99828	0.99657	11.73781	2887	29	11206	96	✓
MOLNIYA1-93	2025	0.07942	0.99623	-0.0532	0.99838	0.99676	11.35469	3009	33	11080	104	✓
MOLNIYA1-93	2030	0.06768	0.99857	-0.01933	0.999	0.998	15.19524	3113	25	10984	121	✓
MOLNIYA1-93	2035	0.06099	0.99857	-0.02083	0.99916	0.99833	15.03378	3193	27	10902	97	✓

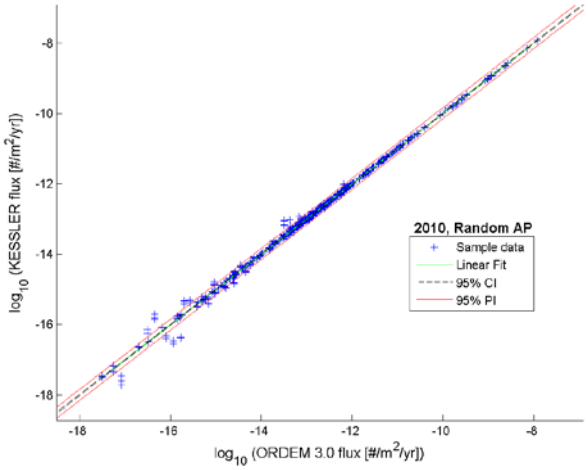

Figure C.2.5.3-1. COSMOS 2191, flux, 2010.

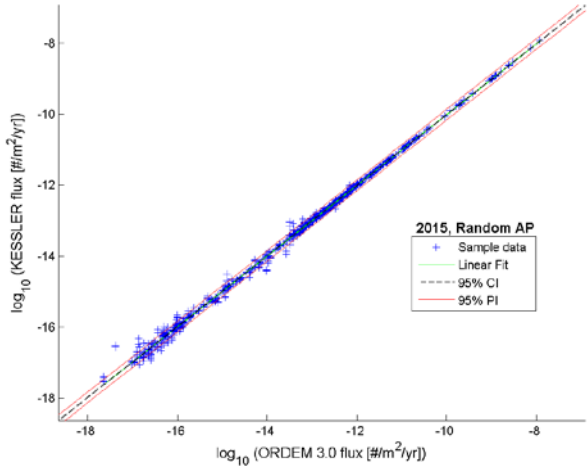

Figure C.2.5.3-2. COSMOS 2191, flux, 2015.

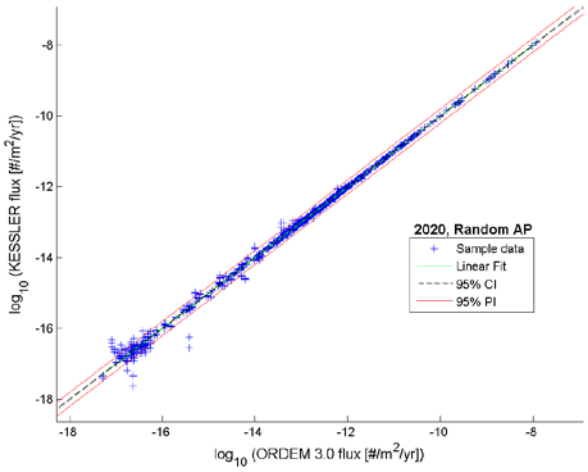

Figure C.2.5.3-3. COSMOS 2191, flux, 2020.

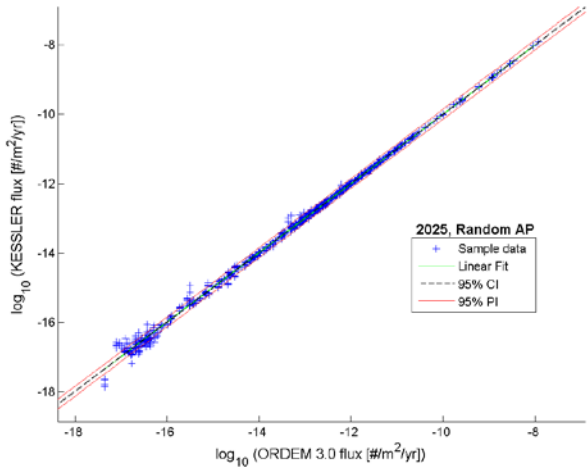

Figure C.2.5.3-4. COSMOS 2191, flux, 2025.

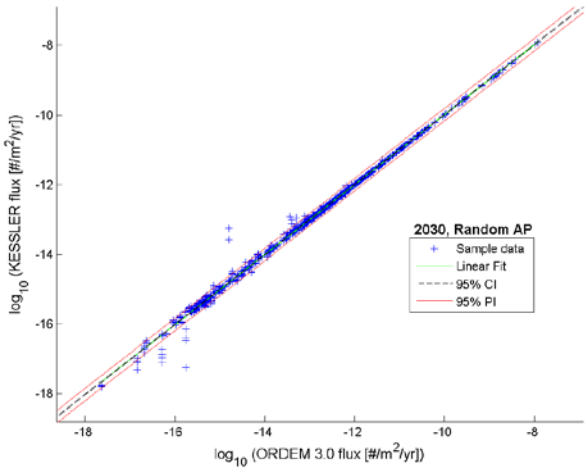

Figure C.2.5.3-5. COSMOS 2191, flux, 2030.

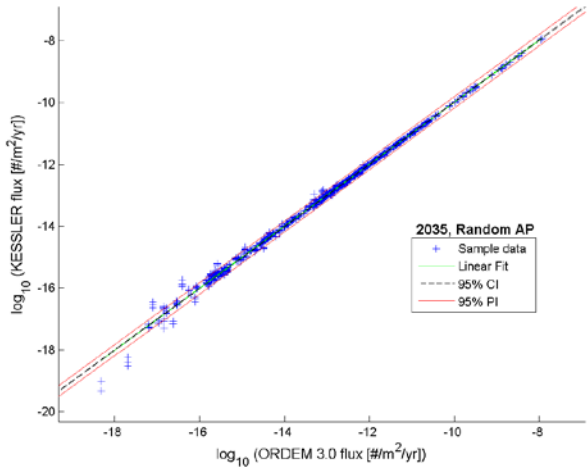

Figure C.2.5.3-6. COSMOS 2191, flux, 2035.

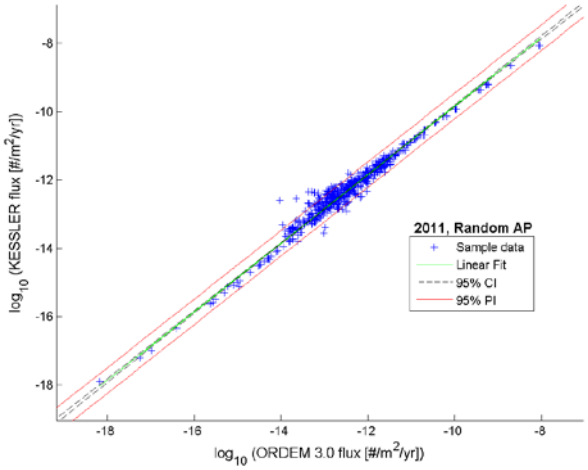

Figure C.2.5.3-7. DIRECTV 12, flux, 2011.

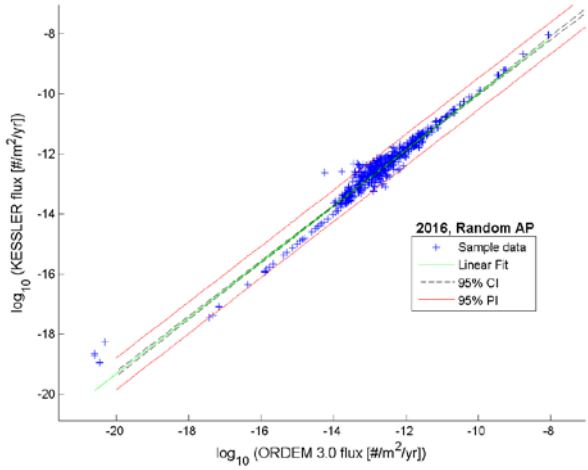

Figure C.2.5.3-8. DIRECTV 12, flux, 2016.

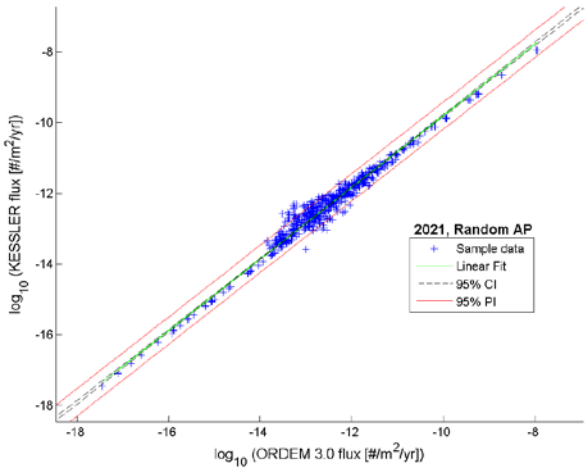

Figure C.2.5.3-9. DIRECTV 12, flux, 2021.

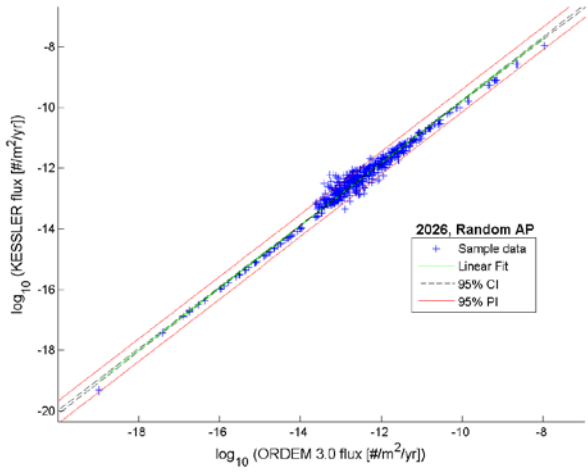

Figure C.2.5.3-10. DIRECTV 12, flux, 2026.

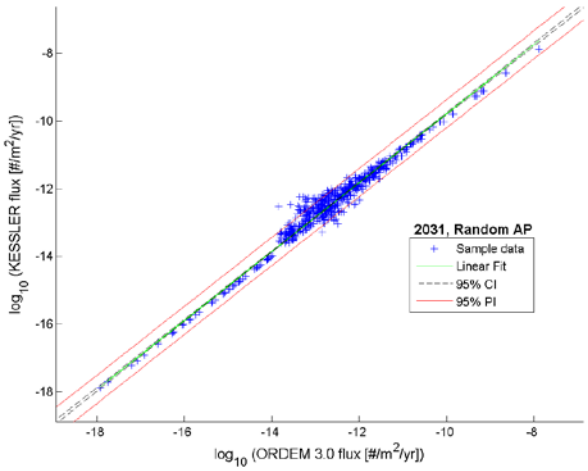

Figure C.2.5.3-11. DIRECTV 12, flux, 2031.

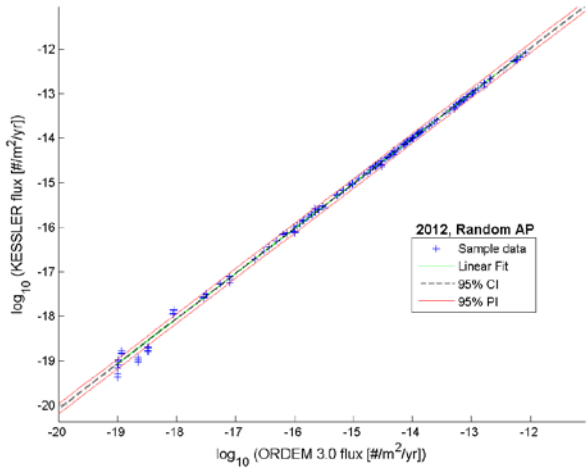

Figure C.2.5.3-12. NAVSTAR 29, flux, 2012.

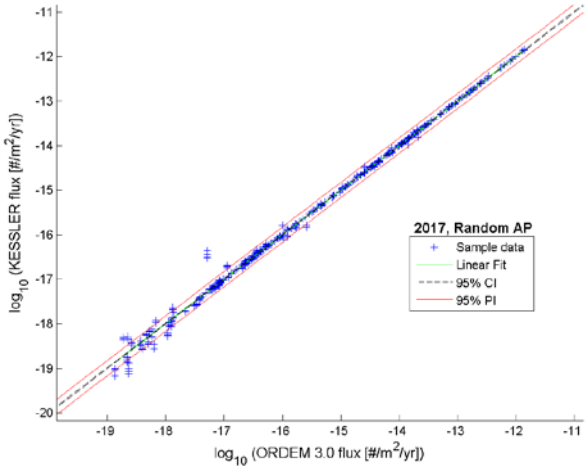

Figure C.2.5.3-13. NAVSTAR 29, flux, 2017.

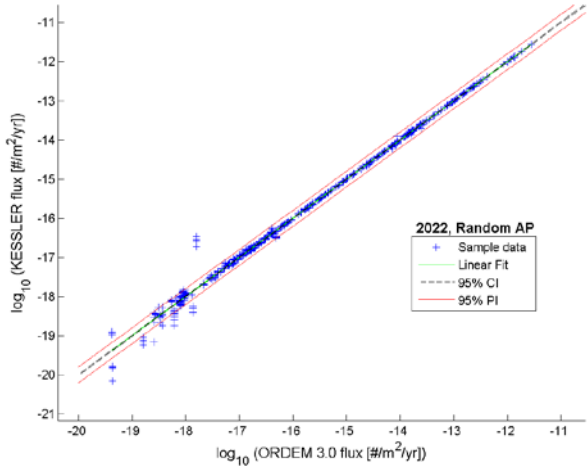

Figure C.2.5.3-14. NAVSTAR 29, flux, 2022.

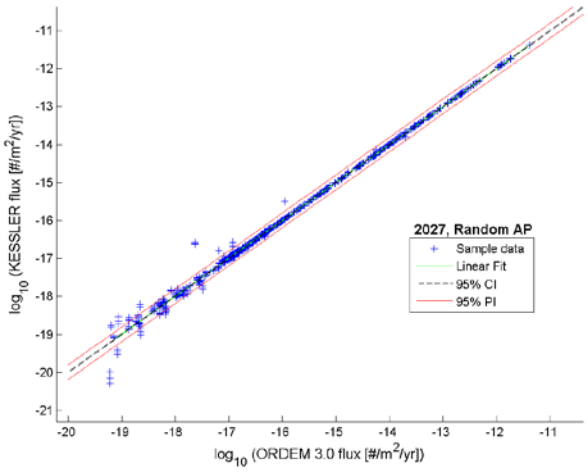

Figure C.2.5.3-15. NAVSTAR 29, flux, 2027.

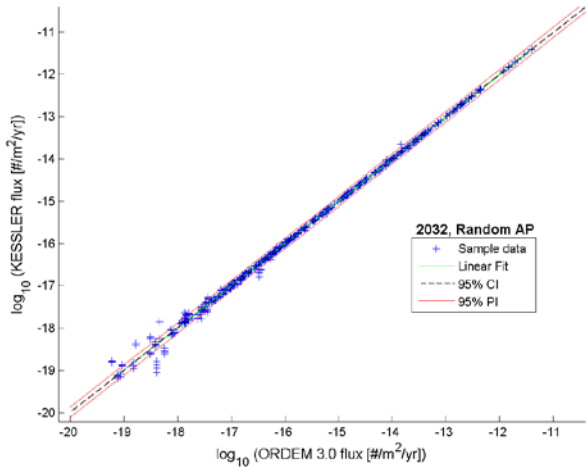

Figure C.2.5.3-16. NAVSTAR 29, flux, 2032.

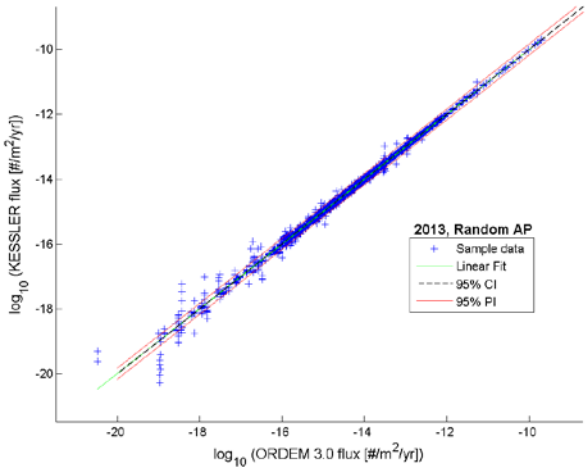

Figure C.2.5.3-17. SATCOM K1, flux, 2013.

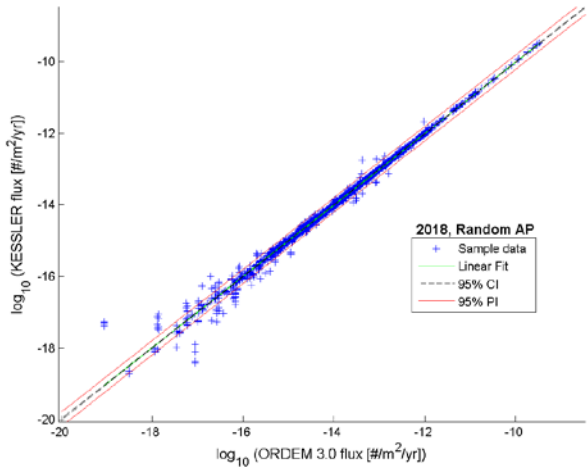

Figure C.2.5.3-18. SATCOM K1, flux, 2018.

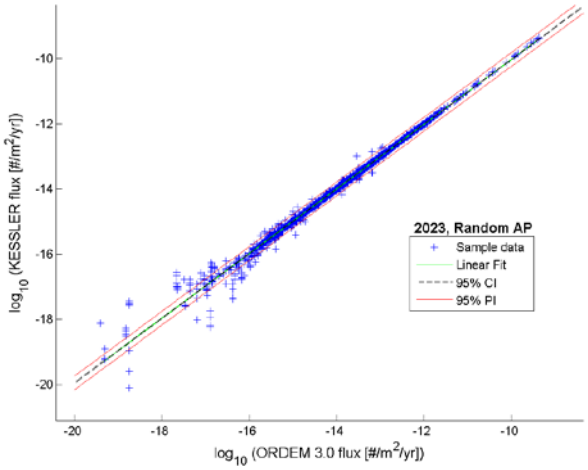

Figure C.2.5.3-19. SATCOM K1, flux, 2023.

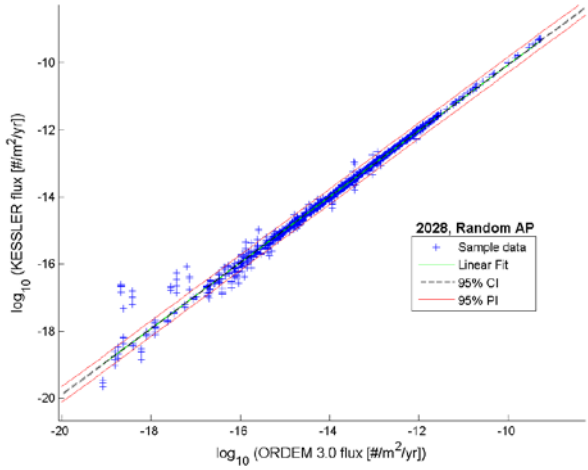

Figure C.2.5.3-20. SATCOM K1, flux, 2028.

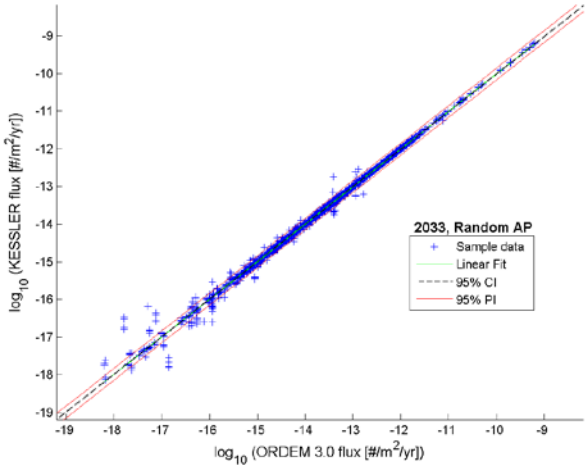

Figure C.2.5.3-21. SATCOM K1, flux, 2033.

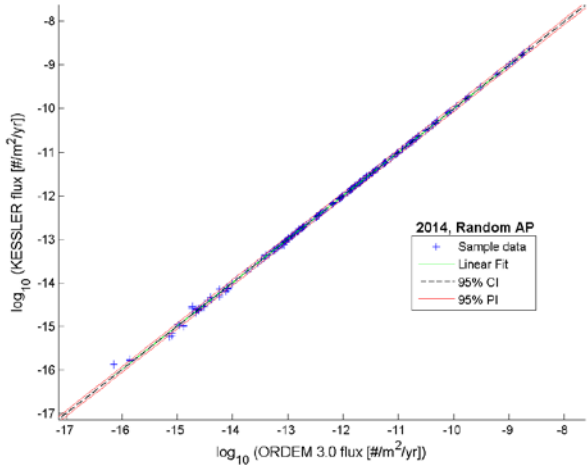

Figure C.2.5.3-22. TRMM, flux, 2014.

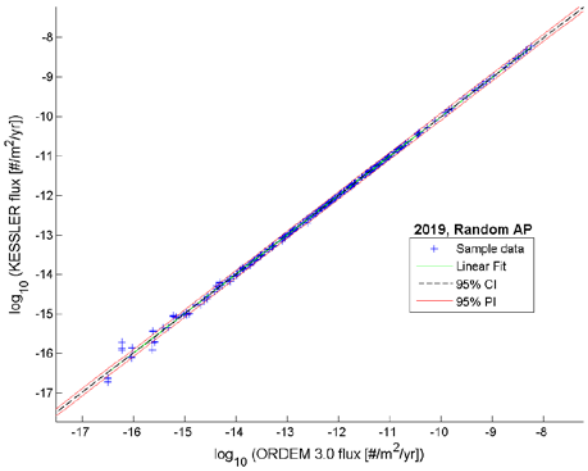

Figure C.2.5.3-23. TRMM, flux, 2019.

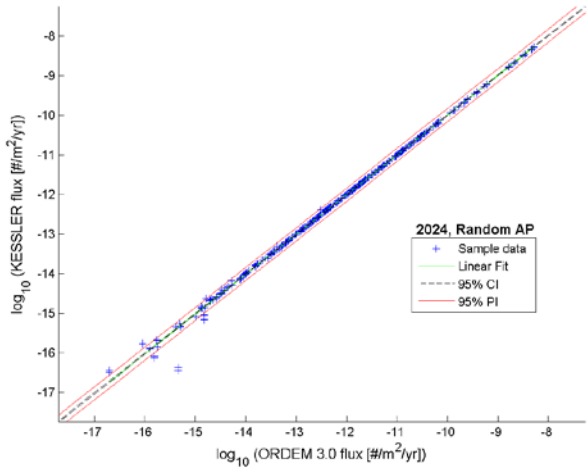

Figure C.2.5.3-24. TRMM, flux, 2024.

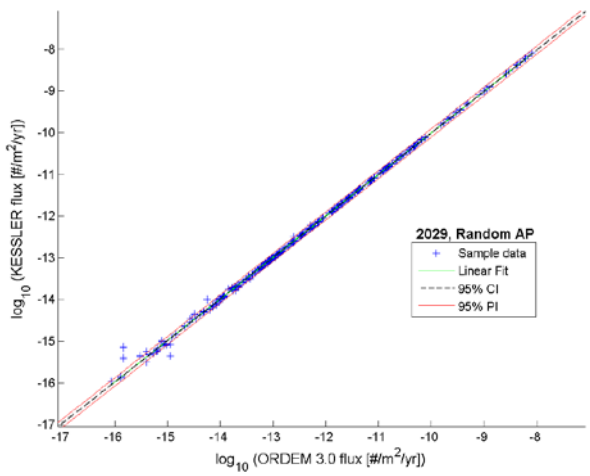

Figure C.2.5.3-25. TRMM, flux, 2029.

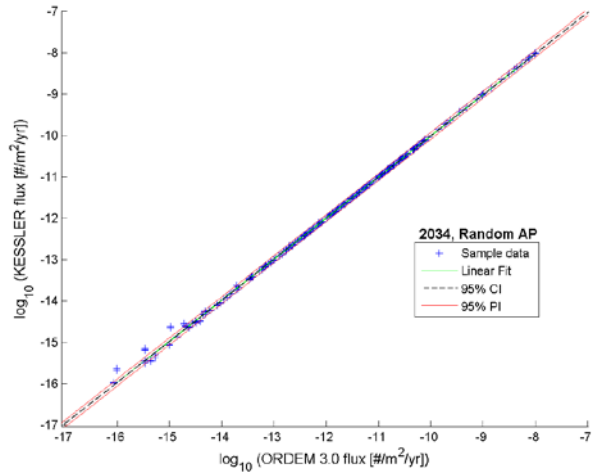

Figure C.2.5.3-26. TRMM, flux, 2034.

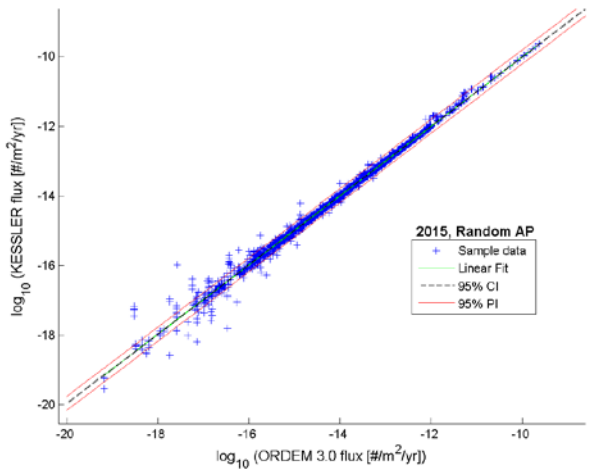

Figure C.2.5.3-27. CZ-3A DEB, flux, 2015.

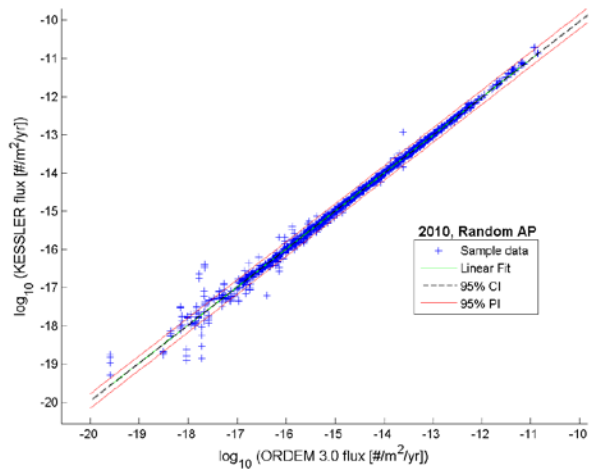

Figure C.2.5.3-28. MOLNIYA1-93, flux, 2010.

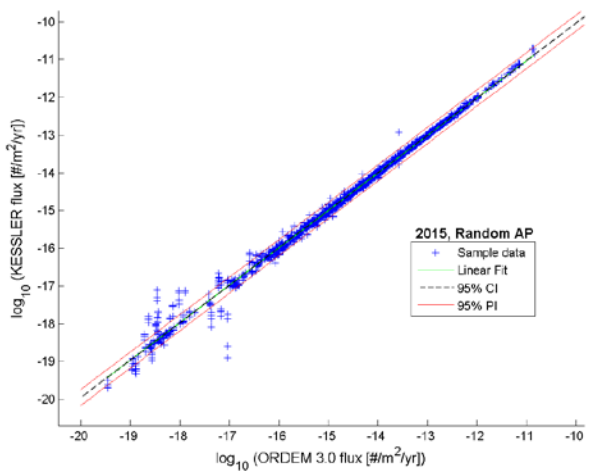

Figure C.2.5.3-29. MOLNIYA1-93, flux, 2015.

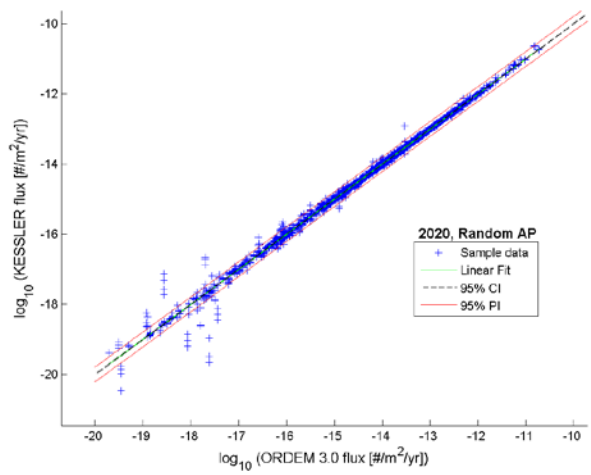

Figure C.2.5.3-30. MOLNIYA1-93, flux, 2020.

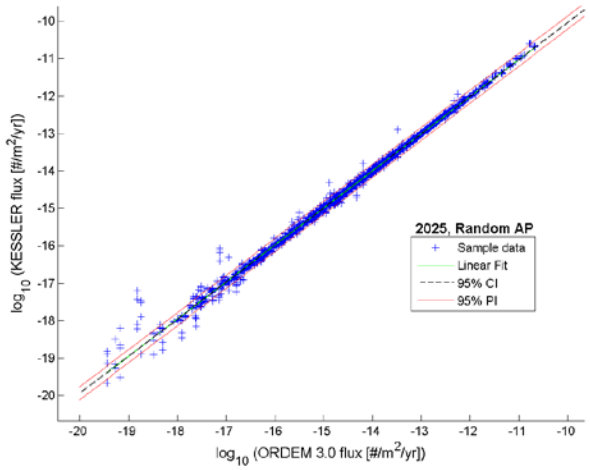

Figure C.2.5.3-31. MOLNIYA1-93, flux, 2025.

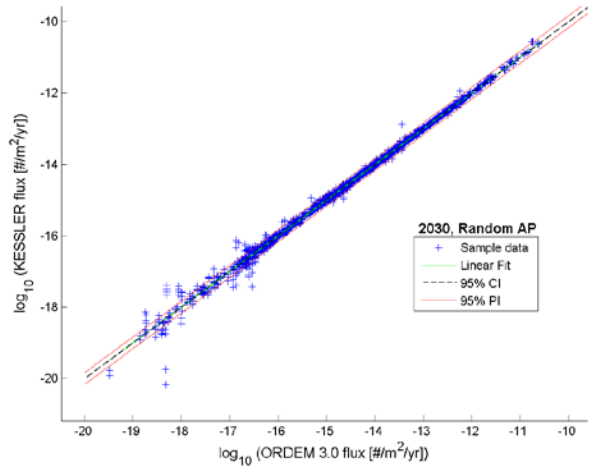

Figure C.2.5.3-32. MOLNIYA1-93, flux, 2030.

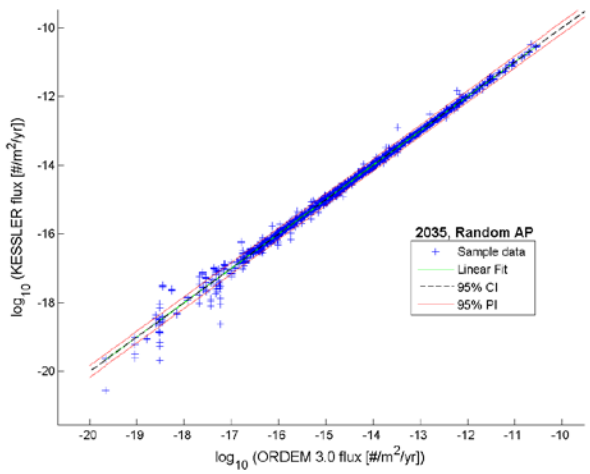

Figure C.2.5.3-33. MOLNIYA1-93, flux, 2035.

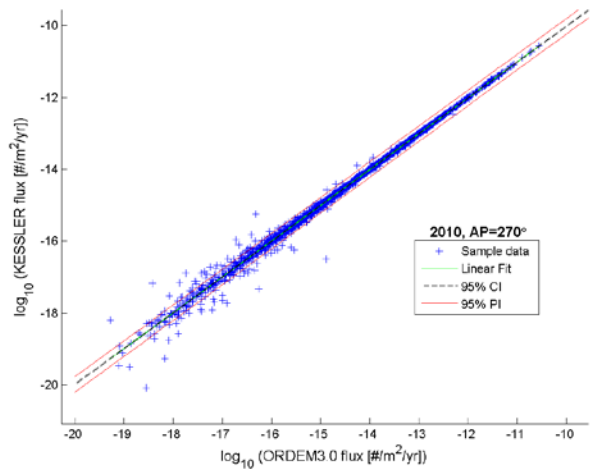

Figure C.2.5.3-34. MOLNIYA1-93, flux, 2010, AP=270°.

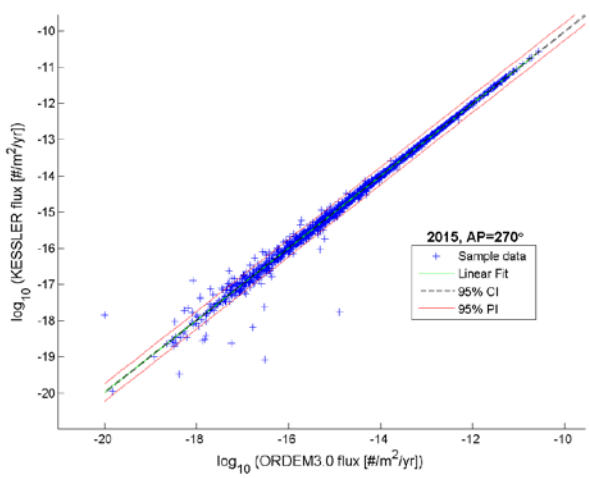

Figure C.2.5.3-35. MOLNIYA1-93, flux, 2015, AP=270°.

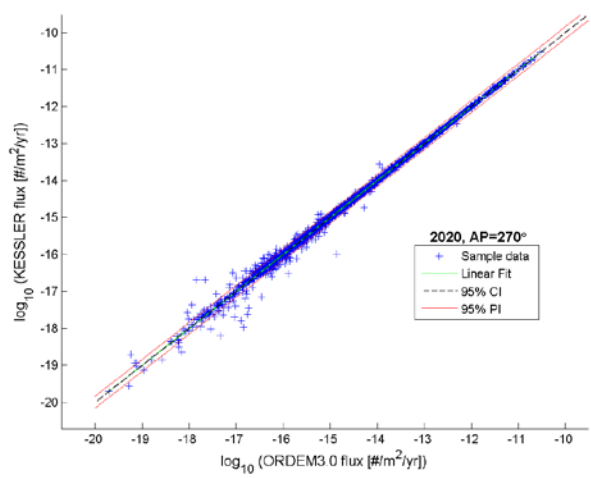

Figure C.2.5.3-36. MOLNIYA1-93, flux, 2020, AP=270°.

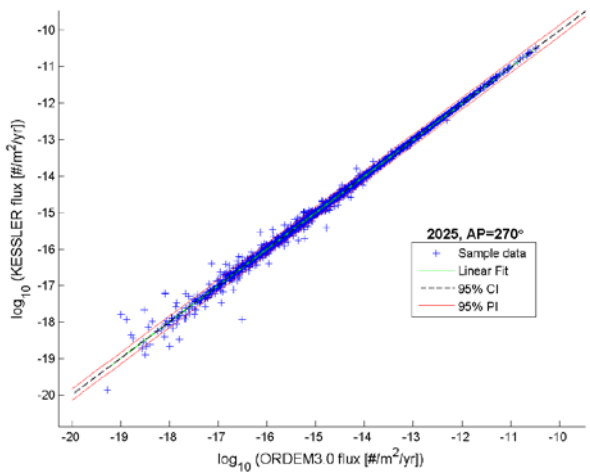

Figure C.2.5.3-37. MOLNIYA1-93, flux, 2025, AP=270°.

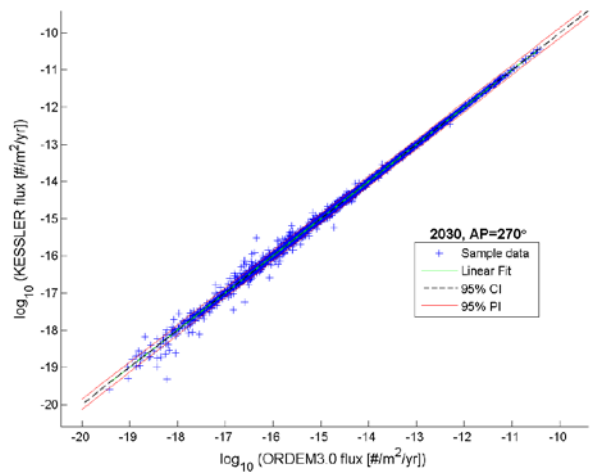

Figure C.2.5.3-38. MOLNIYA1-93, flux, 2030, AP=270°.

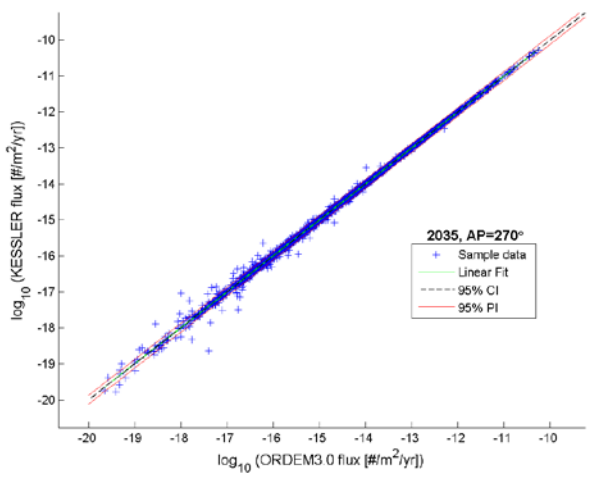

Figure C.2.5.3-39. MOLNIYA1-93, flux, 2035, AP=270°.

3.0 Telescope Mode Verification

This section outlines the verification steps taken to ensure the output of the ORDEM 3.0 is valid in telescope mode.

3.1. SETUP

As shown in Table C.3.1-1, there was one test that was run to verify ORDEM 3.0 output in telescope mode.

TABLE C.3.1-1 – SUMMARY OF TEL MODE TESTS

Section	Test Name	Size	Chart Type
3.2	ORDEM 3.0 vs KESSLER	MD60	Altitude, linear correlation of flux

Table C.3.1-2 describes the sensors that were used during the analysis verification of the telescope mode. Note that these sensors are spread out through four radar/beam orientations. Table C.3.1-3 shows the yearly output files that were used in the analysis.

TABLE C.3.1-2 – SENSORS USED IN ANALYSIS VERIFICATION, TEL MODE

Sensor Abbrev.	Sensor	Latitude [°]	Beampark azimuth [°]	Beampark elevation [°]	Starting Year
HAY75E	Haystack radar	42.6	90	75	2010
HAY10S	Haystack radar	42.6	180	10	2011
EQUAT	Generic equatorial sensor	0	0	90	2012
ASCENSION	Meter-Class Autonomous Telescope	-7	0	80	2013

TABLE C.3.1-3 – SENSOR TELESCOPES USED IN VERIFICATION, GIVEN YEARS

Sensor Name	Years
HAY75E	2010, 2014, 2018, 2022, 2026
HAY10S	2011, 2015, 2019, 2023, 2027
EQUAT	2012, 2016, 2020, 2024, 2028
ASCENSION	2013, 2017, 2021, 2025, 2029

3.2. ORDEM 3.0 VS. KESSLER

This analysis requires a comparison of two data sets – ORDEM 3.0 and KESSLER – in telescope mode. Each data set consists of output files for each test sensor, given the test sensor's year (see Tables C.3.1-2 and C.3.1-3).

The altitude distribution was chosen for this comparison analysis. The altitude was calculated by reading in the *alt_low* and *alt_high* columns stored in the IGLOOFLUX_TEL.OUT output file. For the KESSLER runs, the appropriate columns in the output files of LEO_KESSLER_TELE and GEO_KESSLER_TELE programs were averaged and the result was used in this comparison. A Ç^2 test was used to compare the binned altitude distributions between ORDEM 3.0 and KESSLER.

An additional comparison was made between the actual flux values (Flux MD60) produced by ORDEM 3.0 and KESSLER to ensure a close match for a fixed elevation. The results of this comparison are in section 3.2.2.

Table C.3.2-1 shows the test objectives that were completed in this section.

TABLE C.3.2-1 – TELESCOPE/RADAR MODE χ^2 TEST

Objective	Passed
Use test sensors, each with various years	✓
χ^2 test between binned distributions, ORDEM 3.0 and KESSLER	✓
Demonstrate symmetry between two models	✓
Generate figures for comparison	✓

3.2.1. *Altitude*

Table C.3.2.1-1 shows the test sensors used in the statistical comparison of altitude distributions between ORDEM 3.0 and KESSLER runs.

The following figures in this section pair the altitude distribution between ORDEM 3.0 and KESSLER runs. Note that the majority of the debris flux is stored in the first bin (*i.e.*, LEO). In order to better represent the correlation between ORDEM 3.0 and KESSLER, the x-axis (altitude [km]) is shown on a log scale. Info was added to each figure to show the start and end points of the LEO domain (200 km-2000 km).

TABLE C.3.2.1-1 – ORDEM 3.0 VS. KESSLER, ALTITUDE

Sat No.	Satellite Name	Year	χ^2 parameter	Passed
1	ASCENSION	2013	1.54E-05	✓
1	ASCENSION	2017	1.45E-05	✓
1	ASCENSION	2021	1.32E-05	✓
1	ASCENSION	2025	1.41E-05	✓
1	ASCENSION	2029	1.38E-05	✓
2	EQUAT	2012	1.71E-05	✓
2	EQUAT	2016	1.65E-05	✓
2	EQUAT	2020	1.52E-05	✓
2	EQUAT	2024	1.49E-05	✓
2	EQUAT	2028	1.47E-05	✓
3	HAY10S	2011	1.51E-05	✓
3	HAY10S	2015	1.78E-05	✓
3	HAY10S	2019	1.80E-05	✓
3	HAY10S	2023	1.28E-05	✓
3	HAY10S	2027	1.38E-05	✓
4	HAY75E	2010	2.28E-05	✓
4	HAY75E	2014	2.19E-05	✓
4	HAY75E	2018	2.43E-05	✓
4	HAY75E	2022	2.31E-05	✓
4	HAY75E	2026	2.32E-05	✓

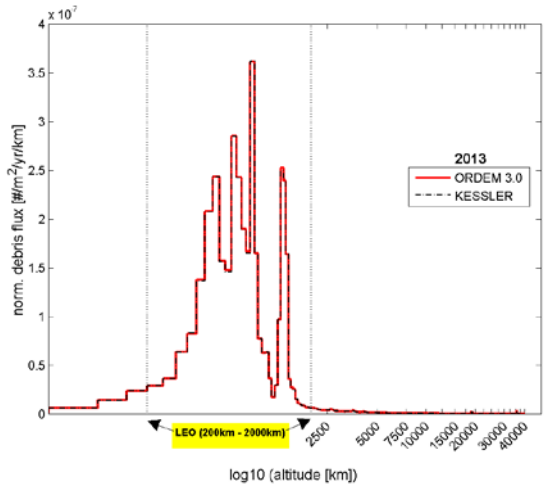

Figure C.3.2.1-1. ASCENSION, altitude, 2013.

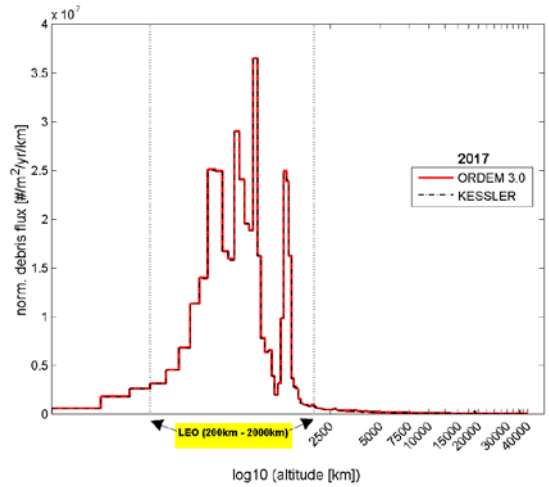

Figure C.3.2.1-2. ASCENSION, altitude, 2017.

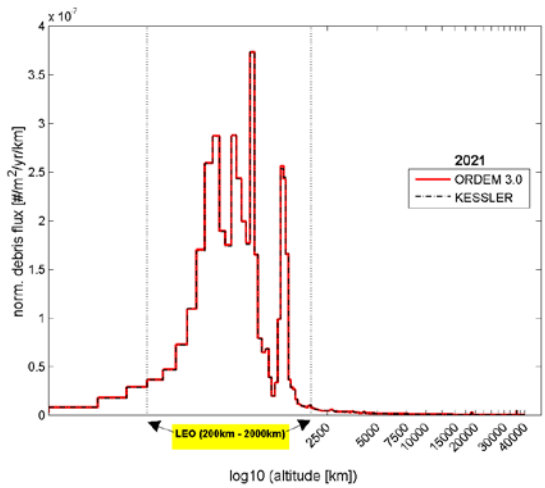

Figure C.3.2.1-3. ASCENSION, altitude, 2021.

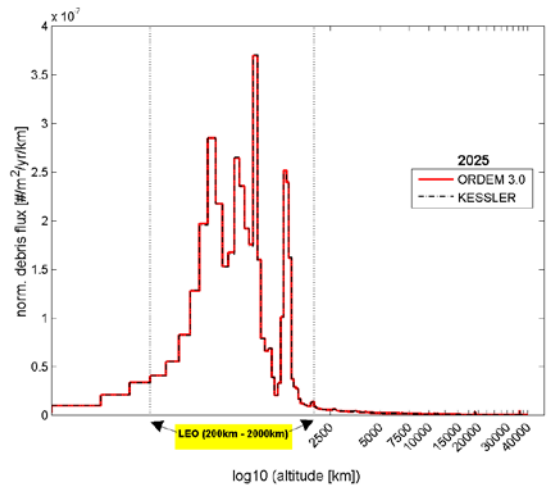

Figure C.3.2.1-4. ASCENSION, altitude, 2025

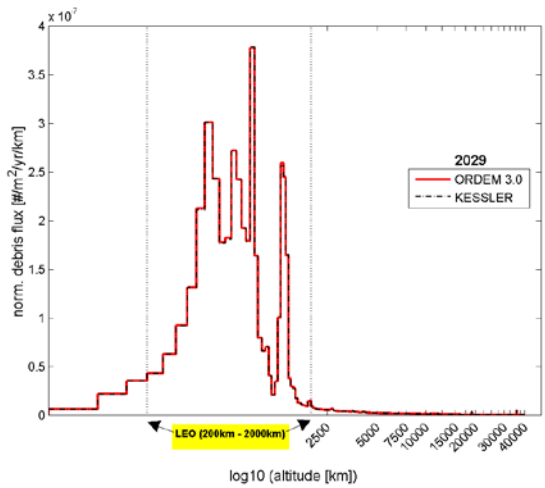

Figure C.3.2.1-5. ASCENSION, altitude, 2029.

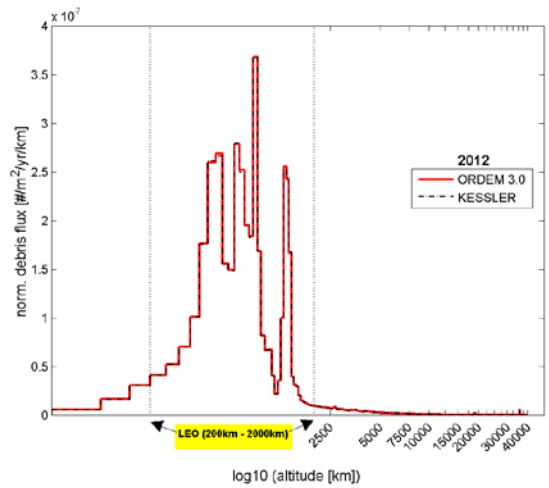

Figure C.3.2.1-6. EQUAT, altitude, 2012.

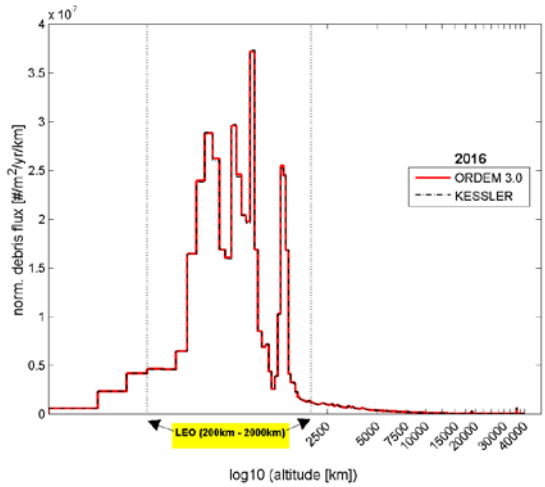

Figure C.3.2.1-7. EQUAT, altitude, 2016.

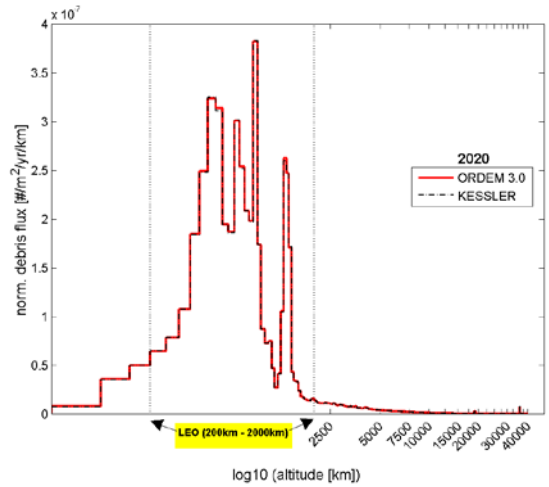

Figure C.3.2.1-8. EQUAT, altitude, 2020.

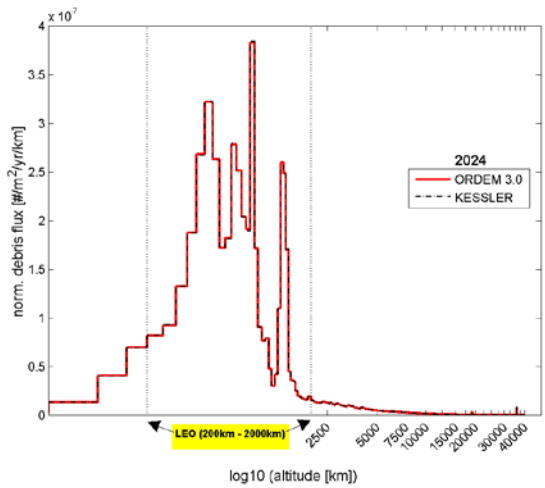

Figure C.3.2.1-9. EQUAT, altitude, 2024.

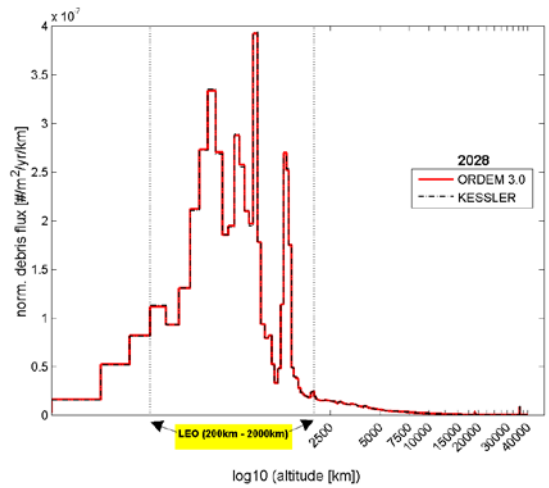

Figure C.3.2.1-10. EQUAT, altitude, 2028.

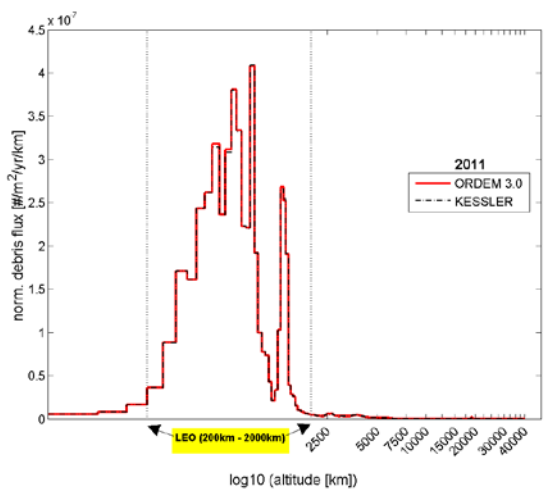

Figure C.3.2.1-11. HAY10S, altitude, 2011.

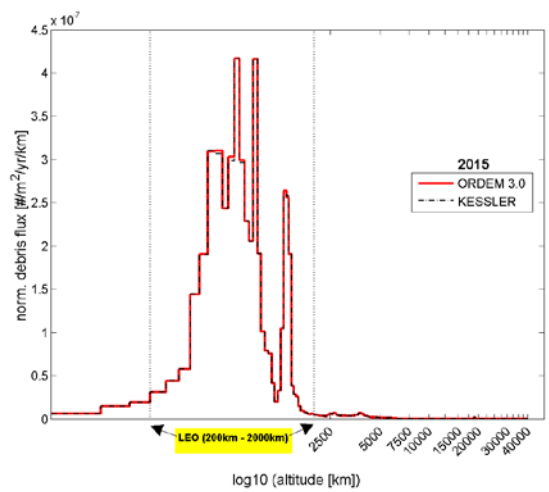

Figure C.3.2.1-12. HAY10S, altitude, 2015.

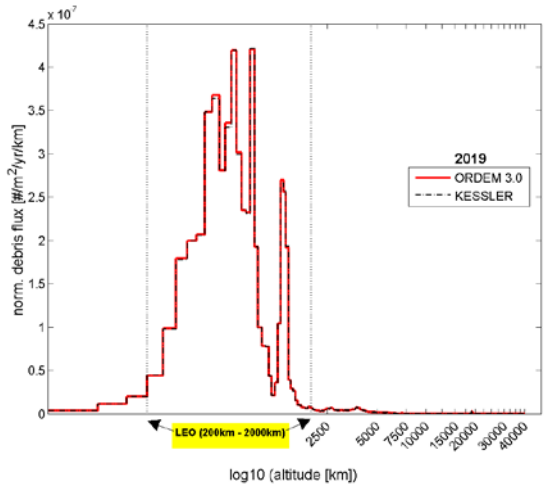

Figure C.3.2.1-13. HAY10S, altitude, 2019.

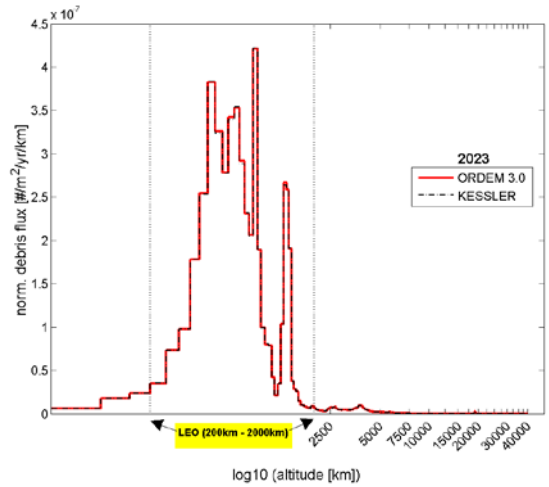

Figure C.3.2.1-14. HAY10S, altitude, 2023.

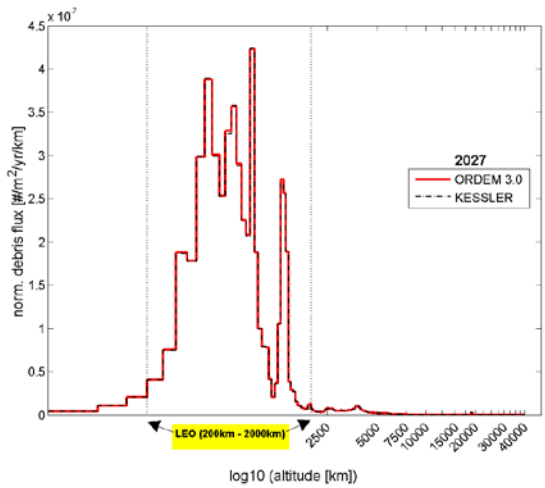

Figure C.3.2.1-15. HAY10S, altitude, 2027.

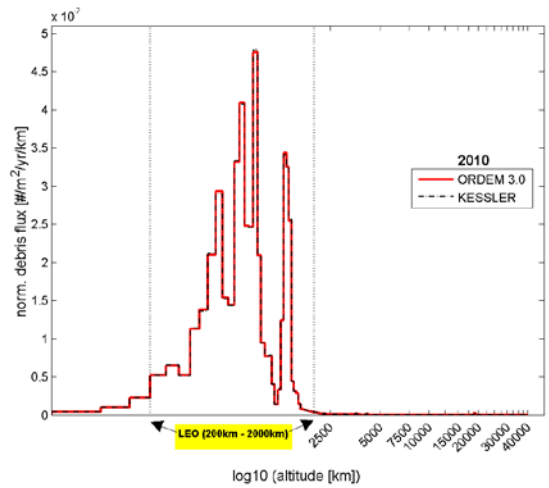

Figure C.3.2.1-16. HAY75E, altitude, 2010.

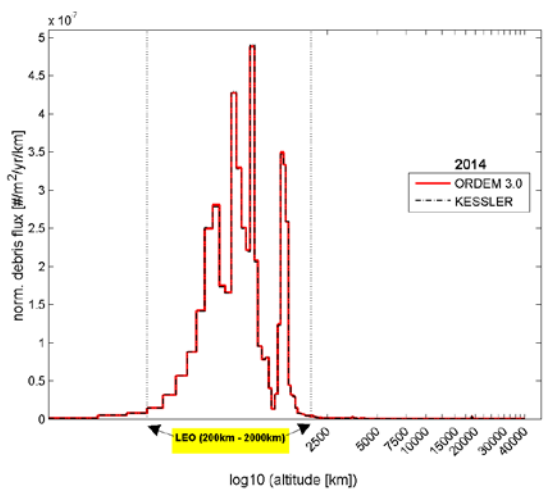

Figure C.3.2.1-17. HAY75E, altitude, 2014.

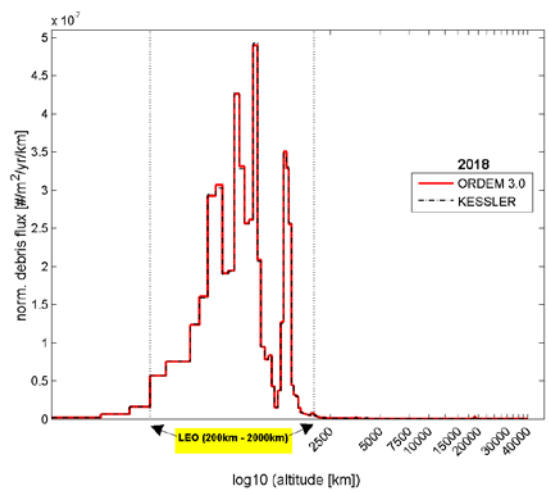

Figure C.3.2.1-18. HAY75E, altitude, 2018.

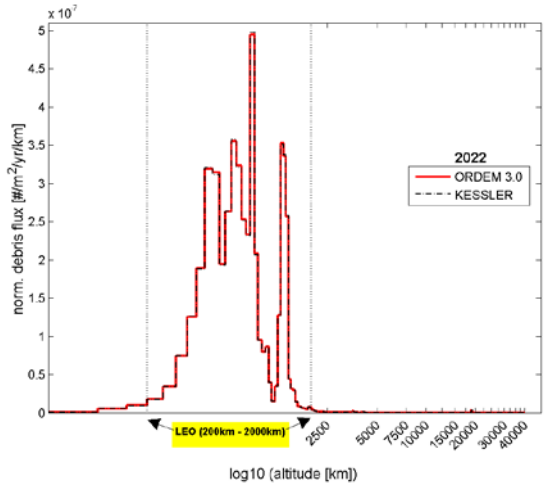

Figure C.3.2.1-19. HAY75E, altitude, 2022.

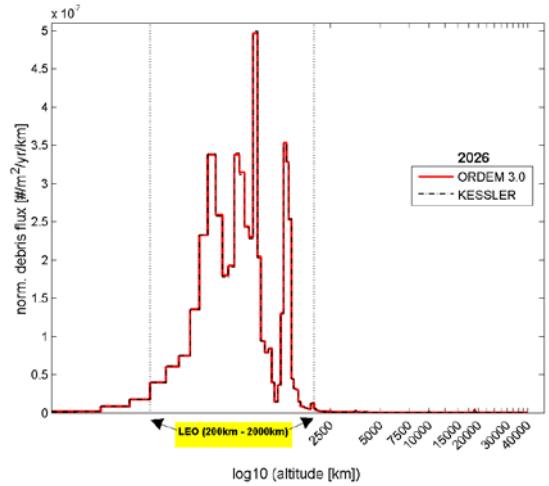

Figure C.3.2.1-20. HAY75E, altitude, 2026.

3.2.2. *Flux*

Table C.3.2.2-1 shows the test objectives that were completed in this section. Table C.3.2.2-2 shows the results of the statistical comparison of flux distributions between ORDEM 3.0 and KESSLER runs using test sensors from section 3.1.

The following figures in this section pair the flux distribution between ORDEM 3.0 and KESSLER runs.

TABLE C.3.2.2-1 – TELESCOPE_MODE

Objective	Passed
Use test sensors, each with various years	✓
Compare MD60 flux values	✓
Compute linear correlation values (coefficient of correlation, covariance, etc.)	✓
Generate figures for comparison	✓

TABLE C.3.2.2-2 –ORDEM 3.0 VS. KESSLER, FLUX

Satellite Name	Year	Std Error of Mean	Slope	Y-int	Coef. of Corr.	Coef. of Det.	Std. Covar.	Non-Zero Pairs	Single Pairs	Zero Pairs	# Outside of P.I.	Passed
ASCENSION	2013	0.00230	0.99999	-0.00020	1.00000	0.99999	2.15344	798	0	0	29	✓
ASCENSION	2017	0.00231	1.00007	0.00054	1.00000	0.99999	2.01212	798	0	0	39	✓
ASCENSION	2021	0.00223	1.00010	0.00085	1.00000	0.99999	1.97929	798	0	0	36	✓
ASCENSION	2025	0.00230	1.00009	0.00075	1.00000	0.99999	1.87846	798	0	0	42	✓
ASCENSION	2029	0.00231	1.00010	0.00083	1.00000	0.99999	1.89768	798	0	0	32	✓
EQUAT	2012	0.00151	0.99997	-0.00011	1.00000	1.00000	1.94323	798	0	0	33	✓
EQUAT	2016	0.00152	0.99996	-0.00024	1.00000	1.00000	1.78631	798	0	0	30	✓
EQUAT	2020	0.00151	0.99998	0.00003	1.00000	1.00000	1.77349	798	0	0	34	✓
EQUAT	2024	0.00156	1.00002	0.00045	1.00000	1.00000	1.76357	798	0	0	28	✓
EQUAT	2028	0.00154	0.99999	0.00006	1.00000	1.00000	1.75121	798	0	0	30	✓
HAY10S	2011	0.00204	1.00001	-0.00009	1.00000	1.00000	4.77733	798	0	0	31	✓
HAY10S	2015	0.00206	0.99996	-0.00065	1.00000	1.00000	4.70652	798	0	0	27	✓
HAY10S	2019	0.00206	0.99996	-0.00072	1.00000	1.00000	4.90005	798	0	0	26	✓
HAY10S	2023	0.00207	1.00001	-0.00011	1.00000	1.00000	4.90633	798	0	0	25	✓
HAY10S	2027	0.00214	0.99999	-0.00033	1.00000	1.00000	4.93240	798	0	0	26	✓
HAY75E	2010	0.00231	0.99983	-0.00207	1.00000	0.99999	5.20333	798	0	0	33	✓
HAY75E	2014	0.00231	0.99981	-0.00228	1.00000	0.99999	5.09563	798	0	0	28	✓
HAY75E	2018	0.00235	0.99975	-0.00290	1.00000	0.99999	5.29295	798	0	0	31	✓
HAY75E	2022	0.00234	0.99980	-0.00239	1.00000	0.99999	5.23945	798	0	0	30	✓
HAY75E	2026	0.00263	0.99982	-0.00215	1.00000	0.99999	5.21496	798	0	0	28	✓

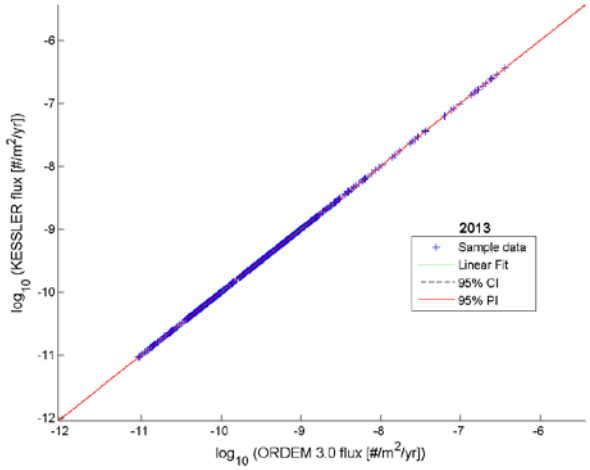

Figure C.3.2.2-1 . ASCENSION, flux, 2013.

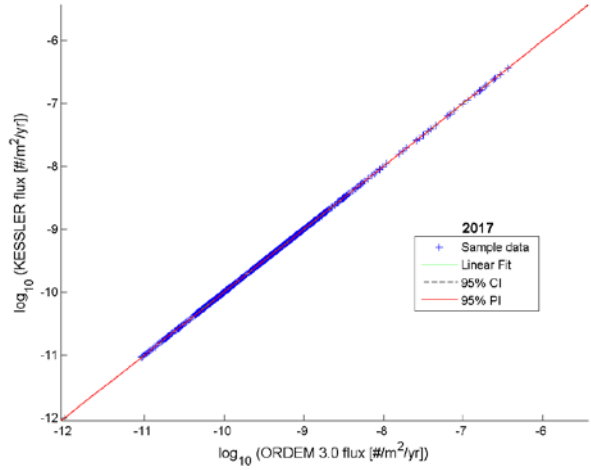

Figure C.3.2.2-2. ASCENSION, flux, 2017.

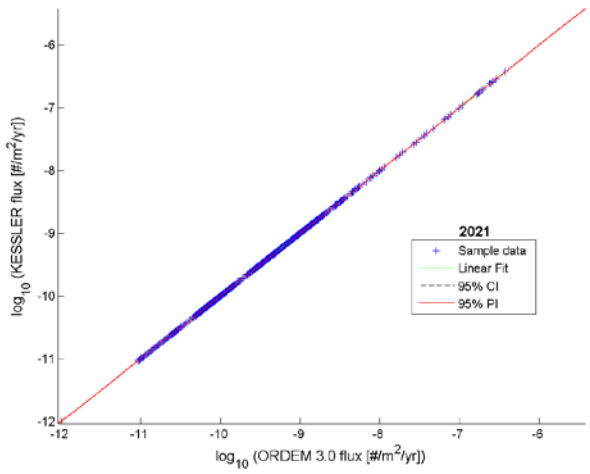

Figure C.3.2.2-3. ASCENSION, flux, 2021.

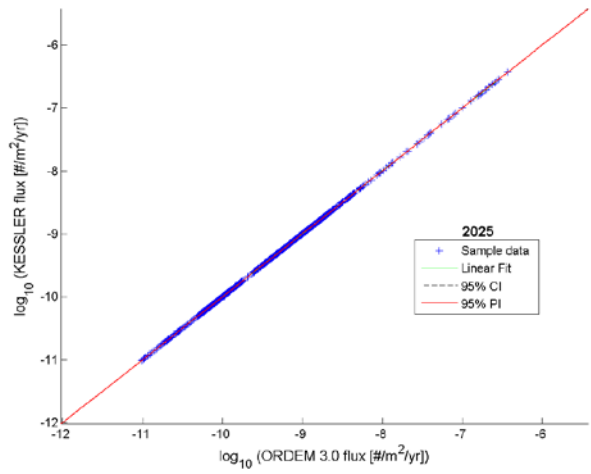

Figure C.3.2.2-4. ASCENSION, flux, 2025.

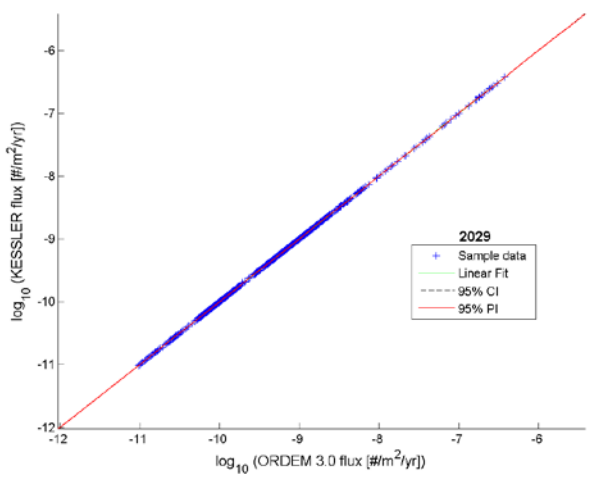

Figure C.3.2.2-5. ASCENSION, flux, 2029.

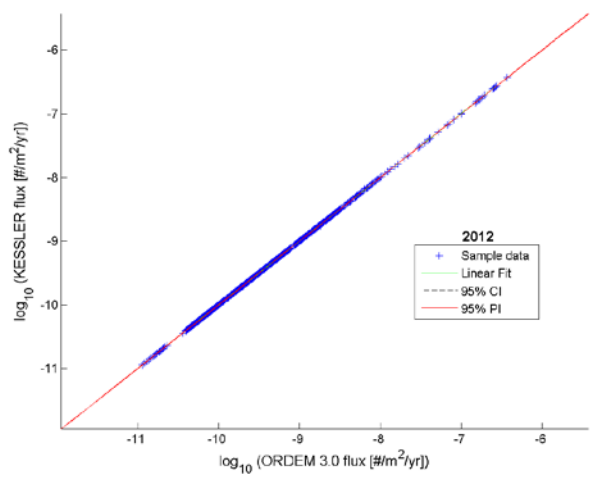

Figure C.3.2.2-6. EQUAT, flux, 2012.

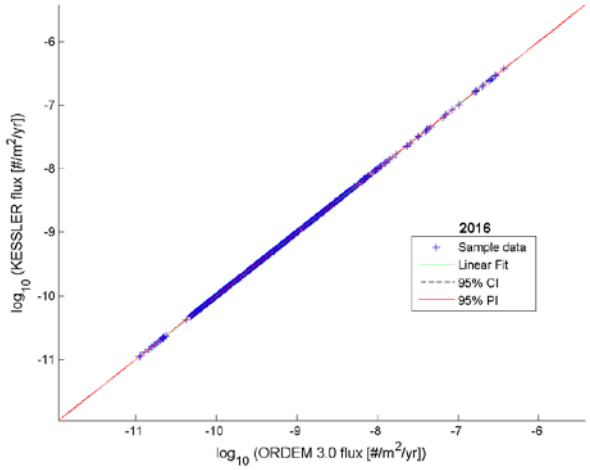

Figure C.3.2.2-7. EQUAT, flux, 2016.

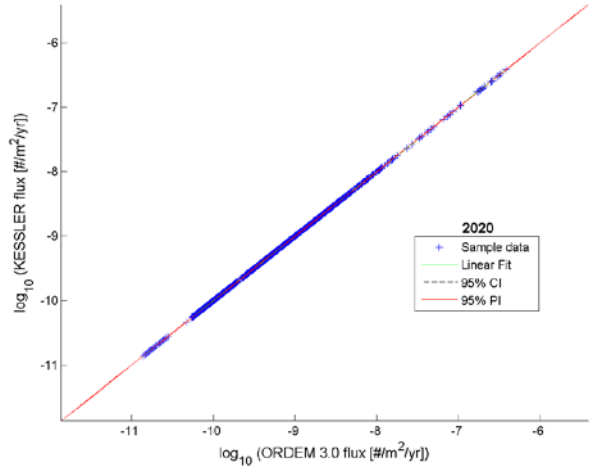

Figure C.3.2.2-8. EQUAT, flux, 2020.

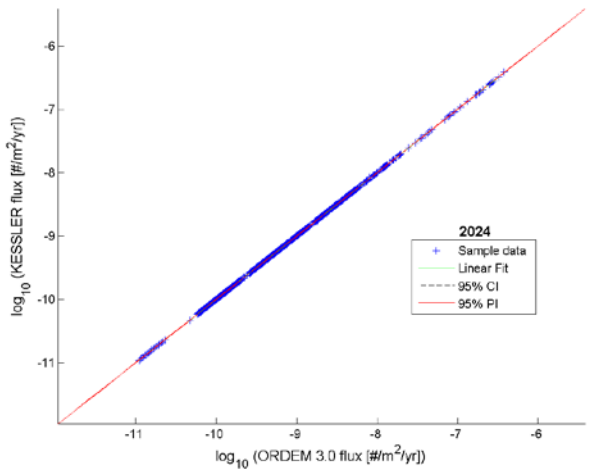

Figure C.3.2.2-9. EQUAT, flux, 2024.

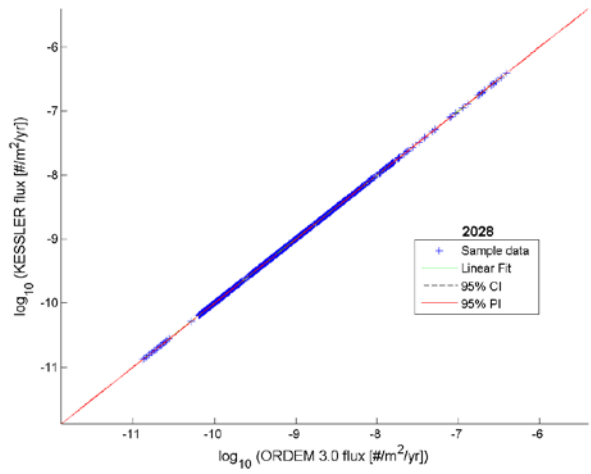

Figure C.3.2.2-10. EQUAT, flux, 2028.

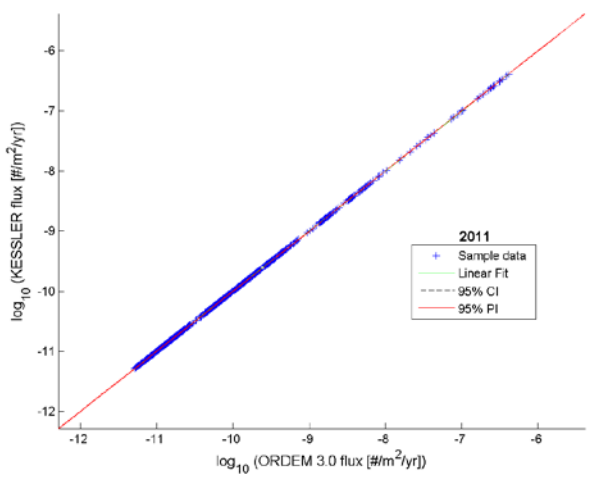

Figure C.3.2.2-11. HAY10S, flux, 2011.

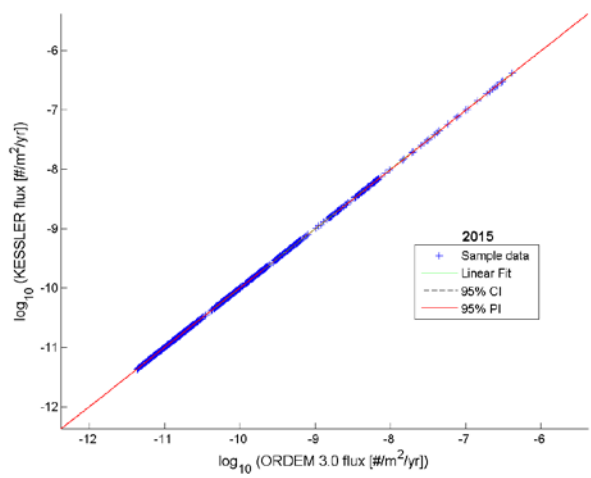

Figure C.3.2.2-12. HAY10S, flux, 2015.

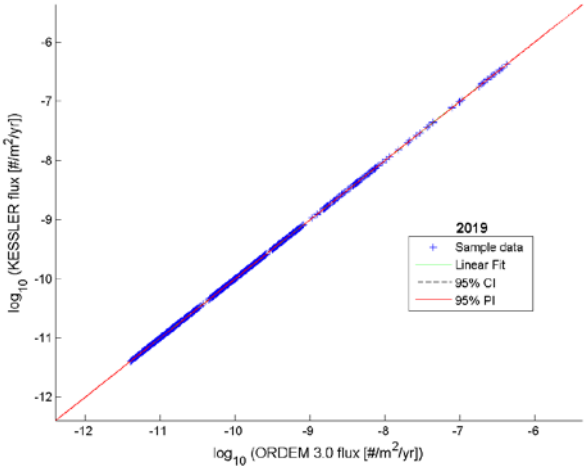

Figure C.3.2.2-13. HAY10S, flux, 2019.

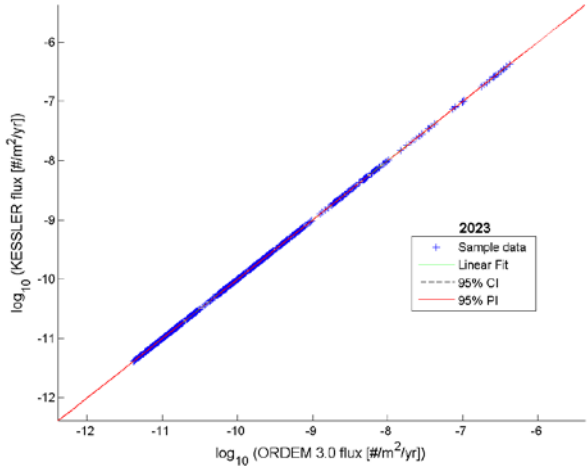

Figure C.3.2.2-14. HAY10S, flux, 2023.

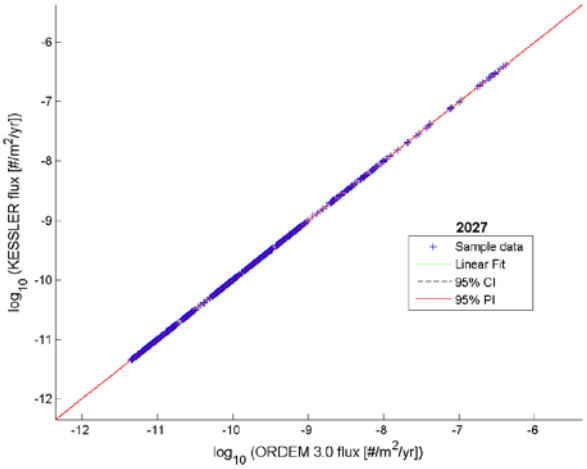

Figure C.3.2.2-15. HAY10S, flux, 2027.

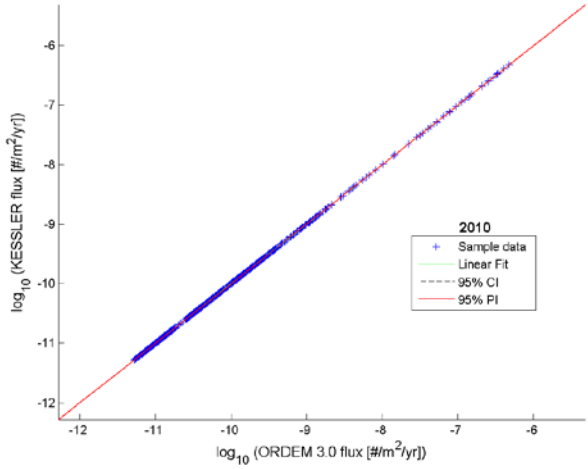

Figure C.3.2.2-16. HAY75E, flux, 2010.

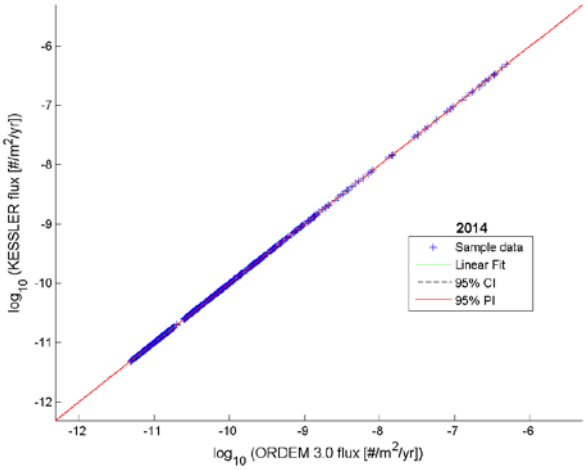

Figure C.3.2.2-17. HAY75E, flux, 2014.

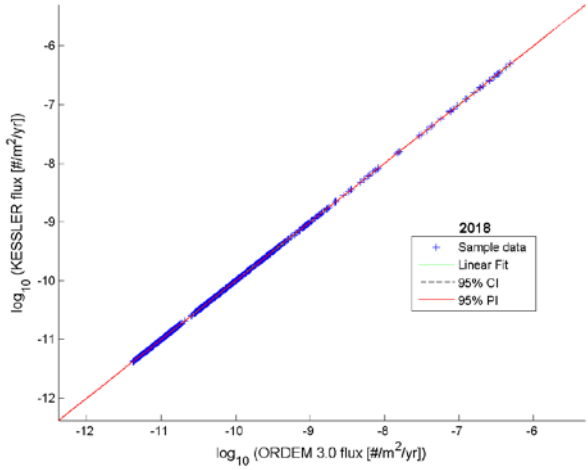

Figure C.3.2.2-18. HAY75E, flux, 2018.

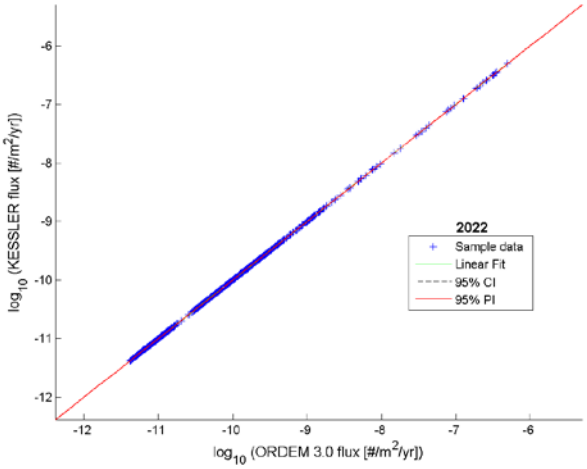

Figure C.3.2.2-19. HAY75E, flux, 2022.

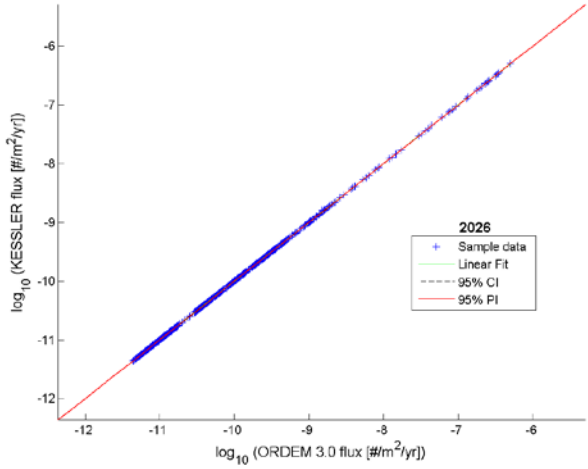

Figure C.3.2.2-20. HAY75E, flux, 2026.

Appendix D: Testing Verification Process

1.0 Accuracy and Uncertainties

This section provides a detailed description of any discrepancies between actual and expected results during analysis verification testing.

1.1. RADAR SENSITIVITY

Variations of sensitivity significantly influence the probability of detection for small orbital debris objects (of less than 1 cm size for Haystack and less than 3 cm for HAX). Calculating probability of detection (P_{det}) as a function of signal-to-noise ratio (SNR) at a given probability of false alarm (P_{fa}) is a well-established procedure in radar signal processing. The false alarm probability of $P_{fa} = 10^{-9}$ is usually used by MIT/LL for Haystack and HAX operations during routine observations (Horstman).

Note that radar sensitivity is a function of altitude as illustrated by the radar equation below:

$$SNR = \frac{P_t G_t G_r \lambda^2 E_n}{(4\pi)^3 kTBFLR^4}\ \sigma$$

where SNR is measured at the antenna terminal, P_t is the peak transmit power (W), G_t is transmit antenna gain on axis, G_r is receive antenna gain on axis, » is transmitter wavelength (m), E_n is pulse integration efficiency factor, $\tilde{A}$ is target RCS (m^2), k is Boltzmann's constant (J/K), T is the system temperature (K), B is bandwidth (Hz), F is a noise figure (the receiver's figure of merit), L is total system losses, and R is antenna to target range (m).

The measurements process that was applied in order to detect the debris population for the LEO environment is subject to the limitations of radar technology. As range increases, the minimum size detectable becomes larger. For data taken during the time frames that contribute to the verification of the ORDEM populations, sensitivity roll-off reduced the coverage for upper altitudes (longer ranges) that approached the sizes of 1 cm region. This means that for some ranges/altitudes and telescope modes, the population of detected 1 cm objects is probably incomplete, and the model can be expected to over-predict the radar detection rate. Therefore, the comparisons between data and model should not be expected to be acceptable in all cases. These cases will be pointed out when they arise.

1.1.1. *RCS Measurement Bias*

The absolute RCS calibration bias obtained from observations derived from an ensemble of calibration satellites is the product of work performed by MIT/LL during observation runs. Historical usage of the calibration satellites over 7 years is presented in Figure D.1.1.2-1. These spacecraft, some hollow metallic spheres in LEO, and some larger spacecraft of more complex

structure in GEO, provide the basis for determining the apparent system bias of the radar, which results in an absolute difference in measured RCS. LEO objects are in the geometrical optical scattering region for both Haystack and HAX; GEO objects behave as point sources. Each radar measures the RCS of the calibration object to calculate a "system sensitivity constant" used to maintain the system calibration. If the measured constant drifts sufficiently from the accepted value, it is adjusted (this " RCS is provided by MIT/LL as auxiliary data to each dataset). The revised value is typically the average of the measured values from the past several days. The data tapes recorded at the Haystack facility contain only the averaged constant (Haystack).

Consider the charts of surface area flux vs. altitude in section 2.3. Note that these charts concerning the 2003 Haystack data are with a 2-dB RCS-bias correction.

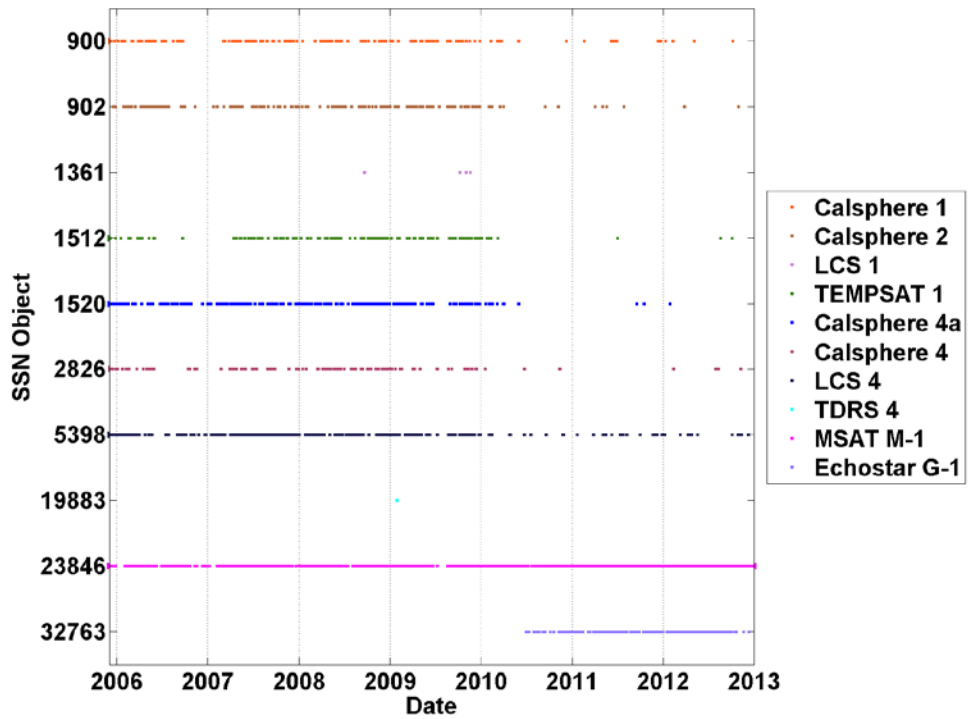

Figure D.1.1.2-1. Historical acquisition of calibration satellites, Haystack & HAX radars.

1.2. RADAR SENSORS

The validation charts in this appendix compare the ORDEM 3.0 population with data from ground-based sensors that are routinely used by the ODPO to study the orbital debris environment and its evolution in the LEO region. The primary set of instruments for debris and intact object tracking is the SSN, which reliably supports multiple sensors with sensitivity of less than 10 cm. The SSN data has been used to populate the ORDEM 3.0 files from 1995 to 2007.

Three other radar systems are used by the ODPO to extract statistical data from the debris environment. These are Goldstone, Haystack, and HAX. The data collected per year (with number of observation hours, number of detections, and other radar-specific information) are presented below in Table D.1.3-1 through Table D.1.3-3.

TABLE D.1.3-1 – HAYSTACK DATA

Year	Haystack data	Range-window (km)	Alt-window (km)	Obs. hrs	Detection #
1999	75˚E,WFC7	312-1297	302-1261	210.2	449
2000	75˚E,WFC7	312-1297	302-1261	264.9	522
2001	75˚E,WFC7	312-1297	302-1261	250.6	503
2002,near	75˚E,WFC7	1030-2015	1000-1961	175.5	377
2002,far	75˚E,WFC7	312-1297	302-1261	171.3	250
2003	75˚E,WFC4	312-1885	302-1837	633.3	1560

TABLE D.1.3-2 – HAX DATA

Year	Haystack data	Range-window (km)	Alt-window (km)	Obs. hrs	Detection #
1999	75˚E,WFC6	417-1172	404-1139	579.2	310
2000	75˚E,WFC6	417-1172	404-1139	580.3	339
2001	75˚E,WFC6	417-1172	404-1139	618.4	333
2002,near	75˚E,WFC6	1031-1786	1002-1738	226.8	106
2002,far	75˚E,WFC6	417-1172	404-1139	241.8	49
2003	75˚E,WFC4	312-1885	302-1837	541.8	438

TABLE D.1.3-3 – GOLDSTONE DATA

Year	Obs. Hrs	Detection #
2001	39.8	623
2005	92.8	1304
2006	58.3	907
2007	77.0	1545

2.0 LEO Region

This section provides a detailed description of the testing validation results of data sets representing the LEO region for ORDEM 3.0. This includes both 10 µm to ~2 mm and > 3 mm size ranges.

2.1. IN-SITU STS WINDOW AND RADIATOR IMPACTS (10 µm to ~2 mm)

The figures in this section plot data down to 1 mm FSH diameters. This is partially because the damage equations begin to break down below this value, and because there is some uncertainty whether the FSH dataset is complete below this value due to possible incomplete recording of features where only the hole in the covering tape was recorded. Nevertheless, this data gives a very good look at the model predictions for particles up to 1-2 mm in size.

The red curve in Figure D.2.1-1 is the cumulative number of facesheet hole features created from medium density (MD) particles as a function of hole diameter. The black curve is the ORDEM model prediction. The dotted black lines represent the upper and lower 1-sigma range possible from the predicted curve based on Poisson statistics alone. Figure D.2.1-2 is similar to D.2.1-1, but the red curve represents the cumulative number of facesheet hole features created from high density (HD) particles as a function of hole diameter. Note that the single largest impact feature has some uncertainty associated with it. The plots show three possible interpretations of the feature size, where the largest value is probably an extreme upper limit.

Figure D.2.1-3 shows the differential fit for the MD facesheet hole data. With a P-value of 0.622, the model can be considered a high-quality match to the data. Figures D.2.1-4, D.2.1-5, and D.2.1-6 show the differential fit and P-value for the HD facesheet hole data, with different assumptions about the appropriate feature size of the largest impact feature. The P-values range from 0.496 to 0.694 (depending on the size of the largest feature). These values indicate the overall match to the model is of high quality, despite the uncertainty in the size of the largest feature. This reflects the experience with fitting the original data, where the fitting curve was quite insensitive to the precise diameter of this feature.

Figure D.2.1-7 shows the cumulative distribution of the MD window crater diameter data compared against the ORDEM model prediction. The solid red line is the mean of the various Monte Carlo data realizations (note fractional values in places). The pink-shaded region represents the upper and lower 1-sigma ranges in the different Monte Carlo realizations, which represents the uncertainty due to the sampling error of this process. The “correct” data curve that would have resulted if all *U* impactors had, in fact, been identified probably resides within the pink region. As before, the dotted black lines represent the upper and lower 1-sigma range possible from the predicted curve based on Poisson statistics alone. Note that the data stays mostly within the 1-sigma Poisson range as expected, except on the largest end where the sampling error is largest. Figure D.2.1-8 is similar to D.2.1-7, but instead shows data for the HD impactors. Here again, there is an excellent fit between data and model.

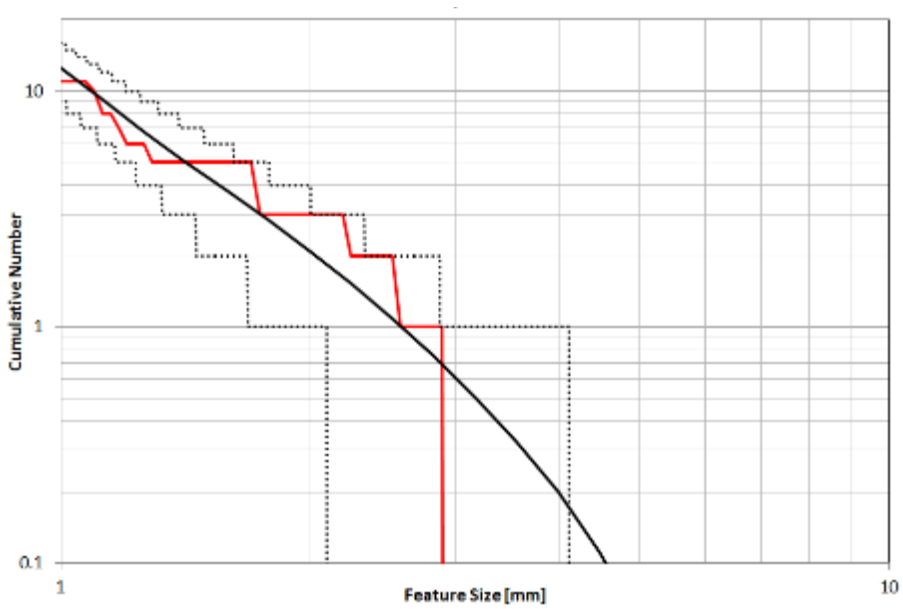

Figure D.2.1-1. Shuttle radiator facesheet hole (MD population).

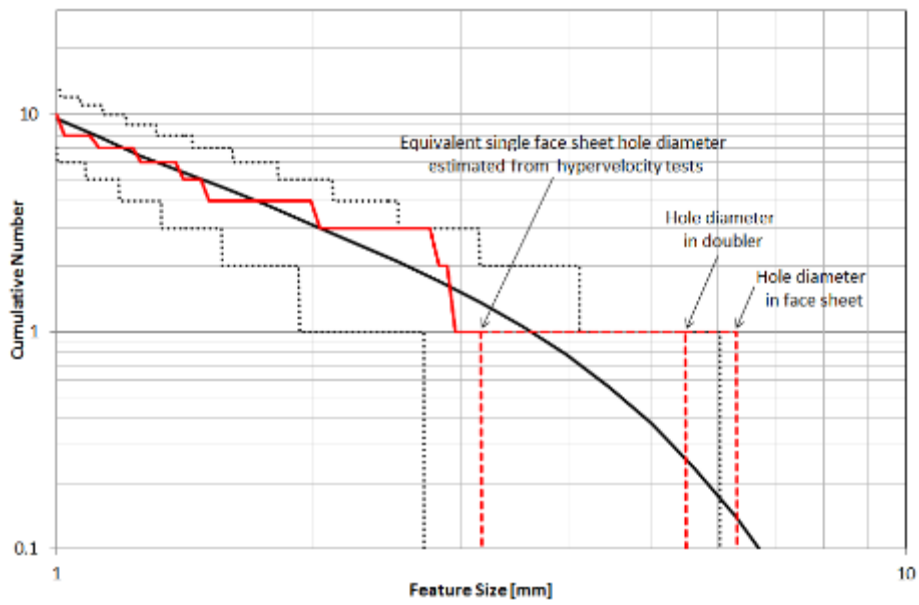

Figure D.2.1-2. Shuttle radiator facesheet hole (HD population).

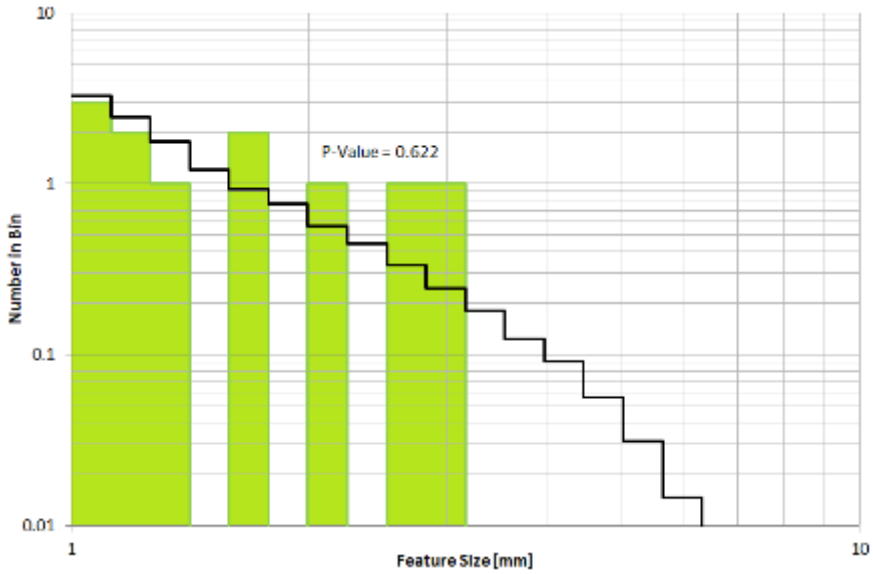

Figure D.2.1-3. Shuttle radiator facesheet hole (MD population), P-value=0.622.

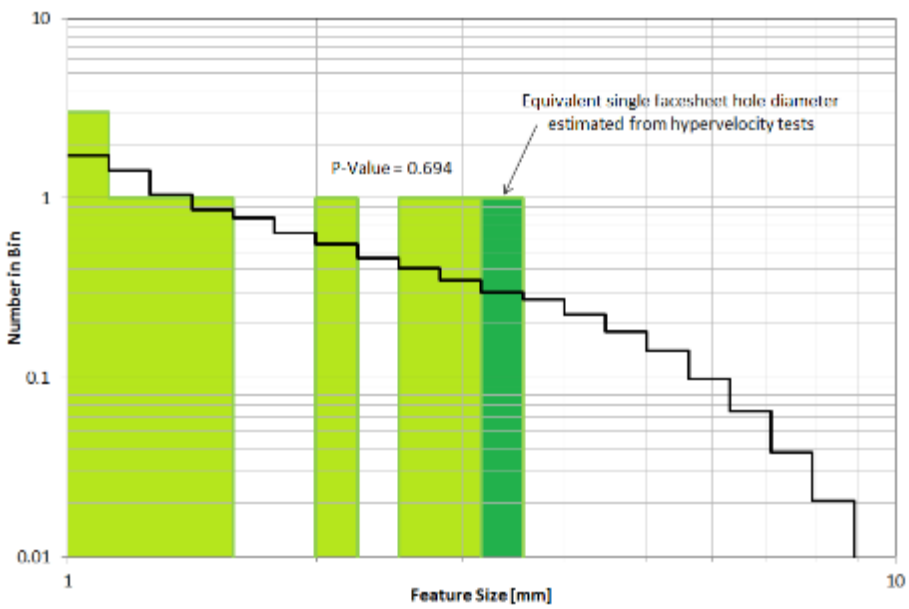

Figure D.2.1-4. Shuttle radiator facesheet hole (HD population), P-value=0.694.

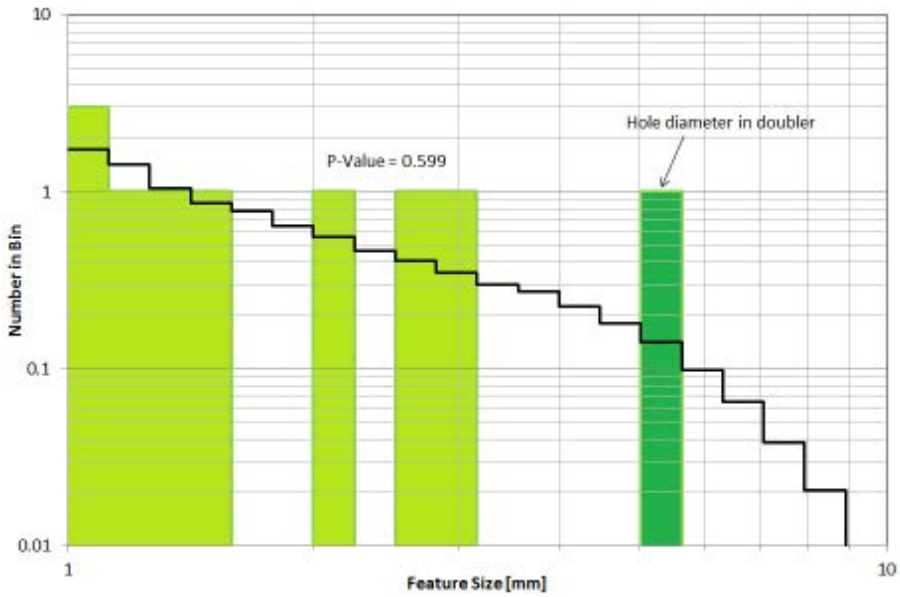

Figure D.2.1-5. Shuttle radiator facesheet hole (HD population), P-value=0.599.

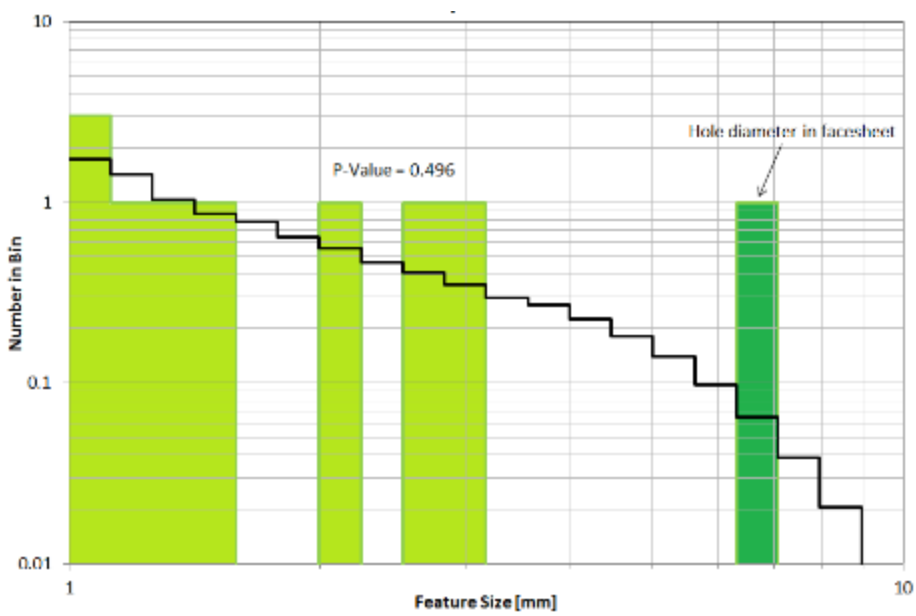

Figure D.2.1-6. Shuttle radiator facesheet hole (HD population), P-value=0.496.

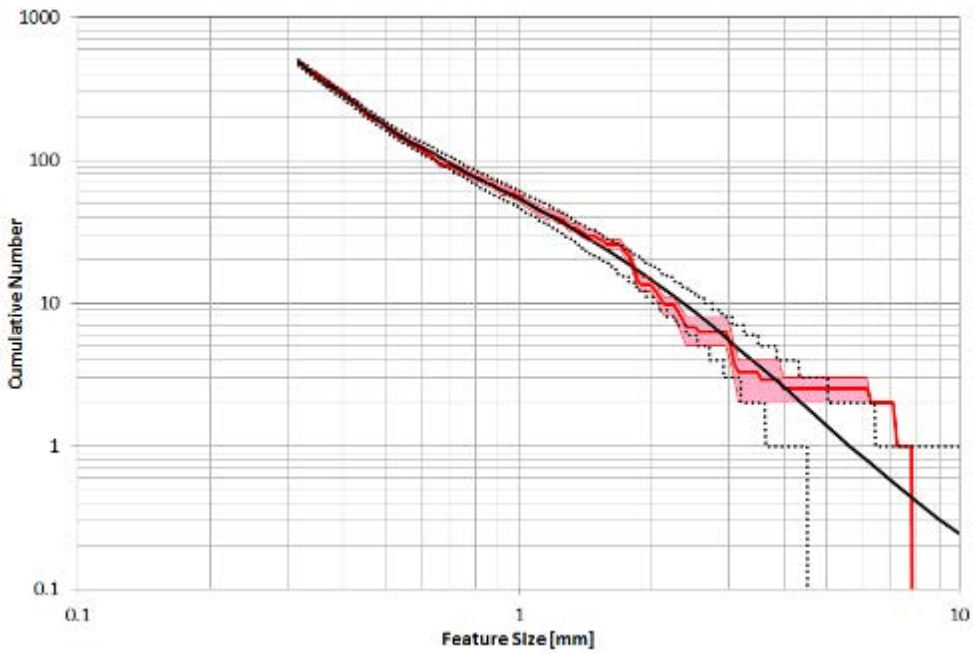

Figure D.2.1-7. Shuttle window crater diameter (MD population).

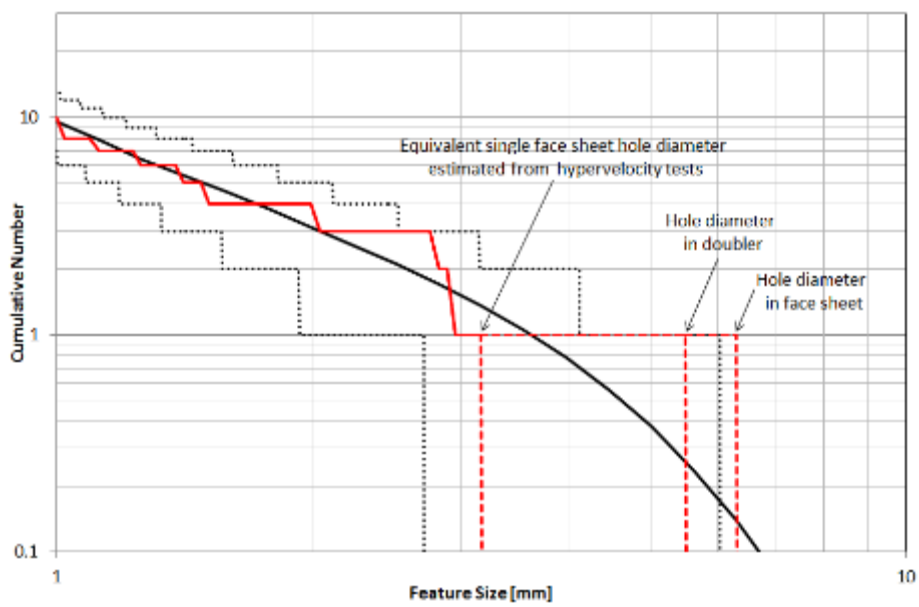

Figure D.2.1-8. Shuttle window crater diameter (HD population).

2.2. SCALED FLUX DEVIATIONS VS. ALTITUDE (> 3 mm)

Table D.2.2-1 shows results for validation of ORDEM 3.0 fluxes for the Haystack (sizes >1 cm, > 3.16 cm and pointing directions 75°E, 20°S) and HAX (size > 3.16 cm, pointing direction 75°E) sensors. Excluded populations in these tests include easily identifiable NaK (by high polarization and ~ 900 km, or ~700 km altitude).

TABLE D.2.2-1 – SCALED FLUX DEVIATION VS. ALTITUDE, HAYSTACK/HAX, NAK EXCLUDED

Test No.	Sensor(s)	Pointing	Obs. Years	Cum. Size	$\check{\zeta}$	$\bar{\zeta}$	ν	Passed
1	Haystack	20°S	1999-2002	>1cm	-1.62	-1.448	-1.45	✗
2	Haystack	75°E	1999-2003	>1cm	-0.33	-0.282	-0.28	✓
3	Haystack Haystack	75°E 20°S	1999-2003, 1999-2002	>1cm	-0.43	-0.589	-0.59	✓
4	Haystack	20°S	1999-2002	>3.16cm	-0.41	-0.466	-0.47	✓
5	Haystack HAX	75°E 75°E	1999-2003 1999-2003	>3.16cm	0.13	0.027	0.03	✓
6	HAX	75°E	1999-2003	>3.16cm	0.05	-0.097	-0.10	✓
7	Haystack	75°E	1999-2003	>3.16cm	0.21	0.120	0.12	✓
8	Haystack Haystack HAX	75°E 20°S 75°E	1999-2003 1999-2002 1999-2003	>3.16cm	0.11	-0.071	-0.07	✓

As mentioned before, the weighted averaging over different data sets is based on the variance that includes the dispersion parameter.

As in the verification section of this document, the last column 'Passed' indicates a successful outcome by a green checkmark (✓), or 'Failed' by a red X (✗). In order for a validation test to be successful, the weighted average must fall within ± 1.0. Given this criteria, only one validation test – Haystack 20°S – was marked as failed. Because Haystack loses sensitivity in detecting 1 cm objects at the longer ranges of 20°S, it is not surprising that the model "overpredicts" the count rate for this mode at longer ranges. This resulted in a deviation outside the limits of what is considered a passed validation test.

Each validation test in Table D.2.2-1 includes a scaled flux deviation ζ vs. altitude chart, a probability distribution function (pdf) histogram supplemented with a normal curve fit – $N(\nu, \sigma)$ using a fitted mean ν, and a pdf histogram supplemented with a normal curve fit of 1-sigma $N(\bar{\zeta}, 1)$. The validation tests performed in this section correctly and completely represent the design specifications and requirements of the ORDEM 3.0 model.

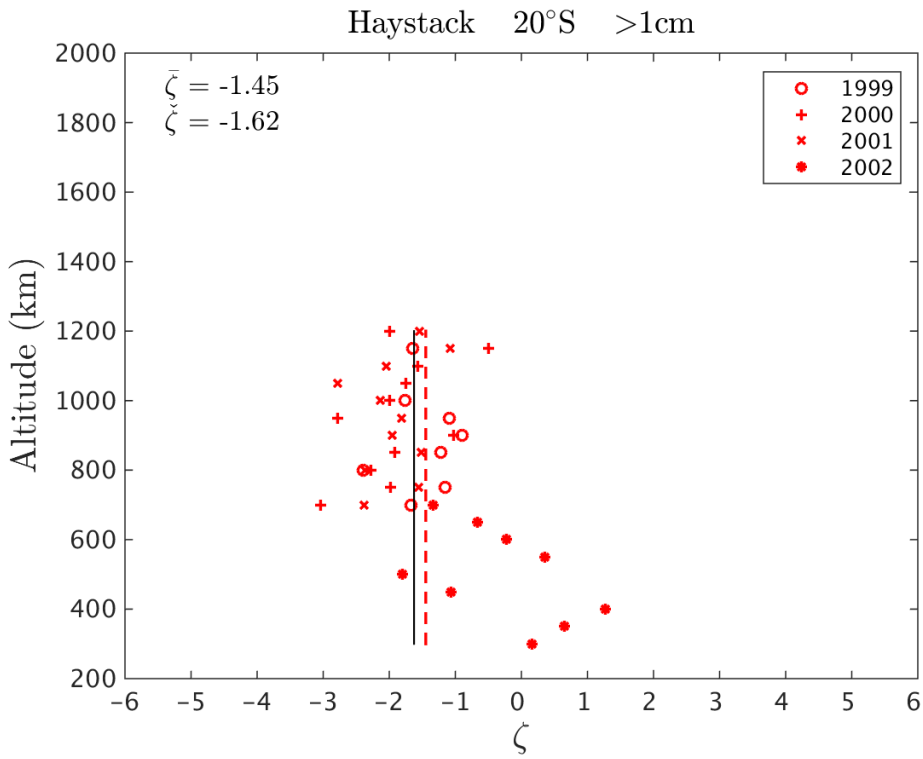

Figure D.2.2-1. Haystack (20°S only), >1 cm.

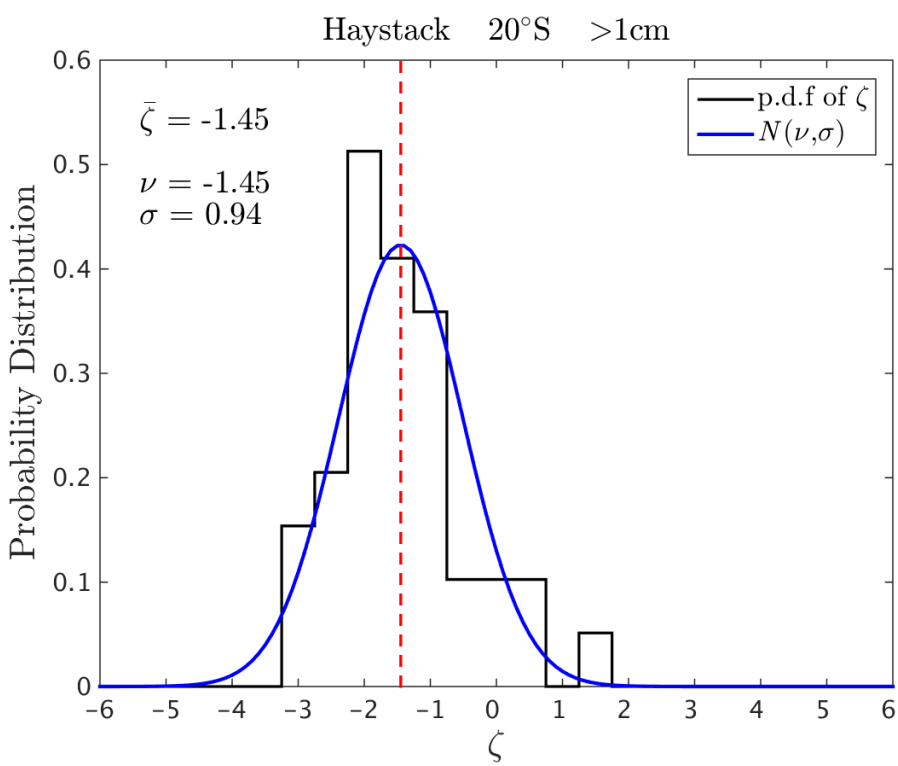

Figure D.2.2-2. Haystack (20°S only), >1 cm, fitted.

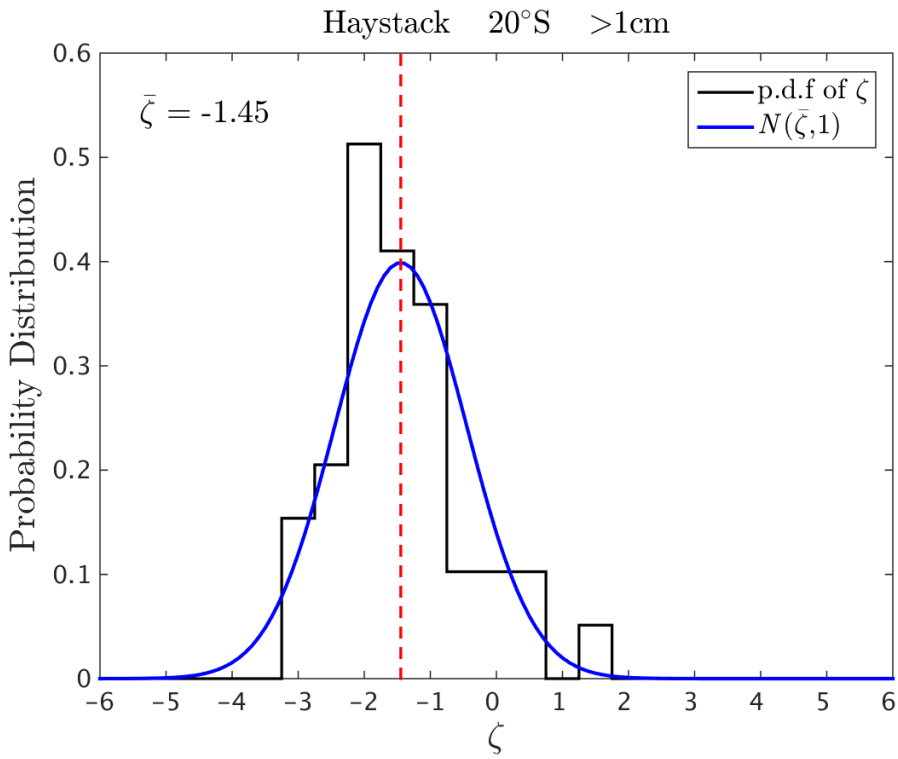

Figure D.2.2-3. Haystack (20°S only), >1 cm, 1-sigma.

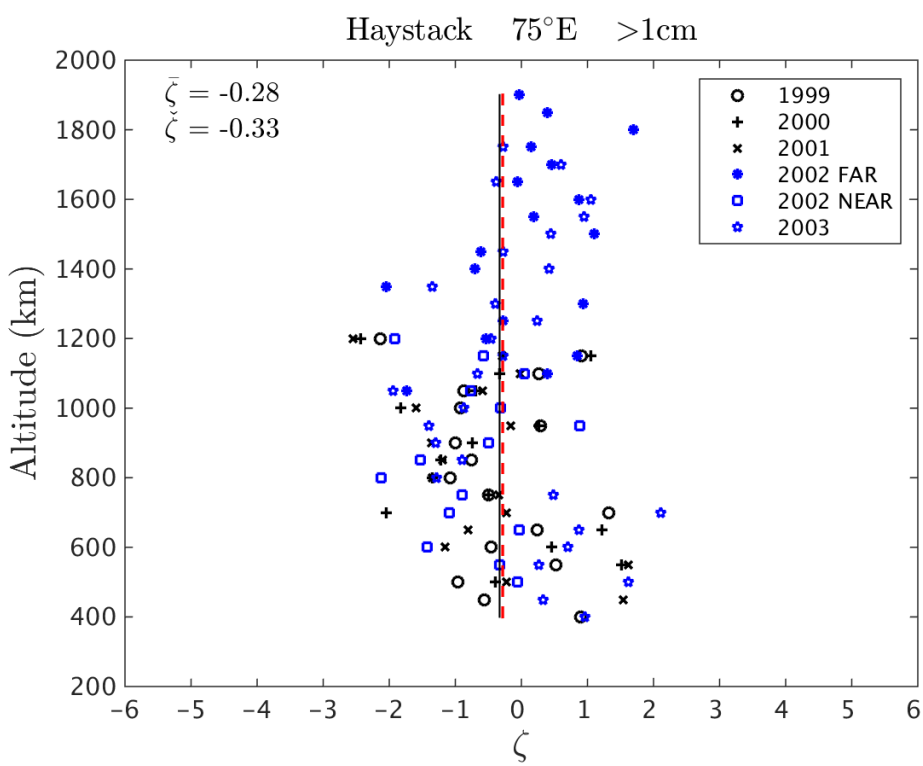

Figure D.2.2-4. Haystack (75°E only), >1 cm.

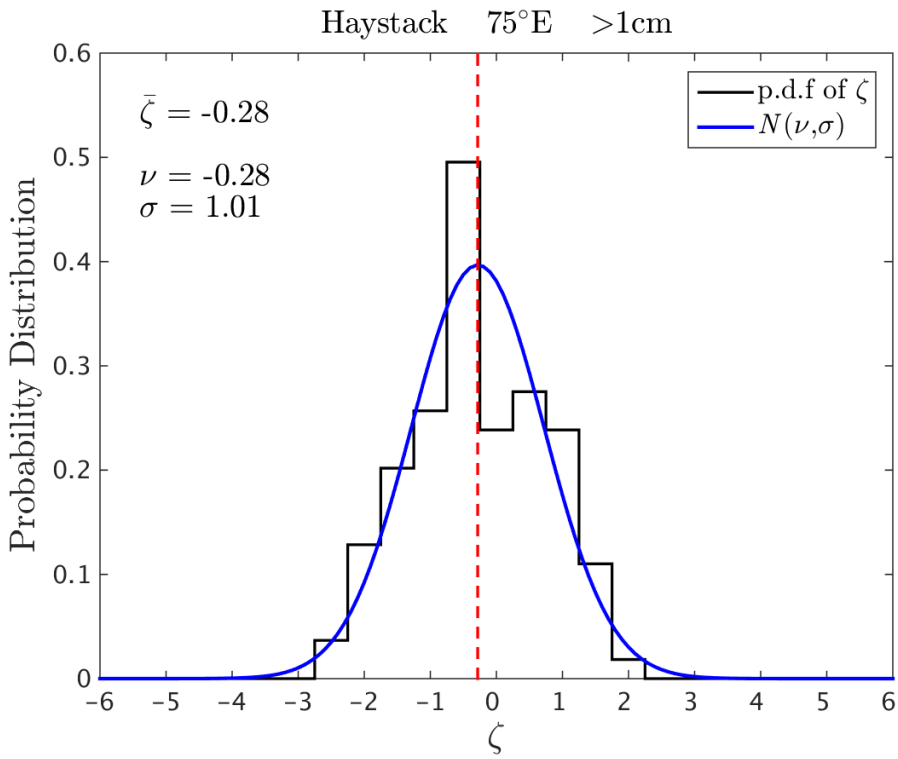

Figure D.2.2-5. Haystack (75°E), >1 cm, fitted.

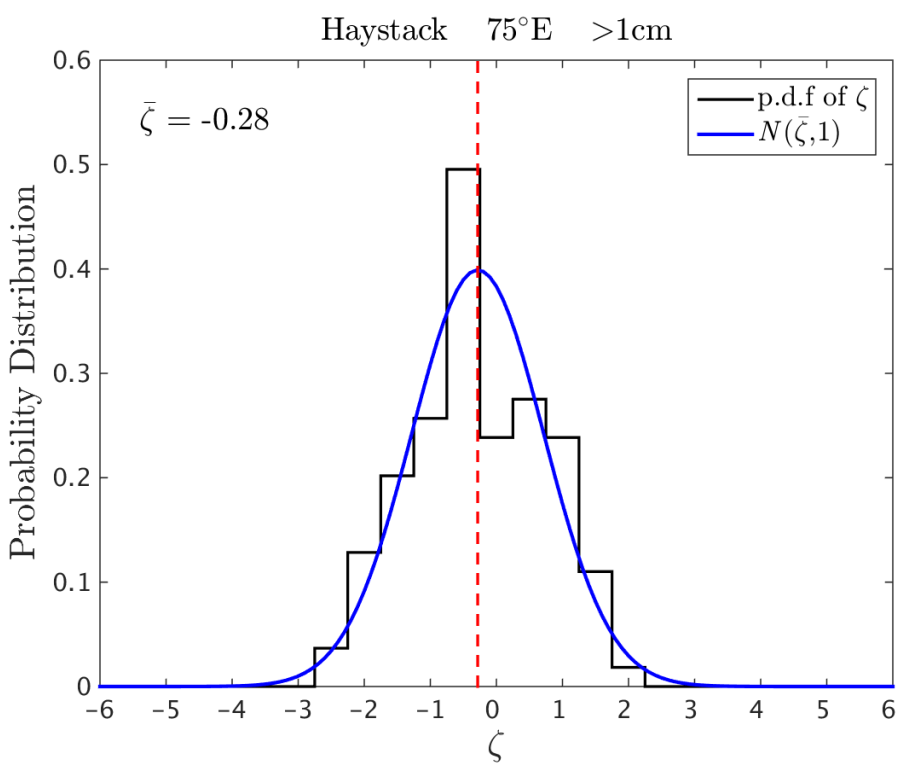

Figure D.2.2-6. Haystack (75°E), >1 cm, 1-sigma.

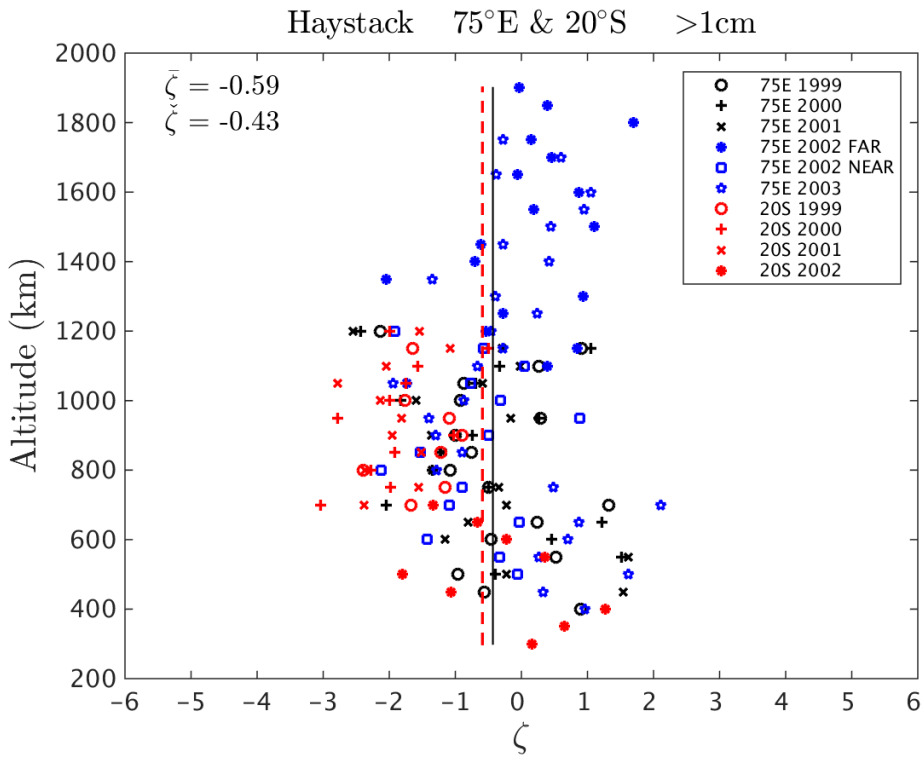

Figure D.2.2-7. Haystack (75°E, 20°S only), >1 cm.

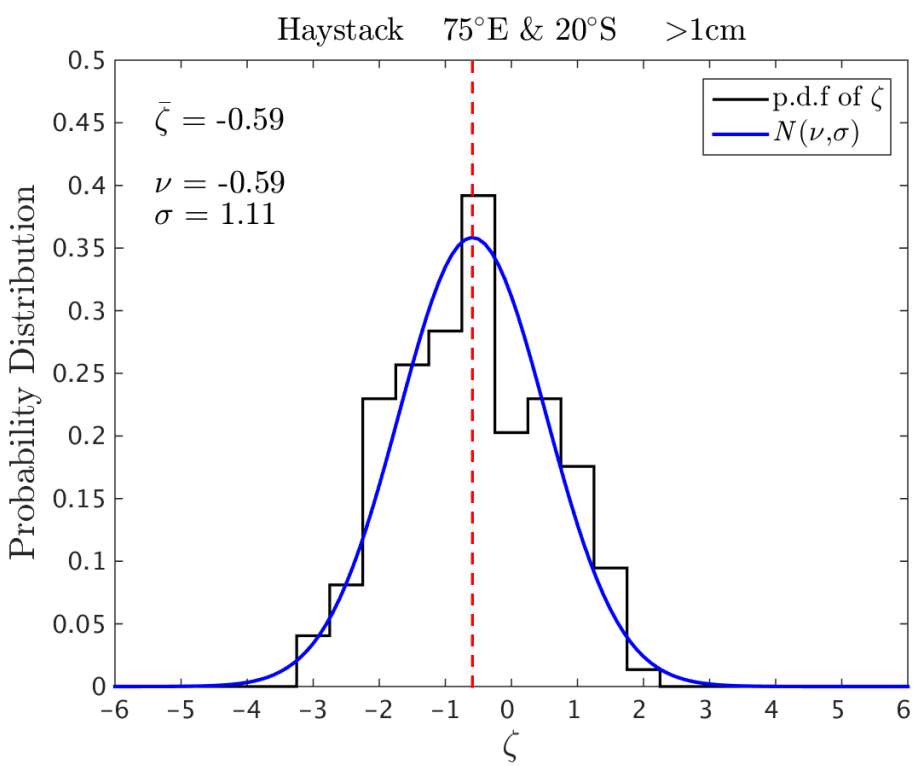

Figure D.2.2-8. Haystack (75°E, 20°S only), >1 cm, fitted.

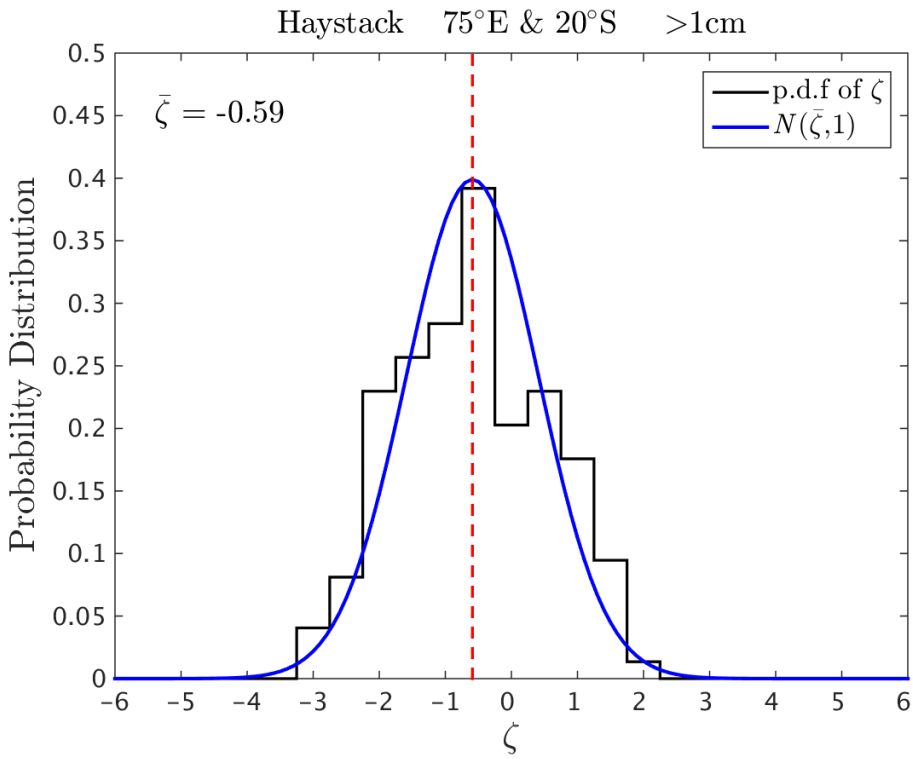

Figure D.2.2-9. Haystack (75°E, 20°S only), >1 cm, 1-sigma.

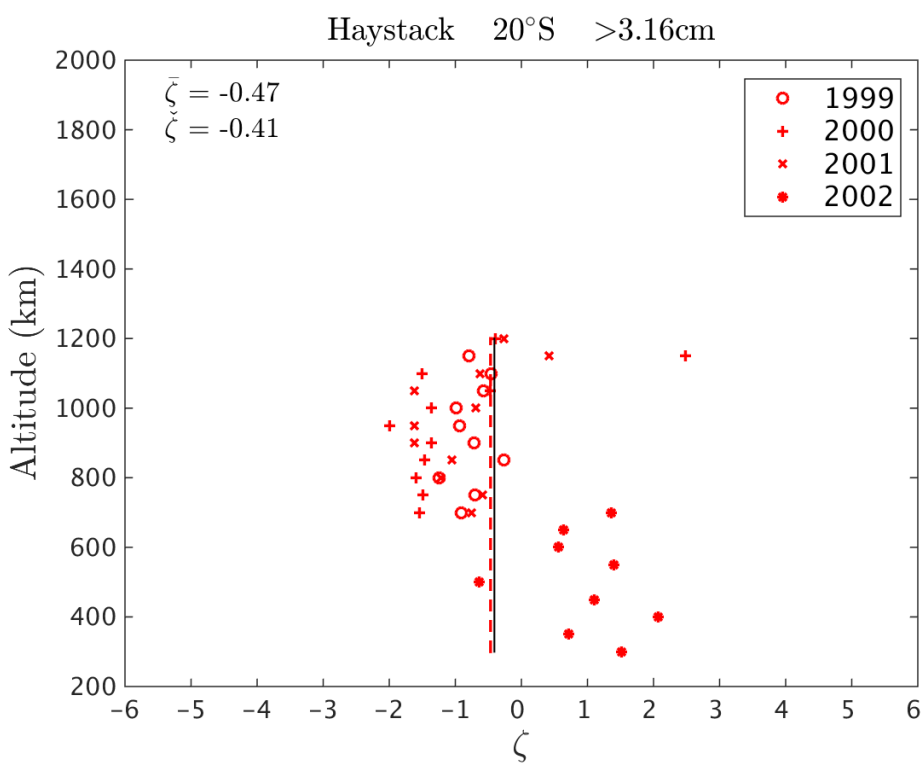

Figure D.2.2-10. Haystack (20°S only), >3.16 cm.

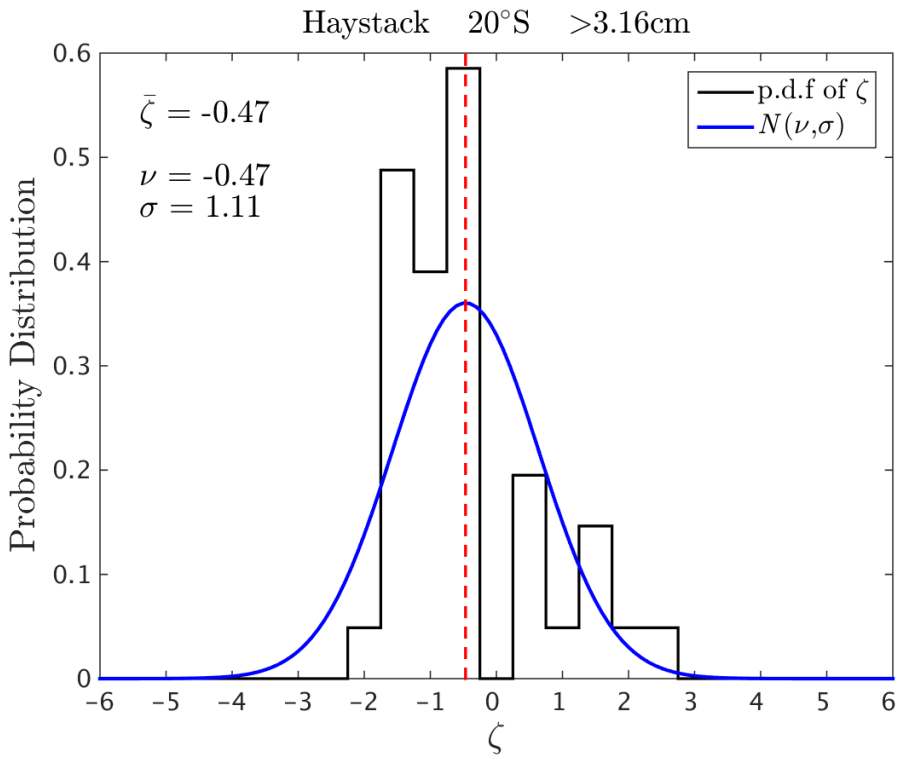

Figure D.2.2-11. Haystack (20°S only), >3.16 cm, fitted.

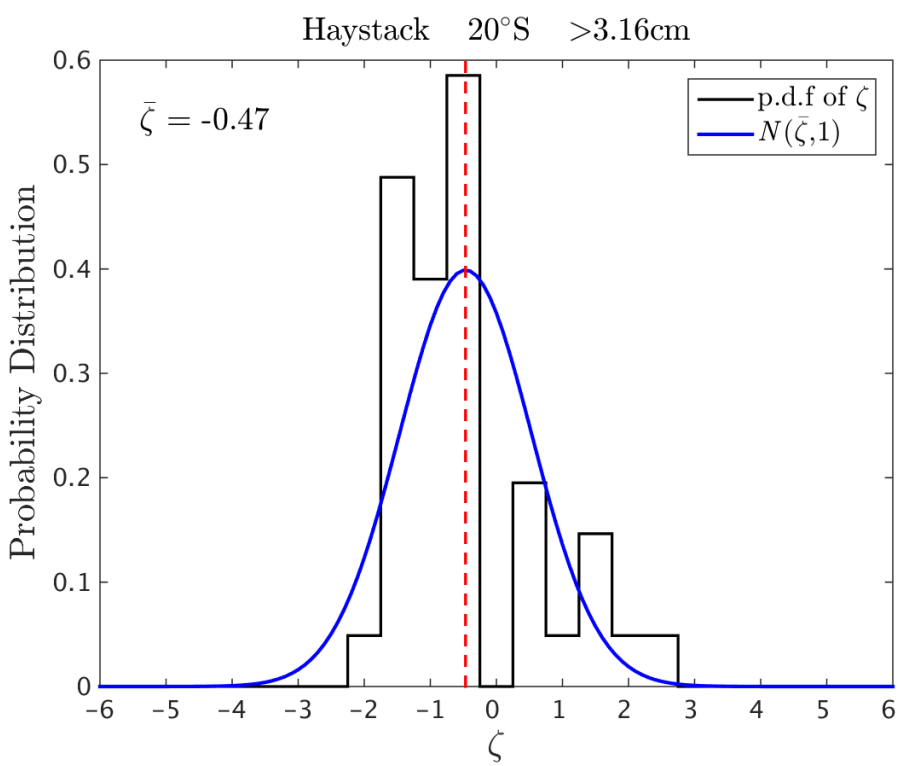

Figure D.2.2-12. Haystack (20°S only), >3.16 cm, 1-sigma.

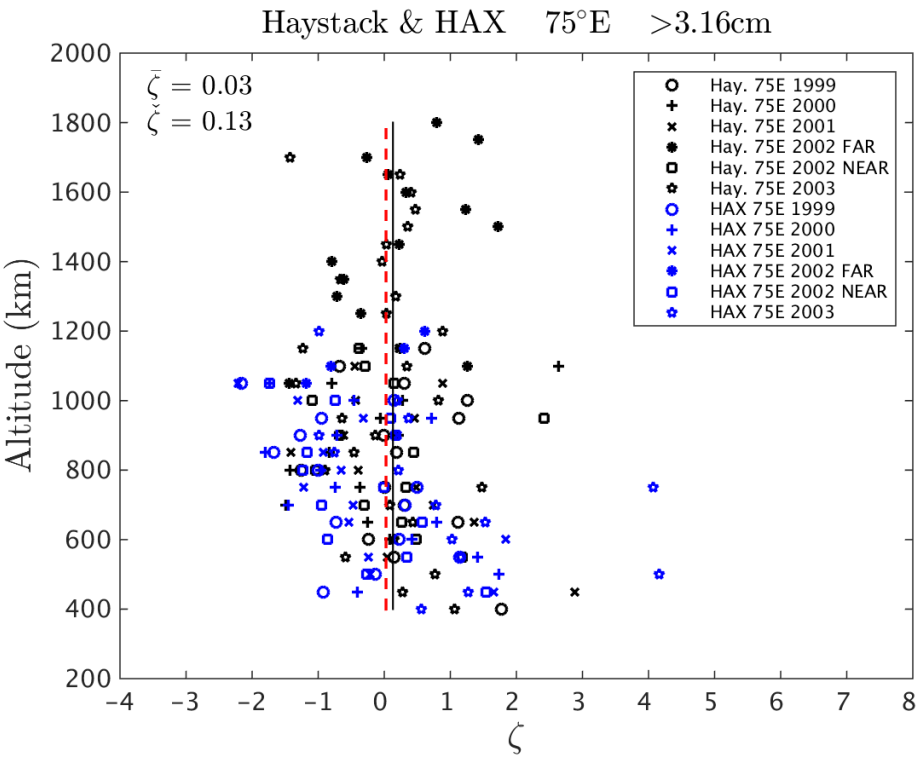

Figure D.2.2-13. Haystack & HAX (75°E), >3.16 cm.

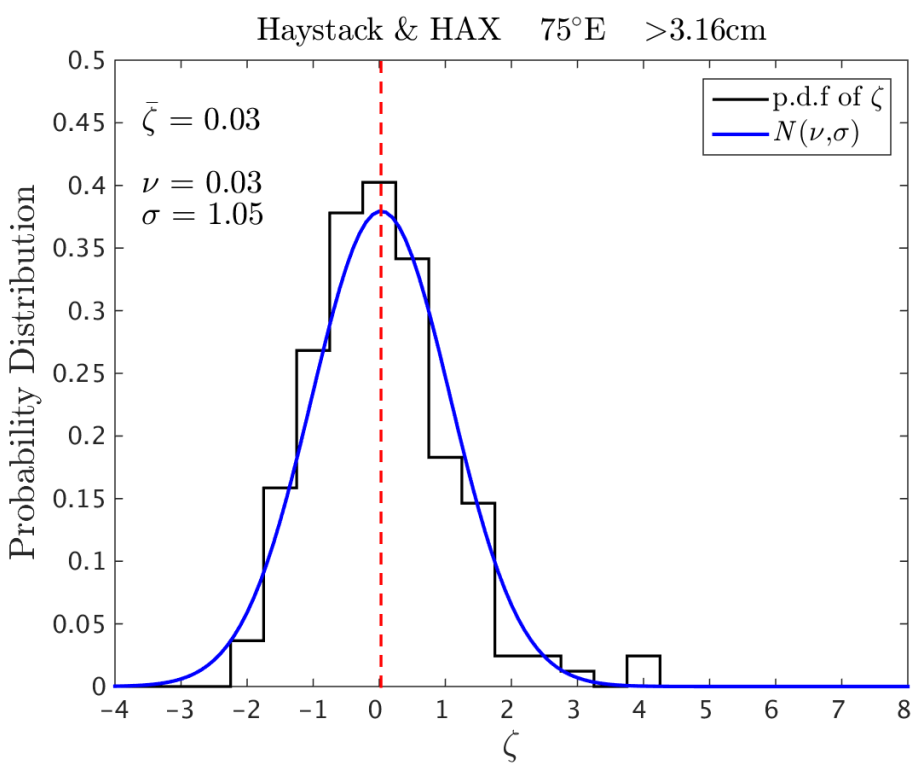

Figure D.2.2-14. Haystack & HAX (75°E), >3.16 cm, fitted.

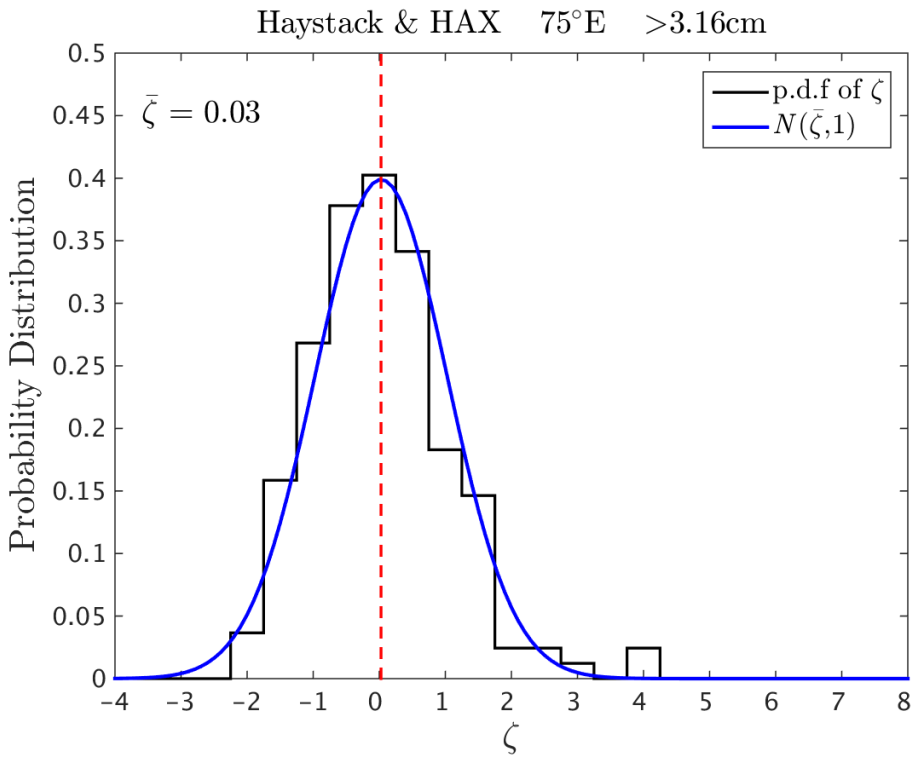

Figure D.2.2-15. Haystack & HAX (75°E), >3.16 cm, 1-sigma.

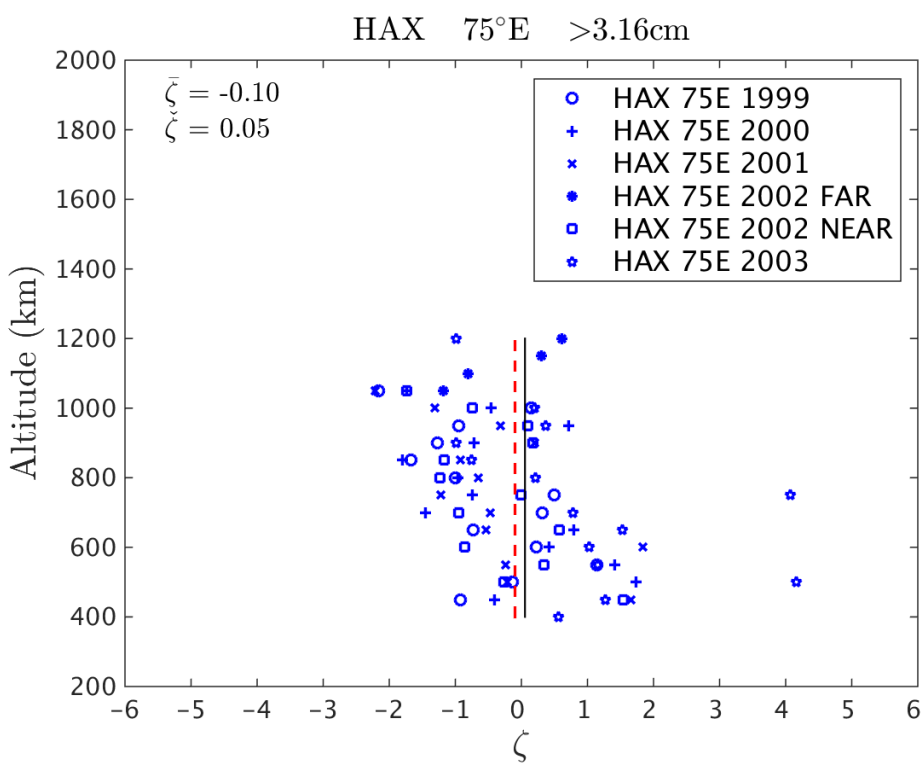

Figure D.2.2-16. HAX (75°E only), >3.16 cm.

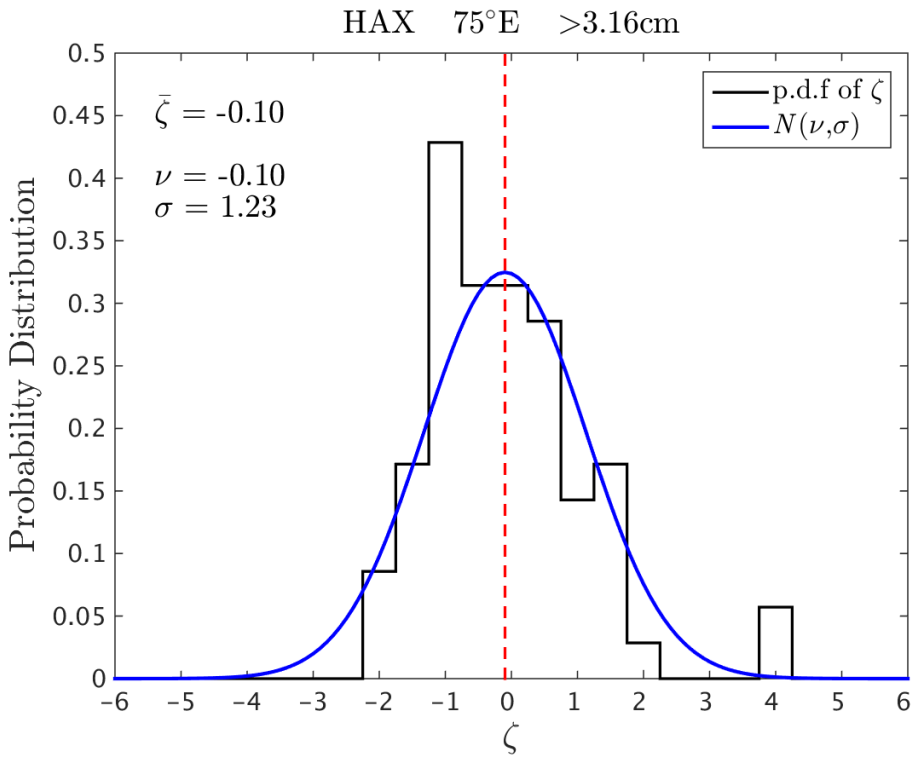

Figure D.2.2-17. HAX (75°E only), >3.16 cm, fitted.

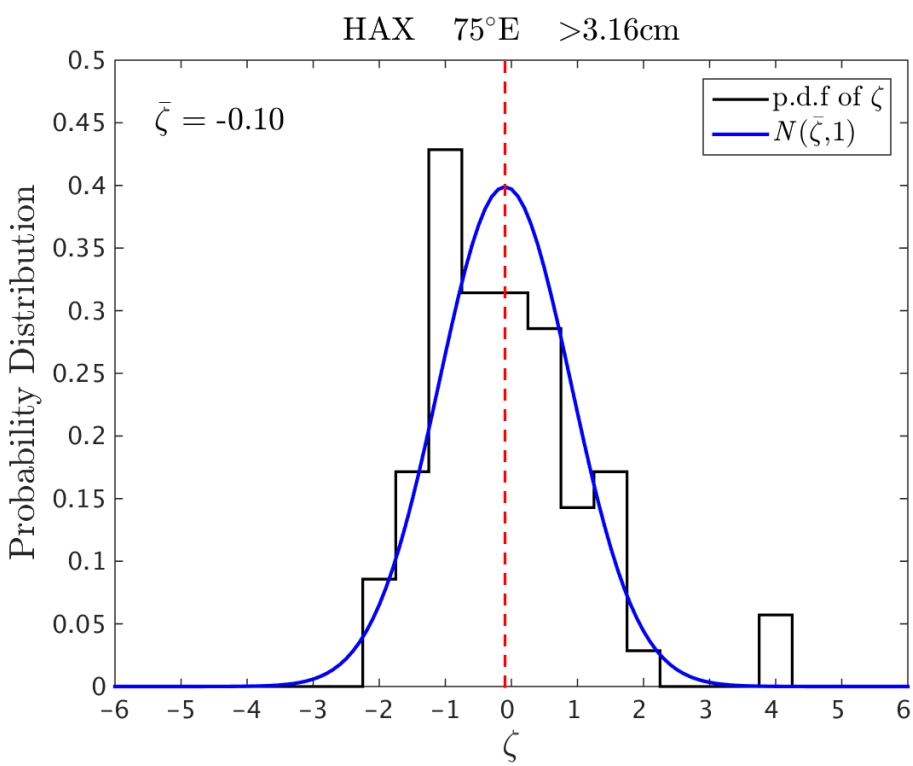

Figure D.2.2-18. HAX (75°E only), >3.16 cm, 1-sigma.

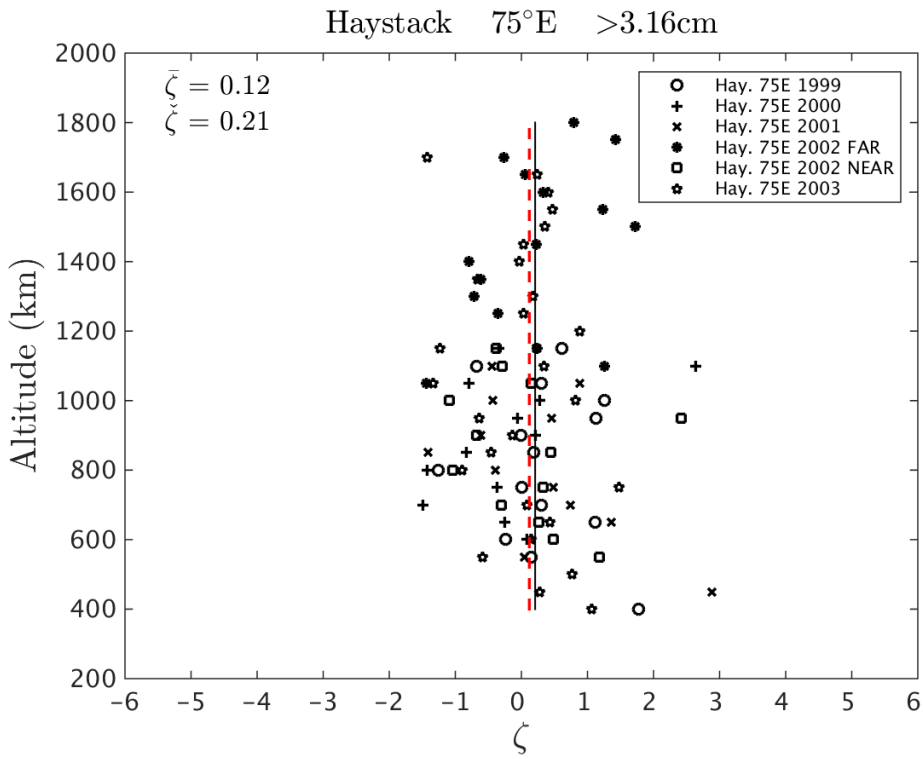

Figure D.2.2-19. Haystack (75°E only), >3.16 cm.

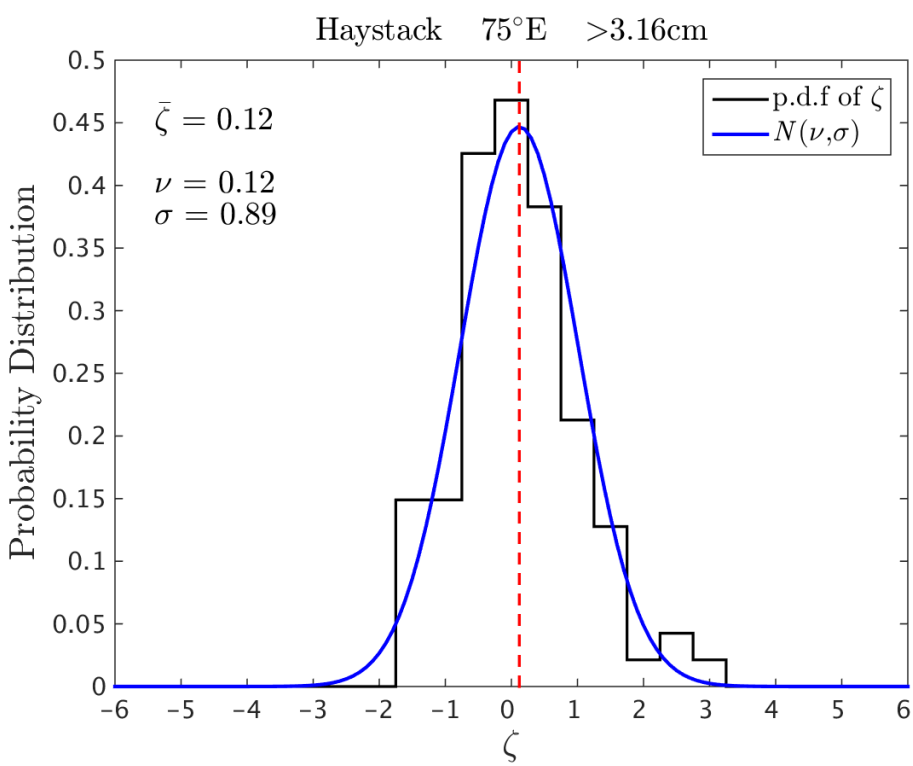

Figure D.2.2-20. Haystack (75°E only), >3.16 cm, fitted.

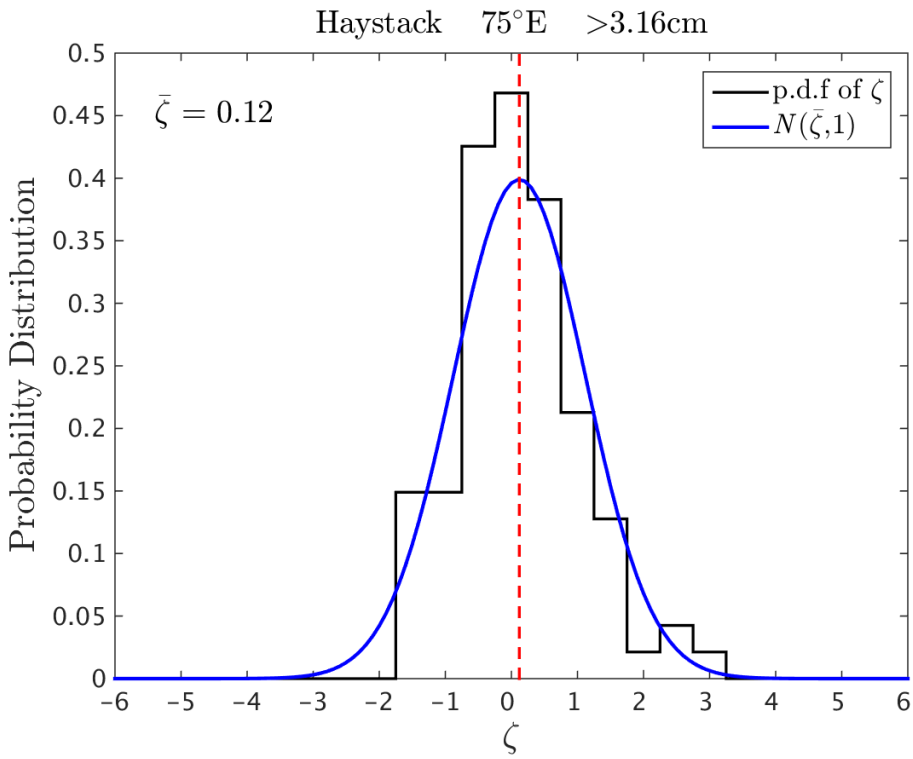

Figure D.2.2-21. Haystack (75°E only), >3.16 cm, 1-sigma.

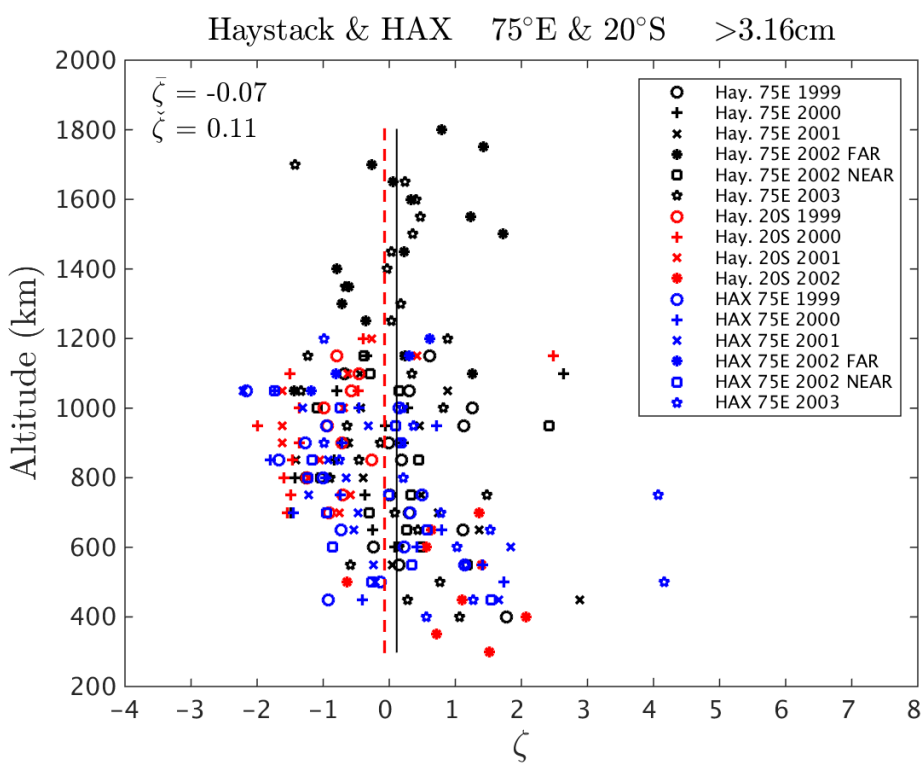

Figure D.2.2-22. Haystack (75°E, 20°S) & HAX (75°E only), >3.16 cm.

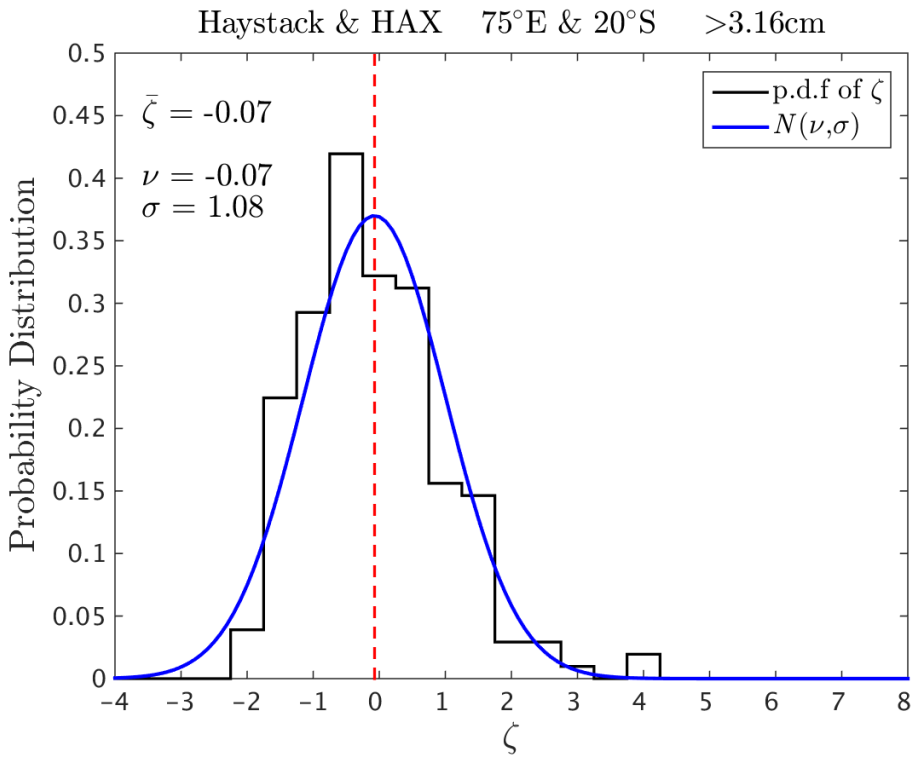

Figure D.2.2-23. Haystack (75°E, 20°S) & HAX (75°E only), >3.16 cm, fitted.

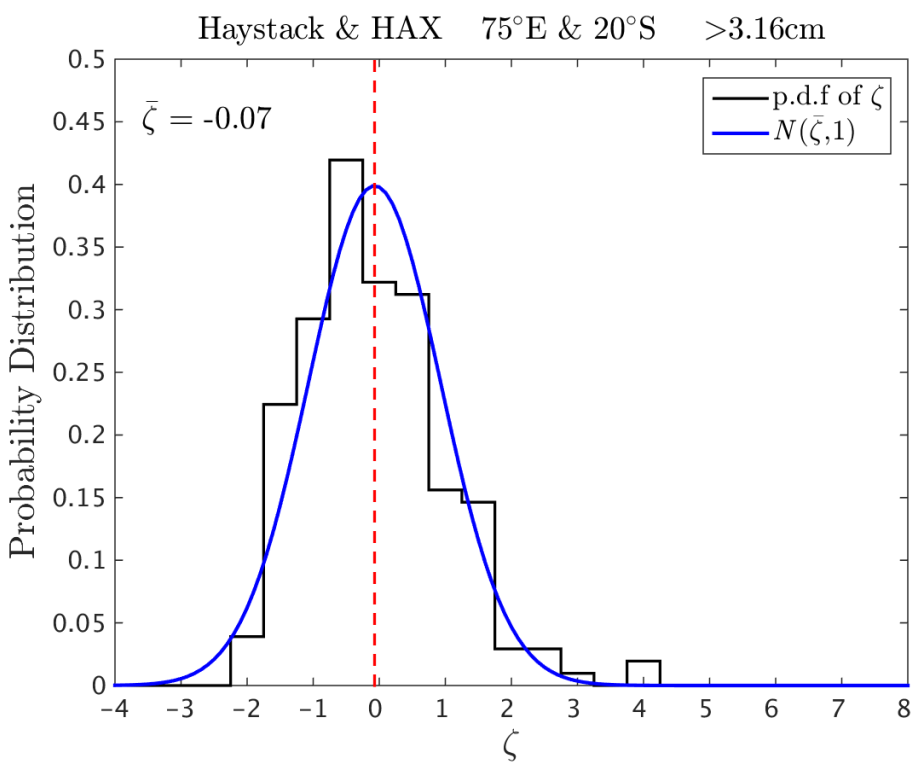

Figure D.2.2-24. Haystack (75°E, 20°S) & HAX (75°E only), >3.16 cm, 1-sigma.

2.2.1. *Kolmogorov-Smirnov Test*

As discussed in the previous section, validation tests were performed on ORDEM 3.0 fluxes for Haystack (sizes >1 cm, > 3.16 cm and pointing directions 75°E, 20°S) and HAX (size > 3.16 cm, pointing direction 20°S) sensors. Excluded populations in these tests include easily identifiable NaK (by high polarization and ~ 900 km, or ~700 km altitude).

The problem is how to fit the "square peg" of Poisson integer values into the "round hole" of a continuous theoretical distribution – in this case a normal distribution. One method is to simply convert the integer value into its equivalent real value. However, this direct conversion is well-known to introduce a bias. Statisticians use the concept of a "continuity correction" to remove this bias. For a Poisson problem, the continuity correction is obtained by adding ½ to the integer value before converting to the equivalent real value. This is especially appropriate for cumulative distributions, which is exactly what is desired for a Kolmogorov-Smirnov (K-S) test.

For each 50-km bin (denoted by the subscript "*i*") per year of observation, let m_i be the integer number of radar detections, f_i the radar-observed flux, μ_i the ORDEM-predicted OD flux, and σ_{μ_i} the ORDEM 3.0 uncertainty calculated for that flux. The expected (mean) value x_i and σ_{x_i} based on ORDEM 3.0 is

$$x_i = \mu_i \cdot \left(\frac{m_i}{f_i}\right), \qquad \sigma_{x_i} = \sigma_{\mu_i} \cdot \left(\frac{m_i}{f_i}\right)$$

Thus, for each 50-km altitude bin (denoted by the subscript "*i*"), ζ_i is

$$\zeta_i = \frac{(m_i + ½) - x_i}{\sqrt{\left(\sqrt{x_i}\right)^2 + \sigma_{x_i}^2}}$$

Note that the scaling in the denominator represents the square root of the sum of the squares of two contributions. One contribution is the sigma introduced by the Poisson process, which is estimated by the square root of the expected mean value x_i. The other is the sigma associated with the ORDEM flux values.

Let *N* stand for the total data points per year of observation and a 50-km altitude bin denoted by the subscript "*j*". For a single set of data, the "unweighted" average $\bar{\zeta}$ is:

$$\bar{\zeta} = \frac{\sum_{j=1}^{N} \zeta_j}{N}$$

Ideally, the distribution in ζ_i values should represent a normal distribution scaled such that the mean is zero, and the standard deviation should be one (1). The p-value, which represents the fraction of random draws from the normal distribution with a *worse* K-S fit, is given for the shifted mean value. In order to pass this goodness-of-fit test between a normal distribution and an empirical distribution, the p-value must be greater than 0.1 (to represent data within the 90th percentile) and the absolute value of the mean should be less than 1.0 (1-sigma).

Table D.2.2.1-1 shows results for a Kolmogorov-Smirnov test on each validation test. As in the verification section of this document, the last column 'Passed' indicates a successful outcome by a green checkmark (✓), or a failure by a red X (✗). The only cases that did not pass were the Haystack 1 cm cases, which were seen to have a distinct bias. However, it is important to remember that the Haystack 20°S cases had issues with completeness because of known radar sensitivities at long range.

TABLE D.2.2.1-1 – K-S TEST RESULTS, HAYSTACK/HAX, NAK EXCLUDED

Test No.	Sensor(s)	Pointing	Obs. Years	Cum. Size	$\bar{\zeta}$	K-S p-value	Passed
1	Haystack	20°S	1999-2002	>1cm	-1.448	0.379	✗
2	Haystack	75°E	1999-2003	>1cm	-0.283	0.842	✓
3	Haystack Haystack	75°E 20°S	1999-2003, 1999-2002	>1cm	-0.590	0.498	✓
4	Haystack	20°S	1999-2002	>3.16cm	-0.467	0.125	✓
5	Haystack HAX	75°E 75°E	1999-2003 1999-2003	>3.16cm	0.027	0.305	✓
6	HAX	75°E	1999-2003	>3.16cm	-0.097	0.163	✓
7	Haystack	75°E	1999-2003	>3.16cm	0.120	0.107	✓
8	Haystack Haystack HAX	75°E 20°S 75°E	1999-2003 1999-2002 1999-2003	>3.16cm	-0.071	0.251	✓

2.2.2. *Log-Likelihood Test*

Perhaps a better way to estimate how good the data fit the model is to use the nature of the Poisson sampling and conduct a log-likelihood (L-L) test. The log-likelihood is a measure of how likely a particular set of integer data values came from a set of model mean predictions. Because it deals with Poisson directly, there is no need to make simplifying assumptions to transform the data.

The quality of the match is computed by summing the log-likelihood in each bin, using the notation in the previous section for the predicted model value x_i and integer data value m_i:

$$\mathcal{L} = \sum_{i=1}^{N} m_i \ln(x_i) - x_i - \ln(m_i!)$$

This value for the data can be compared to the log-likelihood distribution from Monte Carlo data randomly selected from the x_i values using a Poisson sampler.

For this analysis, the uncertainty values σ_{x_i} are included by varying the value of x_i' for each Monte Carlo run to represent the range of possible values based on the model uncertainty. Therefore, for each Monte Carlo run, the randomly selected values m_i are selected from a

Poisson distribution with mean x_i', where x_i' was selected from a distribution centered on x_i' (the model value) with standard deviation σ_{x_i} .

As before, the p-value represents the fraction of random draws from the Poisson means with a *worse* L-L fit. A p-value greater than 0.1 (representing a data match within the 90th percentile) is considered 'Passed'. A p-value of 0.5 indicates a completely nominal fit and large p-values (greater than 0.5) indicate a high-quality match between the model and the data. If the p-value is less than about 0.1, this indicates a low probability that the data could have come from the model and is considered 'Failed'.

Table D.2.2.2-1 shows the results of these tests. This table shows that all the cases are within the 90th percentile confidence, except for some of those that include Haystack 20°S cases. As these south-staring cases are known to have sensitivity issues at longer ranges, these results are not surprising and are considered acceptable.

TABLE D.2.2.2-1 – L-L TEST RESULTS, HAYSTACK/HAX, NAK EXCLUDED

Test No.	Sensor(s)	Pointing	Obs. Years	Cum. Size	L-L p-value	Passed
1	Haystack	20°S	1999-2002	>1cm	0.016	✘
2	Haystack	75°E	1999-2003	>1cm	0.208	✓
3	Haystack Haystack	75°E 20°S	1999-2003, 1999-2002	>1cm	0.064	✘
4	Haystack	20°S	1999-2002	>3.16cm	0.088	✘
5	Haystack HAX	75°E 75°E	1999-2003 1999-2003	>3.16cm	0.227	✓
6	HAX	75°E	1999-2003	>3.16cm	0.132	✓
7	Haystack	75°E	1999-2003	>3.16cm	0.774	✓
8	Haystack Haystack HAX	75°E 20°S 75°E	1999-2003 1999-2002 1999-2003	>3.16cm	0.179	✓

2.3. SURFACE AREA FLUX VS. ALTITUDE (> 3 mm)

The ORDEM 3.0 telescope/radar mode output mimics the surface area flux observed by a ground-sensor, at a specific location on the Earth's surface and with a specific pointing direction (*i.e.*, azimuth and elevation). It presumes a pencil beam with altitude gradations in 50 km increments. The flux in each altitude bin is also graded by size.

2.3.1. *ORDEM 3.0 vs. Haystack/Hax & SSN*

This section displays the comparison of ORDEM 3.0 results with Haystack/HAX and SSN data for altitude in 50 km bins versus orbital debris fluxes for 1 cm and larger objects in LEO. The Haystack/HAX data shown are for the years 1999-2003 with Poisson lower and upper confidence limits at the Poisson single-sided confidence level of 84.13%. ORDEM 3.0 predicted fluxes are shown together with standard errors (1-sigma).

The following figures in this section represent 6 years of data and model predictions. Each year has five charts that are ordered in decreasing debris size, (*i.e.*, >1 m, >31.6 cm, >10 cm, > 3.16 cm, > 1 cm, respectively). Table D.2.3.1-1 shows the observational hours of each of the yearly datasets used in these validation tests.

Note that charts for the 2003 Haystack data include a 2-dB RCS-bias correction.

TABLE D.2.3.1-1 – OBSERVATION HOURS FOR HAYSTACK/HAX

Year	Direction	Obs. Hrs, exclude > 1 cm	Obs. Hrs, > 1 cm
1999	75°E	579.2	210.2
2000	75°E	580.3	264.9
2001	75°E	618.4	250.64
2002	75°E, near	241.8	171.26
2002	75°E, far	226.8	175.5
2003	75°E	541.8	633.3

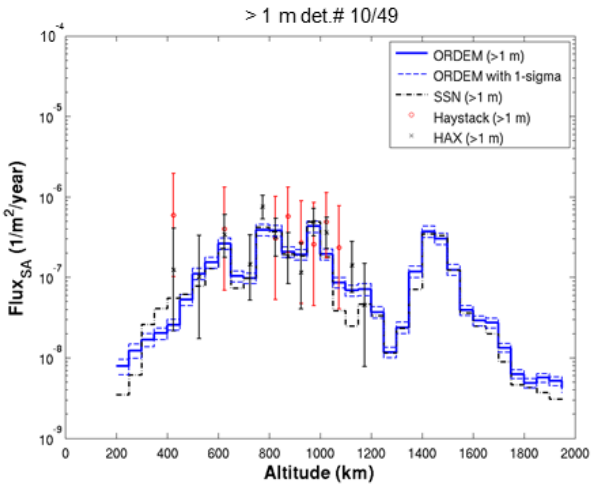

Figure D.2.3.1-1. 1999, 75°E, > 1 m, altitude vs. flux.

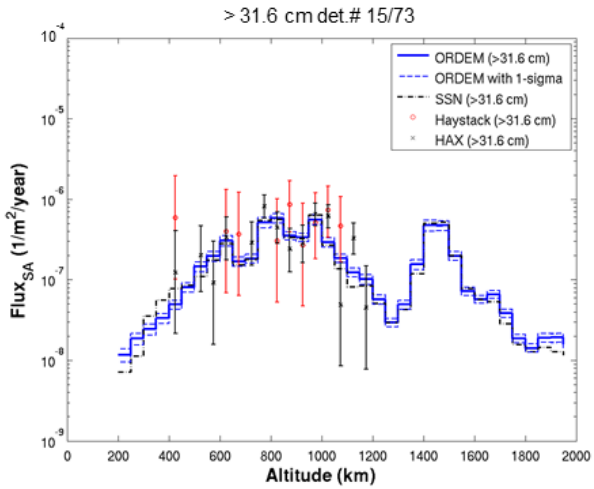

Figure D.2.3.1-1. 1999, 75°E, > 31.6 cm, altitude vs. flux.

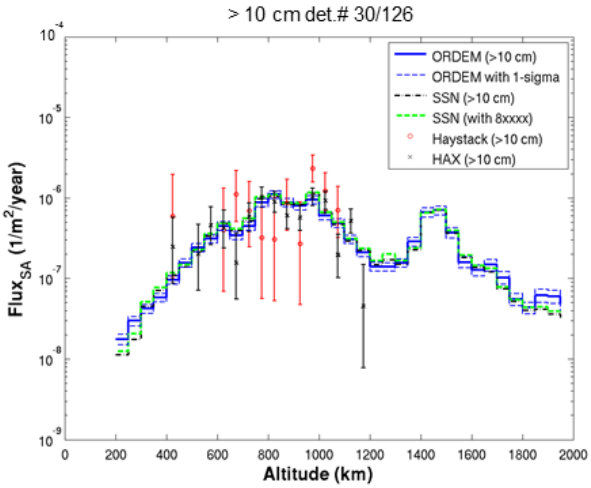

Figure D.2.3.1-3. 1999, 75°E, > 10 cm, altitude vs. flux.

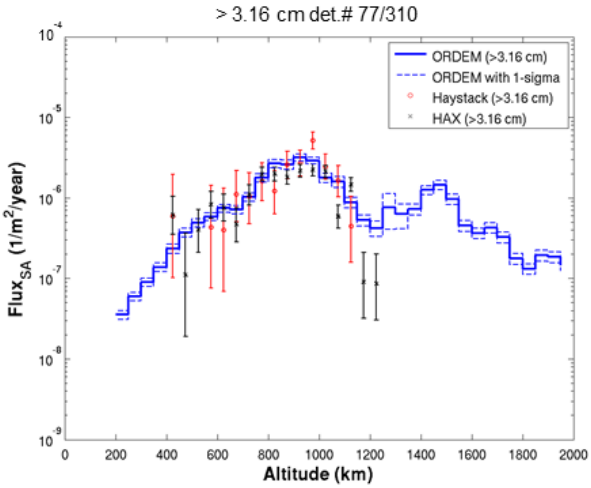

Figure D.2.3.1-4. 1999, 75°E, > 3.16 cm, altitude vs. flux

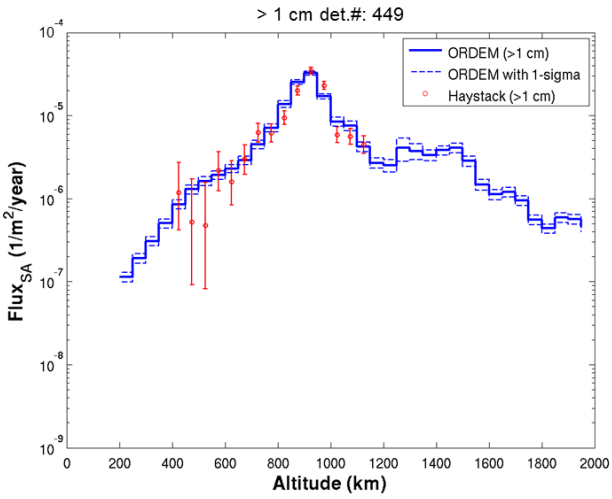

Figure D.2.3.1-5. 1999, 75°E, > 1 cm, altitude vs. flux.

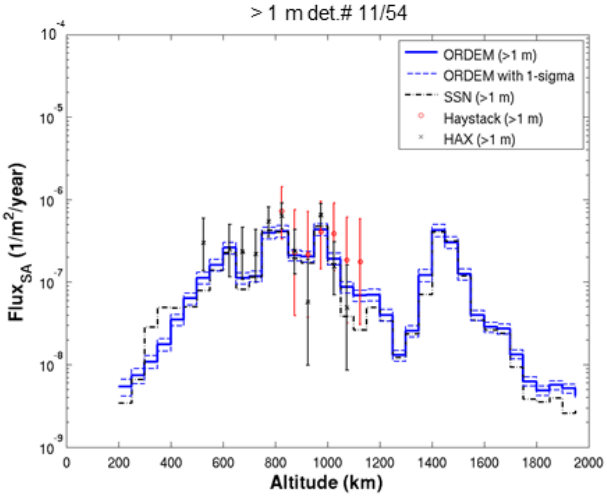

Figure D.2.3.1-6. 2000, 75°E, > 1 m, altitude vs. flux.

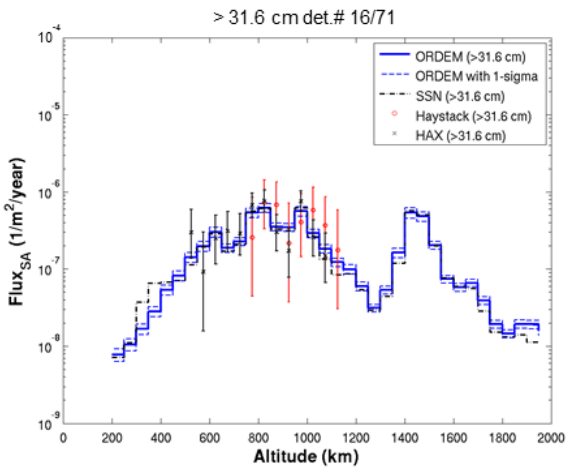

Figure D.2.3.1-7. 2000, 75°E, > 31.6 cm, altitude vs. flux.

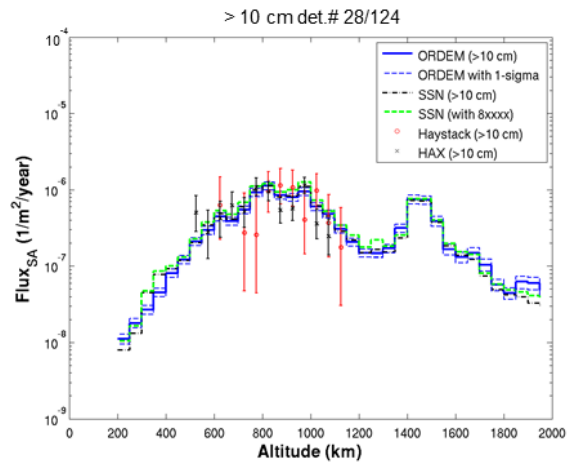

Figure D.2.3.1-8. 2000, 75°E, > 10 cm, altitude vs. flux.

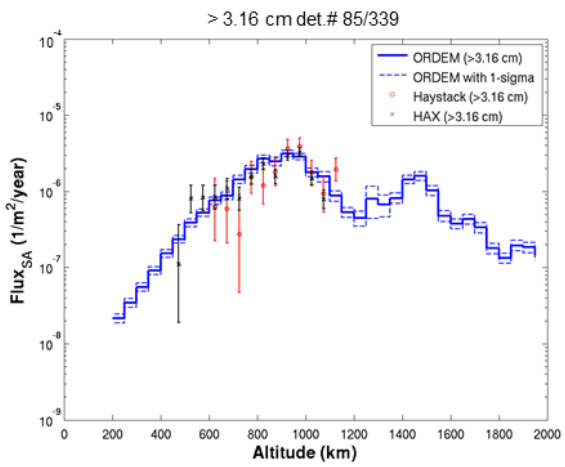

Figure D.2.3.1-9. 2000, 75°E, > 3.16 cm, altitude vs. flux.

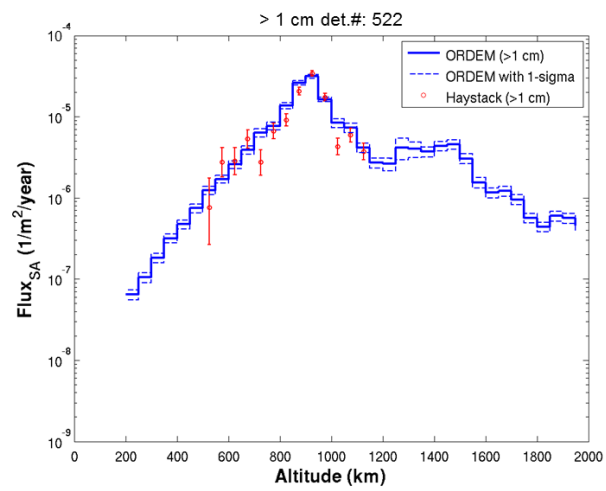

Figure D.2.3.1-10. 2000, 75°E, > 1 cm, altitude vs. flux.

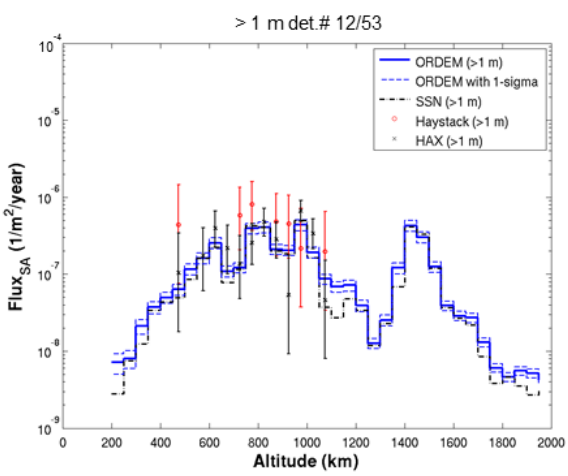

Figure D.2.3.1-11. 2001, 75°E, > 1 m, altitude vs. flux.

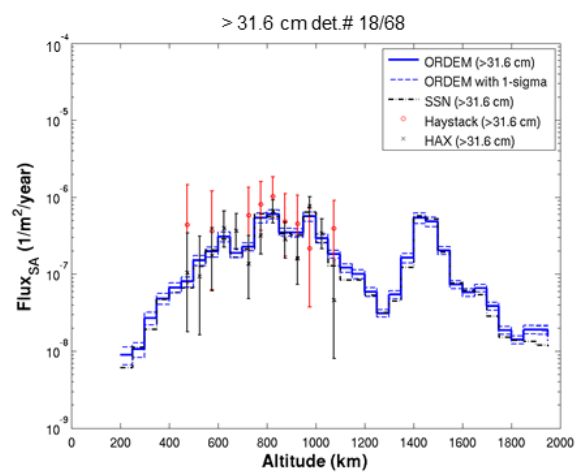

Figure D.2.3.1-12. 2001, 75°E, > 31.6 cm, altitude vs. flux.

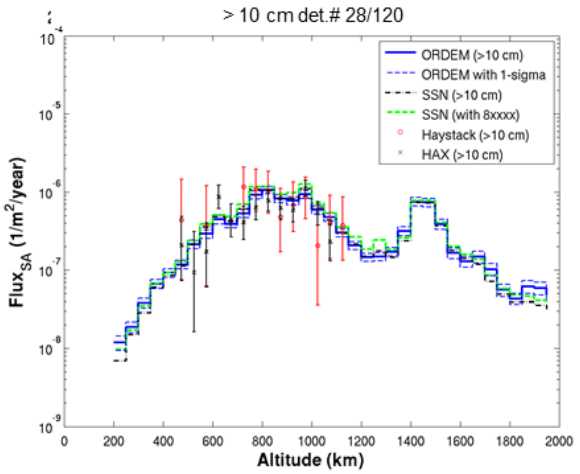

Figure D.2.3.1-13. 2001, 75°E, > 10 cm, altitude vs. flux.

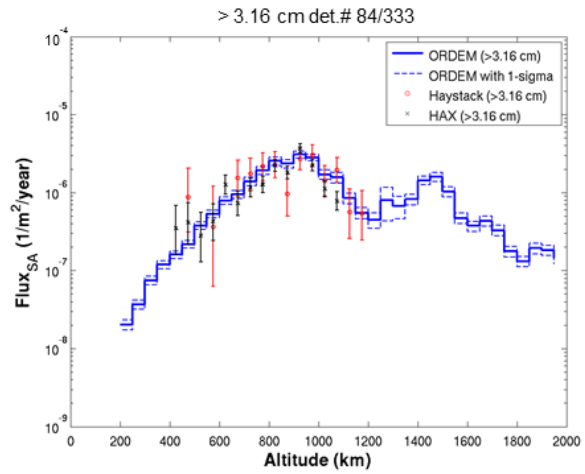

Figure D.2.3.1-14. 2001, 75°E, > 3.16 cm, altitude vs. flux.

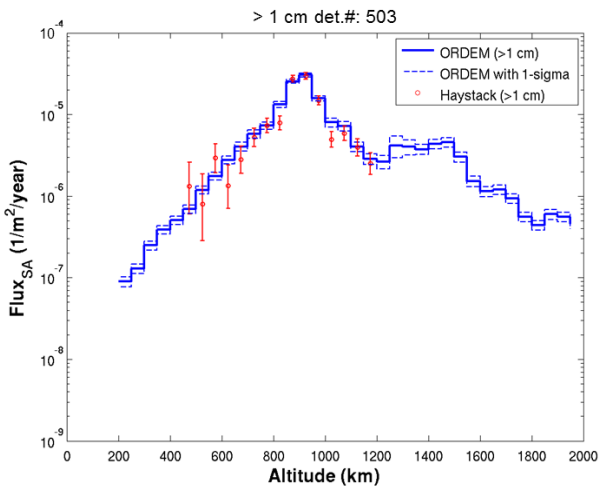

Figure D.2.3.1-15. 2001, 75°E, > 1 cm, altitude vs. flux.

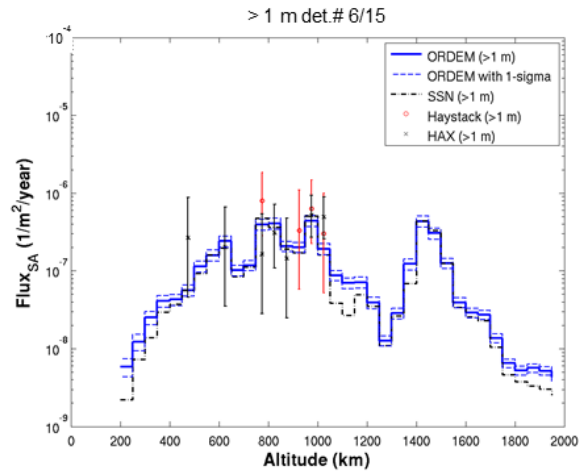

Figure D.2.3.1-16. 2002 near, 75°E, > 1 m, altitude vs. flux.

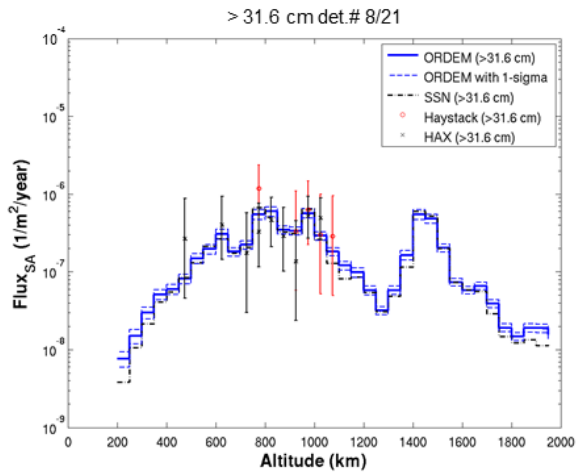

Figure D.2.3.1-17. 2002 near, 75°E, > 31.6 cm, altitude vs. flux.

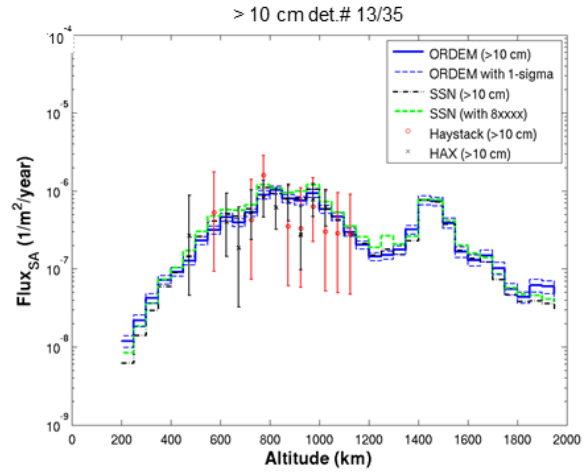

Figure D.2.3.1-18. 2002 near, 75°E, > 10 cm, altitude vs. flux.

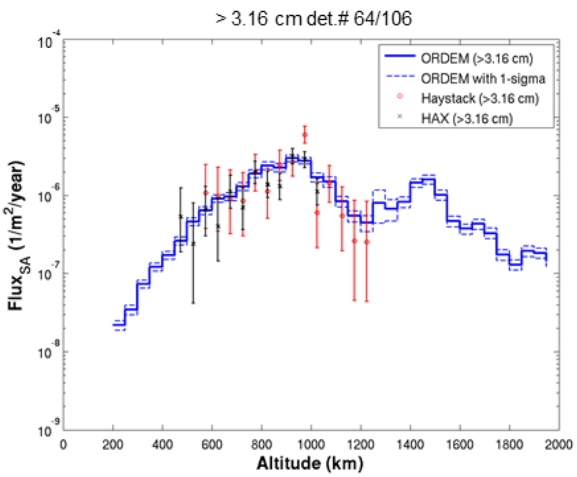

Figure D.2.3.1-19. 2002 near, 75°E, > 3.16 cm, altitude vs. flux.

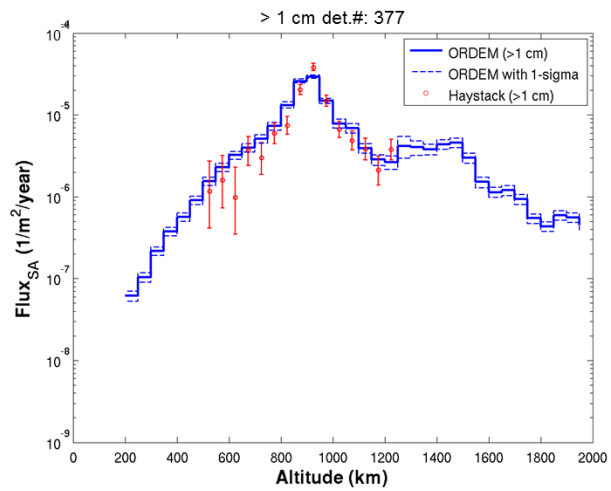

Figure D.2.3.1-20. 2002 near, 75°E, > 1 cm, altitude vs. flux.

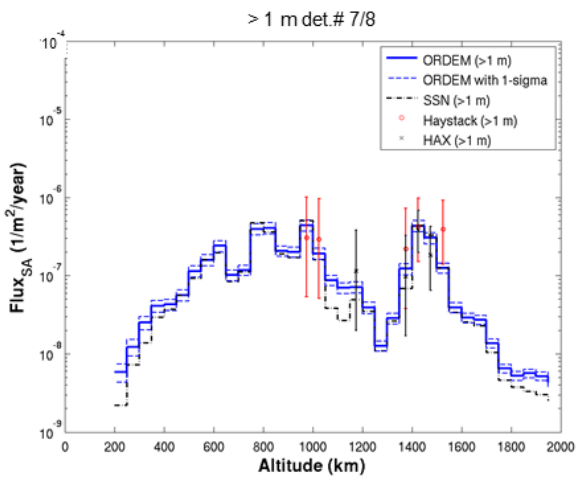

Figure D.2.3.1-21. 2002 far, 75°E, > 1 m, altitude vs. flux.

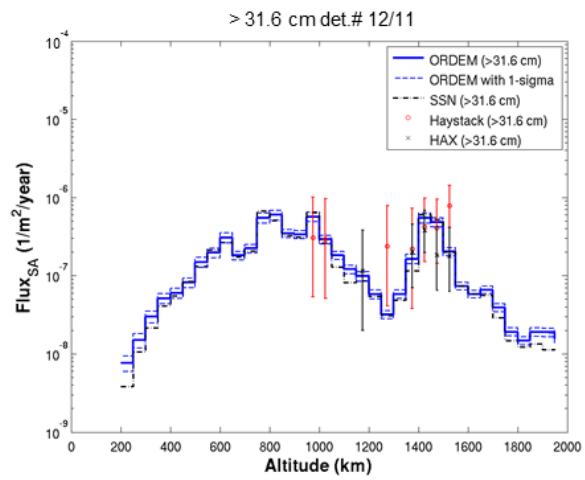

Figure D.2.3.1-22. 2002 far, 75°E, > 31.6 cm, altitude vs. flux.

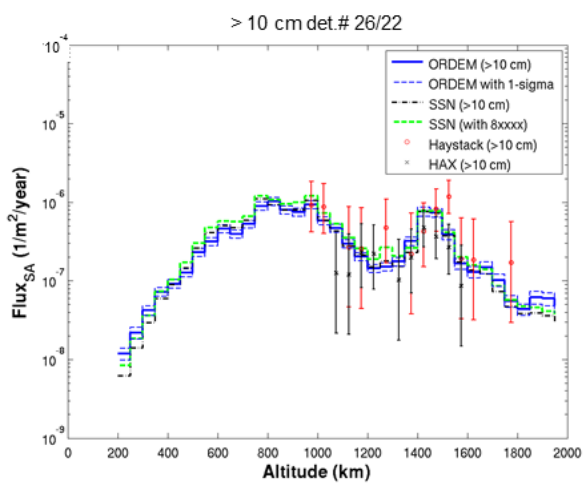

Figure D.2.3.1-23. 2002 far, 75°E, > 10 cm, altitude vs. flux.

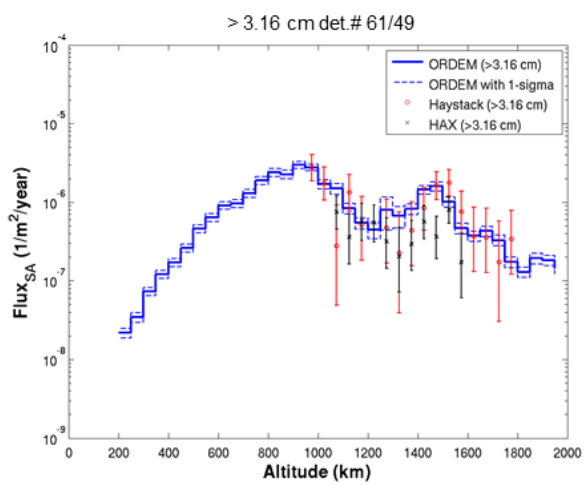

Figure D.2.3.1-24. 2002 far, 75°E, > 3.16 cm, altitude vs. flux.

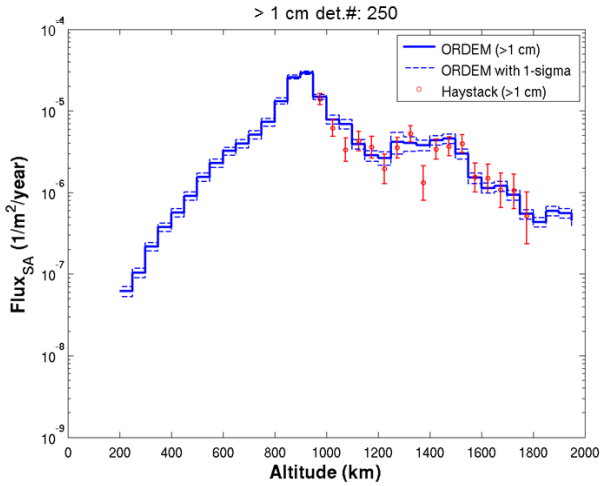

Figure D.2.3.1-25. 2002 far, 75°E, > 1 cm, altitude vs. flux.

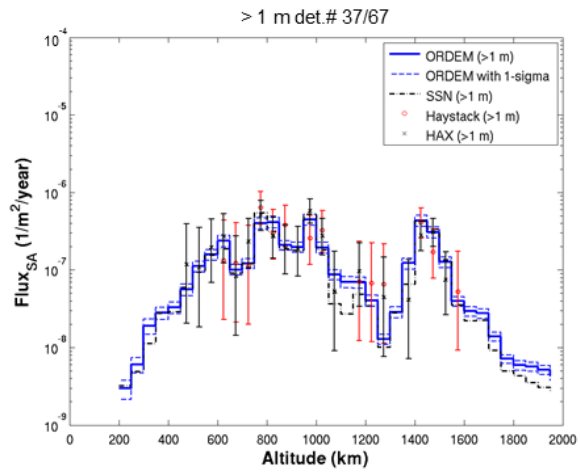

Figure D.2.3.1-26. 2003, 75°E, > 1 m, altitude vs. flux.

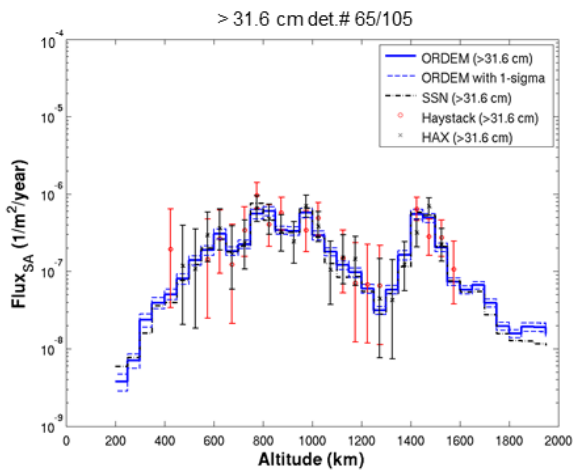

Figure D.2.3.1-27. 2003, 75°E, > 31.6 cm, altitude vs. flux.

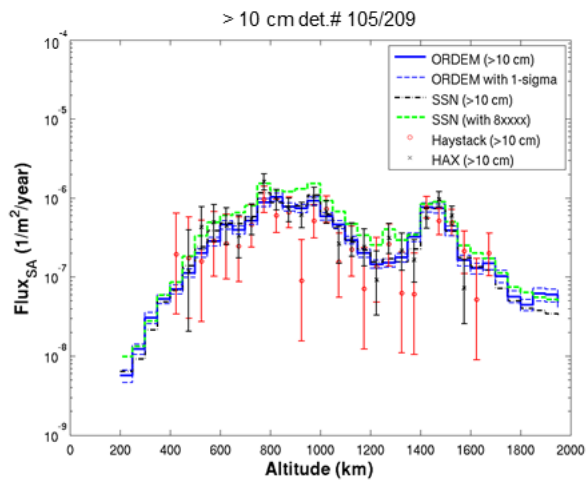

Figure D.2.3.1-28. 2003, 75°E, > 10 cm, altitude vs. flux.

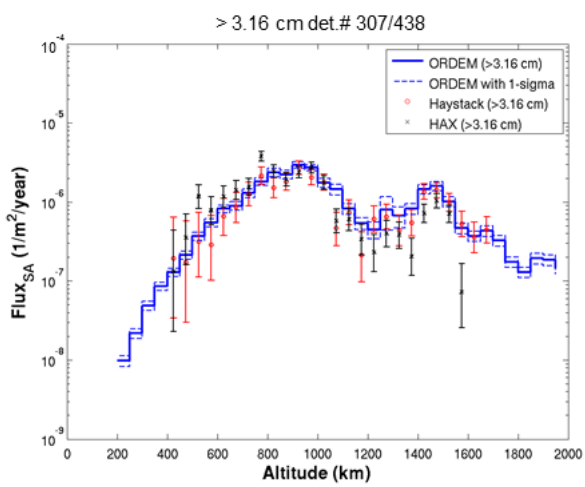

Figure D.2.3.1-29. 2003, 75°E, > 3.16 cm, altitude vs. flux.

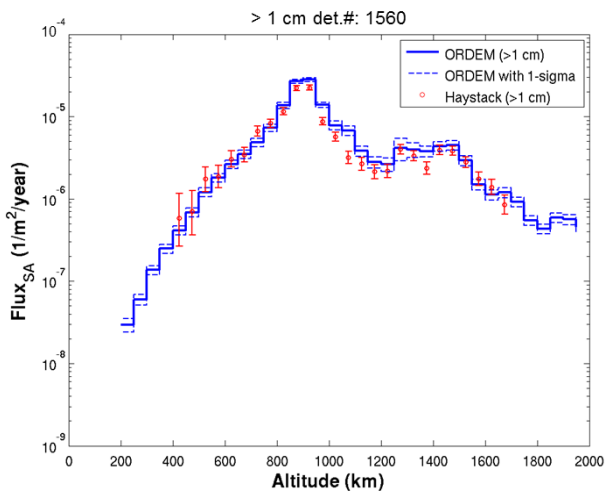

Figure D.2.3.1-30. 2003, 75°E, > 1 cm, altitude vs. flux.

2.3.2. *ORDEM 3.0 vs. Goldstone & SSN*

This section displays the comparison of ORDEM 3.0 results with Goldstone data for altitude in 50 km bins versus orbital debris fluxes for 3.16 mm and larger objects in LEO. The Goldstone data shown are for the years of 2001 and 2005-2007 with Poisson lower and upper confidence limits at the Poisson single-sided confidence level of 84.13. ORDEM 3.0 predicted fluxes are shown together with standard errors (1-sigma).

The following figures in this section represent one year of data and model predictions. Each chart contains data of debris larger than 3.16 mm. Goldstone data at higher altitudes (> 1000 km) is known to be unreliable and is therefore not displayed.

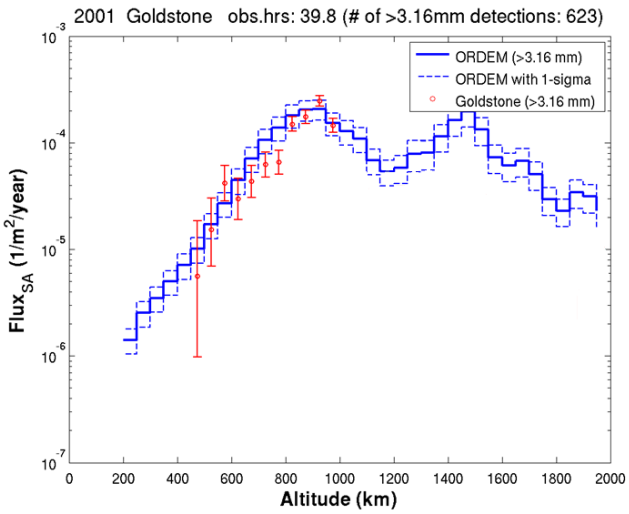

Figure D.2.3.2-1. 2001, Goldstone, altitude vs. flux.

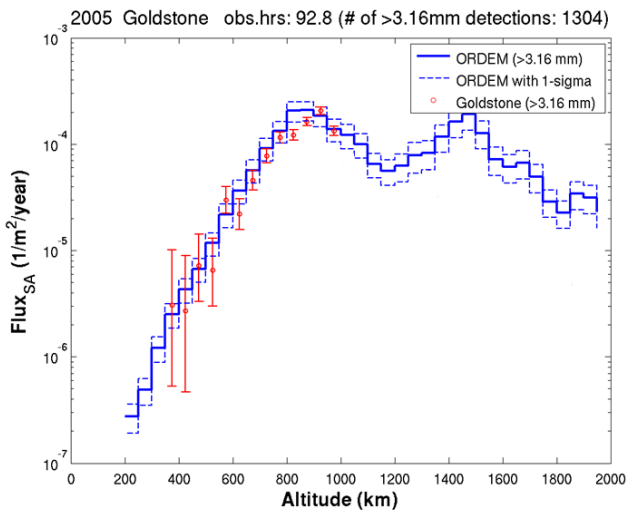

Figure D.2.3.2-2. 2005, Goldstone, altitude vs. flux.

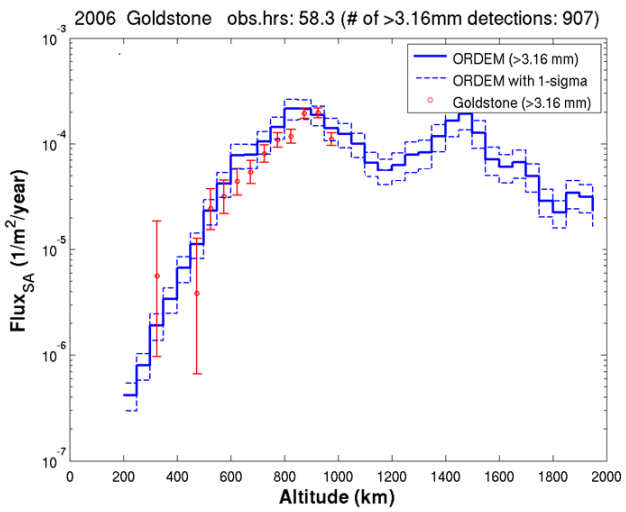

Figure D.2.3.2-3. 2006, Goldstone, altitude vs. flux.

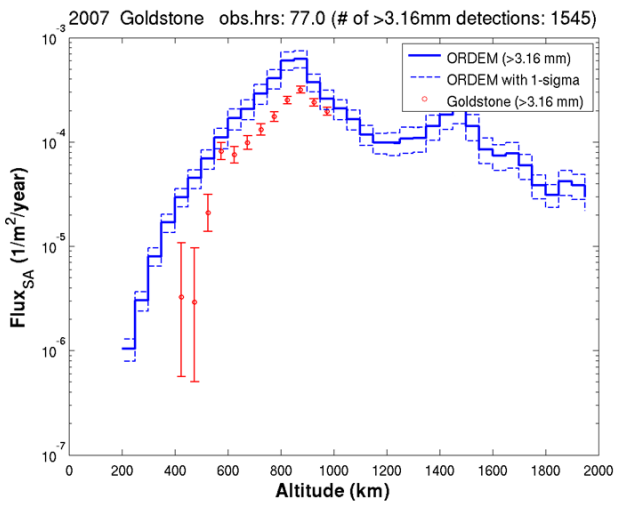

Figure D.2.3.2-4. 2007, Goldstone, altitude vs. flux.

2.4. SURFACE AREA FLUX VS. SIZE (> 3 mm)

This section displays the comparison of ORDEM 3.0 results with the radar sensor data (Haystack/HAX, Goldstone) and SSN data for cumulative size in half decade $\log_{10}$ bins versus orbital debris flux. A cumulative spline fit is used between decades. Size ranges are between 1 cm and 1 m. ORDEM 3.0 predicted fluxes are shown together with standard errors (1-sigma).

2.4.1. *ORDEM 3.0 vs. Haystack/Hax & SSN*

The Haystack/HAX data shown in the following figures are for the years of 1999-2003 with Poisson lower and upper confidence limits at the Poisson single-sided confidence level of 84.13. Table 2.4.1-1 lists the year, altitude ranges, and number of charts for each yearly set.

TABLE D.2.4.1-1 – SIZE VS. FLUX, HAYSTACK/HAX & SSN, YEARS AND ALTITUDE RANGES

Year	Altitude Range	# Charts	Figures
1999	400km-1200km	16	F.2.4.1-1 thru F.2.4.1-16
2000	450km-1150km	14	F.2.4.1-17 thru F.2.4.1-30
2001	400km-1150km	15	F.2.4.1-31 thru F.2.4.1-45
2002, near	400km-1100km	14	F.2.4.1-46 thru F.2.4.1-59
2002, far	1050km-1650km	12	F.2.4.1-60 thru F.2.4.1-71
2003	400km-1650km	25	F.2.4.1-72 thru F.2.4.1-96

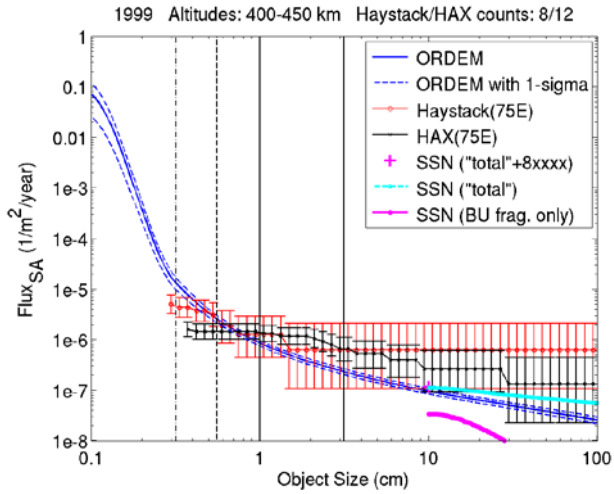

Figure D.2.4.1-1. 1999, Hay./HAX, 400-450 km, size vs. flux.

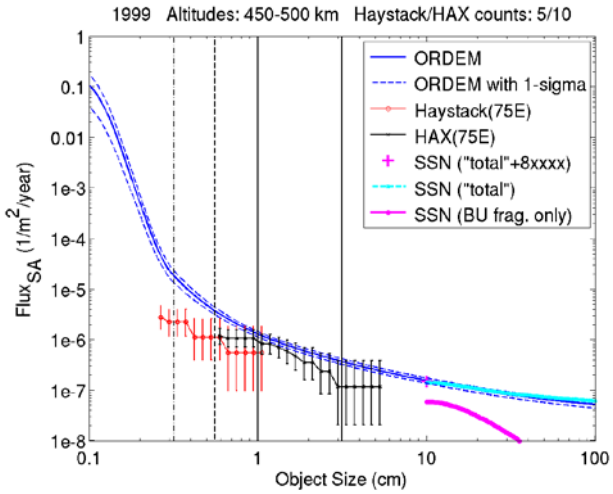

Figure D.2.4.1-2. 1999, Hay./HAX, 450-500 km, size vs. flux.

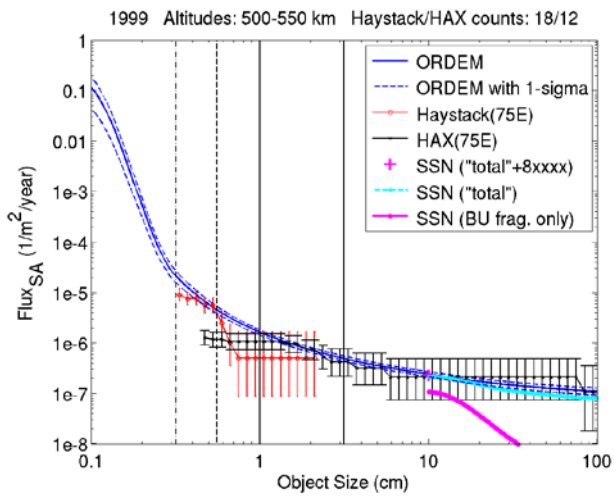

Figure D.2.4.1-3. 1999, Hay./HAX, 500-550 km, size vs. flux.

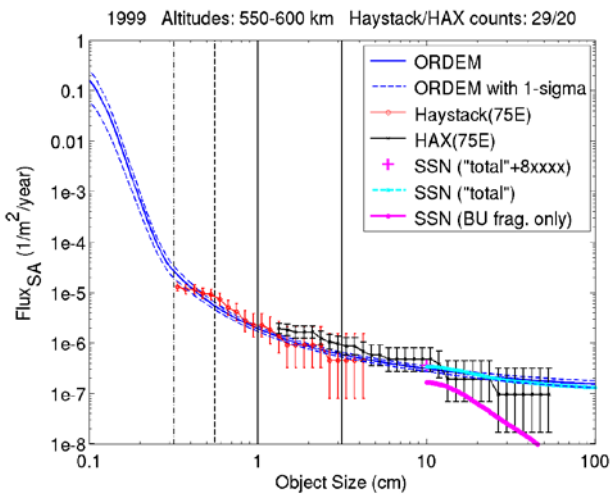

Figure D.2.4.1-4. 1999, Hay./HAX, 550-600 km, size vs. flux.

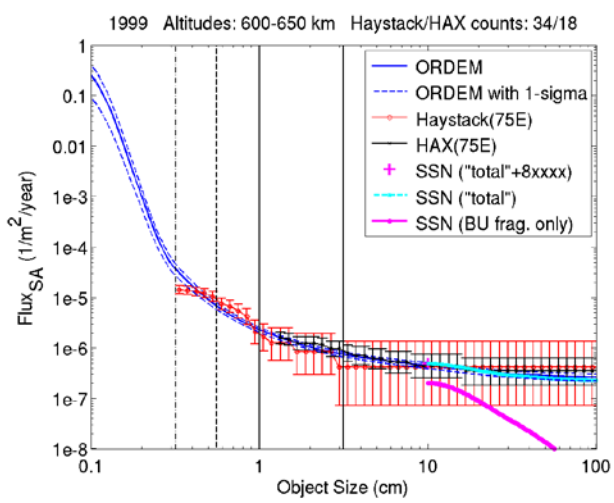

Figure D.2.4.1-5. 1999, Hay./HAX, 600-650 km, size vs. flux.

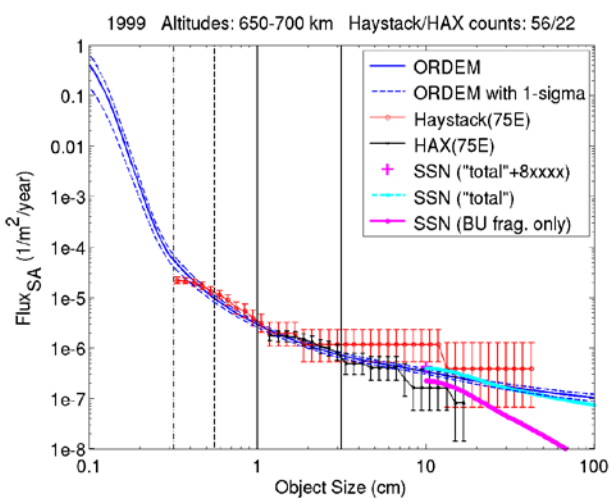

Figure D.2.4.1-6. 1999, Hay./HAX, 650-700 km, size vs. flux.

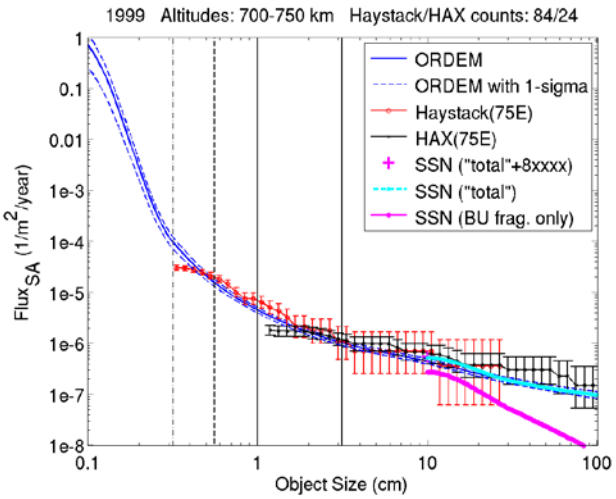

Figure D.2.4.1-7. 1999, Hay./HAX, 700-750 km, size vs. flux.

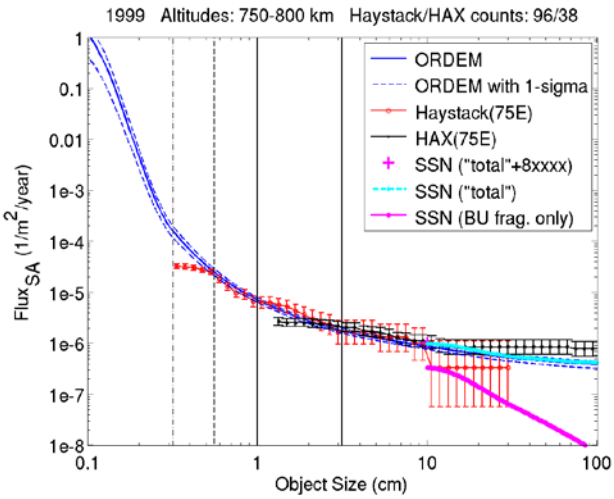

Figure D.2.4.1-8. 1999, Hay./HAX, 750-800 km, size vs. flux.

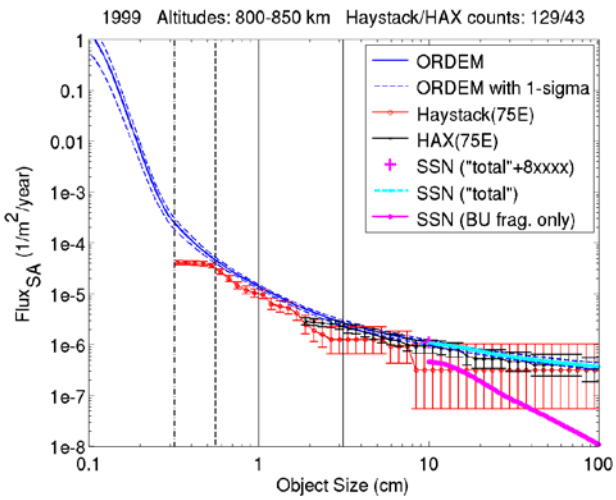

Figure D.2.4.1-9. 1999, Hay./HAX, 800-850 km, size vs. flux.

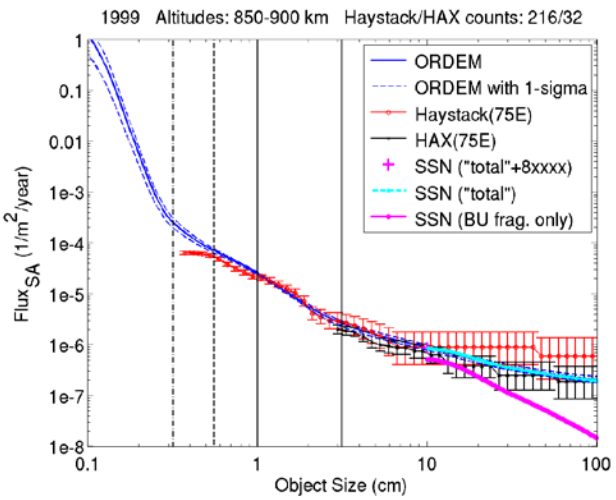

Figure D.2.4.1-10. 1999, Hay./HAX, 850-900 km, size vs. flux.

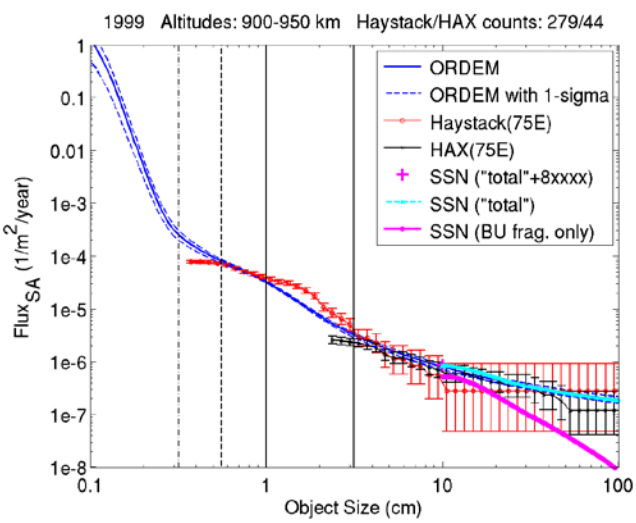

Figure D.2.4.1-11. 1999, Hay./HAX, 900-950 km, size vs. flux.

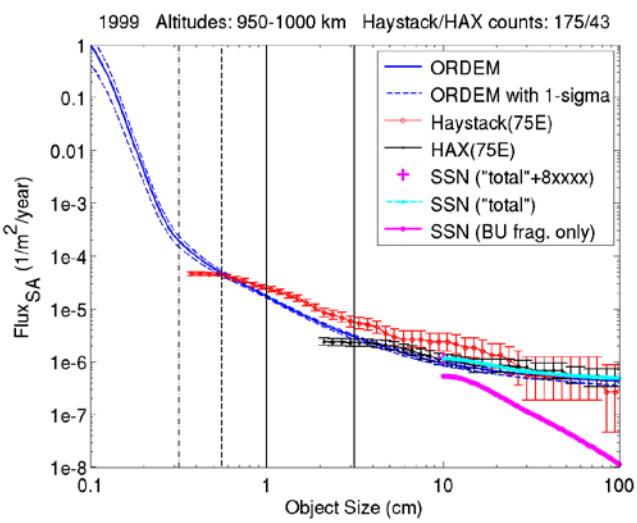

Figure D.2.4.1-12. 1999, Hay./HAX, 950-1000 km, size vs. flux.

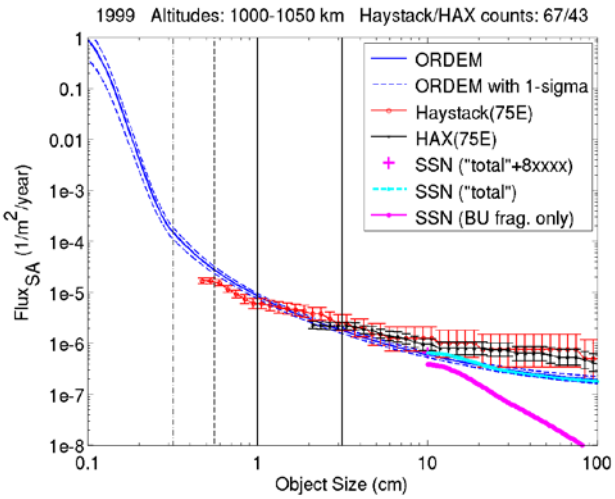

Figure D.2.4.1-13. 1999, Hay./HAX, 1000-1050 km, size vs. flux.

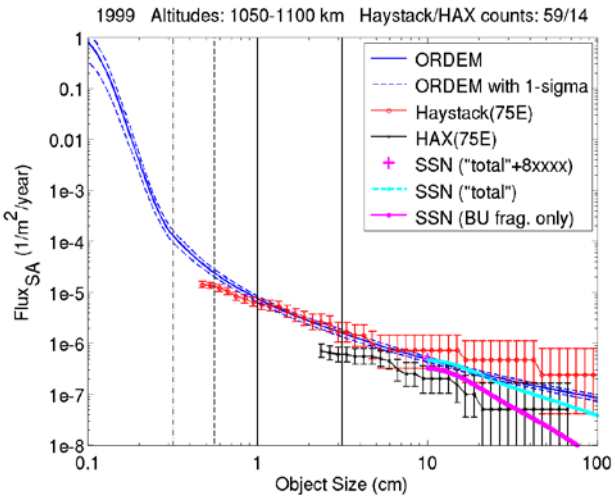

Figure D.2.4.1-14. 1999, Hay./HAX, 1050-1100 km, size vs. flux.

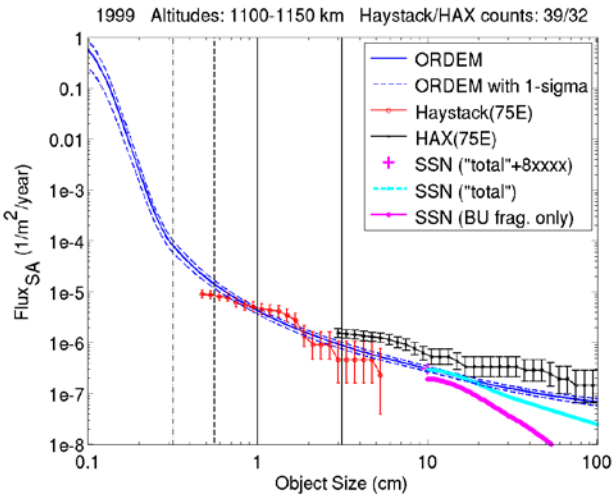

Figure D.2.4.1-15. 1999, Hay./HAX, 1100-1150 km, size vs. flux.

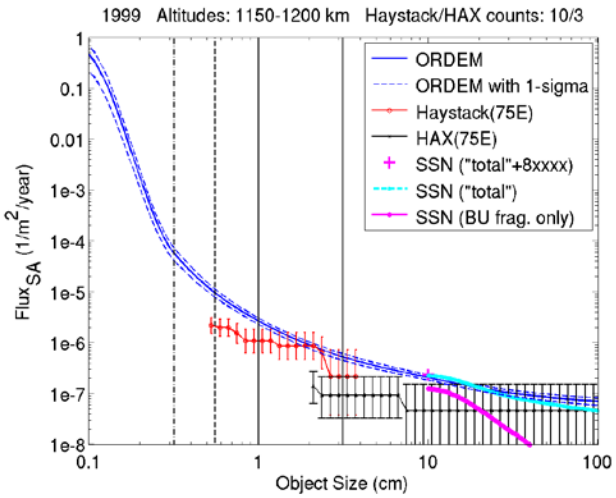

Figure D.2.4.1-16. 1999, Hay./HAX, 1150-1200 km, size vs. flux.

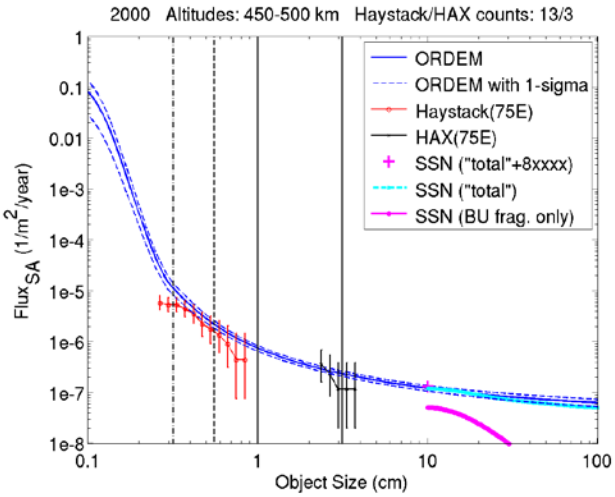

Figure D.2.4.1-17. 2000, Hay./HAX, 450-500 km, size vs. flux.

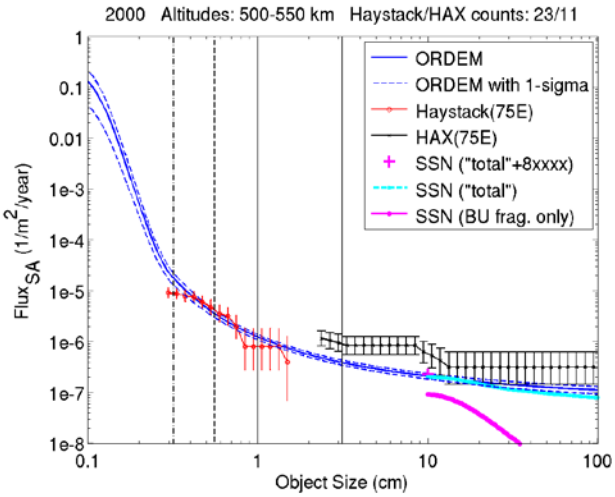

Figure D.2.4.1-18. 2000, Hay./HAX, 500-550 km, size vs. flux.

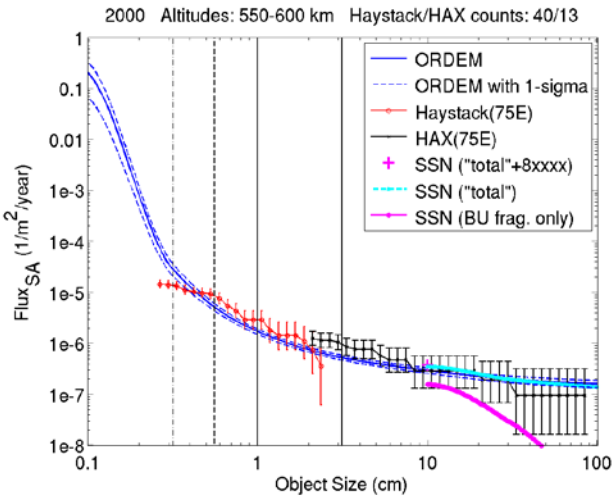

Figure D.2.4.1-19. 2000, Hay./HAX, 550-600 km, size vs. flux.

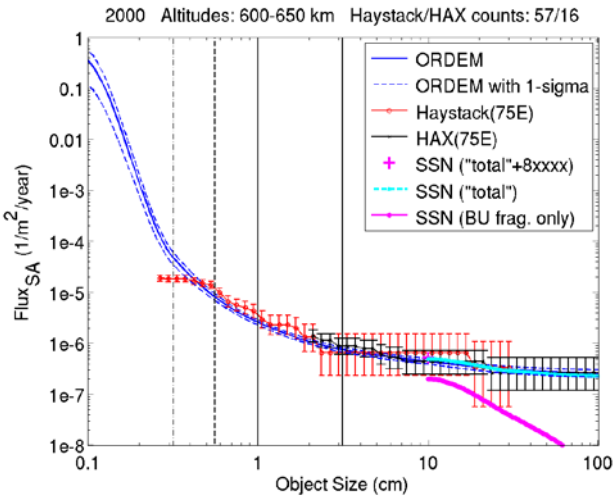

Figure D.2.4.1-20. 2000, Hay./HAX, 600-650 km, size vs. flux.

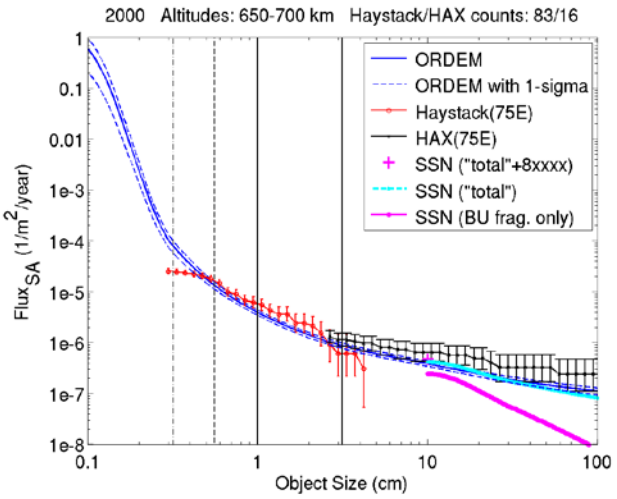

Figure D.2.4.1-21. 2000, Hay./HAX, 650-700 km, size vs. flux.

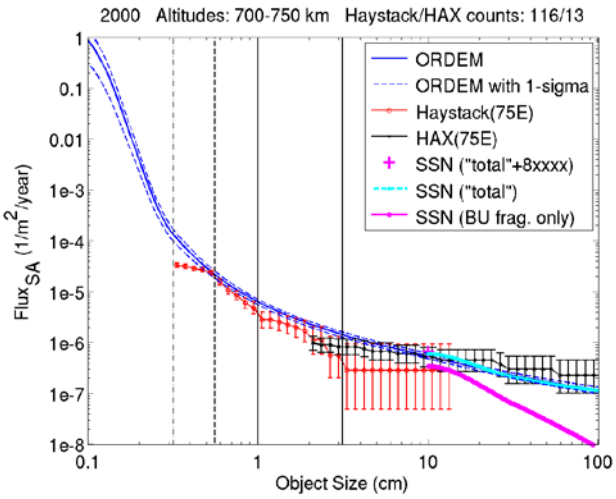

Figure D.2.4.1-22. 2000, Hay./HAX, 700-750 km, size vs. flux.

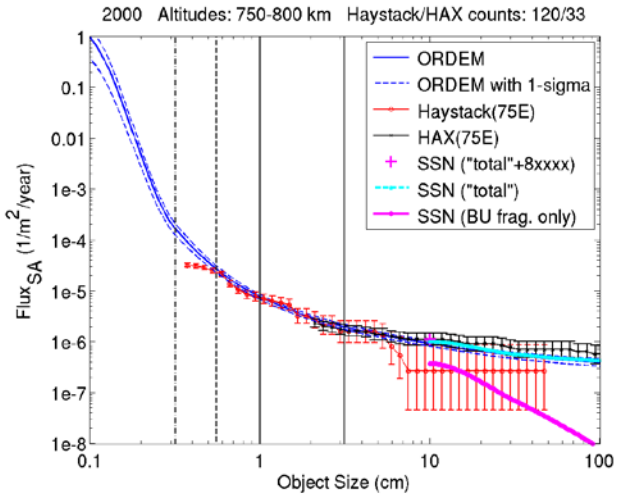

Figure D.2.4.1-23. 2000, Hay./HAX, 750-800 km, size vs. flux.

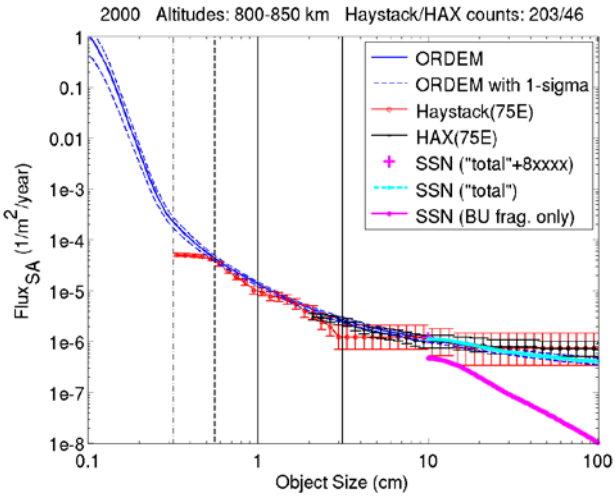

Figure D.2.4.1-24. 2000, Hay./HAX, 800-850 km, size vs. flux.

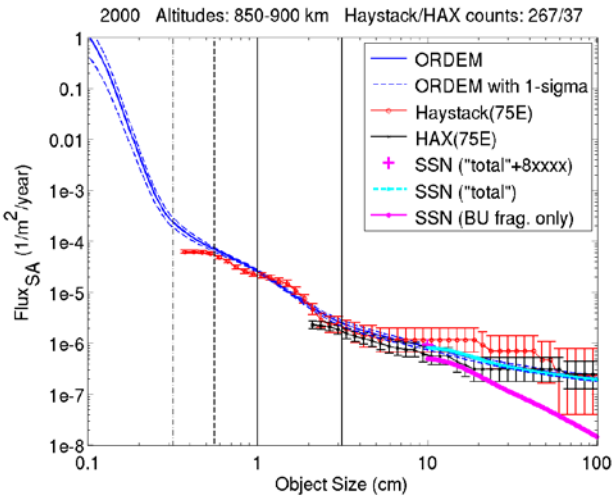

Figure D.2.4.1-25. 2000, Hay./HAX, 850-900 km, size vs. flux.

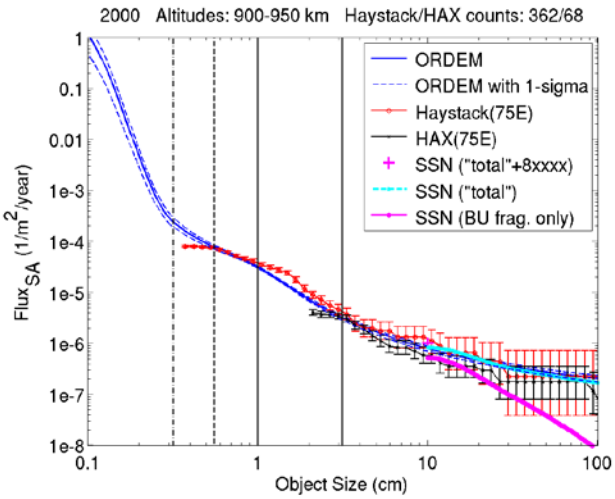

Figure D.2.4.1-26. 2000, Hay./HAX, 900-950 km, size vs. flux.

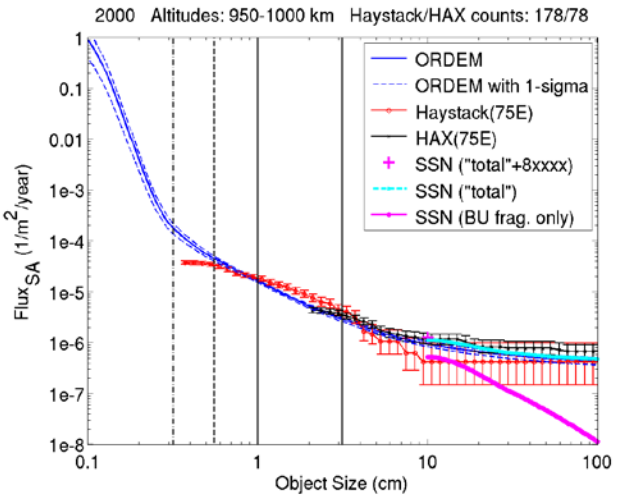

Figure D.2.4.1-27. 2000, Hay./HAX, 950-1000 km, size vs. flux.

x

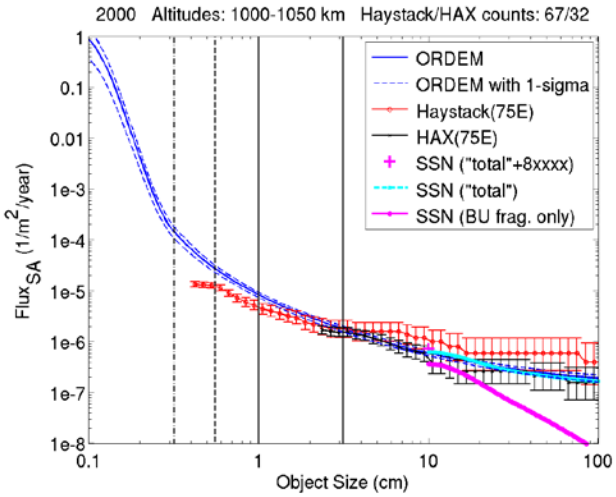

Figure D.2.4.1-28. 2000, Hay./HAX, 1000-1050 km, size vs. flux.

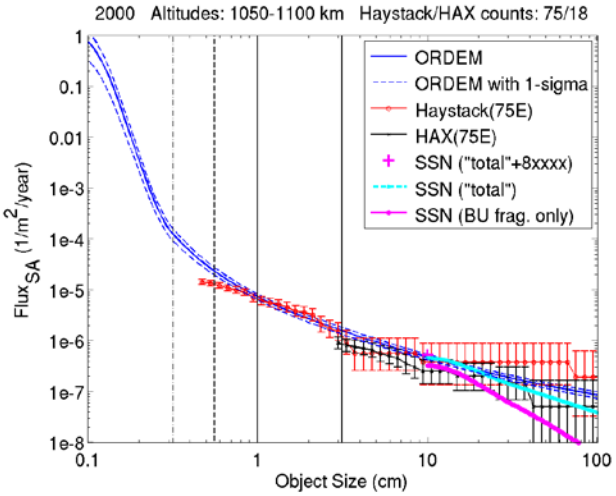

Figure D.2.4.1-29. 2000, Hay./HAX, 1050-1100 km, size vs. flux.

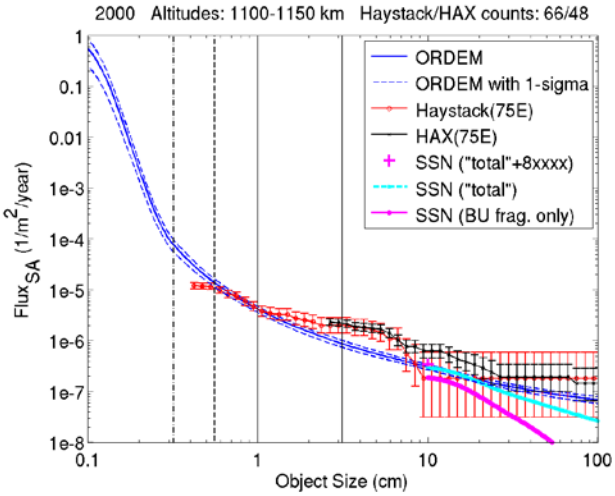

Figure D.2.4.1-30. 2000, Hay./HAX, 1100-1150 km, size vs. flux.

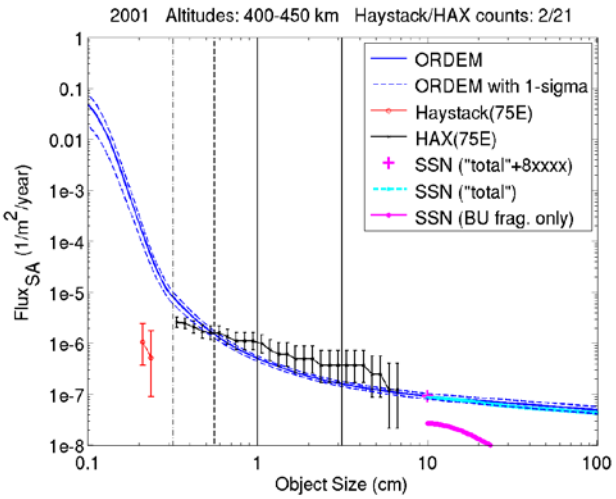

Figure D.2.4.1-31. 2001, Hay./HAX, 400-450 km, size vs. flux.

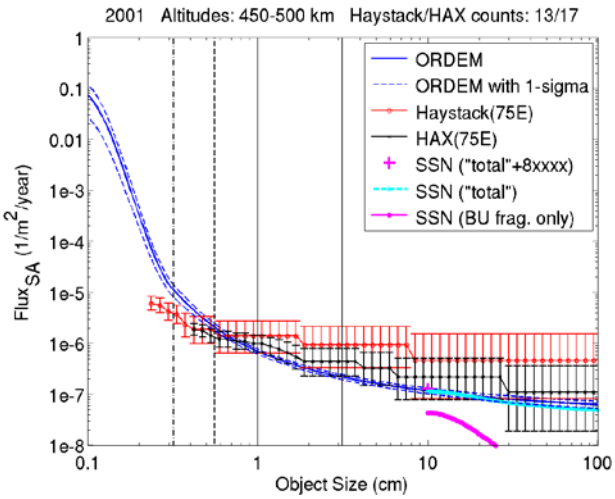

Figure D.2.4.1-32. 2001, Hay./HAX, 450-500 km, size vs. flux.

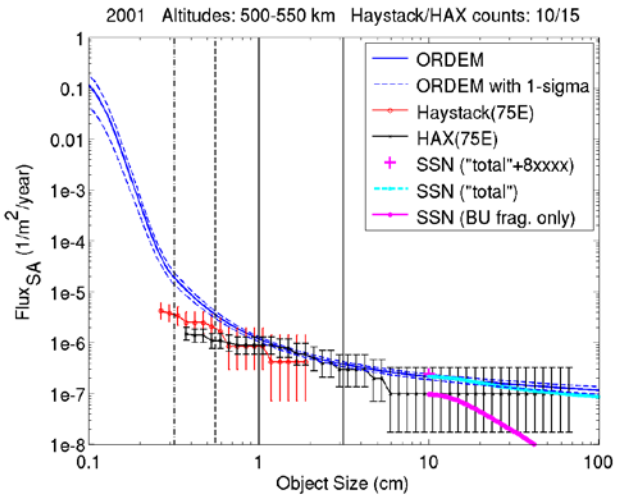

Figure D.2.4.1-33. 2001, Hay./HAX, 500-550 km, size vs. flux.

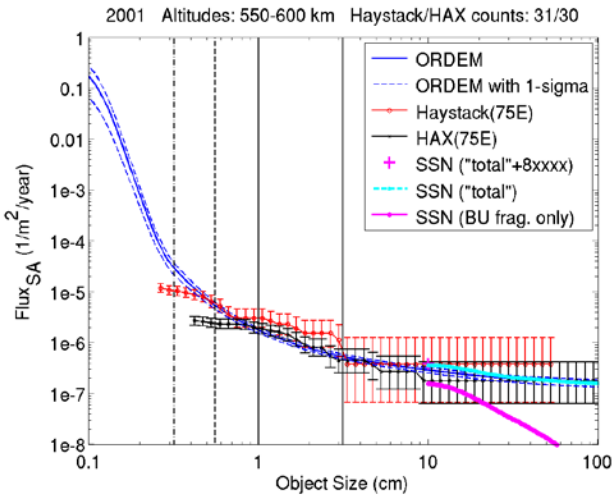

Figure D.2.4.1-34. 2001, Hay./HAX, 550-600 km, size vs. flux.

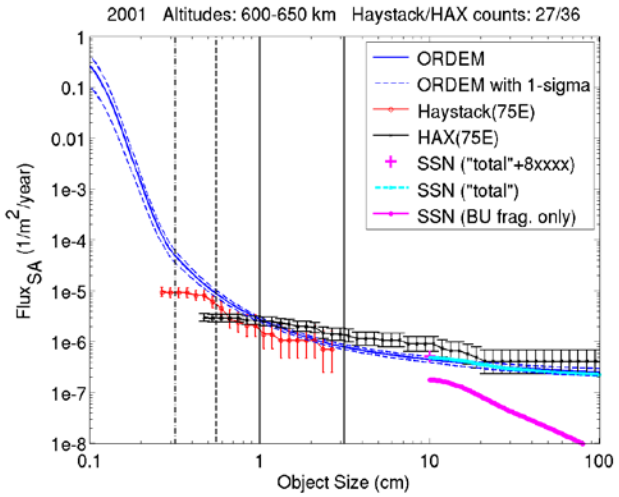

Figure D.2.4.1-35. 2001, Hay./HAX, 600-650 km, size vs. flux.

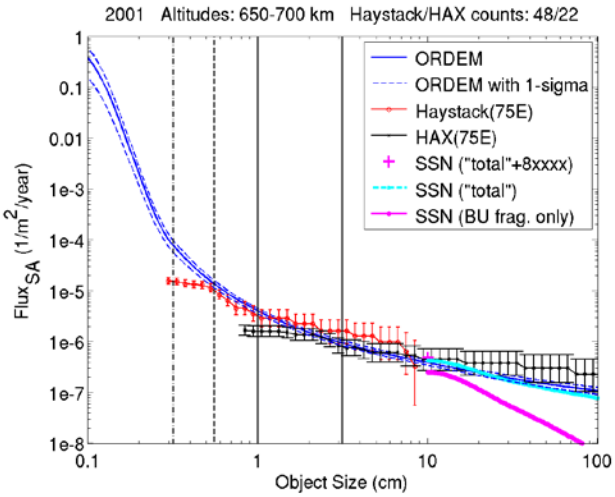

Figure D.2.4.1-36. 2001, Hay./HAX, 650-700 km, size vs. flux.

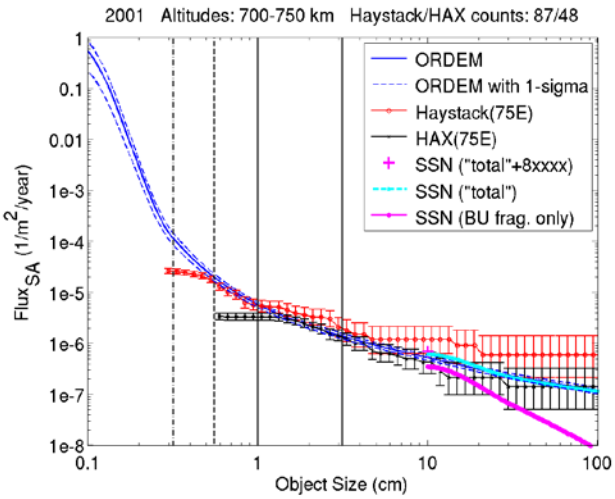

Figure D.2.4.1-37. 2001, Hay./HAX, 700-750 km, size vs. flux.

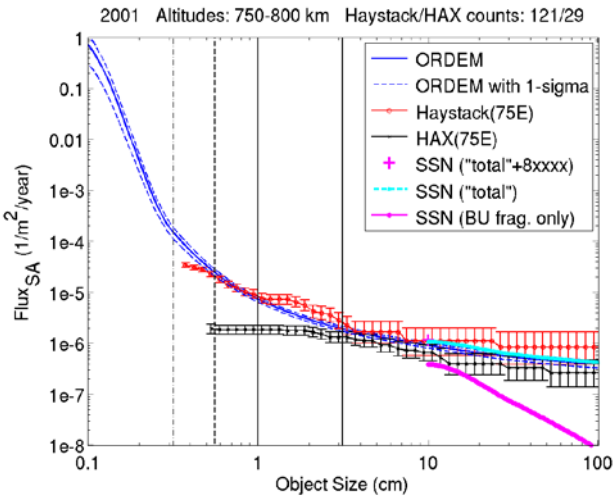

Figure D.2.4.1-38. 2001, Hay./HAX, 750-800 km, size vs. flux.

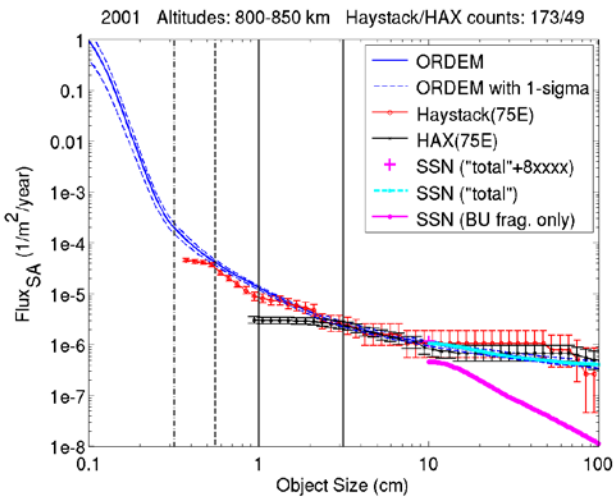

Figure D.2.4.1-39. 2001, Hay./HAX, 800-850 km, size vs. flux.

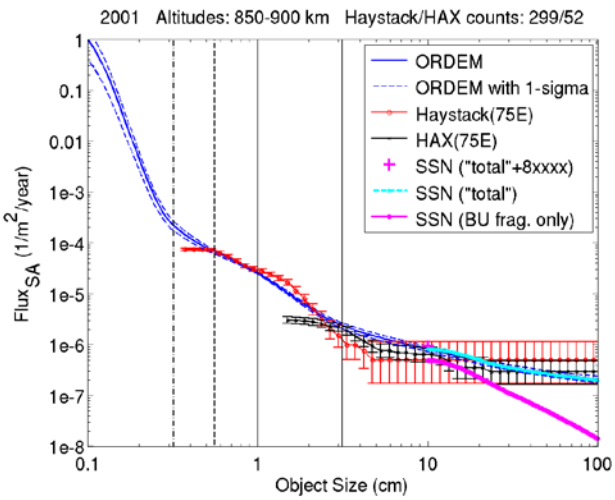

Figure D.2.4.1-40. 2001, Hay./HAX, 850-900 km, size vs. flux.

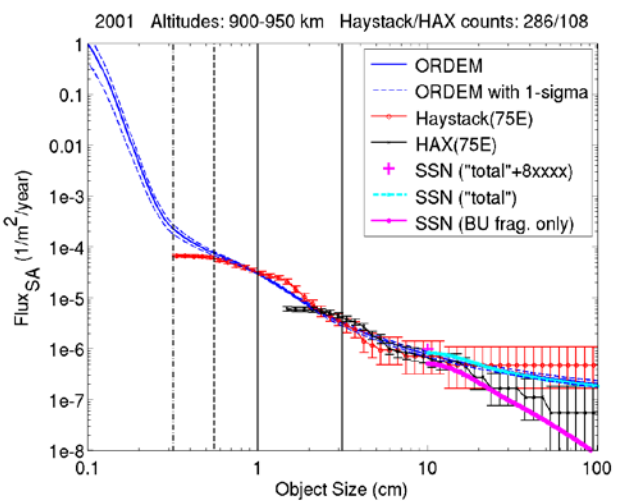

Figure D.2.4.1-41. 2001, Hay./HAX, 900-950 km, size vs. flux.

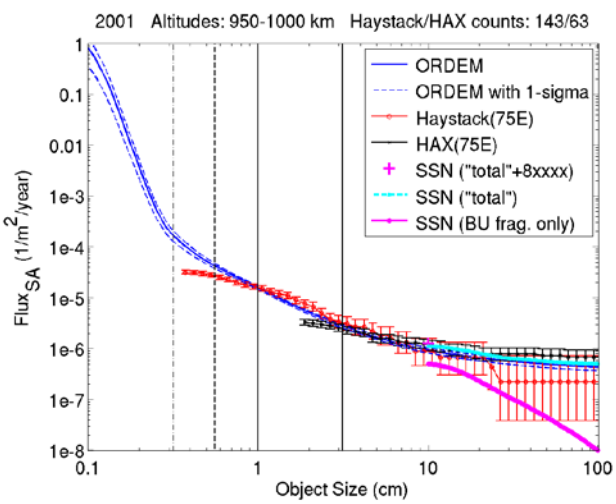

Figure D.2.4.1-42. 2001, Hay./HAX, 950-1000 km, size vs. flux.

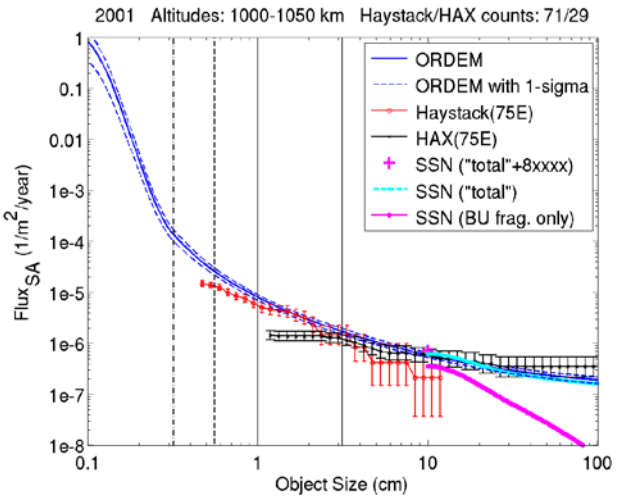

Figure D.2.4.1-43. 2001, Hay./HAX, 1000-1050 km, size vs. flux.

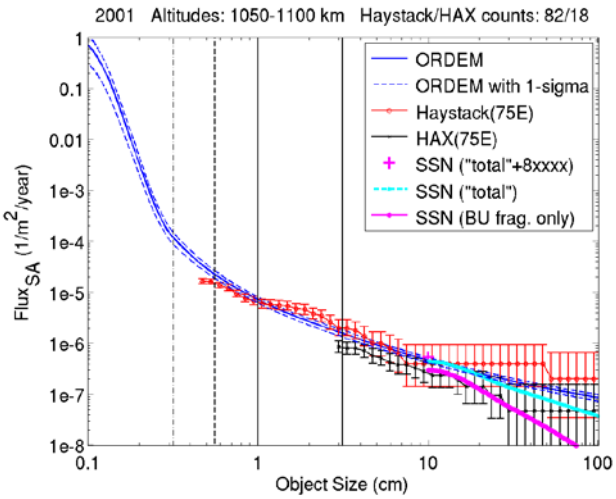

Figure D.2.4.1-44. 2001, Hay./HAX, 1050-1100 km, size vs. flux.

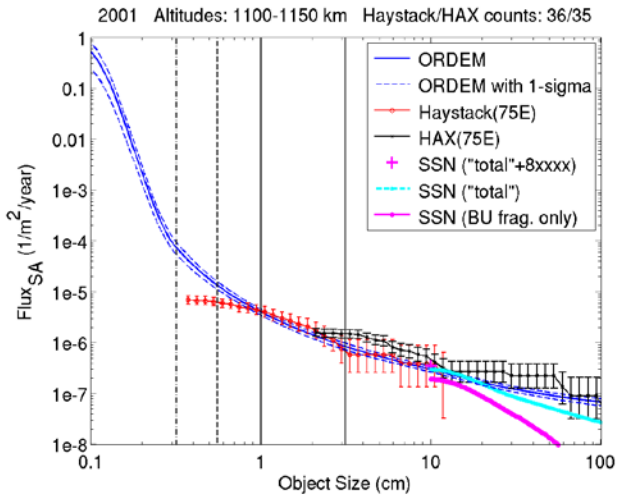

Figure D.2.4.1-45. 2001, Hay./HAX, 1100-1150 km, size vs. flux.

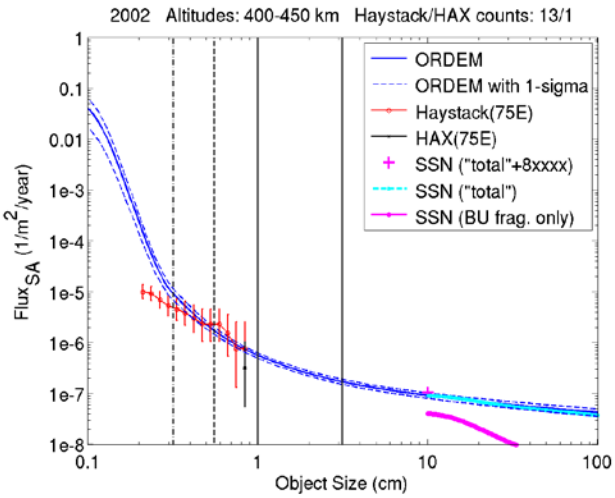

Figure D.2.4.1-46. 2002 near, Hay./HAX, 400-450 km, size vs. flux.

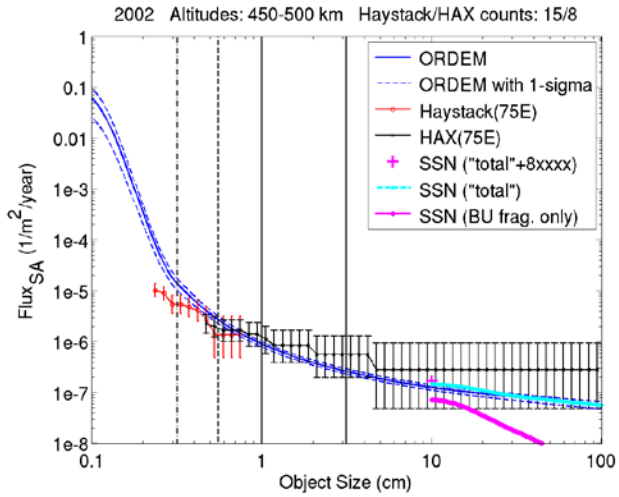

Figure D.2.4.1-47. 2002 near, Hay./HAX, 450-500 km, size vs. flux.

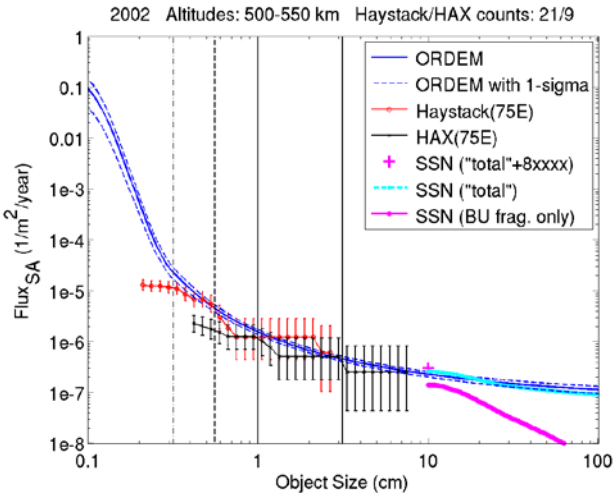

Figure D.2.4.1-48. 2002 near, Hay./HAX, 500-550 km, size vs. flux.

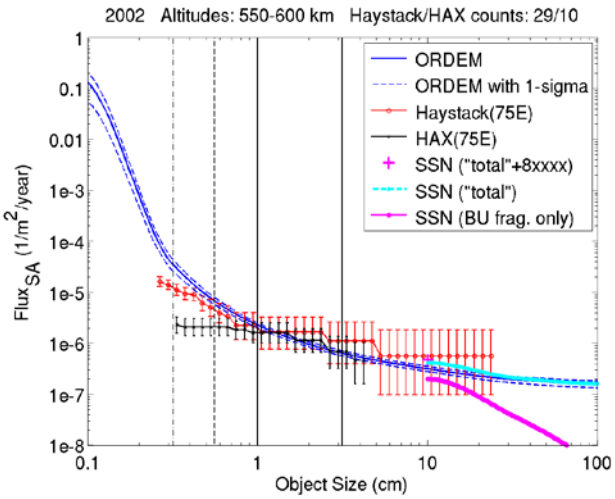

Figure D.2.4.1-49. 2002 near, Hay./HAX, 550-600 km, size vs. flux.

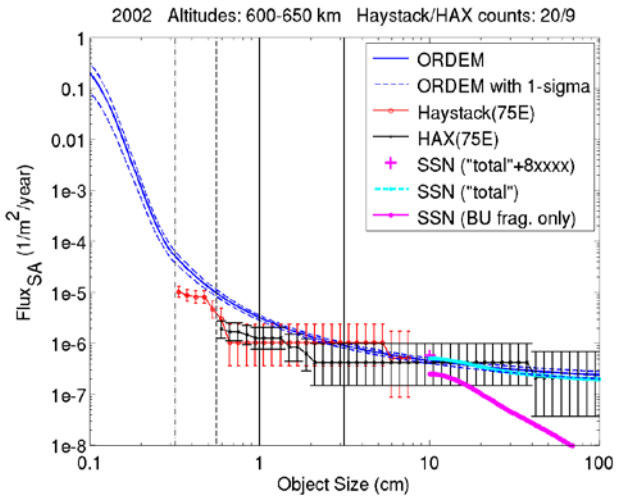

Figure D.2.4.1-50. 2002 near, Hay./HAX, 600-650 km, size vs. flux.

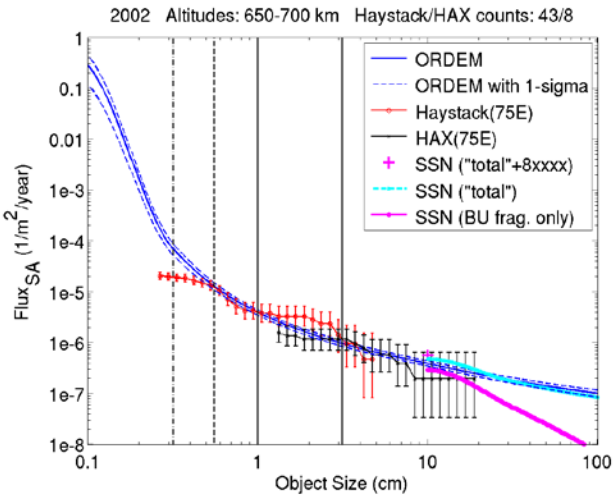

Figure D.2.4.1-51. 2002 near, Hay./HAX, 650-700 km, size vs. flux.

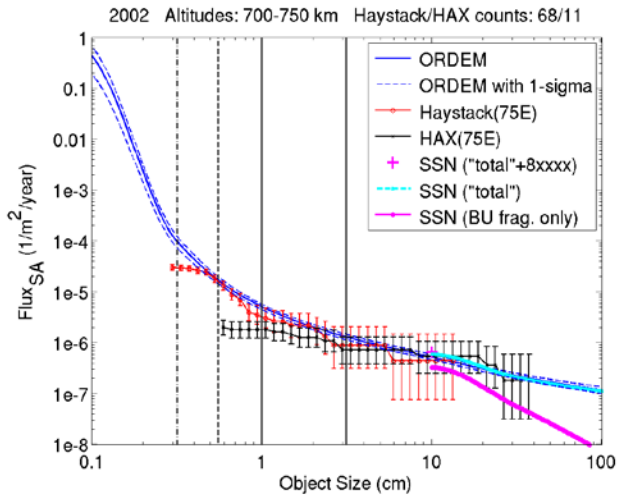

Figure D.2.4.1-52. 2002 near, Hay./HAX, 700-750 km, size vs. flux.

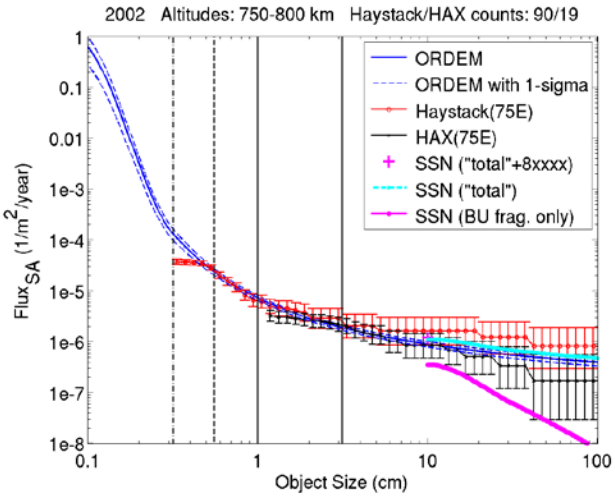

Figure D.2.4.1-53. 2002 near, Hay./HAX, 750-800 km, size vs. flux.

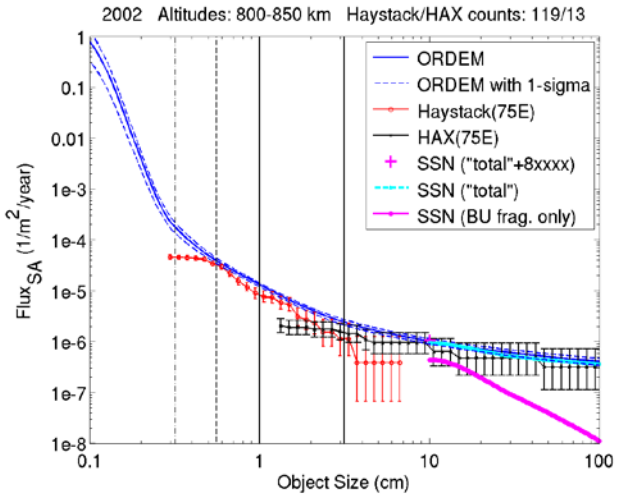

Figure D.2.4.1-54. 2002 near, Hay./HAX, 800-850 km, size vs. flux.

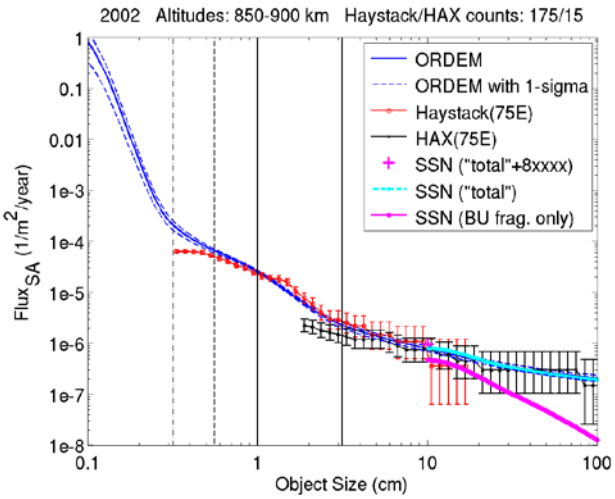

Figure D.2.4.1-55. 2002 near, Hay./HAX, 850-900 km, size vs. flux.

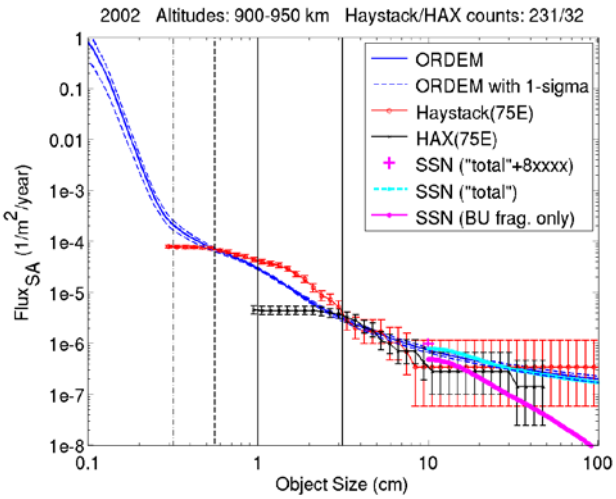

Figure D.2.4.1-56. 2002 near, Hay./HAX, 900-950 km, size vs. flux.

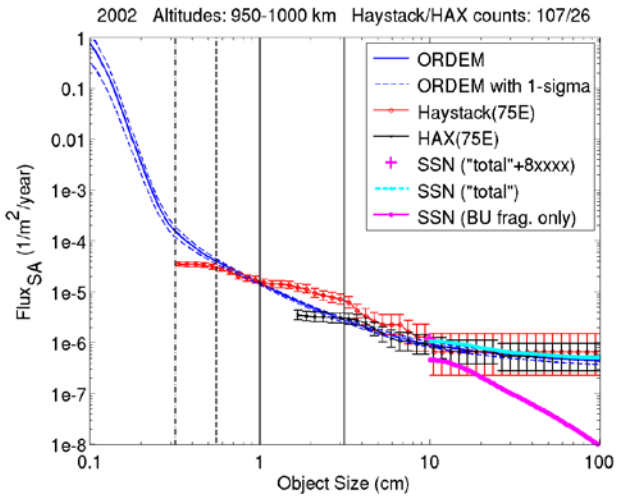

Figure D.2.4.1-57. 2002 near, Hay./HAX, 950-1000 km, size vs. flux.

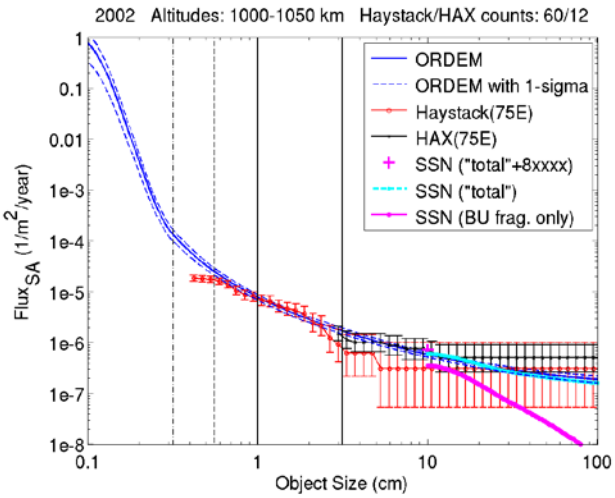

Figure D.2.4.1-58. 2002 near, Hay./HAX, 1000-1050 km, size vs. flux.

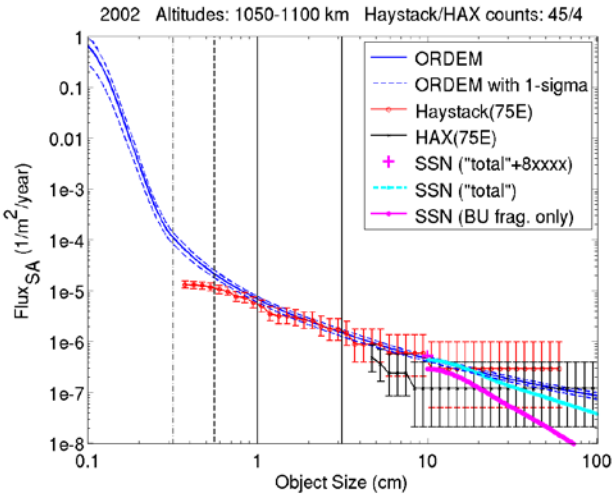

Figure D.2.4.1-59. 2002 near, Hay./HAX, 1050-1100 km, size vs. flux.

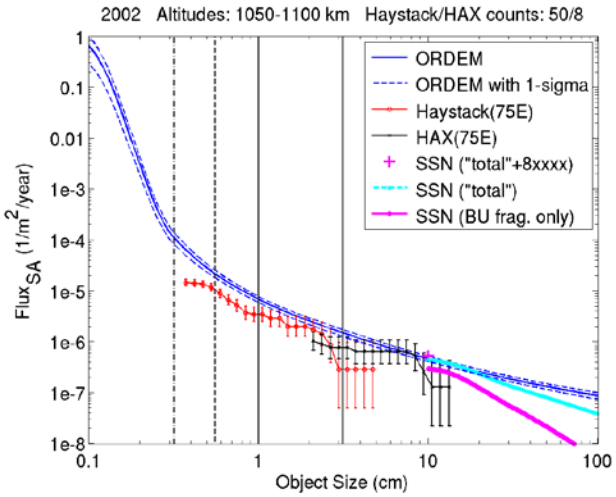

Figure D.2.4.1-60. 2002 far, Hay./HAX, 1050-1100 km, size vs. flux.

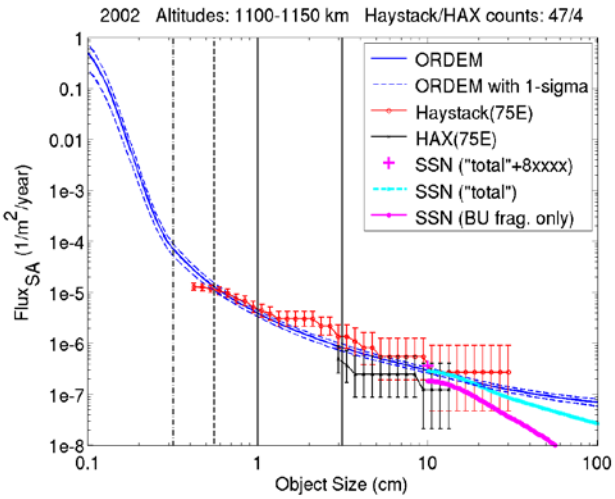

Figure D.2.4.1-61. 2002 far, Hay./HAX, 1100-1150 km, size vs. flux.

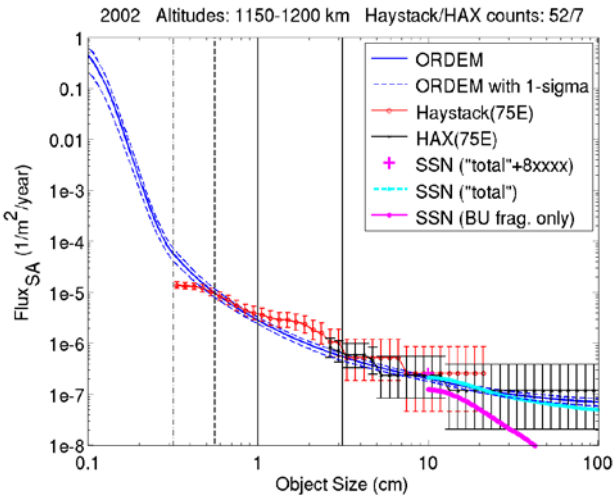

Figure D.2.4.1-62. 2002 far, Hay./HAX, 1150-1200 km, size vs. flux.

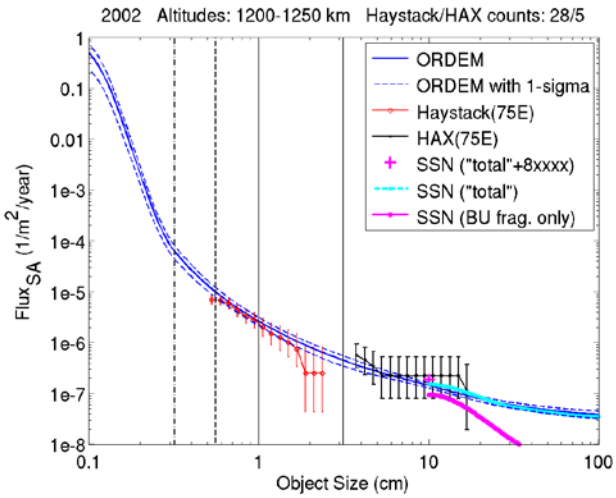

Figure D.2.4.1-63. 2002 far, Hay./HAX, 1200-1250 km, size vs. flux.

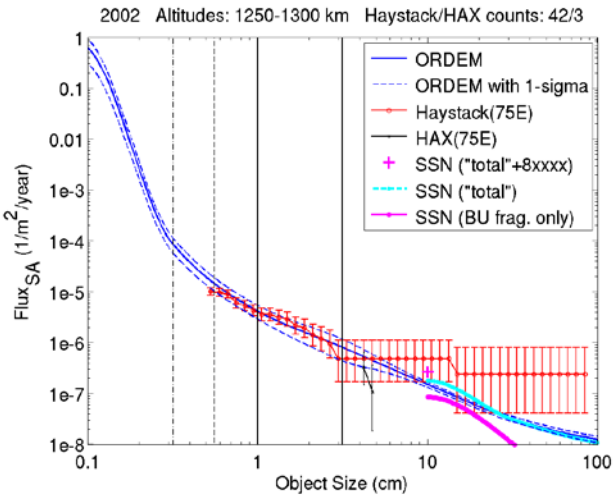

Figure D.2.4.1-64. 2002 far, Hay./HAX, 1250-1300 km, size vs. flux.

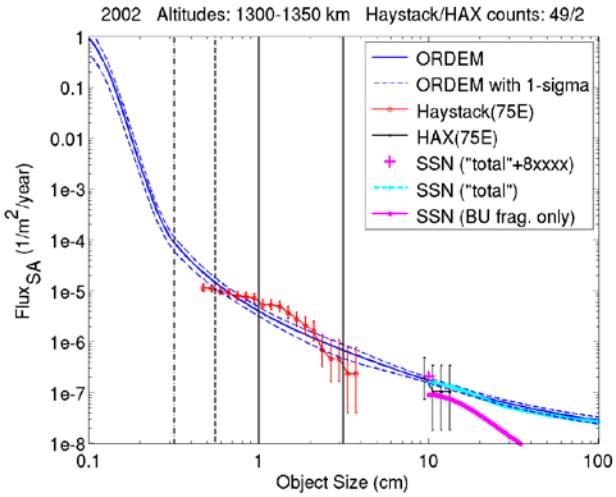

Figure D.2.4.1-65. 2002 far, Hay./HAX, 1300-1350 km, size vs. flux.

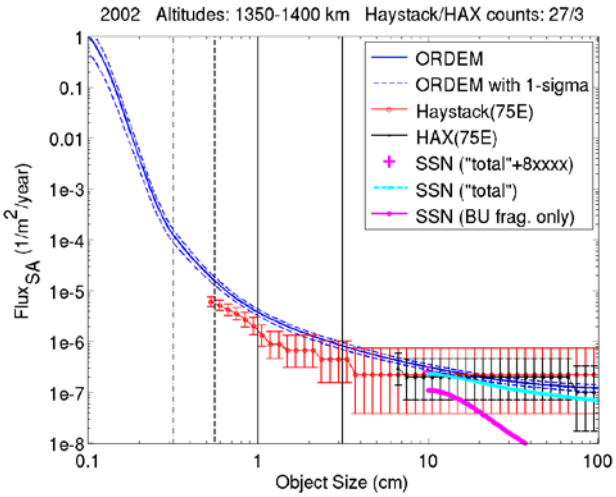

Figure D.2.4.1-66. 2002 far, Hay./HAX, 1350-1400 km, size vs. flux.

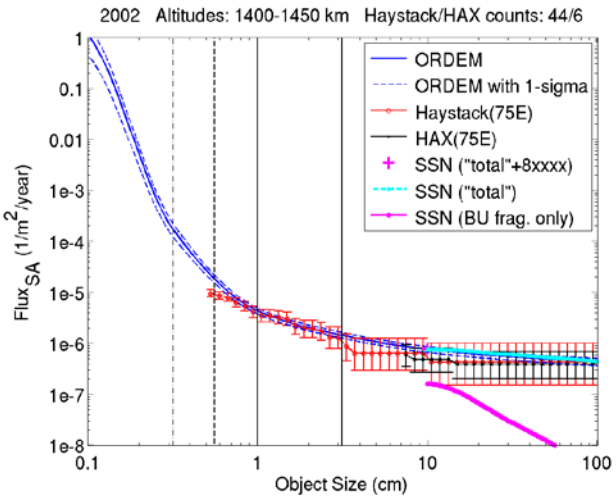

Figure D.2.4.1-67. 2002 far, Hay./HAX, 1400-1450 km, size vs. flux.

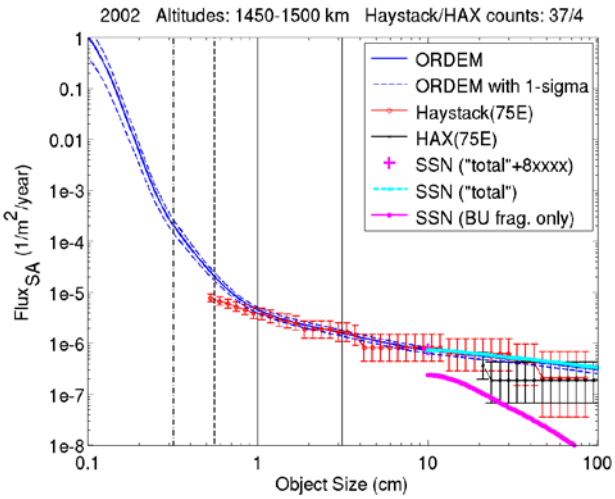

Figure D.2.4.1-68. 2002 far, Hay./HAX, 1450-1500 km, size vs. flux.

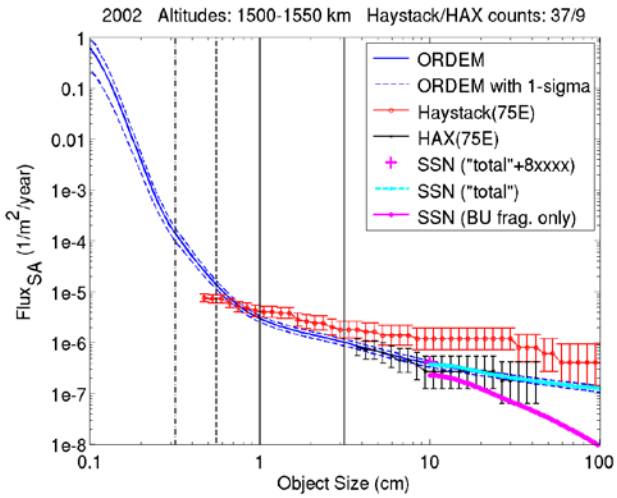

Figure D.2.4.1-69. 2002 far, Hay./HAX, 1500-1550 km, size vs. flux.

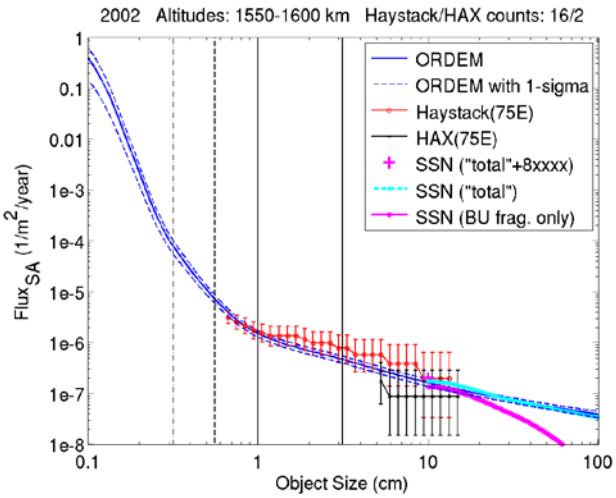

Figure D.2.4.1-70. 2002 far, Hay./HAX, 1550-1600 km, size vs. flux.

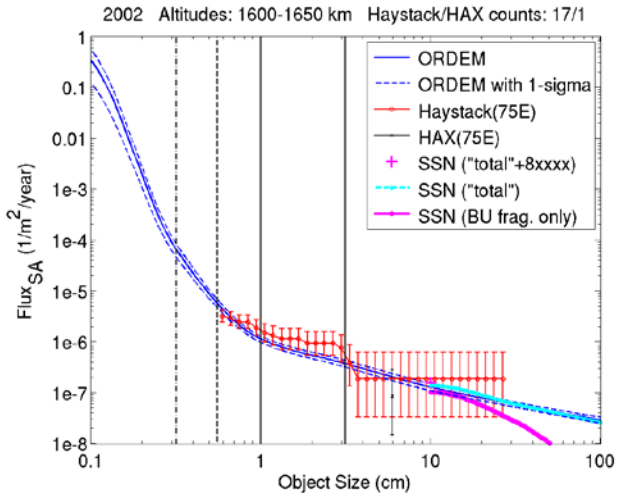

Figure D.2.4.1-71. 2002 far, Hay./HAX, 1600-1650 km, size vs. flux.

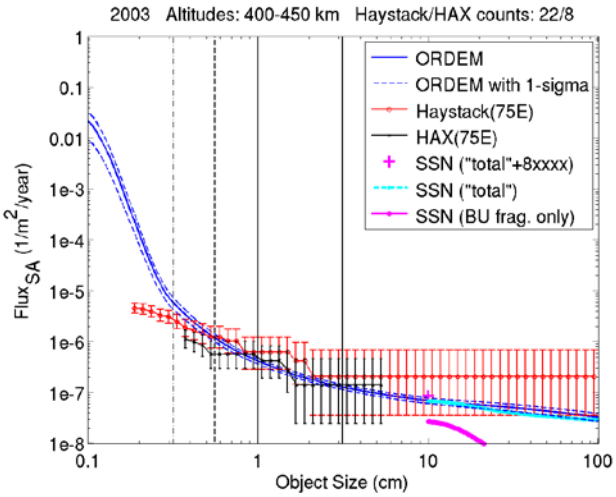

Figure D.2.4.1-72. 2003, Hay./HAX, 400-450 km, size vs. flux.

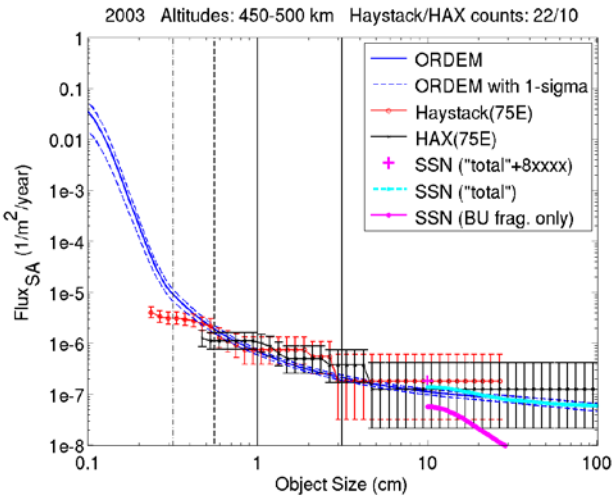

Figure D.2.4.1-73. 2003, Hay./HAX, 450-500 km, size vs. flux.

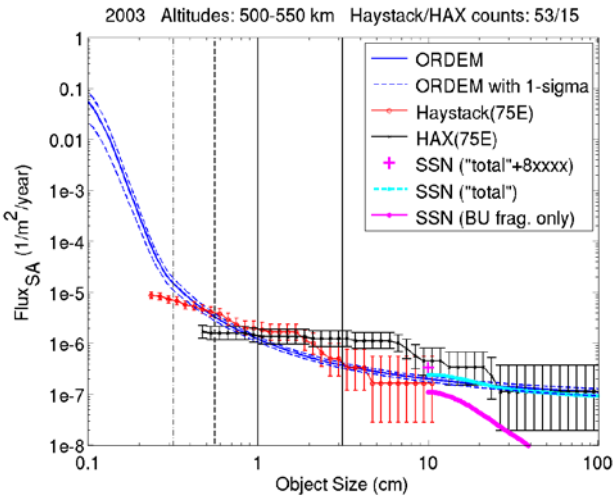

Figure D.2.4.1-74. 2003, Hay./HAX, 500-550 km, size vs. flux.

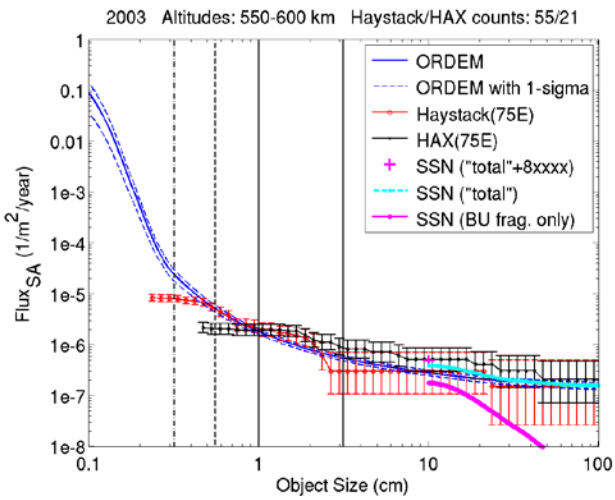

Figure D.2.4.1-75. 2003, Hay./HAX, 550-600 km, size vs. flux.

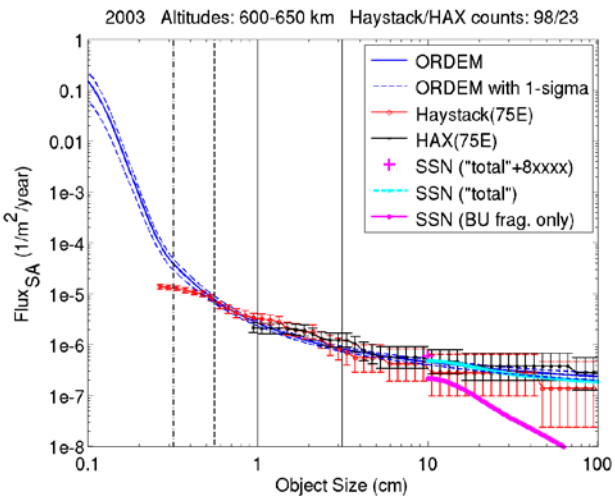

Figure D.2.4.1-76. 2003, Hay./HAX, 600-650 km, size vs. flux.

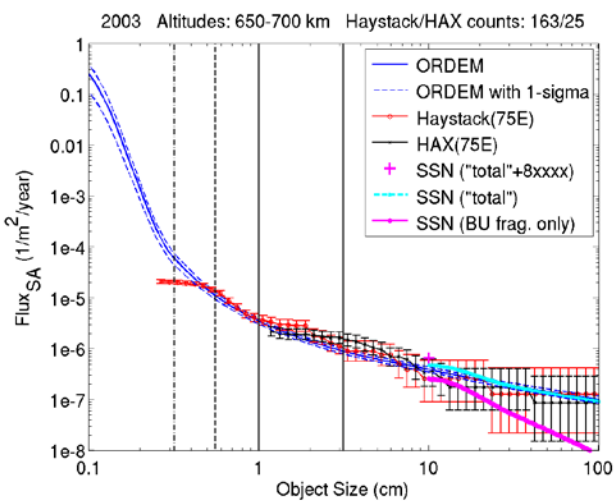

Figure D.2.4.1-77. 2003, Hay./HAX, 650-700 km, size vs. flux.

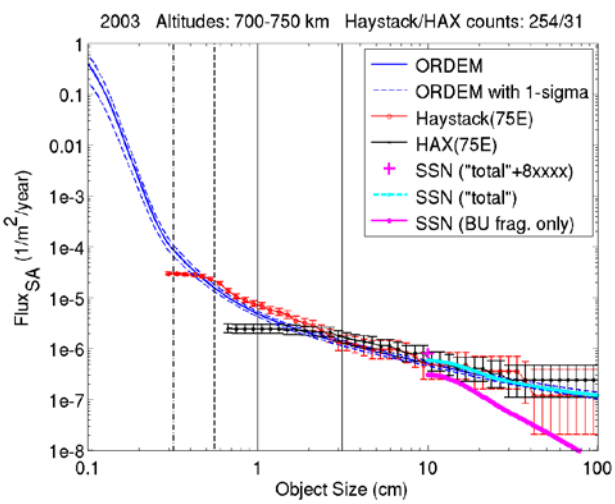

Figure D.2.4.1-78. 2003, Hay./HAX, 700-750 km, size vs. flux.

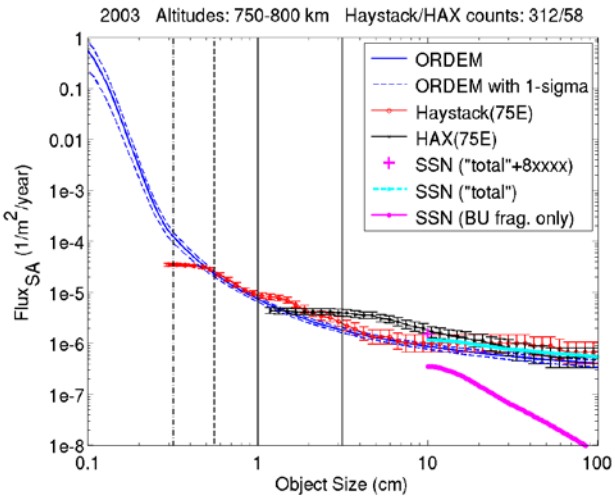

Figure D.2.4.1-79. 2003, Hay./HAX, 750-800 km, size vs. flux.

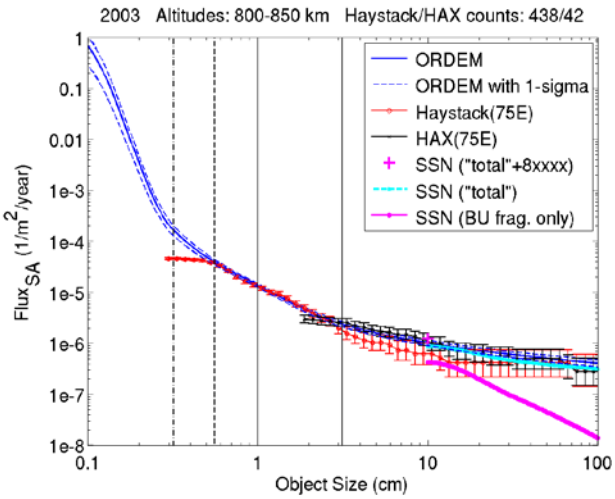

Figure D.2.4.1-80. 2003, Hay./HAX, 800-850 km, size vs. flux.

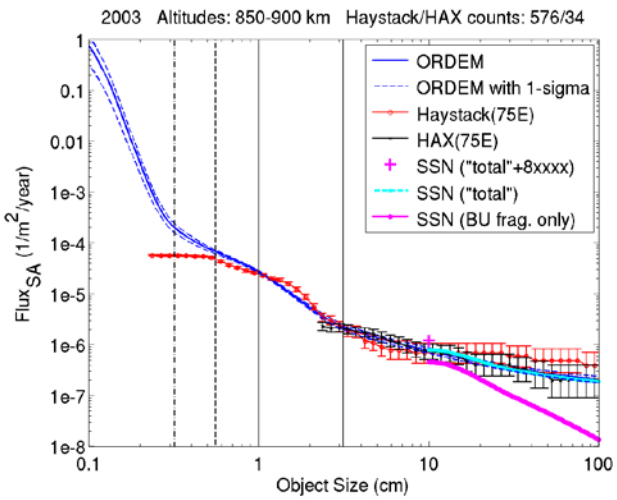

Figure D.2.4.1-81. 2003, Hay./HAX, 850-900 km, size vs. flux.

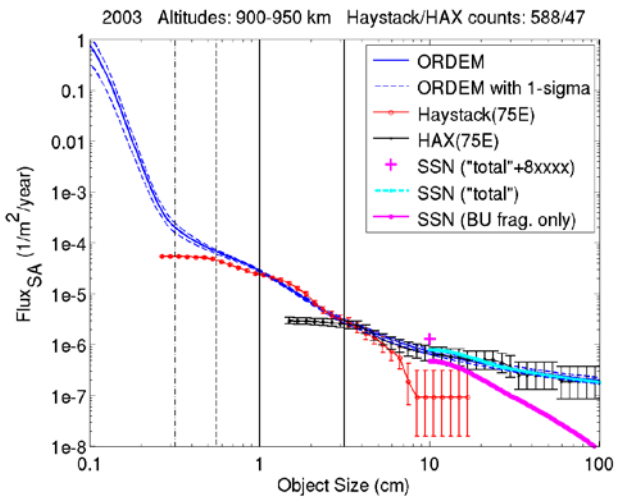

Figure D.2.4.1-82. 2003, Hay./HAX, 900-950 km, size vs. flux.

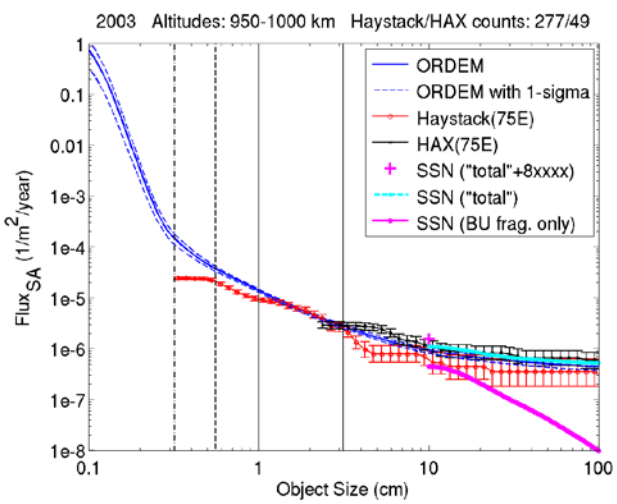

Figure D.2.4.1-83. 2003, Hay./HAX, 950-1000 km, size vs. flux.

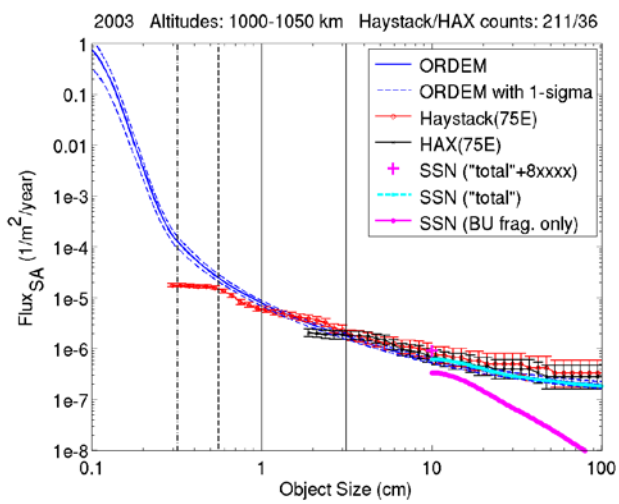

Figure D.2.4.1-84. 2003, Hay./HAX, 1000-1050 km, size vs. flux.

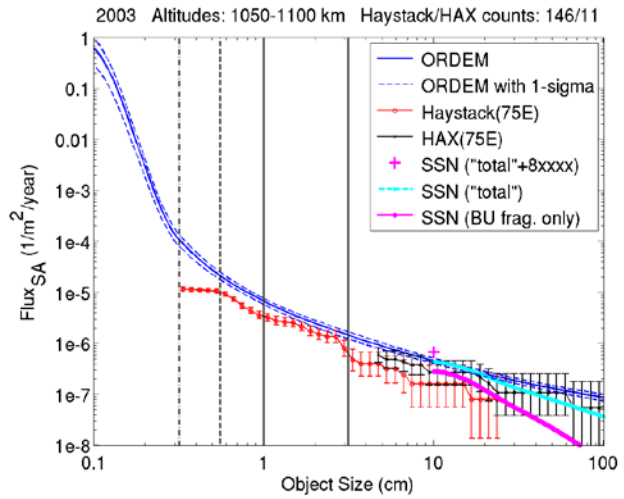

Figure D.2.4.1-85. 2003, Hay./HAX, 1050-1100 km, size vs. flux.

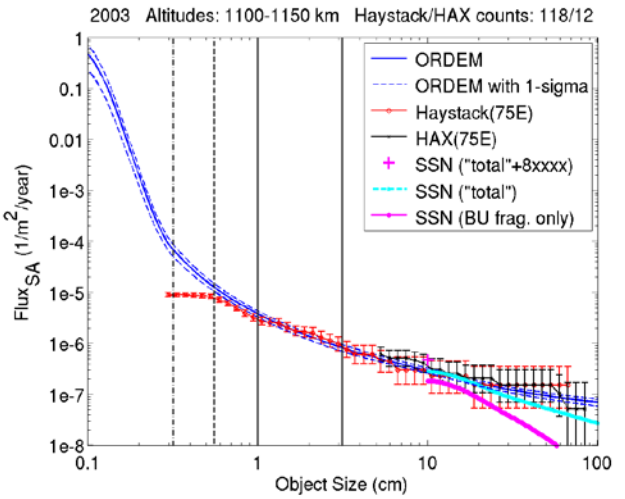

Figure D.2.4.1-86. 2003, Hay./HAX, 1100-1150 km, size vs. flux.

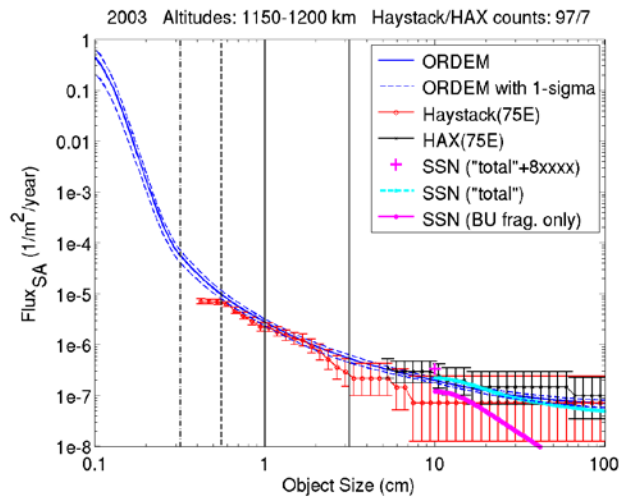

Figure D.2.4.1-87. 2003, Hay./HAX, 1150-1200 km, size vs. flux.

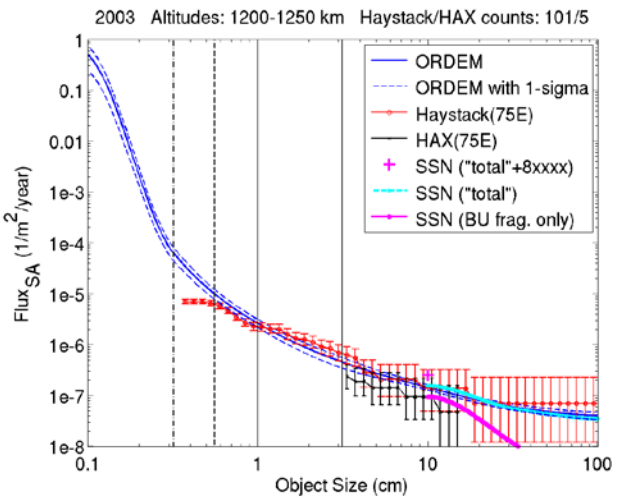

Figure D.2.4.1-88. 2003, Hay./HAX, 1200-1250 km, size vs. flux.

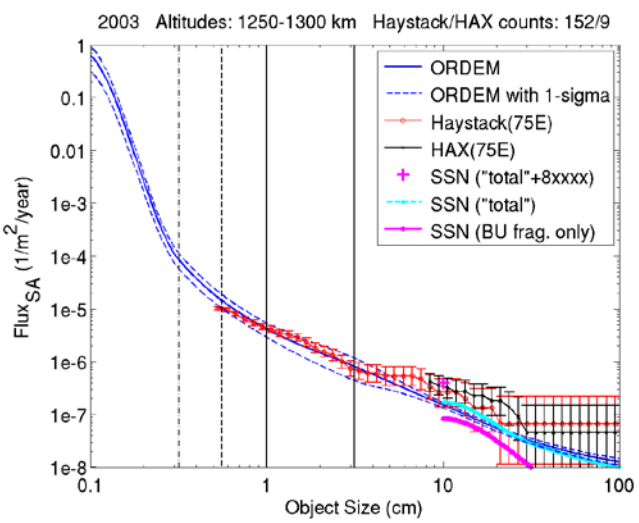

Figure D.2.4.1-89. 2003, Hay./HAX, 1250-1300 km, size vs. flux.

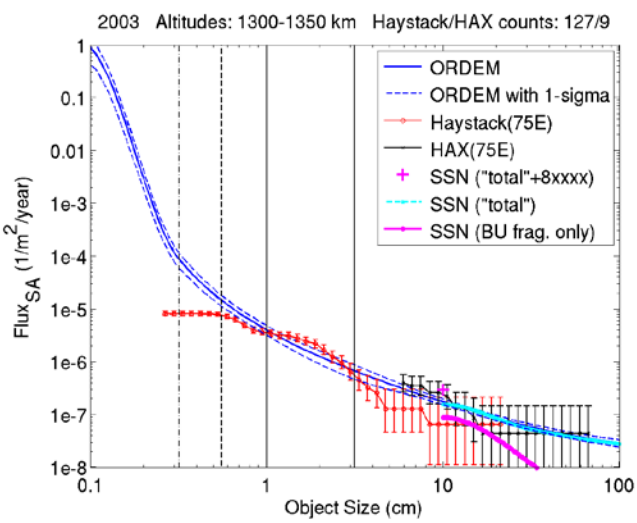

Figure D.2.4.1-90. 2003, Hay./HAX, 1300-1350 km, size vs. flux.

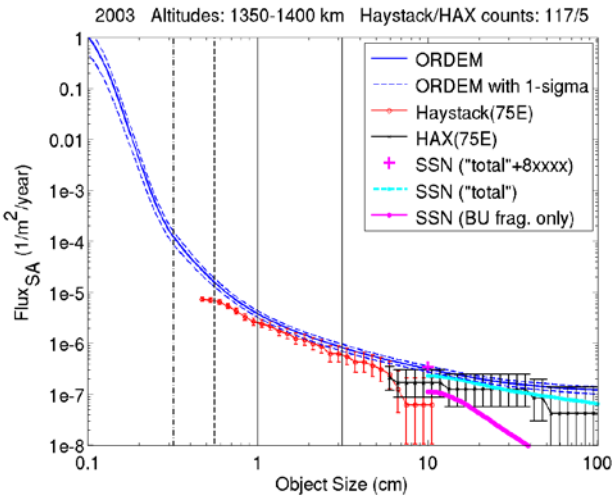

Figure D.2.4.1-91. 2003, Hay./HAX, 1350-1400 km, size vs. flux.

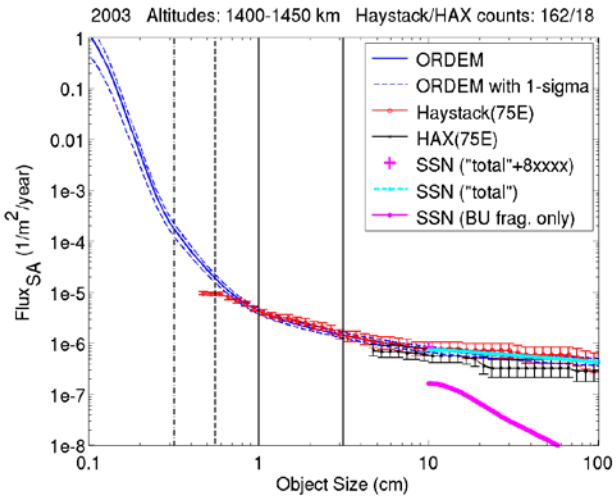

Figure D.2.4.1-92. 2003, Hay./HAX, 1400-1450 km, size vs. flux.

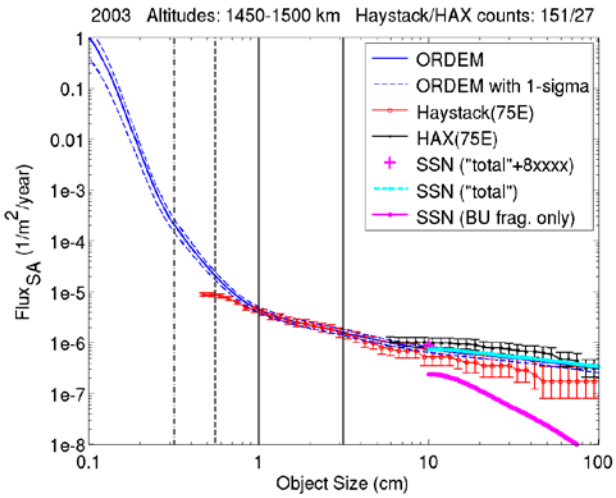

Figure D.2.4.1-93. 2003, Hay./HAX, 1450-1500 km, size vs. flux.

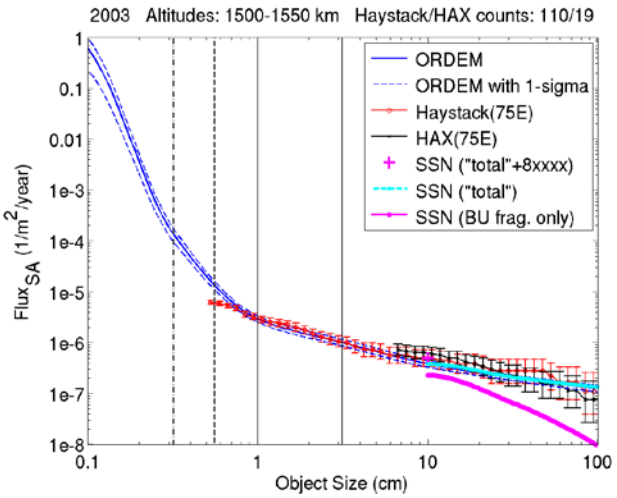

Figure D.2.4.1-94. 2003, Hay./HAX, 1500-1550 m, size vs. flux.

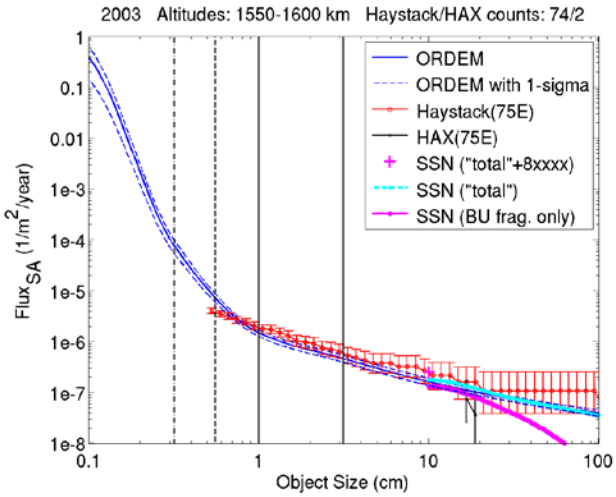

Figure D.2.4.1-95. 2003, Hay./HAX, 1550-1600 m, size vs. flux.

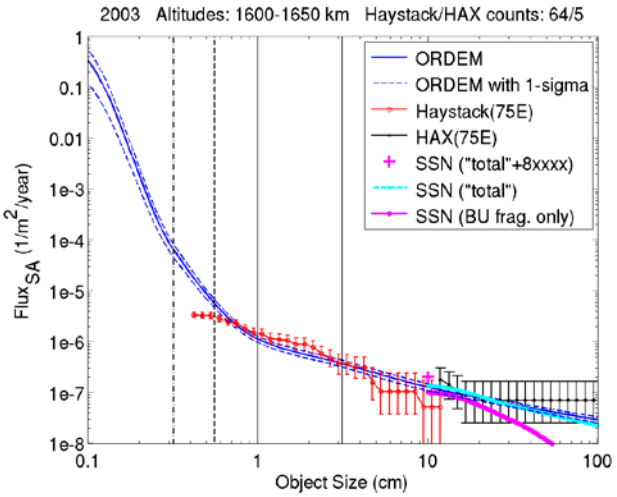

Figure D.2.4.1-96. 2003, Hay./HAX, 1600-1650 km, size vs. flux.

2.4.2. *ORDEM 3.0 vs. Goldstone & SSN*

The Goldstone data shown in the following figures are for the years of 2001 and 2005-2007 with Poisson lower and upper confidence limits at the Poisson single-sided confidence level of 84.13%. Table 2.4.2-1 lists the year, altitude ranges, and number of charts for each yearly set.

TABLE D.2.4.2-1 – SIZE VS. FLUX, GOLDSTONE & SSN, YEARS AND ALTITUDE RANGES

Year	Altitude Range	# Charts	Figures
2001	350km-2000km	33	F.2.4.2-1 thru F.2.4.2-33
2005	350km-2000km	33	F.2.4.2-34 thru F.2.4.2-66
2006	350km-2000km	33	F.2.4.2-67 thru F.2.4.2-99
2007	400km-2000km	32	F.2.4.2-100 thru F.2.4.2-131

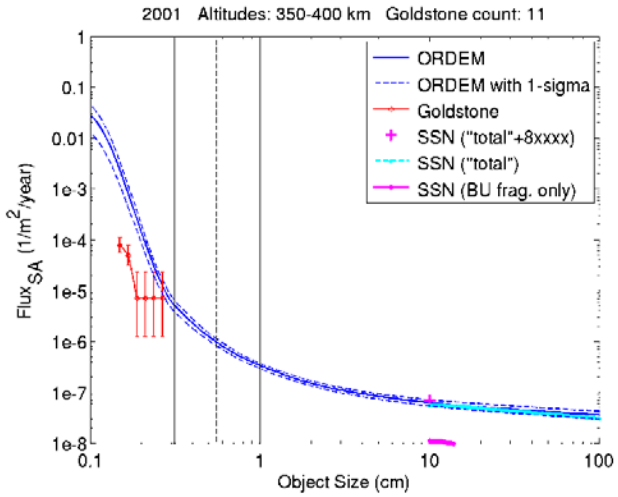

Figure D.2.4.2-1. 2001, Goldstone, 350-400 km, size vs. flux.

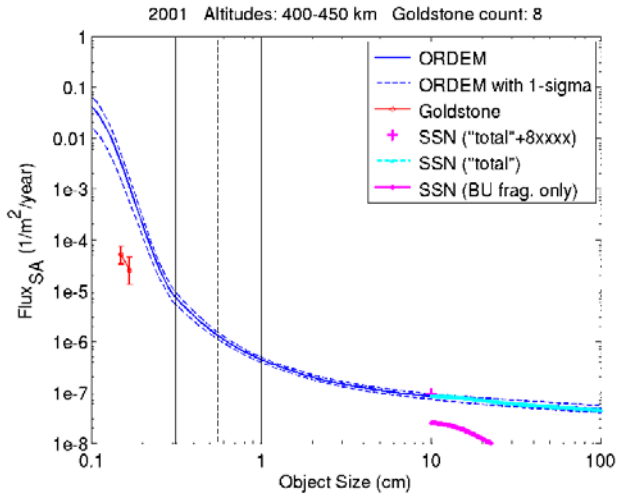

Figure D.2.4.2-2. 2001, Goldstone, 400-450 km, size vs. flux.

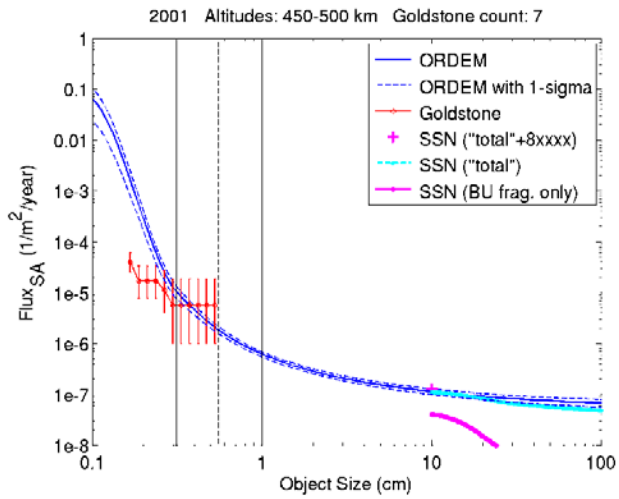

Figure D.2.4.2-3. 2001, Goldstone, 450-500 km, size vs. flux.

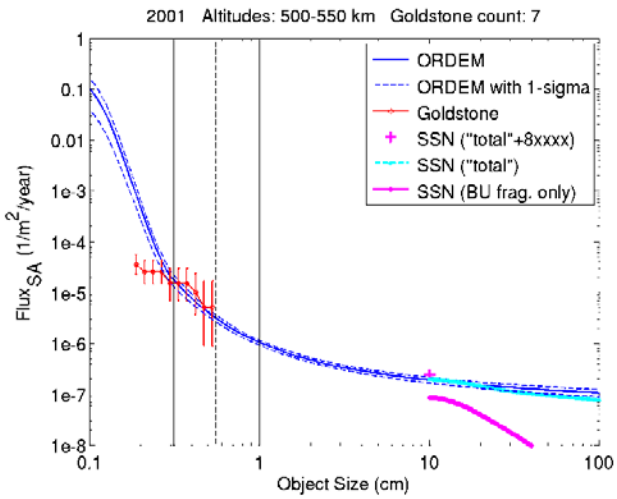

Figure D.2.4.2-4. 2001, Goldstone, 500-550 km, size vs. flux.

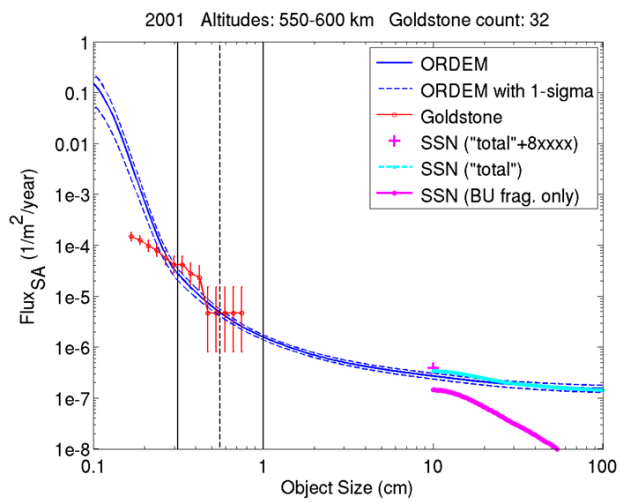

Figure D.2.4.2-5. 2001, Goldstone, 550-600 km, size vs. flux.

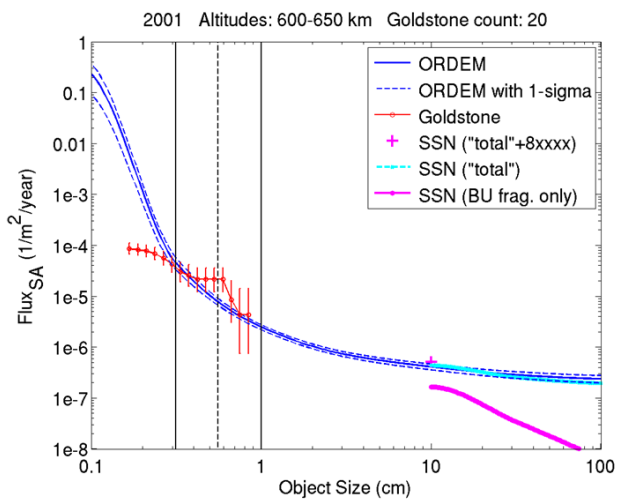

Figure D.2.4.2-6. 2001, Goldstone, 600-650 km, size vs. flux.

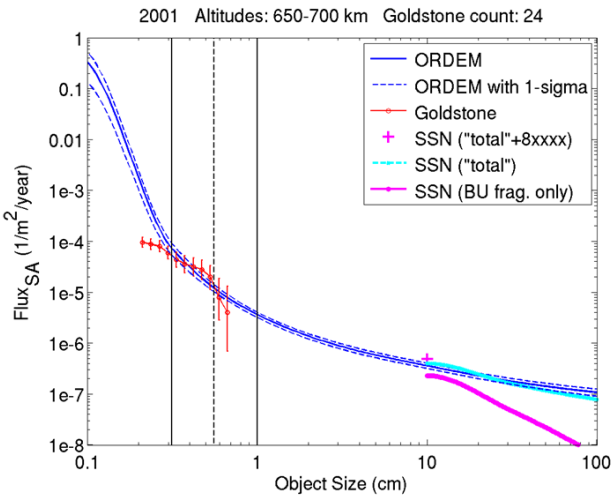

Figure D.2.4.2-7. 2001, Goldstone, 650-700 km, size vs. flux.

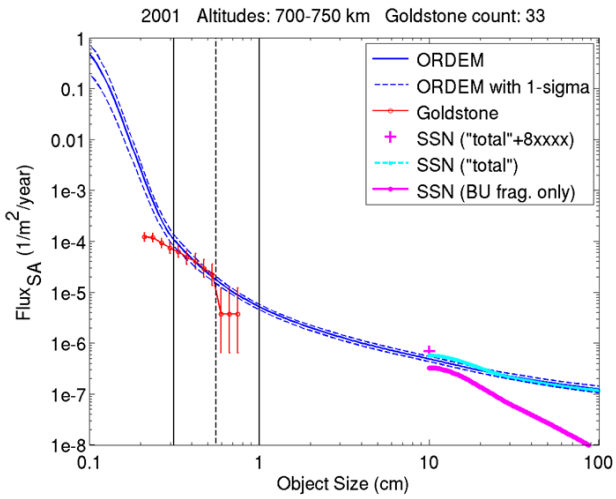

Figure D.2.4.2-8. 2001, Goldstone, 700-750 km, size vs. flux.

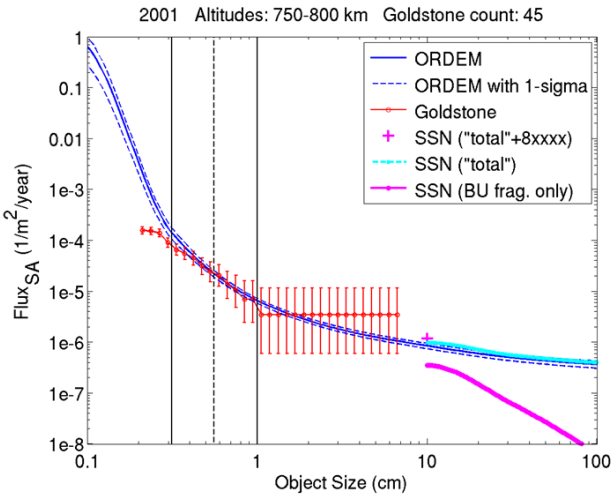

Figure D.2.4.2-9. 2001, Goldstone, 750-800 km, size vs. flux.

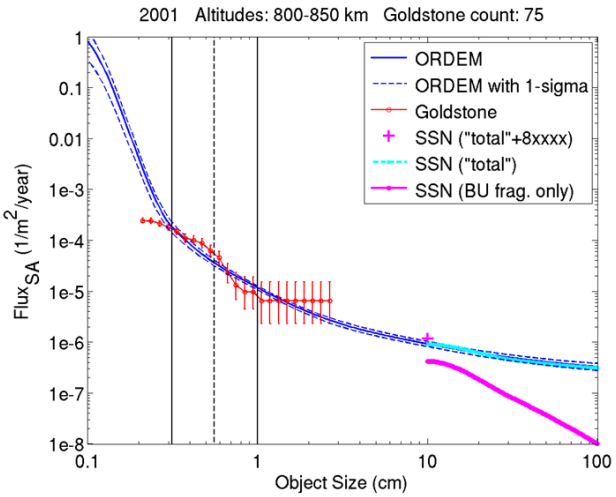

Figure D.2.4.2-10. 2001, Goldstone, 800-850 km, size vs. flux.

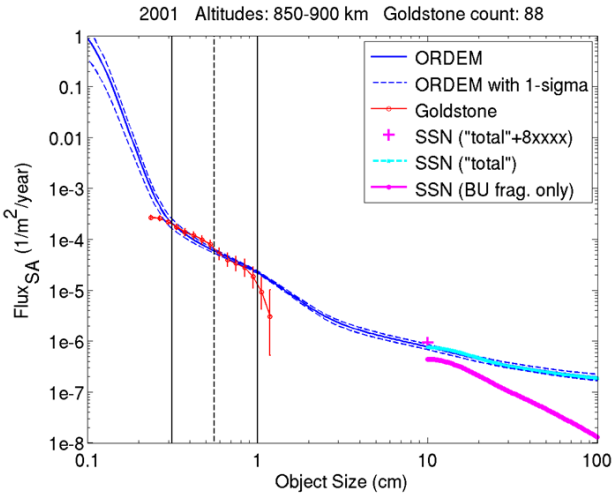

Figure D.2.4.2-11. 2001, Goldstone, 850-900 km, size vs. flux.

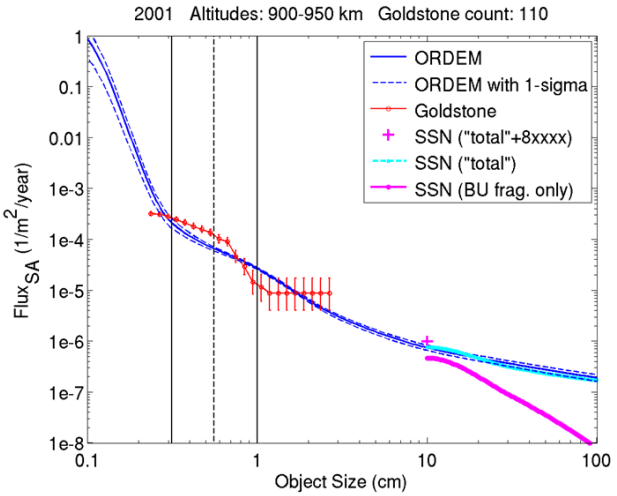

Figure D.2.4.2-12. 2001, Goldstone, 900-950 km, size vs. flux.

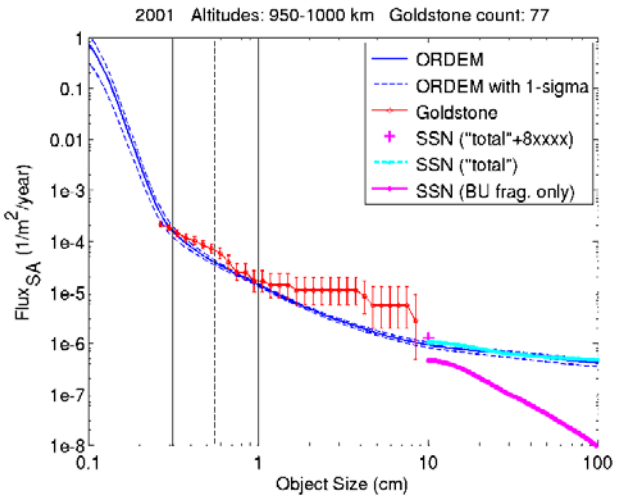

Figure D.2.4.2-13. 2001, Goldstone, 950-1000 km, size vs. flux.

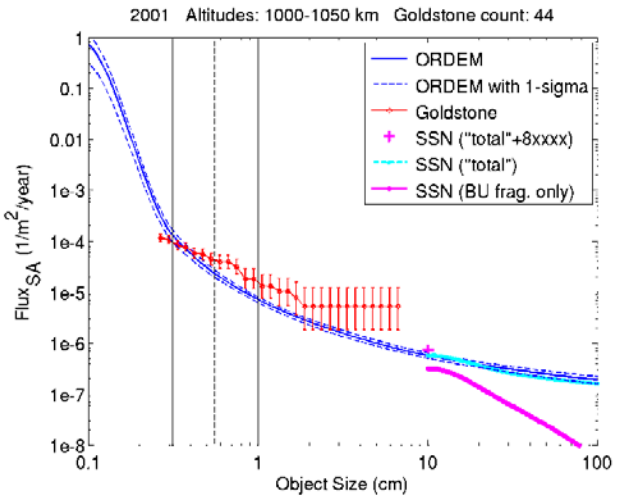

Figure D.2.4.2-14. 2001, Goldstone, 1000-1050 km, size vs. flux.

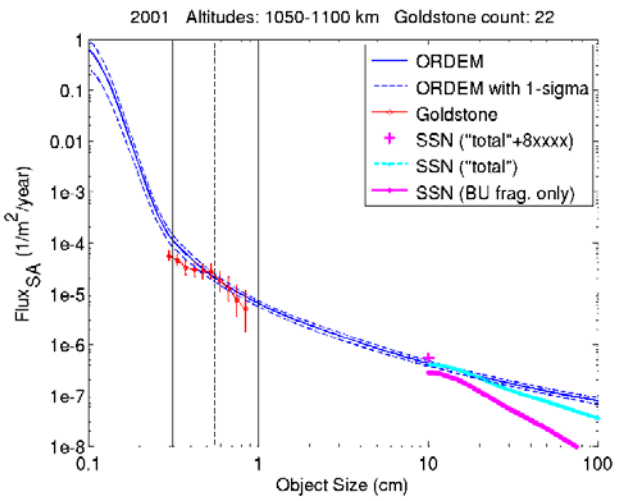

Figure D.2.4.2-15. 2001, Goldstone, 1050-1100 km, size vs. flux.

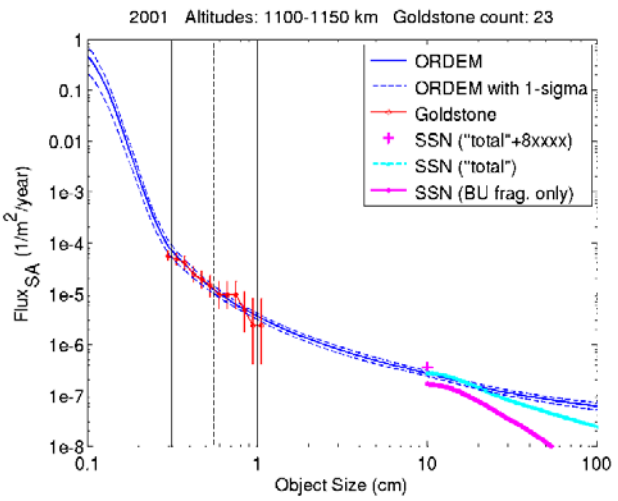

Figure D.2.4.2-16. 2001, Goldstone, 1100-1150 km, size vs. flux.

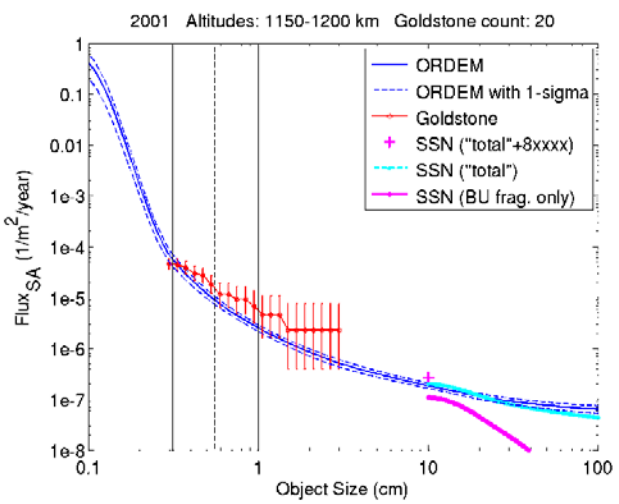

Figure D.2.4.2-17. 2001, Goldstone, 1150-1200 km, size vs. flux.

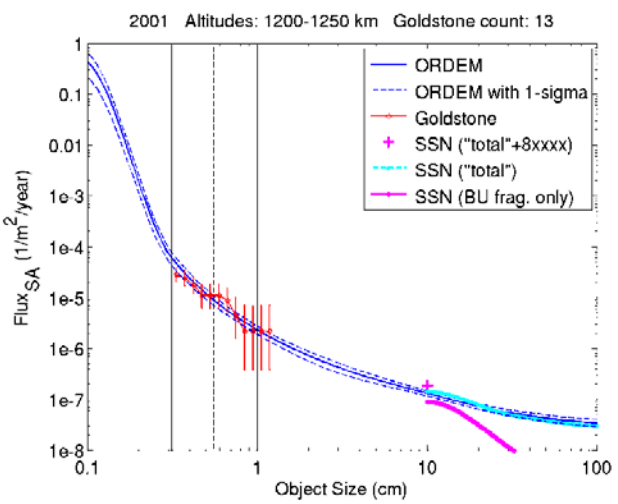

Figure D.2.4.2-18. 2001, Goldstone, 1200-1250 km, size vs. flux.

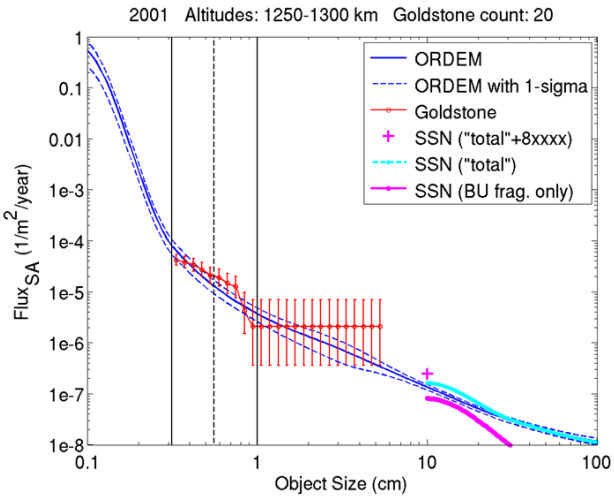

Figure D.2.4.2-19. 2001, Goldstone, 1250-1300 km, size vs. flux.

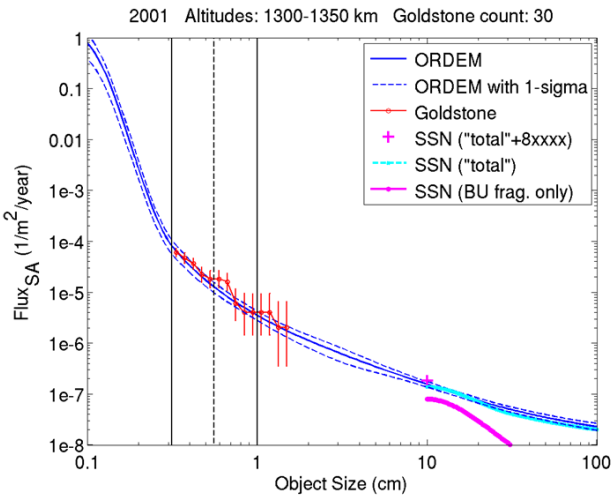

Figure D.2.4.2-20. 2001, Goldstone, 1300-1350 km, size vs. flux.

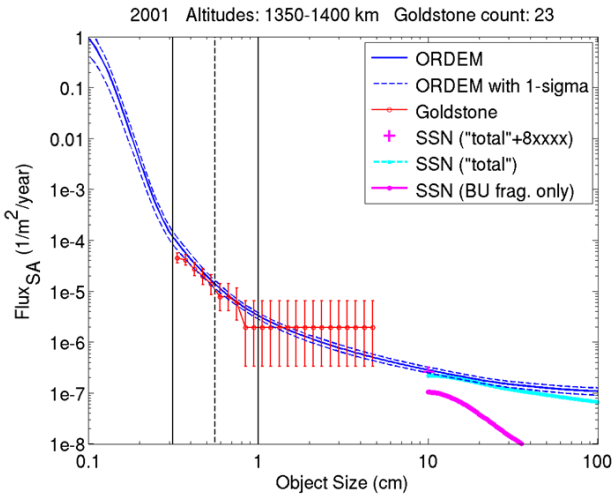

Figure D.2.4.2-21. 2001, Goldstone, 1350-1400 km, size vs. flux.

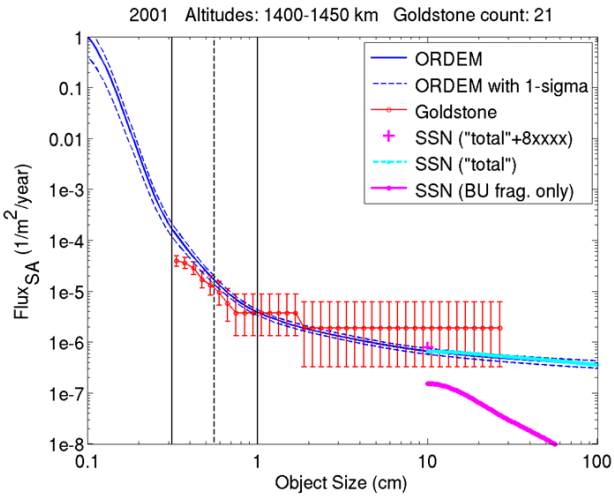

Figure D.2.4.2-22. 2001, Goldstone, 1400-1450 km, size vs. flux.

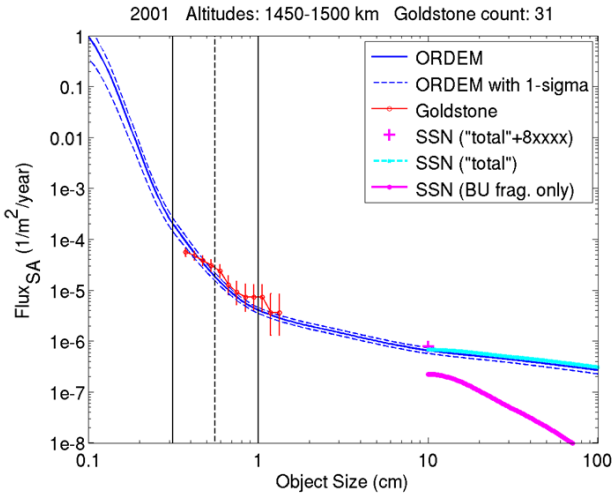

Figure D.2.4.2-23. 2001, Goldstone, 1450-1500 km, size vs. flux.

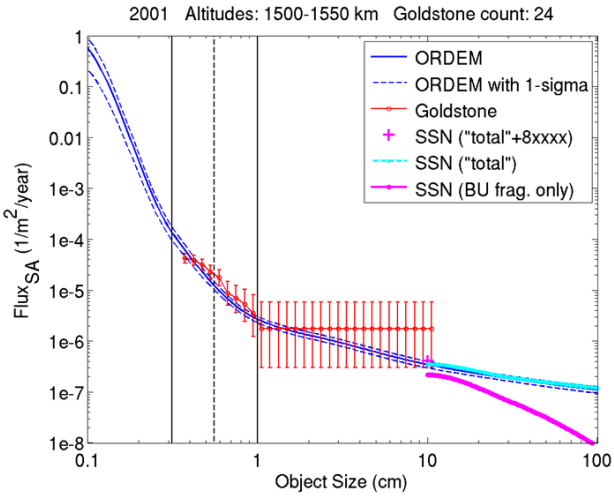

Figure D.2.4.2-24. 2001, Goldstone, 1500-1550 km, size vs. flux.

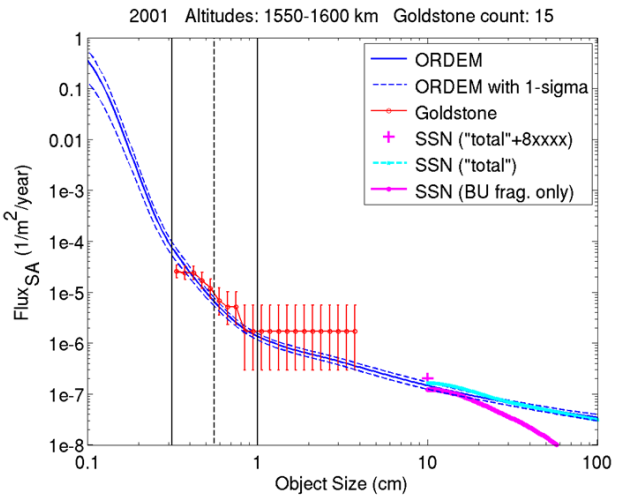

Figure D.2.4.2-25. 2001, Goldstone, 1550-1600 km, size vs. flux.

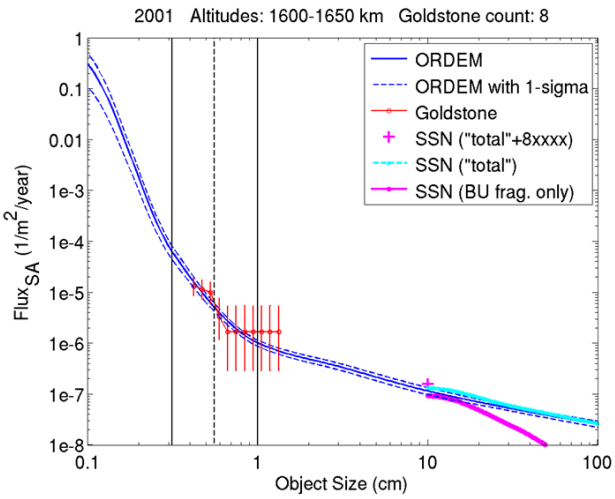

Figure D.2.4.2-26. 2001, Goldstone, 1600-1650 km, size vs. flux.

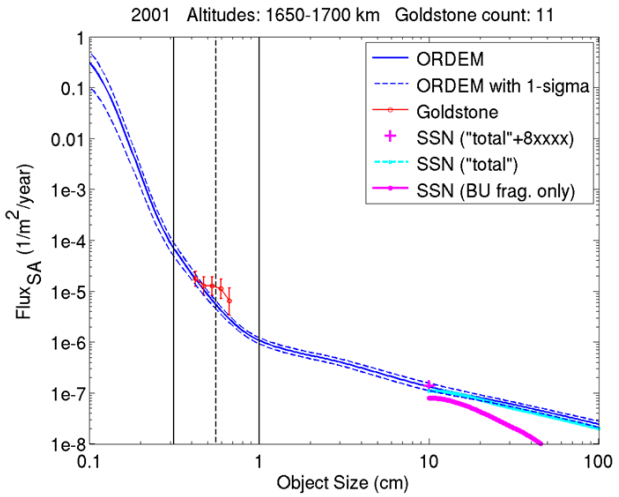

Figure D.2.4.2-27. 2001, Goldstone, 1650-1700 km, size vs. flux.

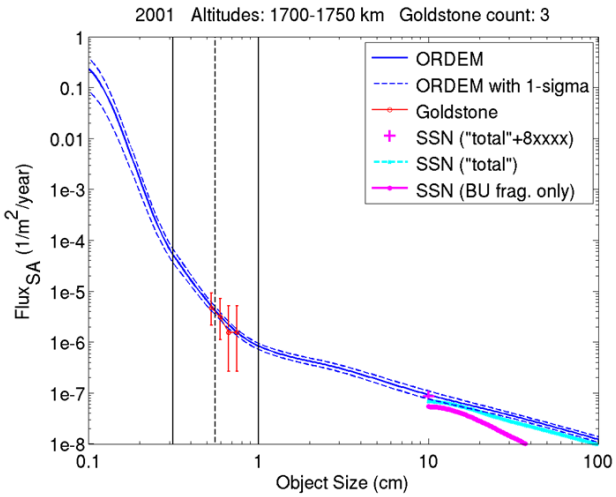

Figure D.2.4.2-28. 2001, Goldstone, 1700-1750 km, size vs. flux.

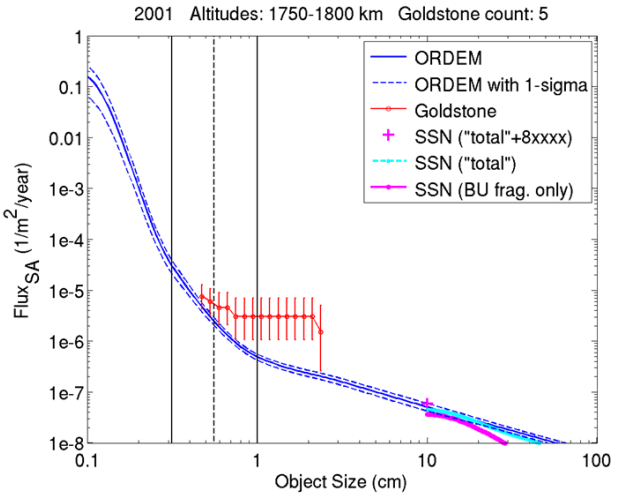

Figure D.2.4.2-29. 2001, Goldstone, 1750-1800 km, size vs. flux.

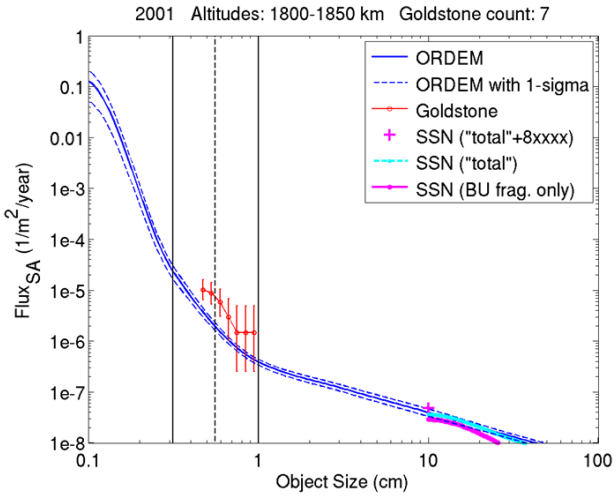

Figure D.2.4.2-30. 2001, Goldstone, 1800-1850 km, size vs. flux.

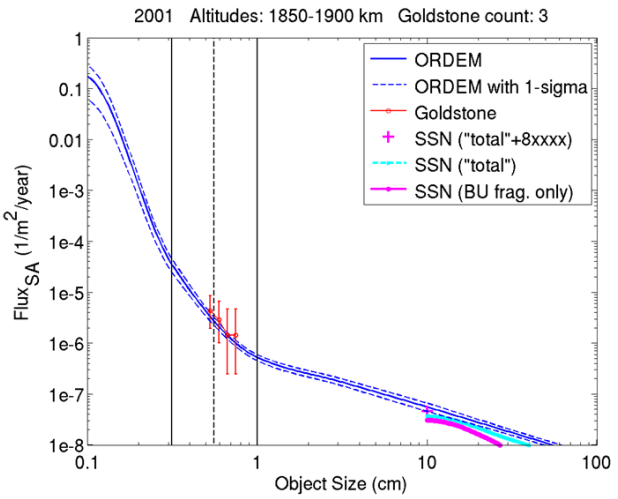

Figure D.2.4.2-31. 2001, Goldstone, 1850-1900 km, size vs. flux.

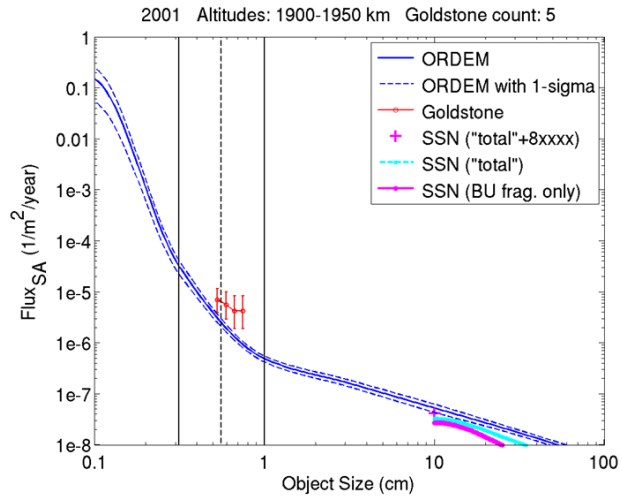

Figure D.2.4.2-32. 2001, Goldstone, 1900-1950 km, size vs. flux.

Goldstone Data
Unavailable
at
1950km - 2000km
in 2001

Figure D.2.4.2-33. 2001, Goldstone, 1950-2000 km, size vs. flux.

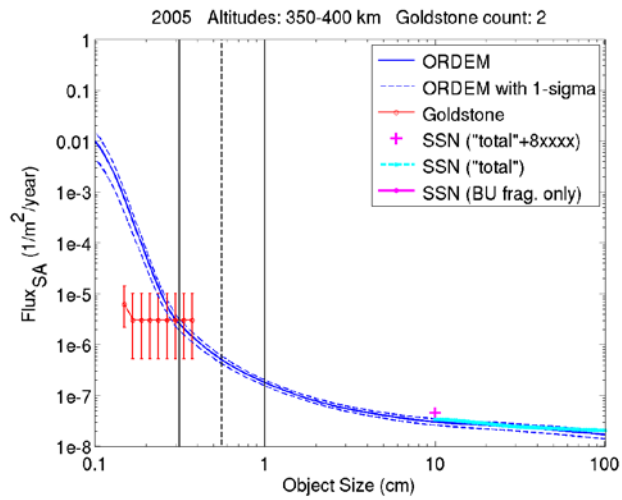

Figure D.2.4.2-34. 2005, Goldstone, 350-400 km, size vs. flux.

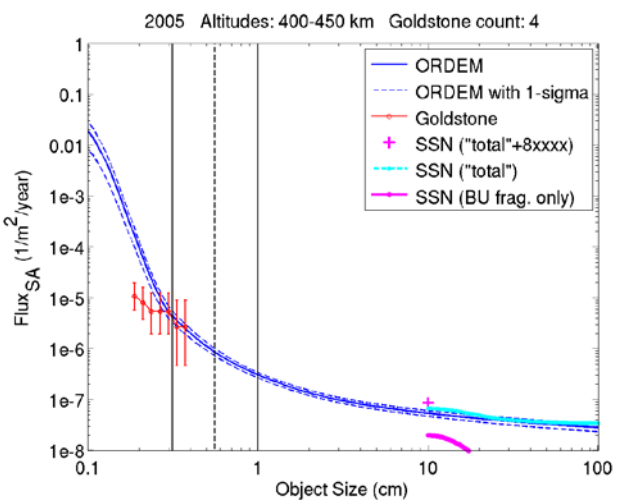

Figure D.2.4.2-35. 2005, Goldstone, 400-450 km, size vs. flux.

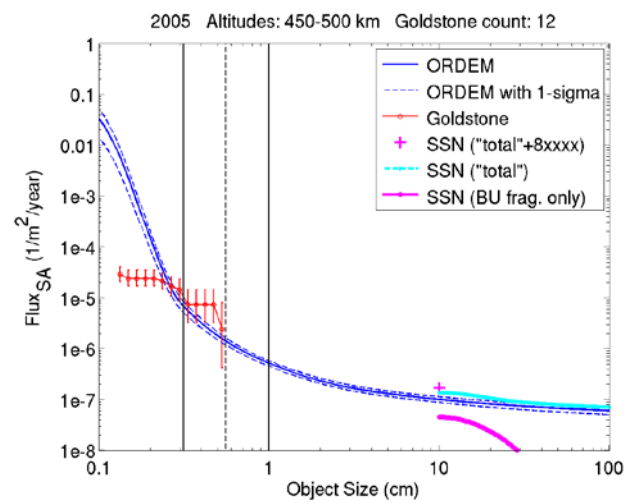

Figure D.2.4.2-36. 2005, Goldstone, 450-500 km, size vs. flux.

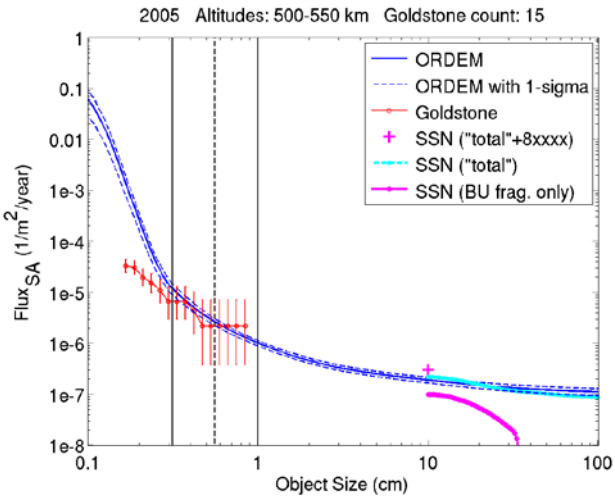

Figure D.2.4.2-37. 2005, Goldstone, 500-550 km, size vs. flux.

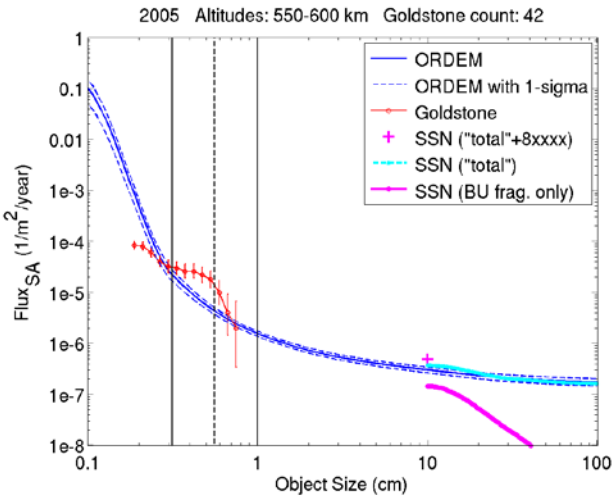

Figure D.2.4.2-38. 2005, Goldstone, 550-600 km, size vs. flux.

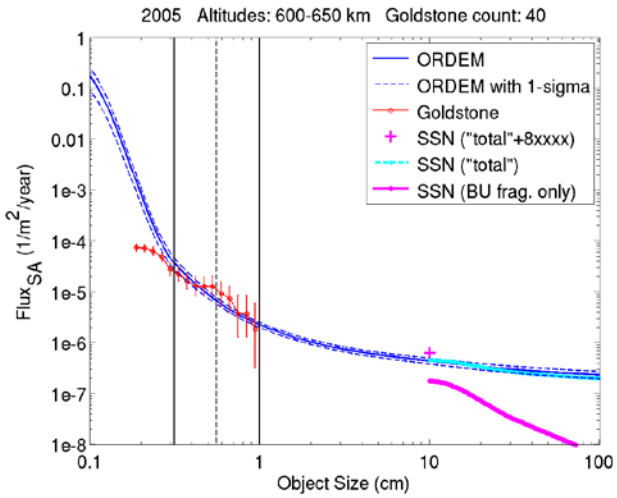

Figure D.2.4.2-39. 2005, Goldstone, 600-650 km, size vs. flux.

Goldstone Data Unavailable at 650km - 700km in 2005

Figure D.2.4.2-40. 2005, Goldstone, 650-700 km, size vs. flux.

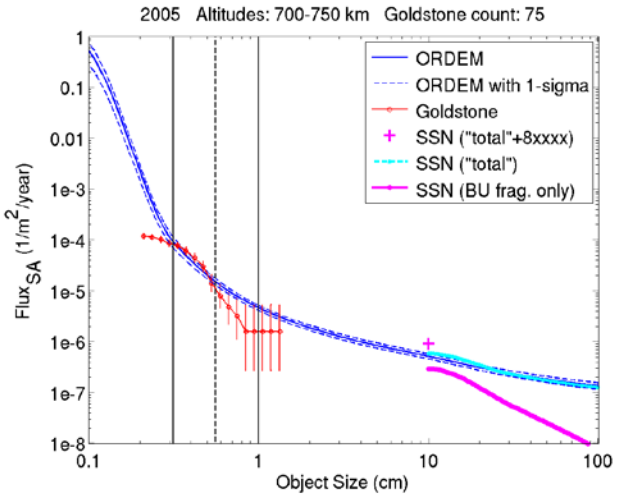

Figure D.2.4.2-41. 2005, Goldstone, 700-750 km, size vs. flux.

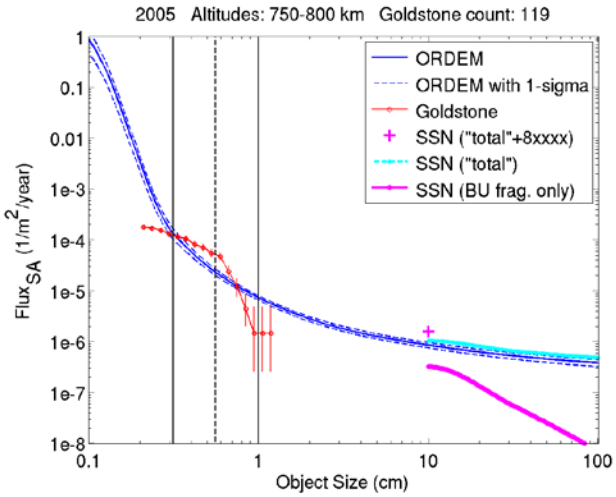

Figure D.2.4.2-42. 2005, Goldstone, 750-800 km, size vs. flux.

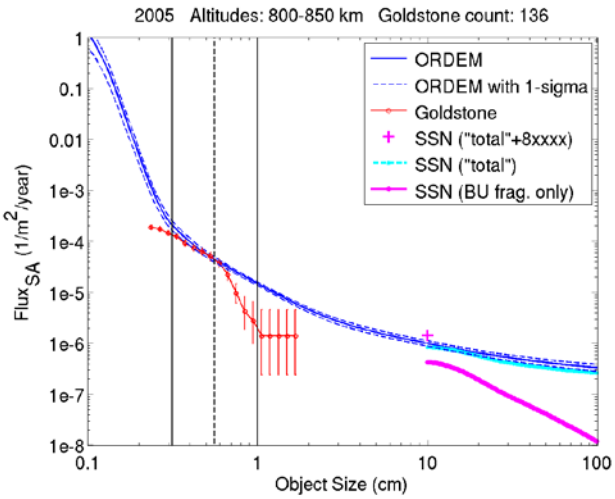

Figure D.2.4.2-43. 2005, Goldstone, 800-850 km, size vs. flux.

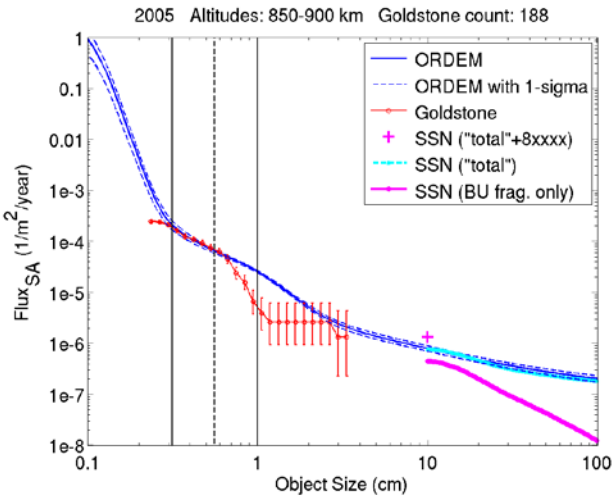

Figure D.2.4.2-44. 2005, Goldstone, 850-900 km, size vs. flux.

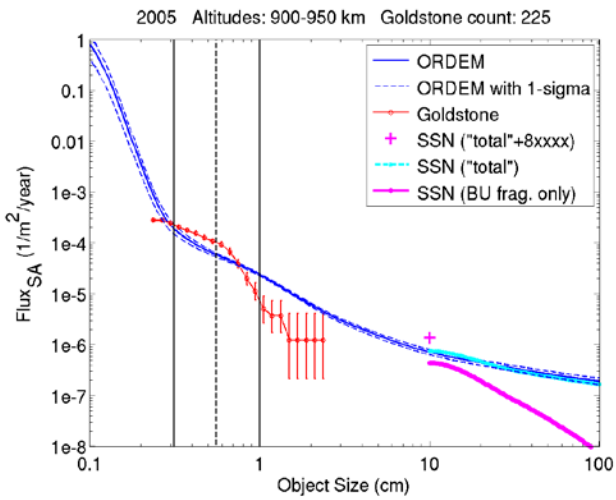

Figure D.2.4.2-45. 2005, Goldstone, 900-950 km, size vs. flux.

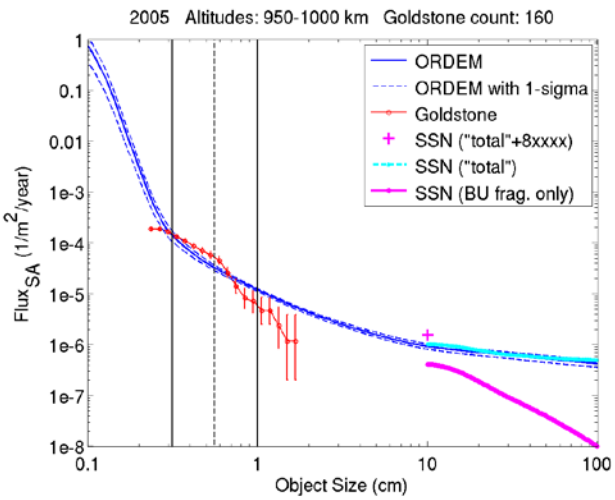

Figure D.2.4.2-46. 2005, Goldstone, 950-1000 km, size vs. flux.

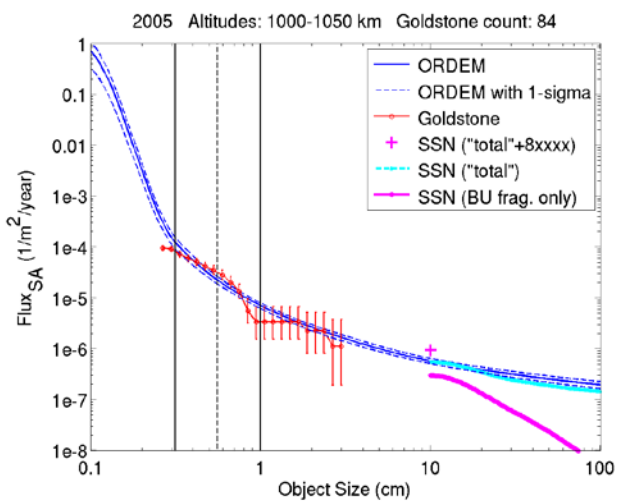

Figure D.2.4.2-47. 2005, Goldstone, 1000-1050 km, size vs. flux.

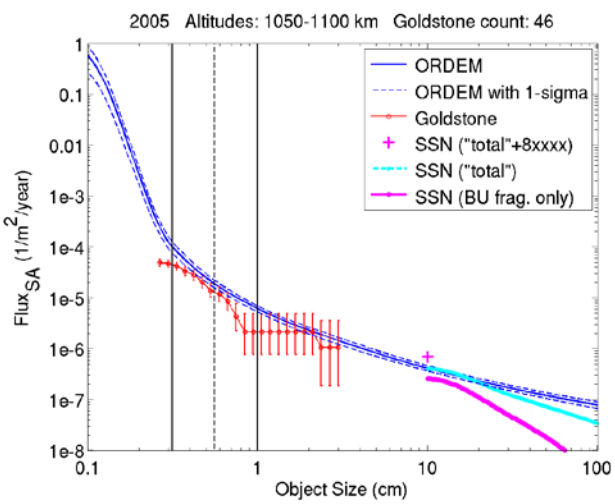

Figure D.2.4.2-48. 2005, Goldstone, 1050-1100 km, size vs. flux.

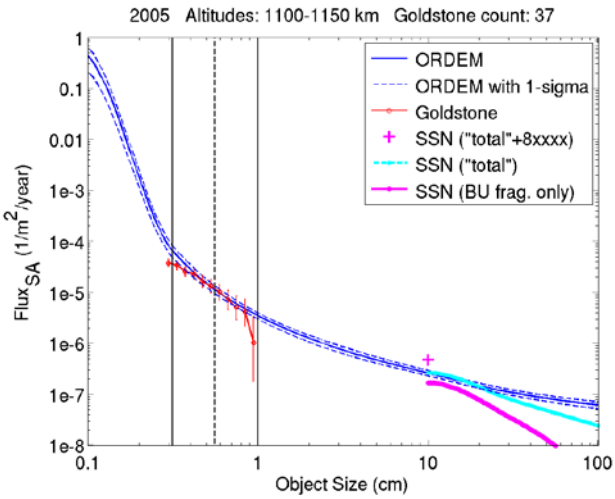

Figure D.2.4.2-49. 2005, Goldstone, 1100-1150 km, size vs. flux.

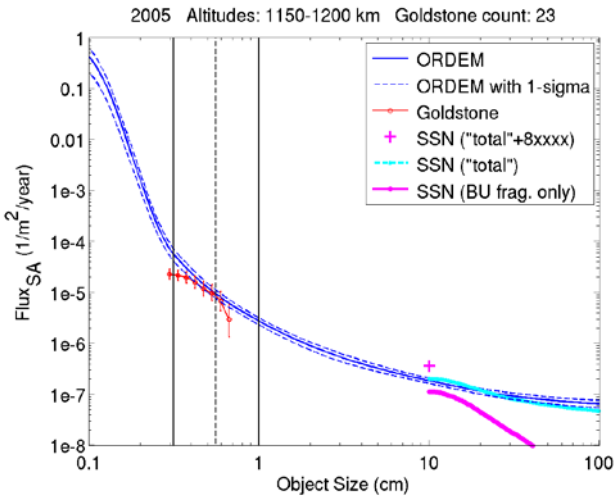

Figure D.2.4.2-50. 2005, Goldstone, 1150-1200 km, size vs. flux.

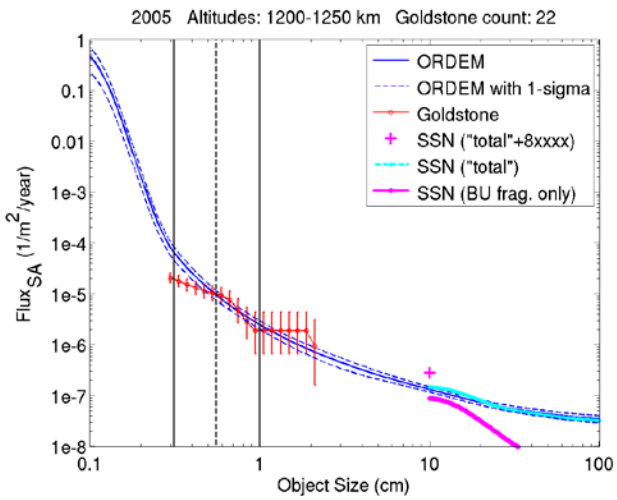

Figure D.2.4.2-51. 2005, Goldstone, 1200-1250 km, size vs. flux.

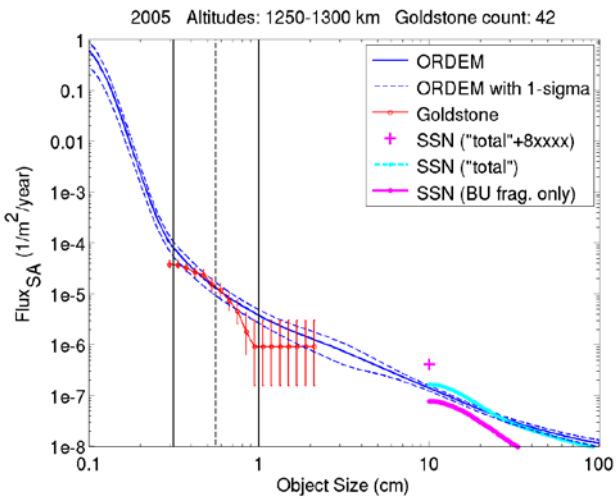

Figure D.2.4.2-52. 2005, Goldstone, 1250-1300 km, size vs. flux.

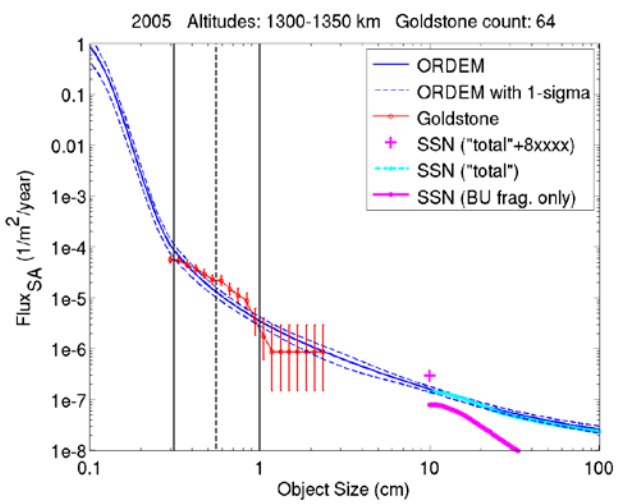

Figure D.2.4.2-53. 2005, Goldstone, 1300-1350 km, size vs. flux.

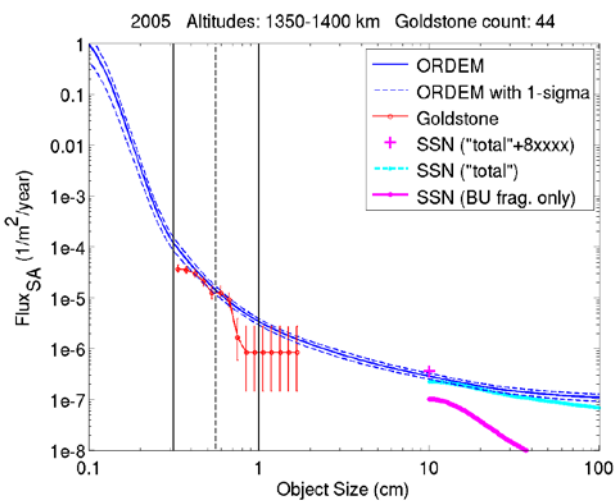

Figure D.2.4.2-54. 2005, Goldstone, 1350-1400 km, size vs. flux.

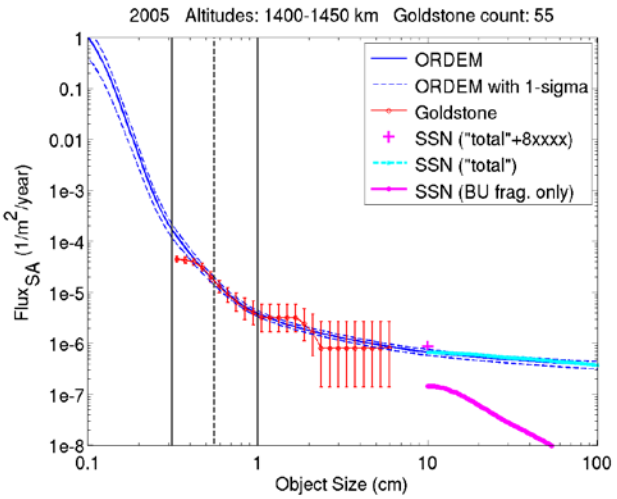

Figure D.2.4.2-55. 2005, Goldstone, 1400-1450 km, size vs. flux.

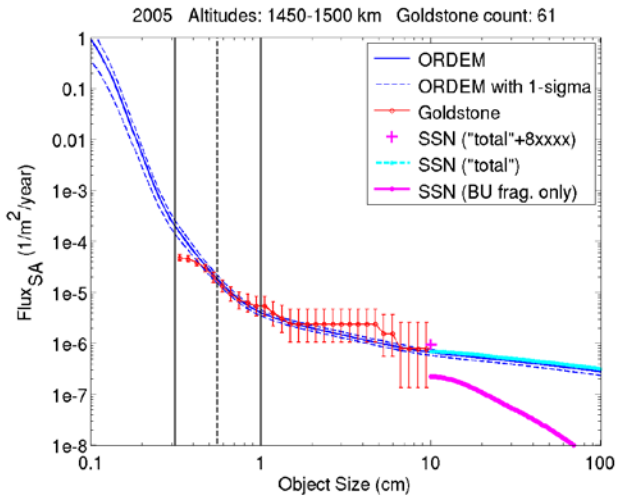

Figure D.2.4.2-56. 2005, Goldstone, 1450-1500 km, size vs. flux.

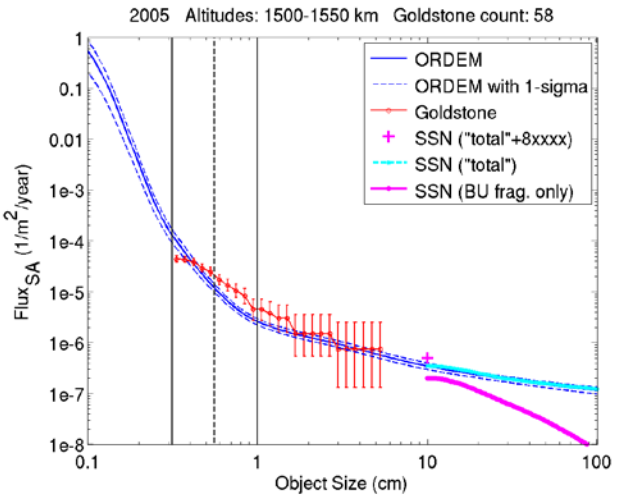

Figure D.2.4.2-57. 2005, Goldstone, 1500-1550 km, size vs. flux.

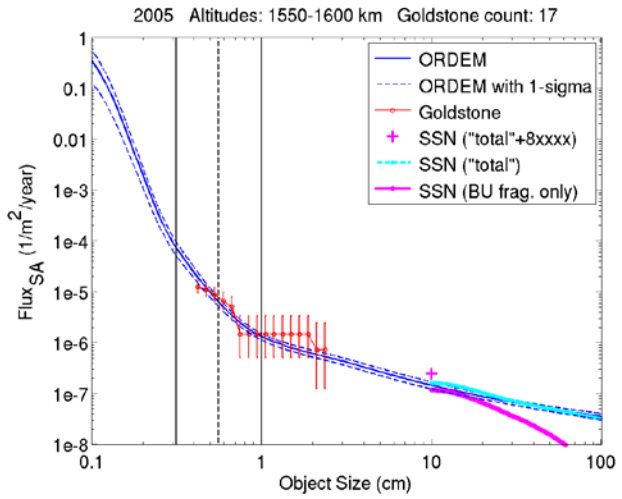

Figure D.2.4.2-58. 2005, Goldstone, 1550-1600 km, size vs. flux.

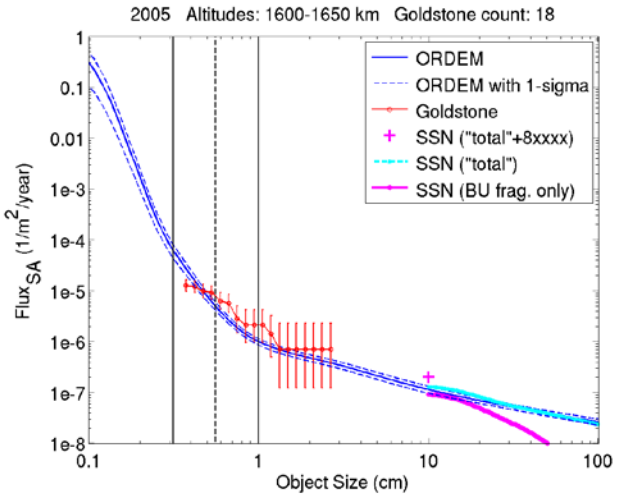

Figure D.2.4.2-59. 2005, Goldstone, 1600-1650 km, size vs. flux.

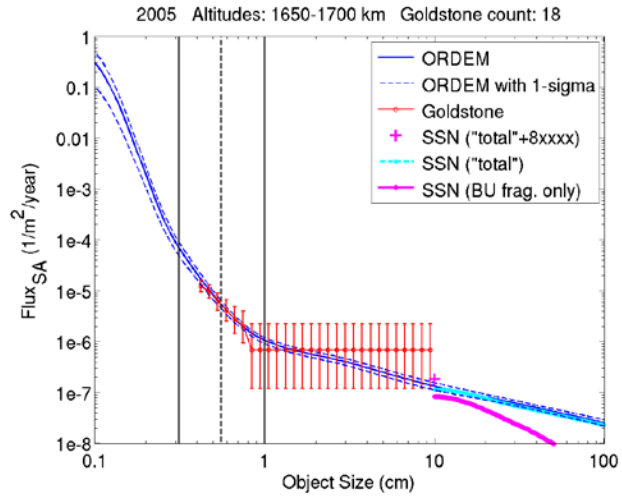

Figure D.2.4.2-60. 2005, Goldstone, 1650-1700 km, size vs. flux.

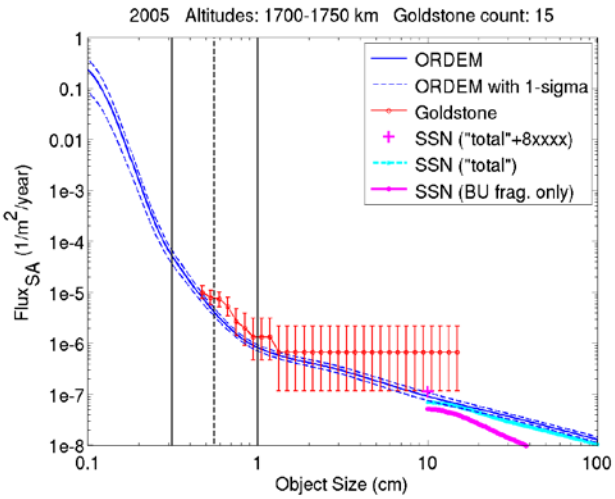

Figure D.2.4.2-61. 2005, Goldstone, 1700-1750 km, size vs. flux.

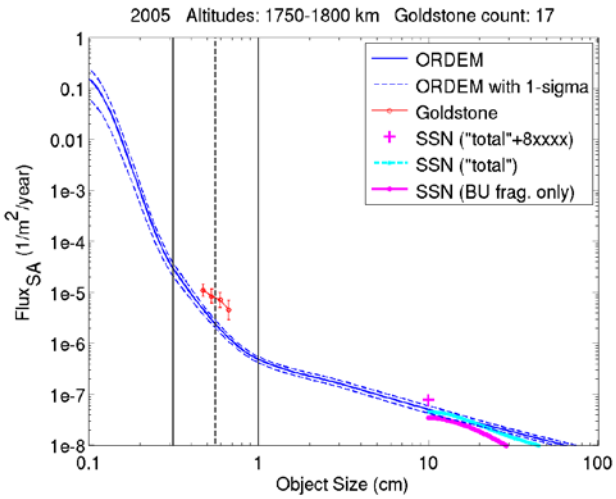

Figure D.2.4.2-62. 2005, Goldstone, 1750-1800 km, size vs. flux.

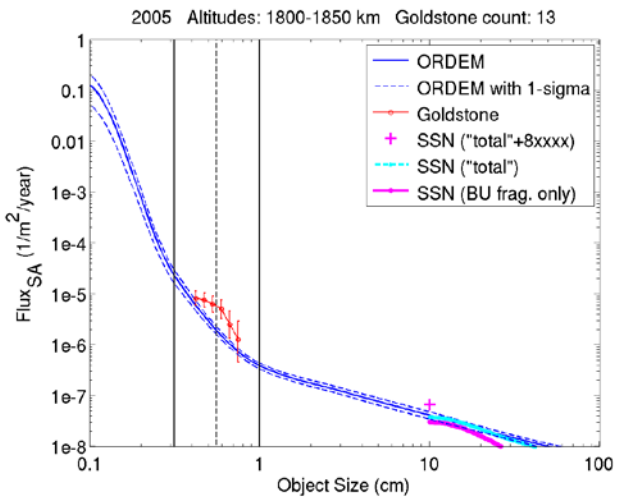

Figure D.2.4.2-63. 2005, Goldstone, 1800-1850 km, size vs. flux.

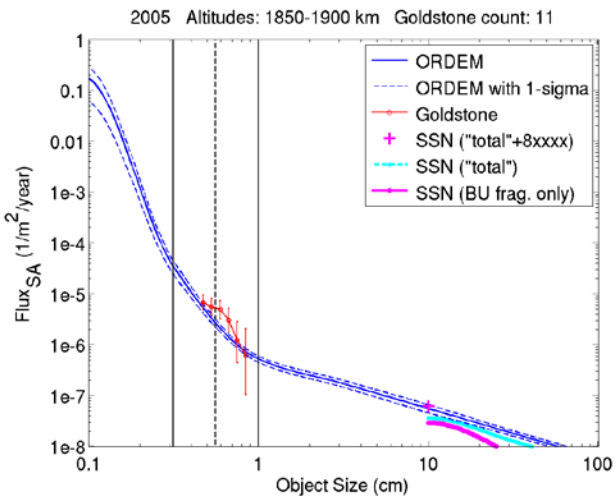

Figure D.2.4.2-64. 2005, Goldstone, 1850-1900 km, size vs. flux.

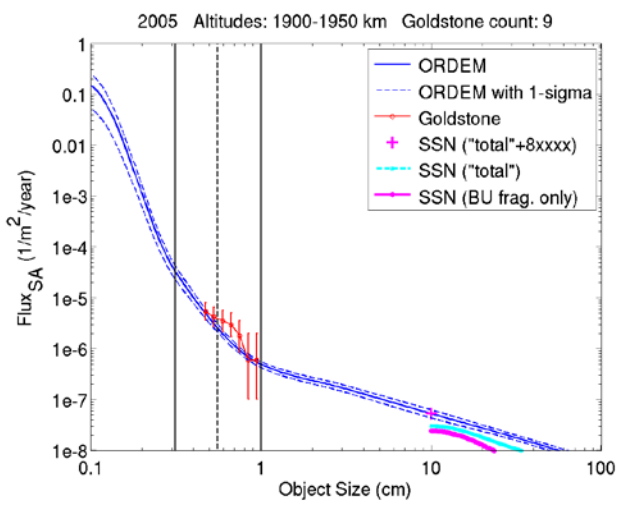

Figure D.2.4.2-65. 2005, Goldstone, 1900-1950 km, size vs. flux.

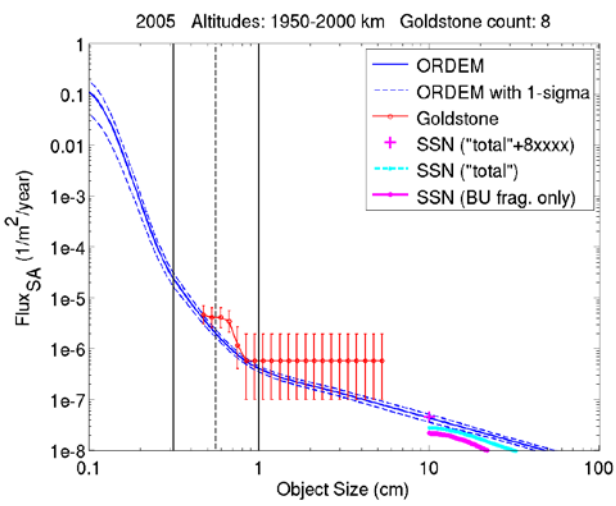

Figure D.2.4.2-66. 2005, Goldstone, 1950-2000 km, size vs. flux.

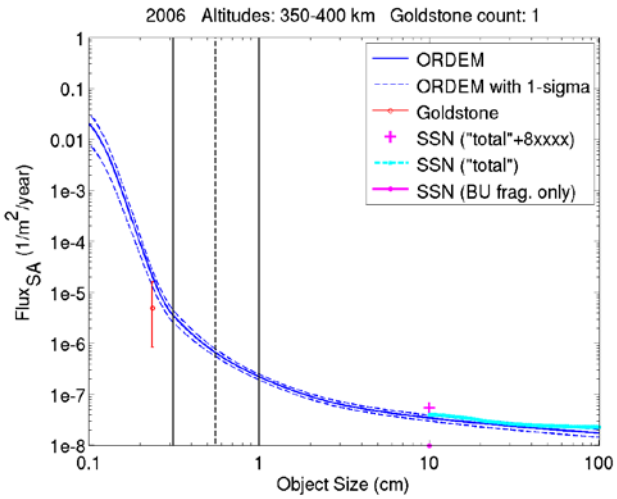

Figure D.2.4.2-67. 2006, Goldstone, 350-400 km, size .vs. flux

Goldstone Data Unavailable at 400km -450km in 2006

Figure D.2.4.2-68. 2006, Goldstone, 400-450 km, size .vs. flux

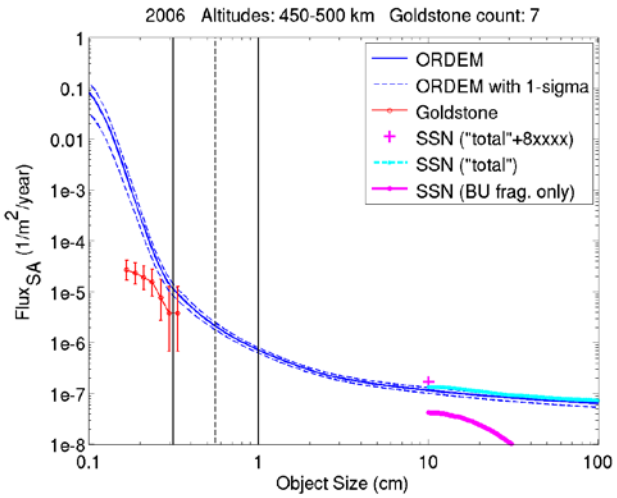

Figure D.2.4.2-69. 2006, Goldstone, 450-500 km, size vs. flux.

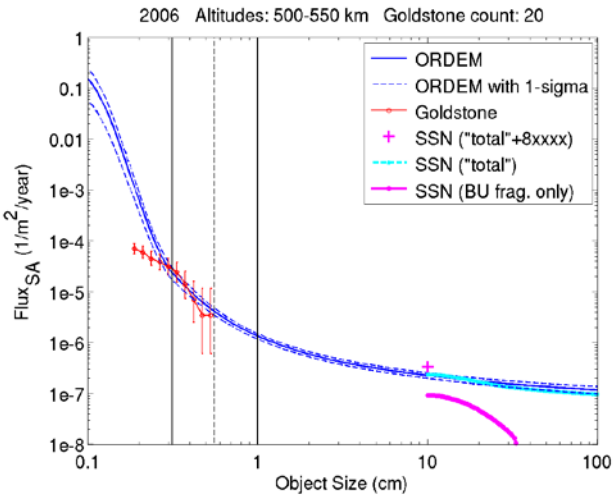

Figure D.2.4.2-70. 2006, Goldstone, 500-550 km, size vs. flux.

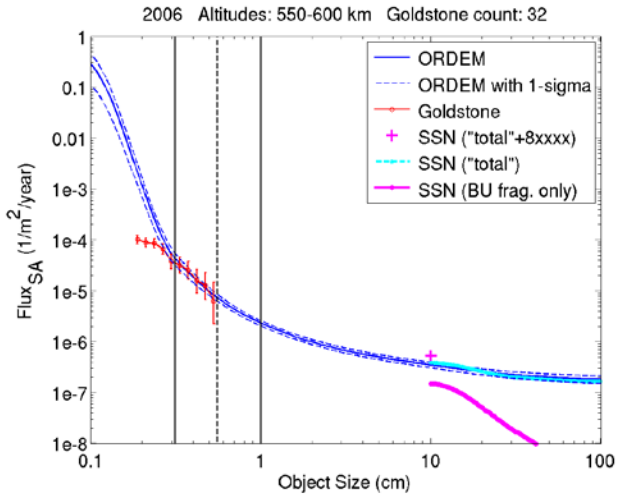

Figure D.2.4.2-71. 2006, Goldstone, 550-600 km, size vs. flux.

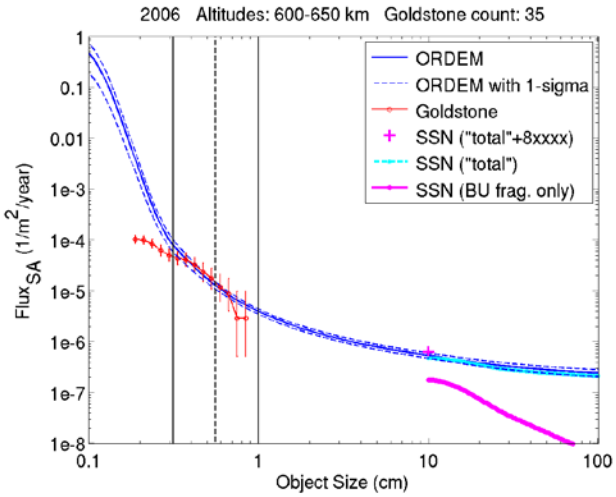

Figure D.2.4.2-72. 2006, Goldstone, 600-650 km, size vs. flux.

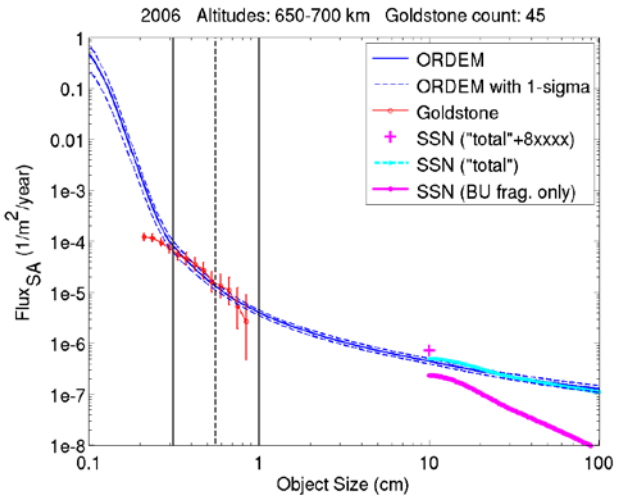

Figure D.2.4.2-73. 2006, Goldstone, 650-700 km, size vs. flux.

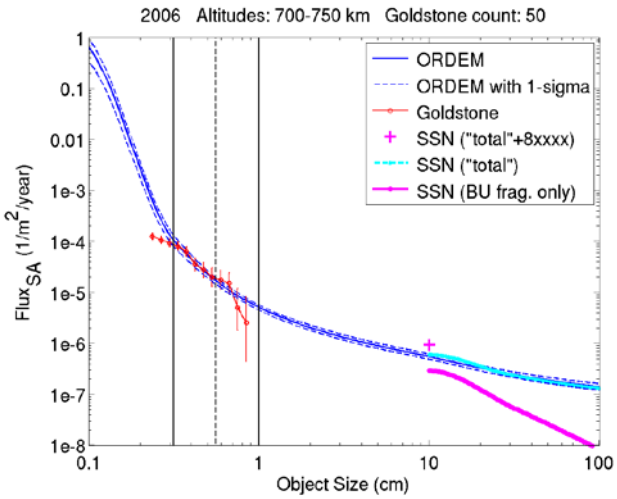

Figure D.2.4.2-74. 2006, Goldstone, 700-750 km, size vs. flux.

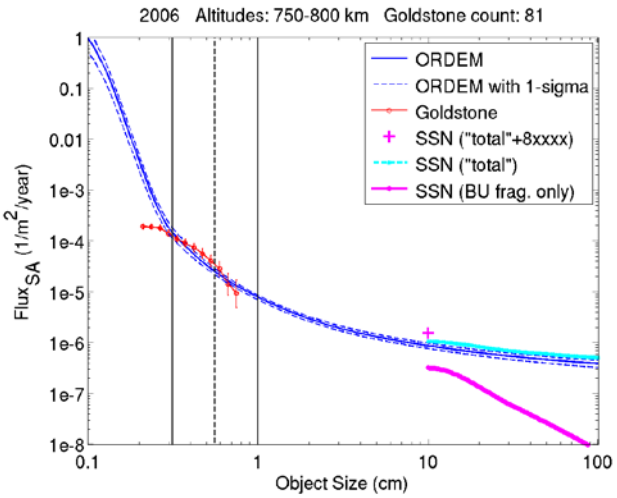

Figure D.2.4.2-75. 2006, Goldstone, 750-800 km, size vs. flux.

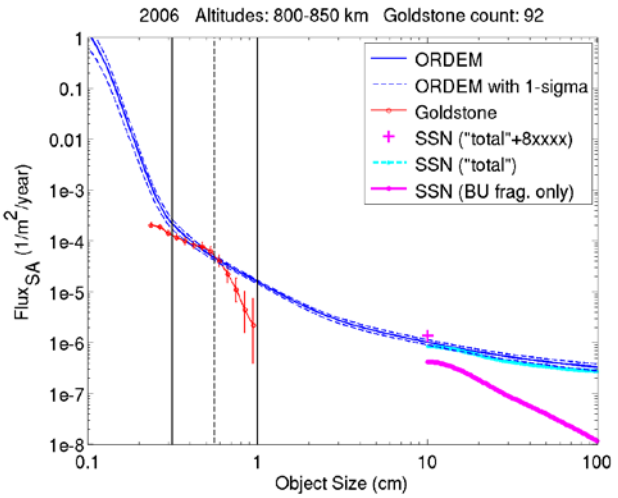

Figure D.2.4.2-76. 2006, Goldstone, 800-850 km, size vs. flux.

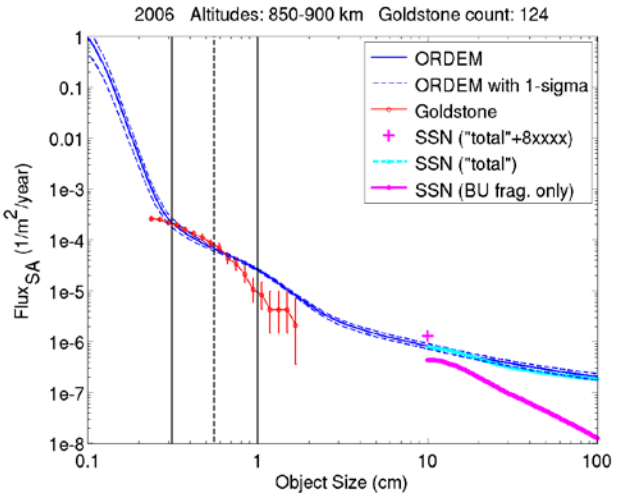

Figure D.2.4.2-77. 2006, Goldstone, 850-900 km, size vs. flux.

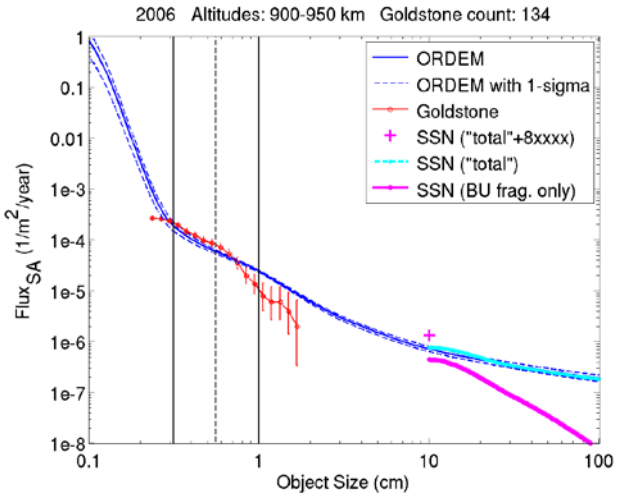

Figure D.2.4.2-78. 2006, Goldstone, 900-950 km, size vs. flux.

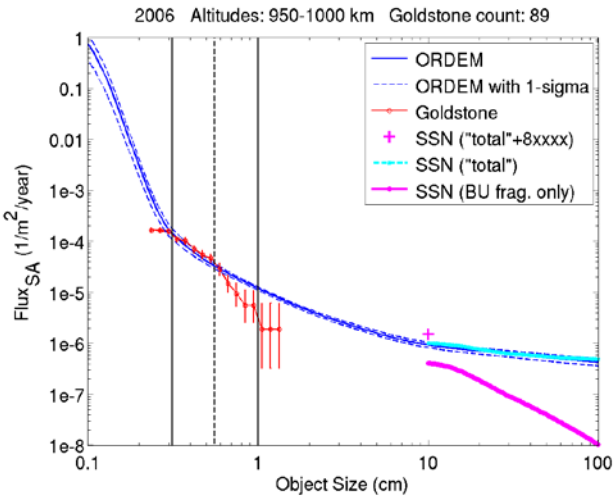

Figure D.2.4.2-79. 2006, Goldstone, 950-1000 km, size vs. flux.

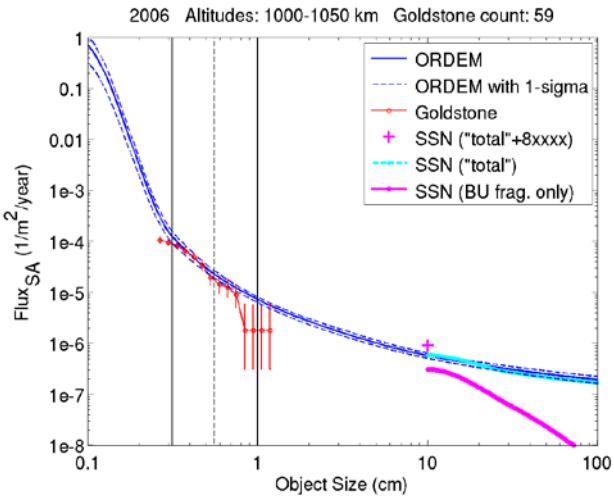

Figure D.2.4.2-80. 2006, Goldstone, 1000-1050 km, size vs. flux.

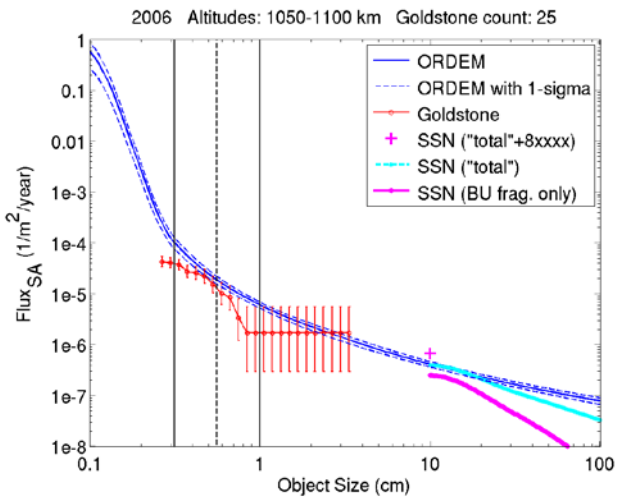

Figure D.2.4.2-81. 2006, Goldstone, 1050-1100 km, size vs. flux.

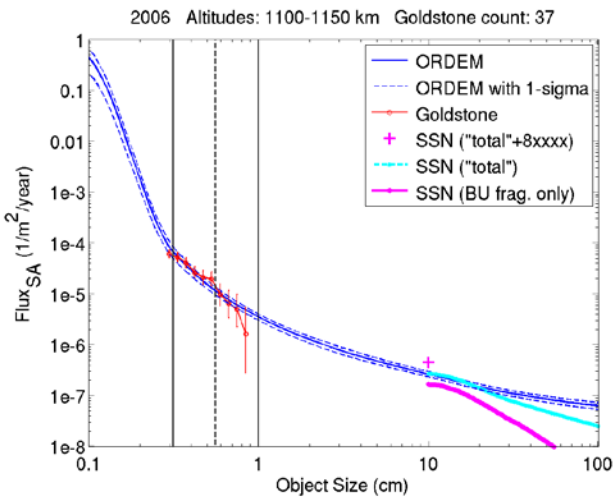

Figure D.2.4.2-82. 2006, Goldstone, 1100-1150 km, size vs. flux.

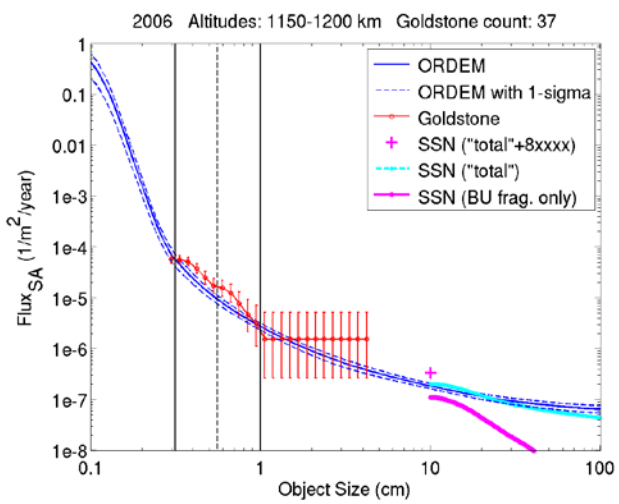

Figure D.2.4.2-83. 2006, Goldstone, 1150-1200 km, size vs. flux.

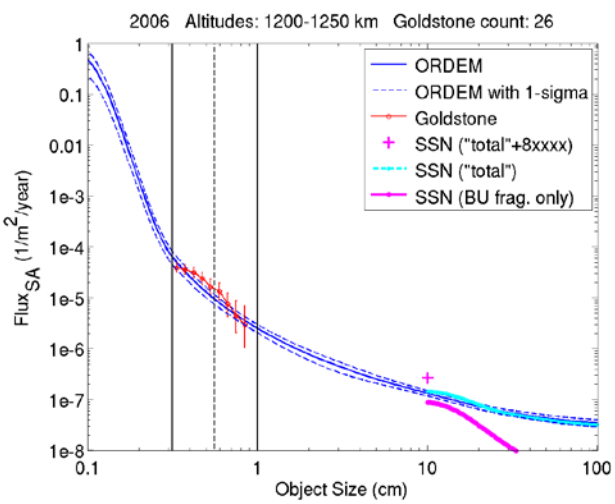

Figure D.2.4.2-84. 2006, Goldstone, 1200-1250 km, size vs. flux.

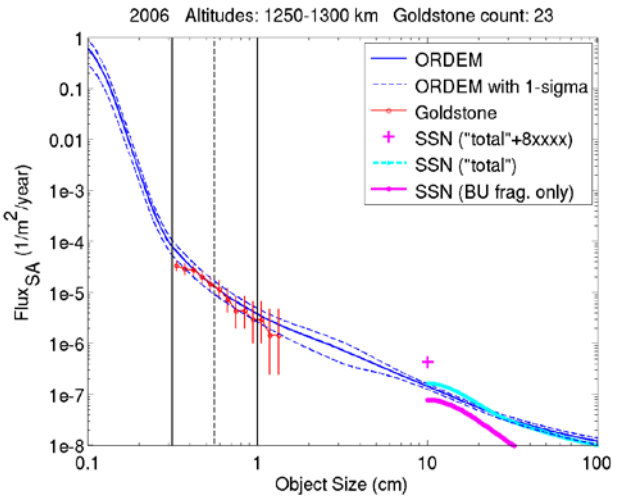

Figure D.2.4.2-85. 2006, Goldstone, 1250-1300 km, size vs. flux.

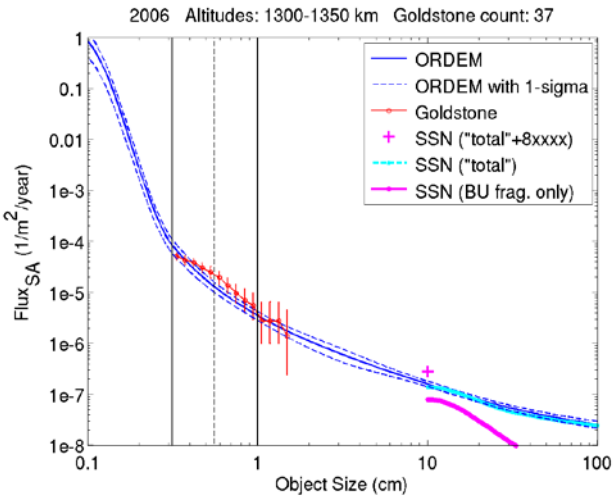

Figure D.2.4.2-86. 2006, Goldstone, 1300-1350 km, size vs. flux.

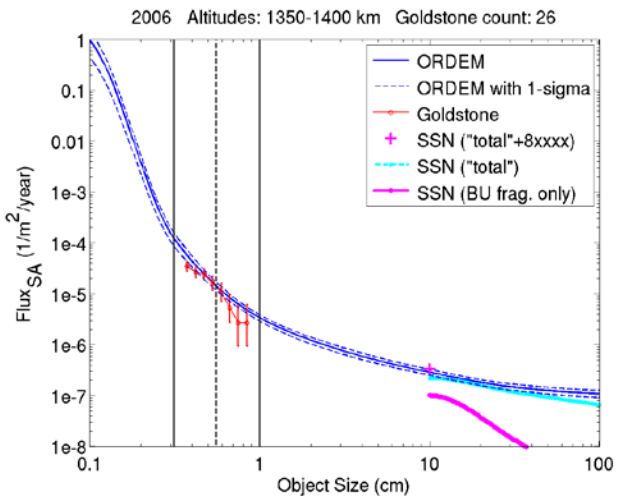

Figure D.2.4.2-87. 2006, Goldstone, 1350-1400 km, size vs. flux.

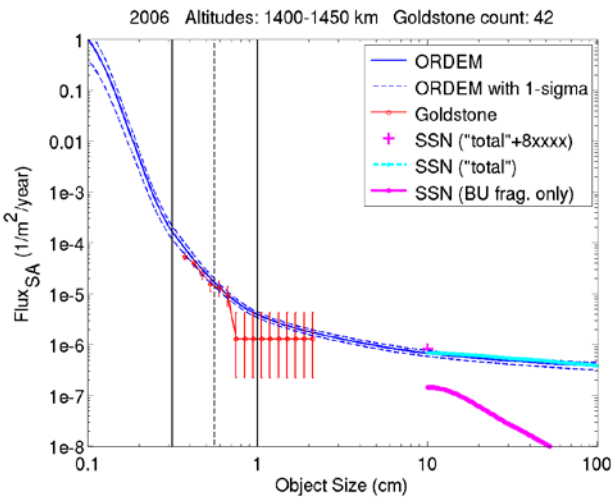

Figure D.2.4.2-88. 2006, Goldstone, 1400-1450 km, size vs. flux.

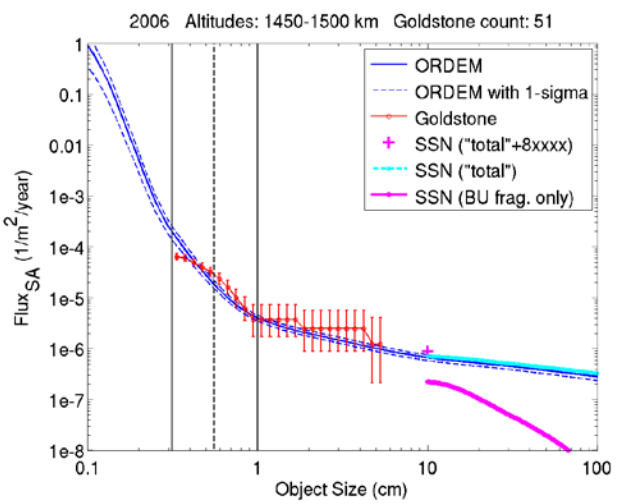

Figure D.2.4.2-89. 2006, Goldstone, 1450-1500 km, size vs. flux.

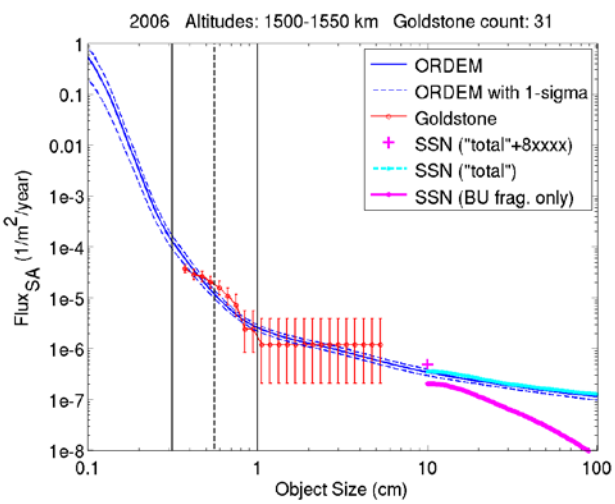

Figure D.2.4.2-90. 2006, Goldstone, 1500-1550 km, size vs. flux.

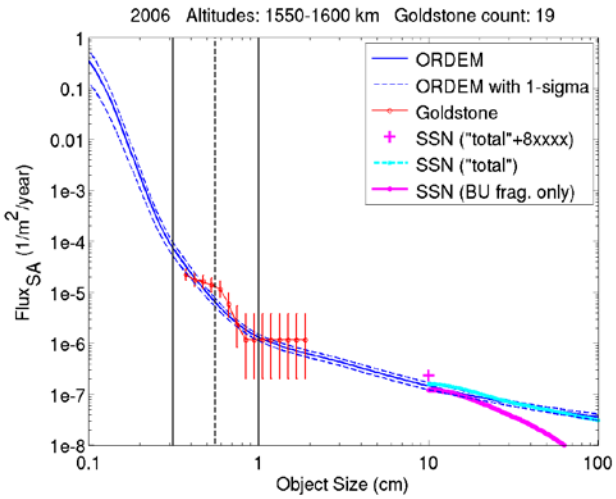

Figure D.2.4.2-91. 2006, Goldstone, 1550-1600 km, size vs. flux.

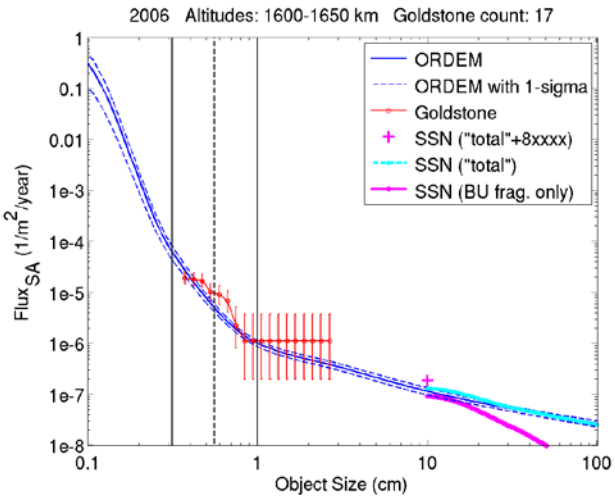

Figure D.2.4.2-92. 2006, Goldstone, 1600-1650 km, size vs. flux.

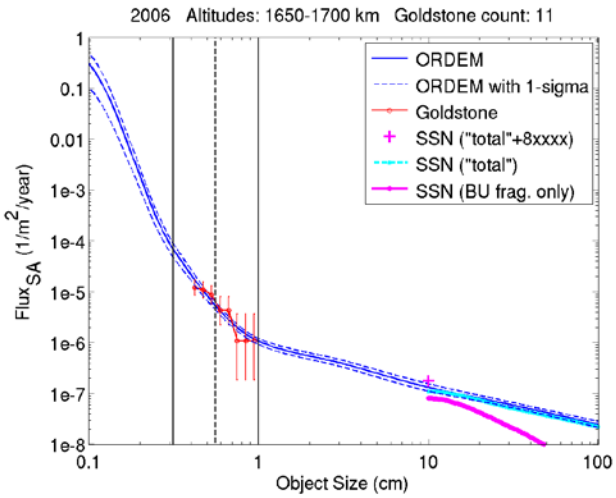

Figure D.2.4.2-93. 2006, Goldstone, 1650-1700 km, size vs. flux.

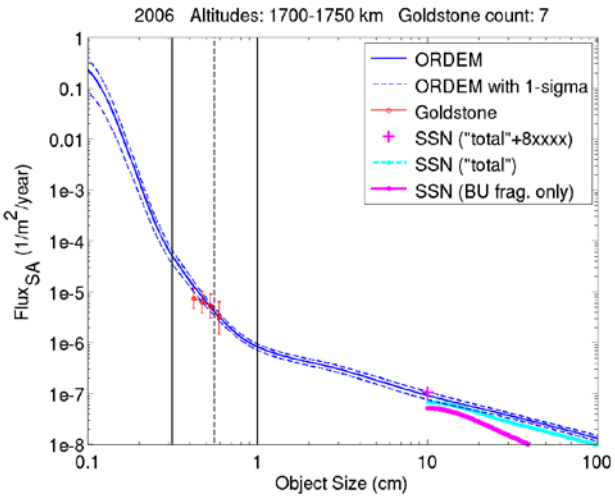

Figure D.2.4.2-94. 2006, Goldstone, 1700-1750 km, size vs. flux.

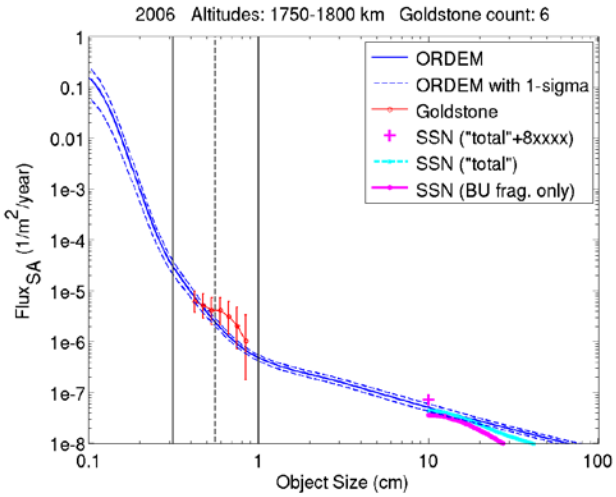

Figure D.2.4.2-95. 2006, Goldstone, 1750-1800 km, size vs. flux.

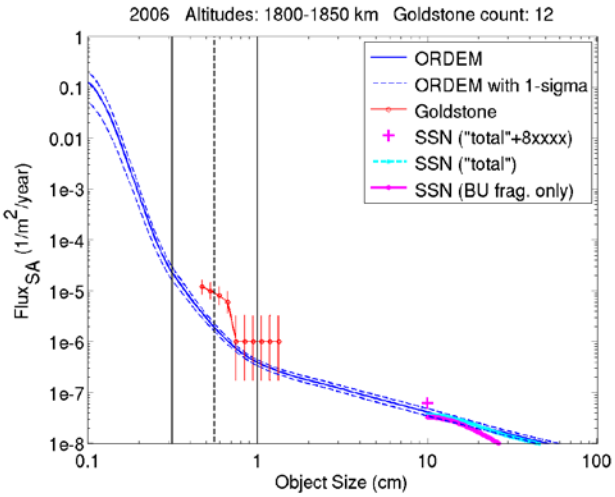

Figure D.2.4.2-96. 2006, Goldstone, 1800-1850 km, size vs. flux.

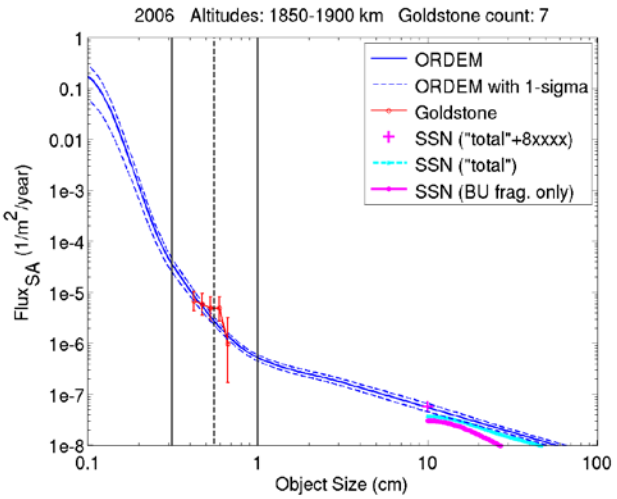

Figure D.2.4.2-97. 2006, Goldstone, 1850-1900 km, size vs. flux.

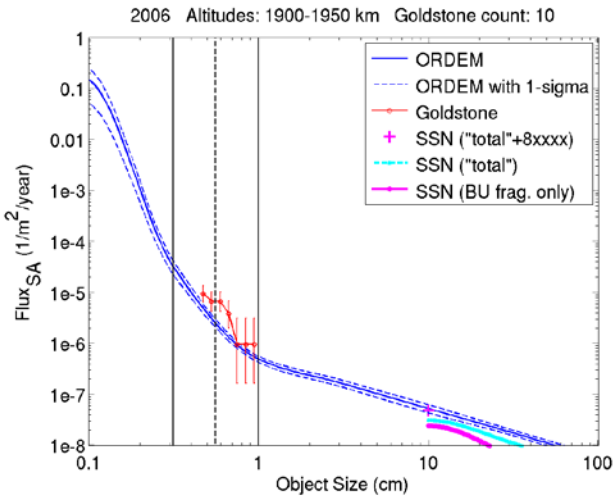

Figure D.2.4.2-98. 2006, Goldstone, 1900-1950 km, size vs. flux.

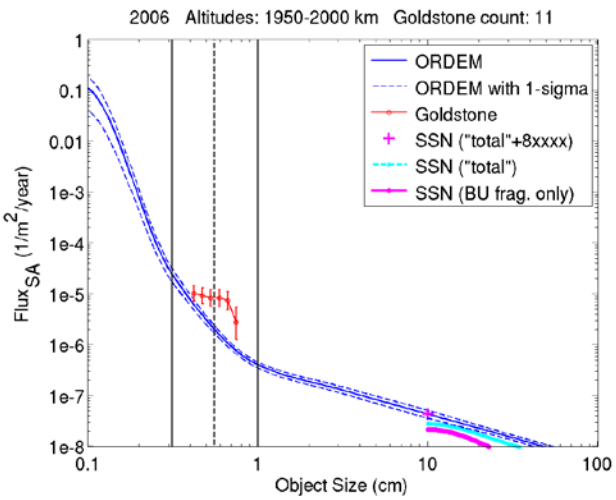

Figure D.2.4.2-99. 2006, Goldstone, 1950-2000 km, size vs. flux.

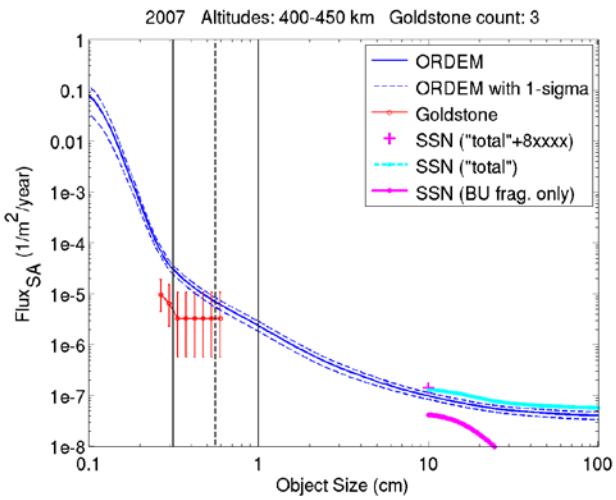

Figure D.2.4.2-100. 2007, Goldstone, 400-450 km, size vs. flux.

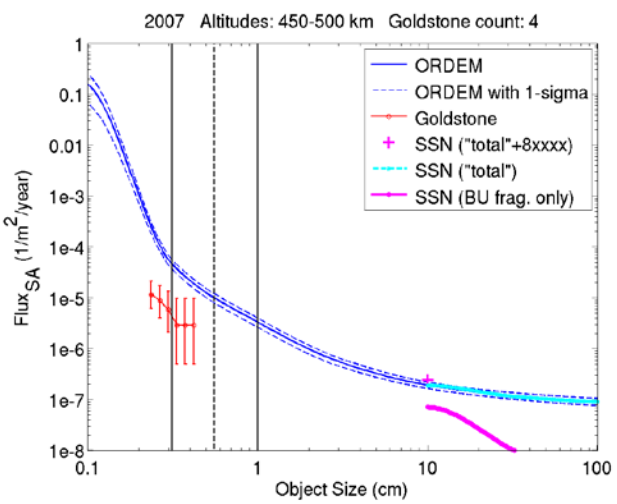

Figure D.2.4.2-101. 2007, Goldstone, 450-500 km, size vs. flux.

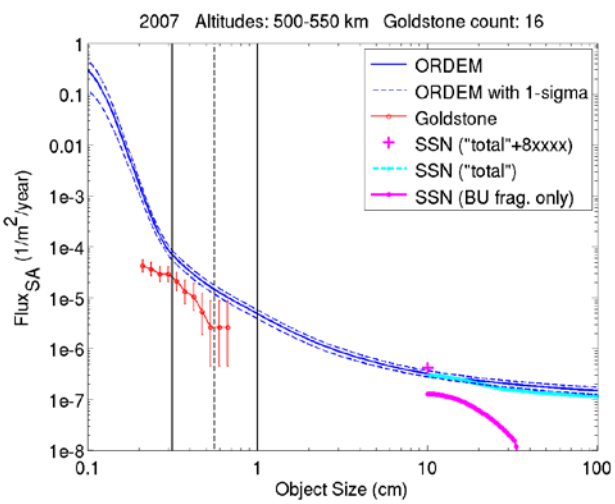

Figure D.2.4.2-102. 2007, Goldstone, 500-550 km, size vs. flux.

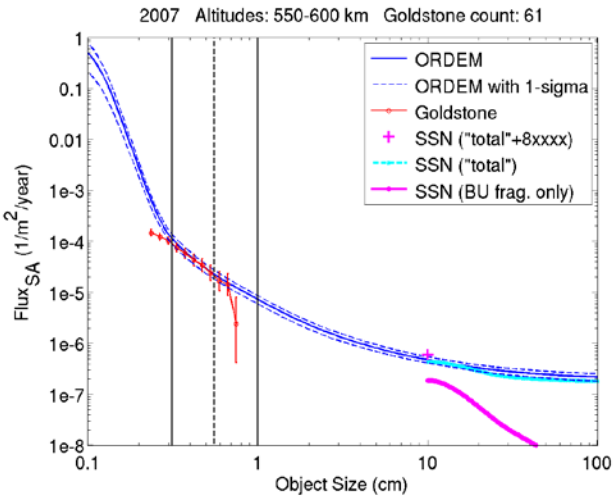

Figure D.2.4.2-103. 2007, Goldstone, 550-600 km, size vs. flux.

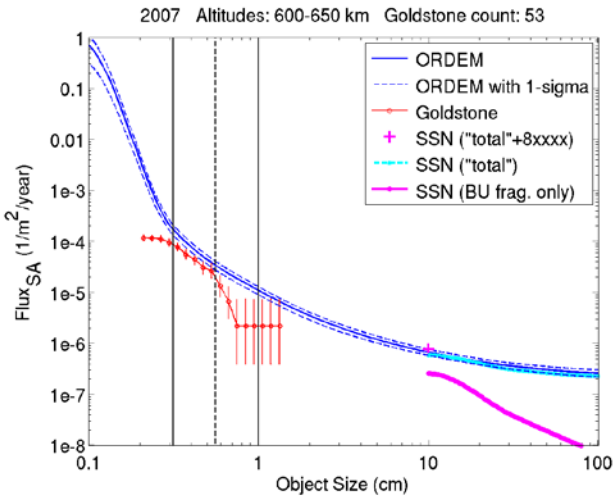

Figure D.2.4.2-104. 2007, Goldstone, 600-650 km, size vs. flux.

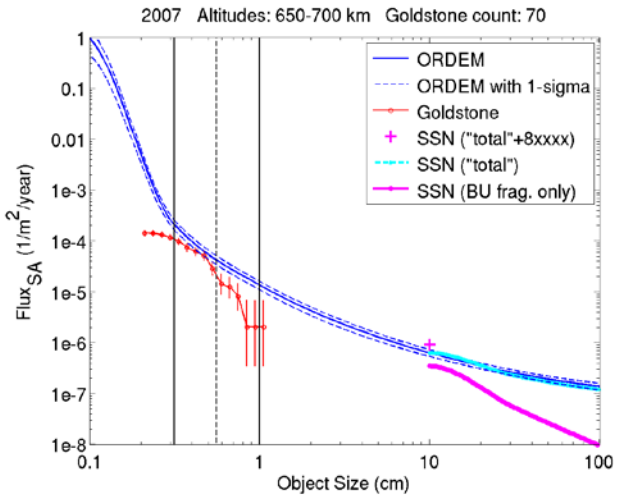

Figure D.2.4.2-105. 2007, Goldstone, 650-700 km, size vs. flux.

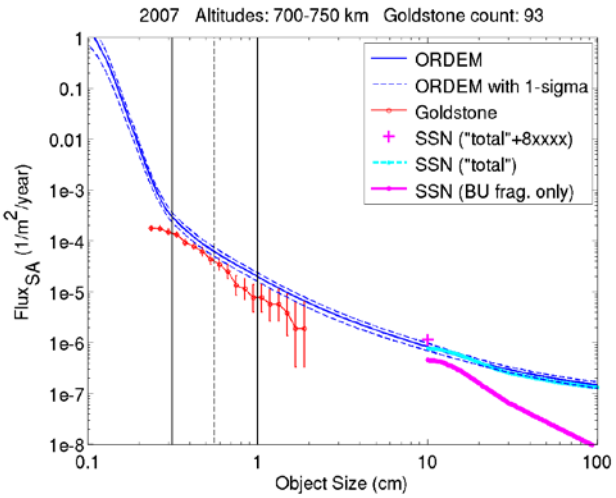

Figure D.2.4.2-106. 2007, Goldstone, 700-750 km, size vs. flux.

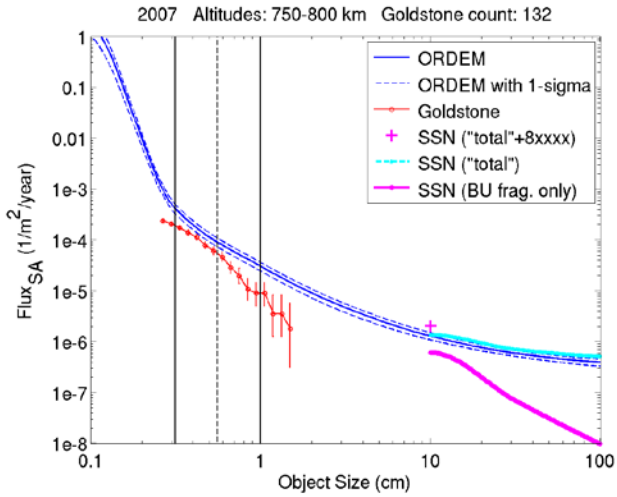

Figure D.2.4.2-107. 2007, Goldstone, 750-800 km, size vs. flux.

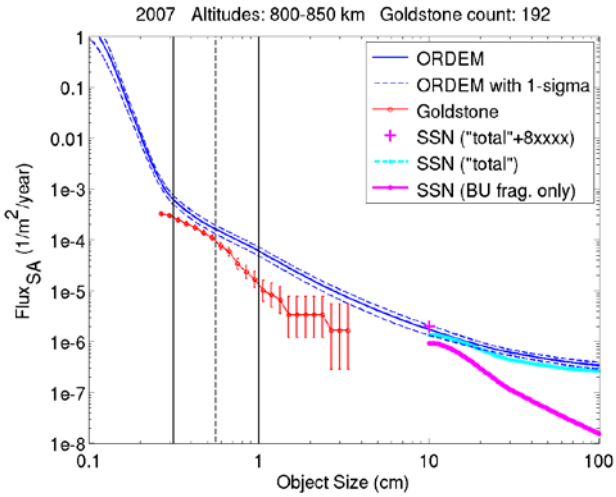

Figure D.2.4.2-108. 2007, Goldstone, 800-850 km, size vs. flux.

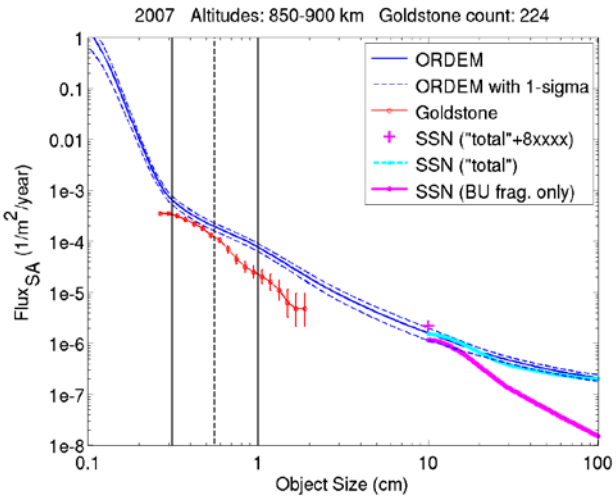

Figure D.2.4.2-109. 2007, Goldstone, 850-900 km, size vs. flux.

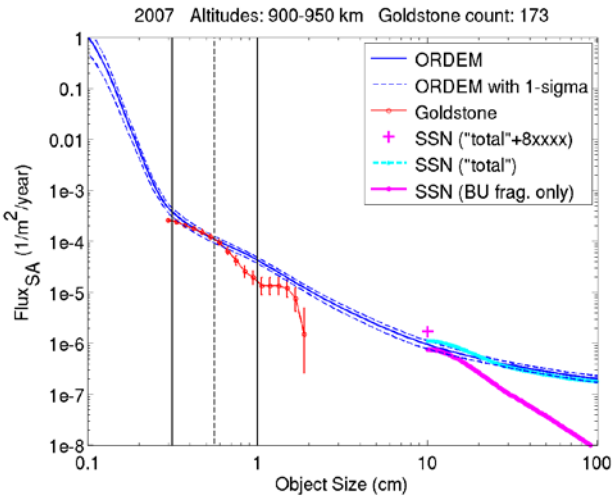

Figure D.2.4.2-110. 2007, Goldstone, 900-950 km, size vs. flux.

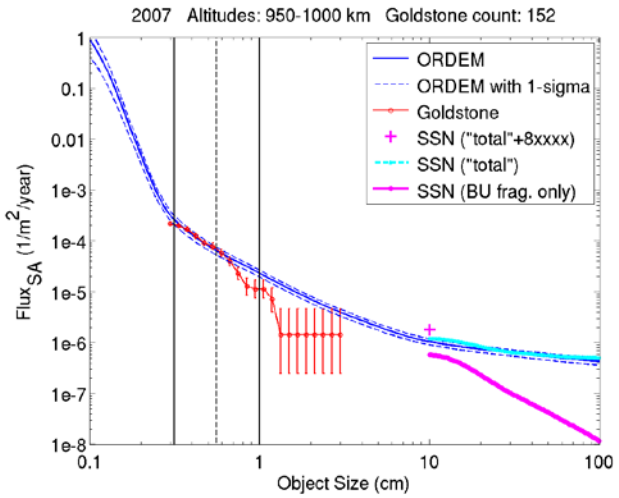

Figure D.2.4.2-111. 2007, Goldstone, 950-1000 km, size vs. flux.

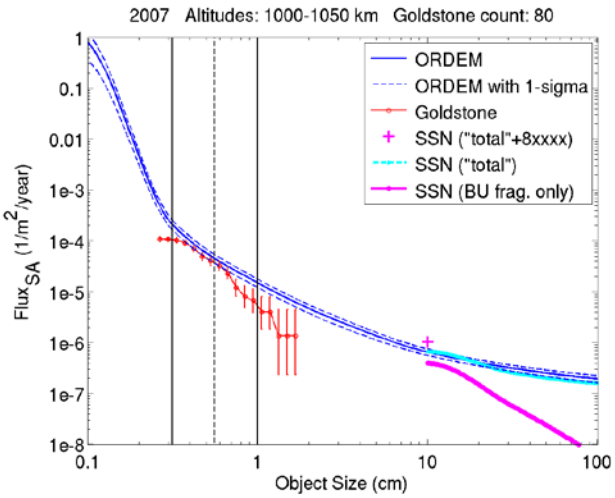

Figure D.2.4.2-112. 2007, Goldstone, 1000-1050 km, size vs. flux.

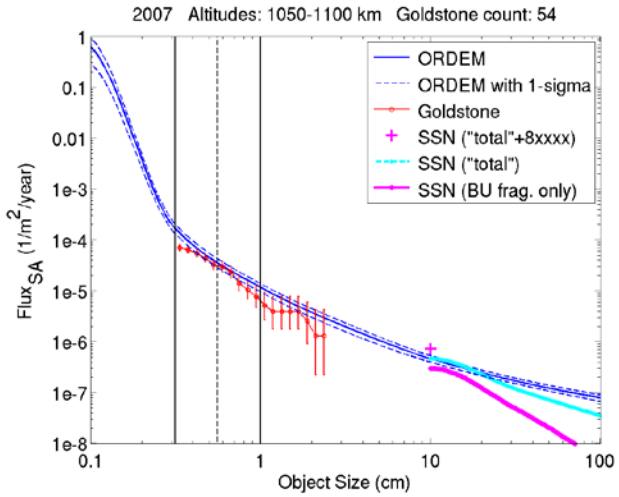

Figure D.2.4.2-113. 2007, Goldstone, 1050-1100 km, size vs. flux.

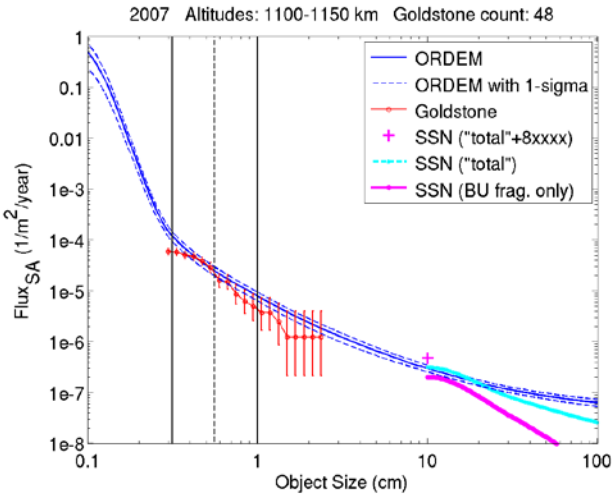

Figure D.2.4.2-114. 2007, Goldstone, 1100-1150 km, size vs. flux.

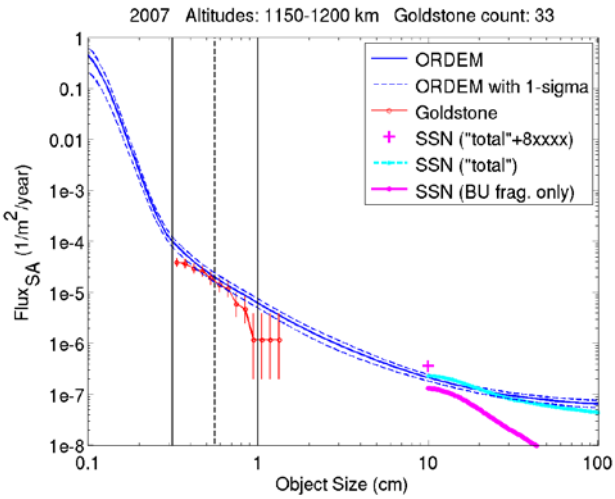

Figure D.2.4.2-115. 2007, Goldstone, 1150-1200 km, size vs. flux.

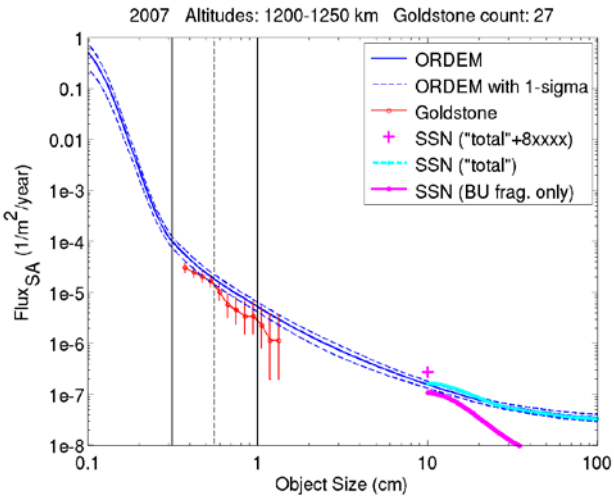

Figure D.2.4.2-116. 2007, Goldstone, 1200-1250 km, size vs. flux.

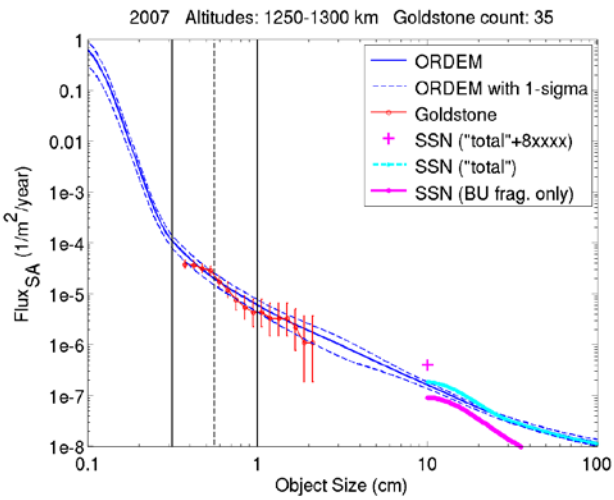

Figure D.2.4.2-117. 2007, Goldstone, 1250-1300 km, size vs. flux.

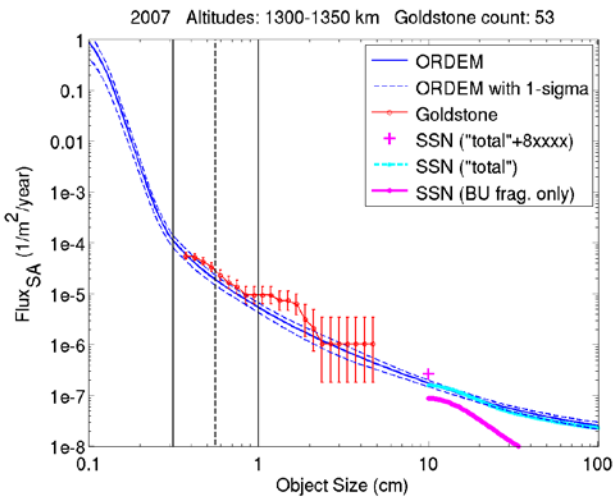

Figure D.2.4.2-118. 2007, Goldstone, 1300-1350 km, size vs. flux.

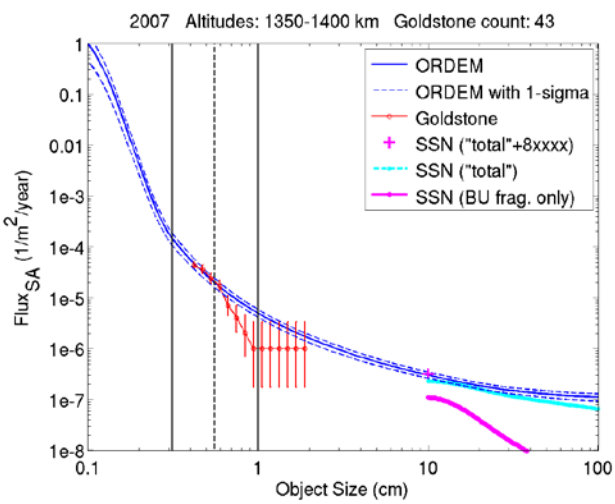

Figure D.2.4.2-119. 2007, Goldstone, 1350-1400 km, size vs. flux.

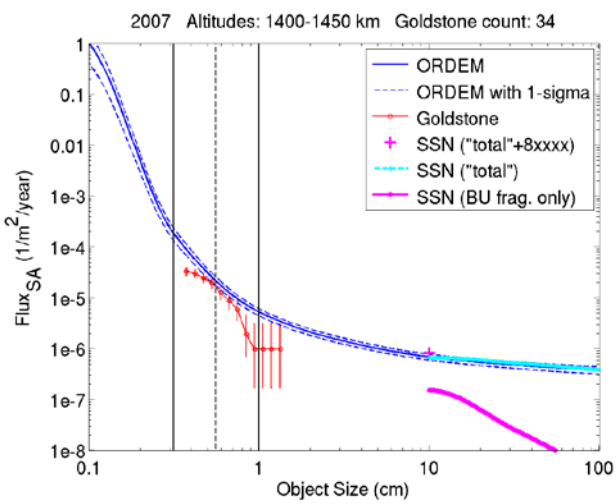

Figure D.2.4.2-120. 2007, Goldstone, 1400-1450 km, size vs. flux.

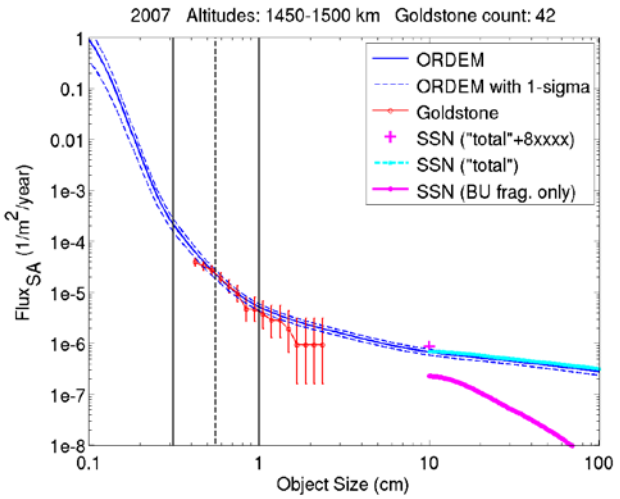

Figure D.2.4.2-121. 2007, Goldstone, 1450-1500 km, size vs. flux.

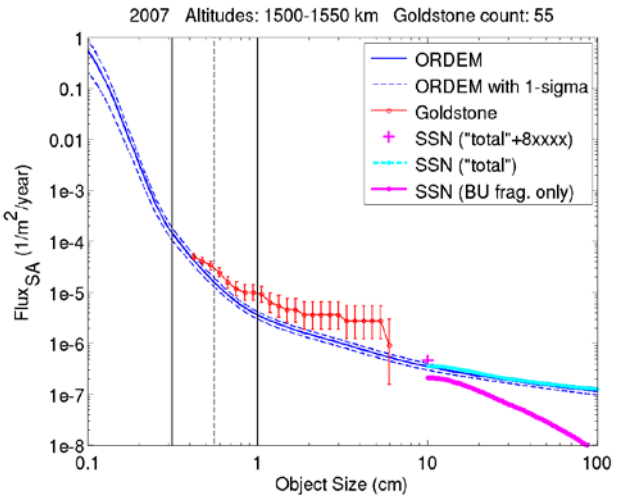

Figure D.2.4.2-122. 2007, Goldstone, 1500-1550 km, size vs. flux.

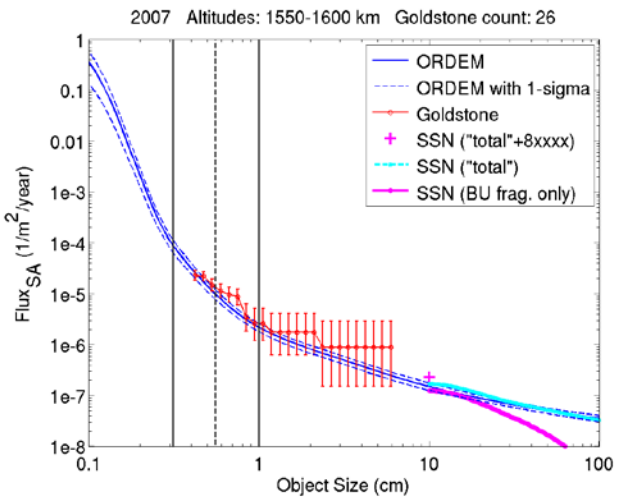

Figure D.2.4.2-123. 2007, Goldstone, 1550-1600 km, size vs. flux.

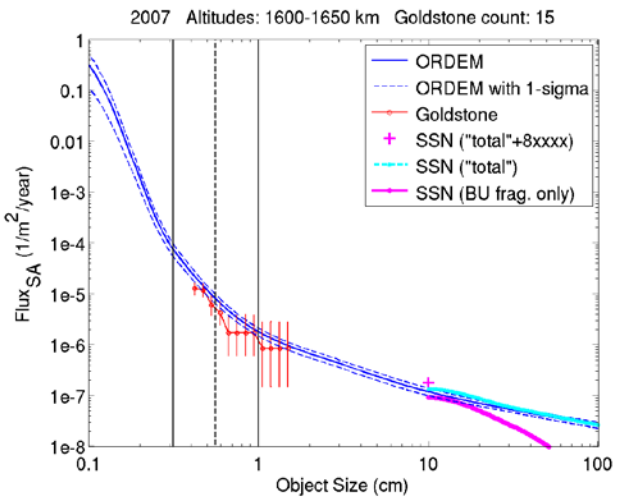

Figure D.2.4.2-124. 2007, Goldstone, 1600-1650 km, size vs. flux.

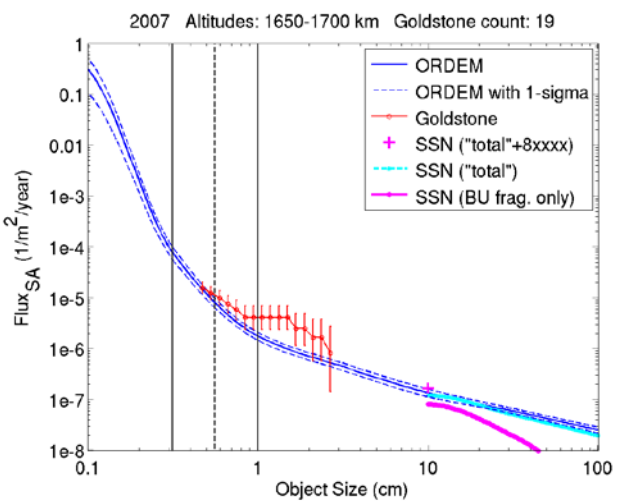

Figure D.2.4.2-125. 2007, Goldstone, 1650-1700 km, size vs. flux.

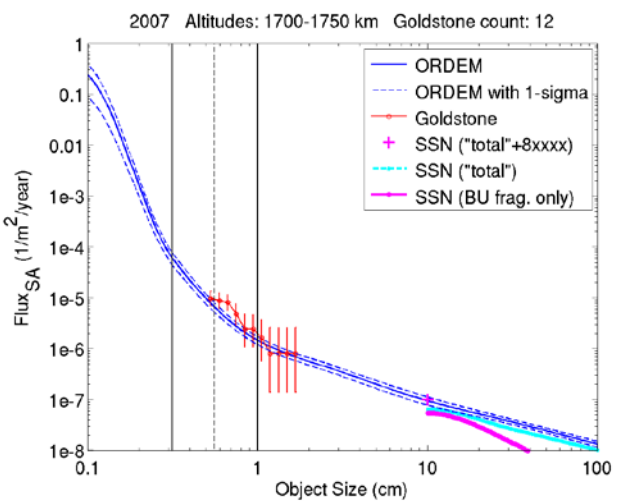

Figure D.2.4.2-126. 2007, Goldstone, 1700-1750 km, size vs. flux.

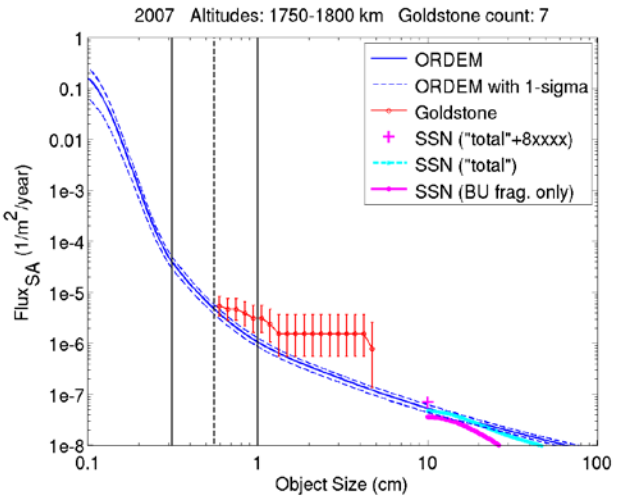

Figure D.2.4.2-127. 2007, Goldstone, 1750-1800 km, size vs. flux.

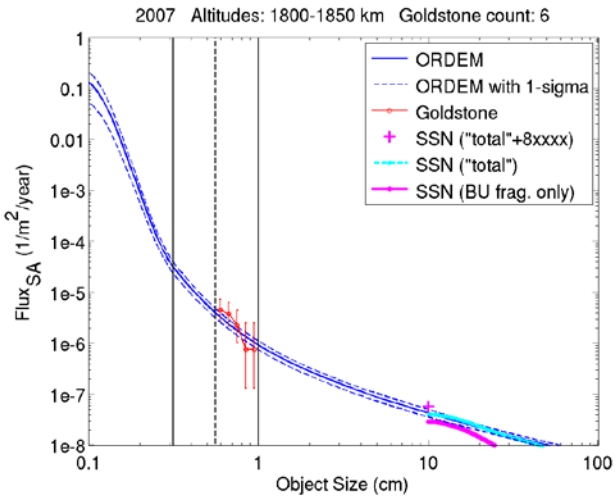

Figure D.2.4.2-128. 2007, Goldstone, 1800-1850 km, size vs. flux.

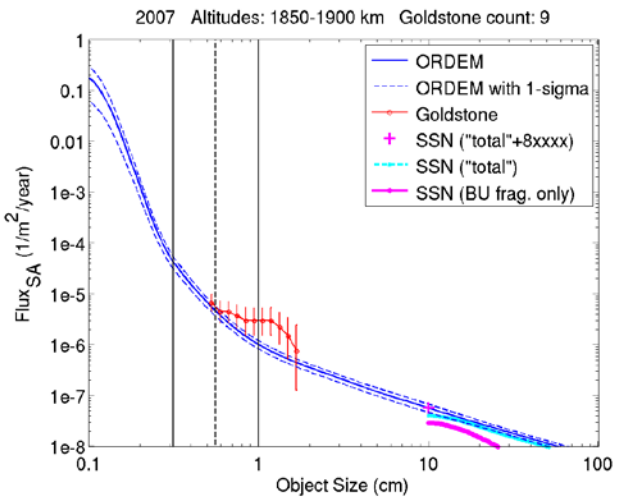

Figure D.2.4.2-129. 2007, Goldstone, 1850-1900 km, size vs. flux.

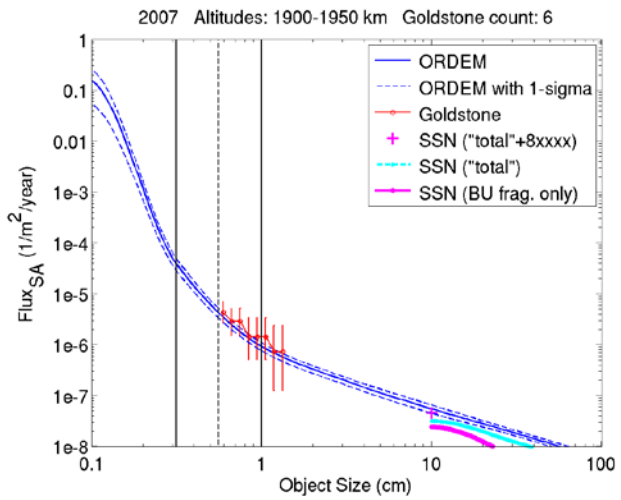

Figure D.2.4.2-130. 2007, Goldstone, 1900-1950 km, size vs. flux.

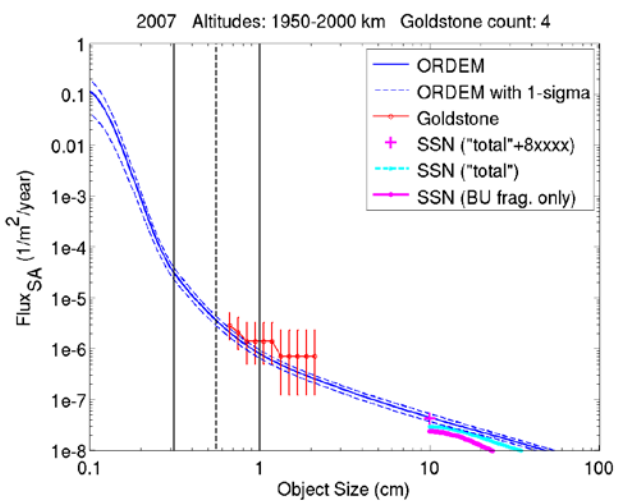

Figure D.2.4.2-131. 2007, Goldstone, 1950-2000 km, size vs. flux.

2.5. CROSS-SECTIONAL AREA FLUX VS. SIZE (> 3 mm)

This figures in this section show the comparison of ORDEM 3.0 results with Goldstone/Haystack/HAX and SSN data for cumulative size in half decade $\log_{10}$ bins versus orbital debris flux. A cumulative spline fit is used between decades. Size ranges are larger than 3.16 mm for the Goldstone data, and between 1 cm and 1 m for the Haystack/HAX data. The years shown are 2001, 2005, and 2006 (the common years for all data). Goldstone/Haystack/HAX data are all shown with Poisson lower and upper confidence limits at the Poisson single-sided confidence level of 84.13%. ORDEM 3.0 predicted fluxes are shown together with standard errors (1-sigma). Table 2.5.1-1 lists the spacecraft, perigee/apogee, and inclination of the charts for each yearly set.

TABLE D.2.5.1-1 – SPACECRAFT PARAMETERS

Spacecraft	Hp x Ha (km)	Inclination (°)
ISS	400 x 400	51.6
HST	560 x 560	28.5
Radarsat2	791 x 792	98.6
Kitsat1	1304 x 1327	66.1

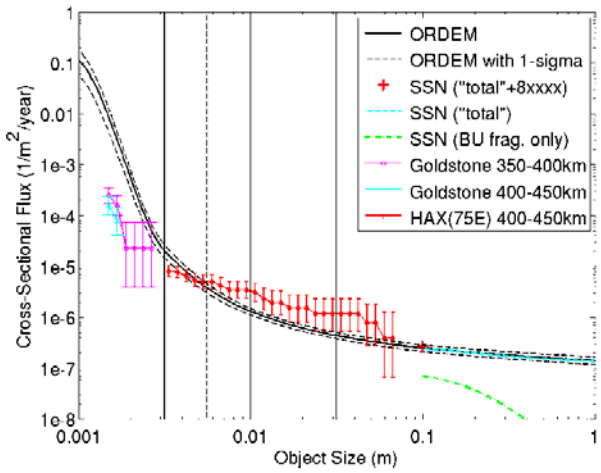

Figure D.2.5.1-1. 2001 ISS (Hp=Ha=400 km, inc=51.6°.

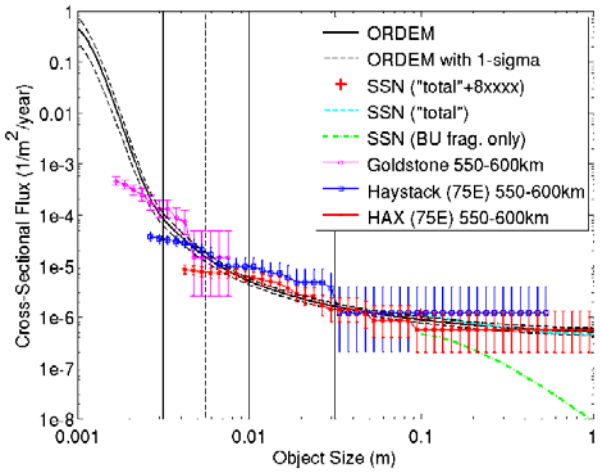

Figure D.2.5.1-1. 2001 HST (Hp=560 km, Ha=565 km, inc=28.5°.

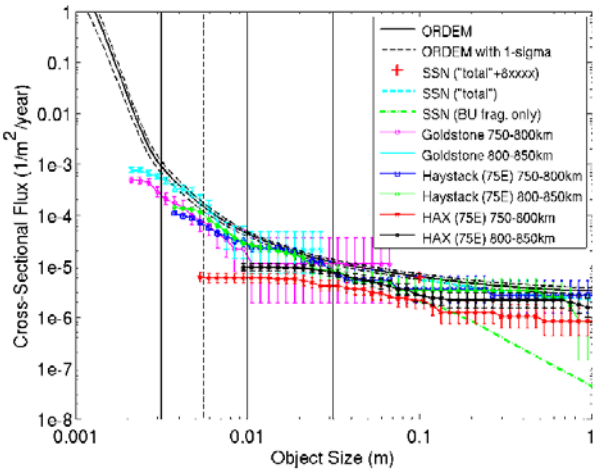

Figure D.2.5.1-3. 2001 RADARSAT2 (Hp=791 km, Ha=792 km, inc=98.6°.

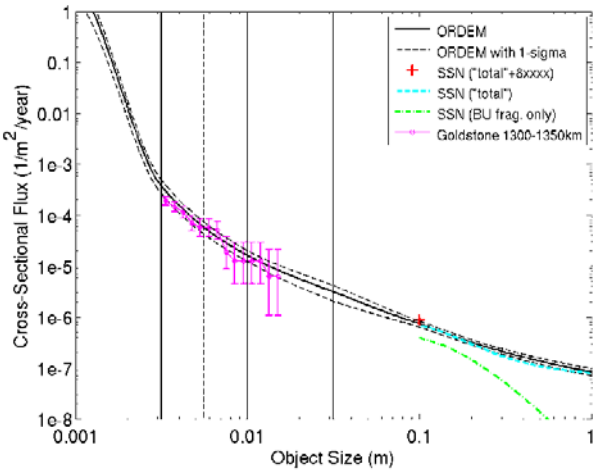

Figure D.2.5.1-4. 2001 KITSAT1 (Hp=1304 km, Ha=1327 km, inc=66.1°.

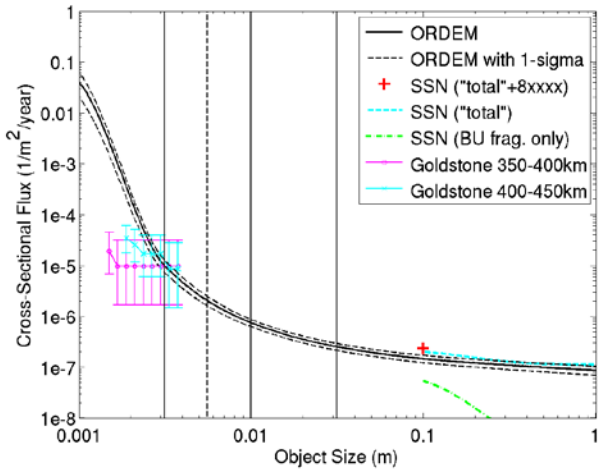

Figure D.2.5.1-5. 2005 ISS (Hp=Ha=400 km, inc=51.6°.

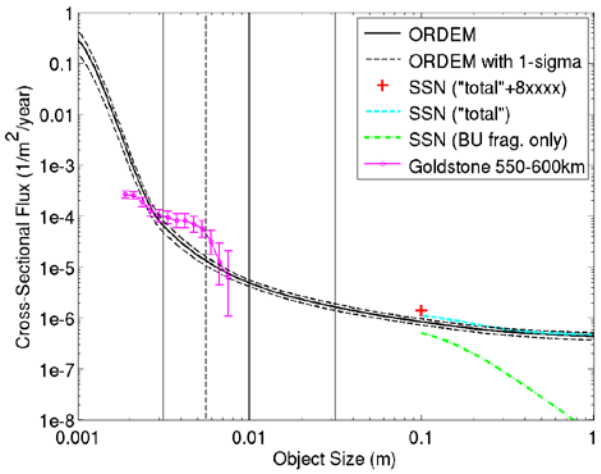

Figure D.2.5.1-6. 2005 HST (Hp=560 km, Ha=565 km, inc=28.5°.

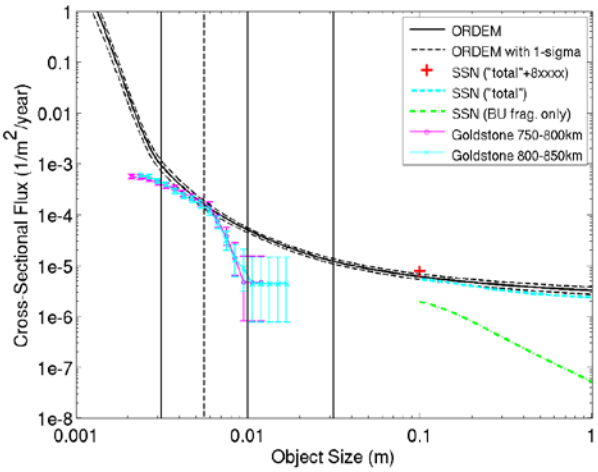

Figure D.2.5.1-7. 2005 RADARSAT2 (Hp=791 km, Ha=792 km, inc=98.6°.

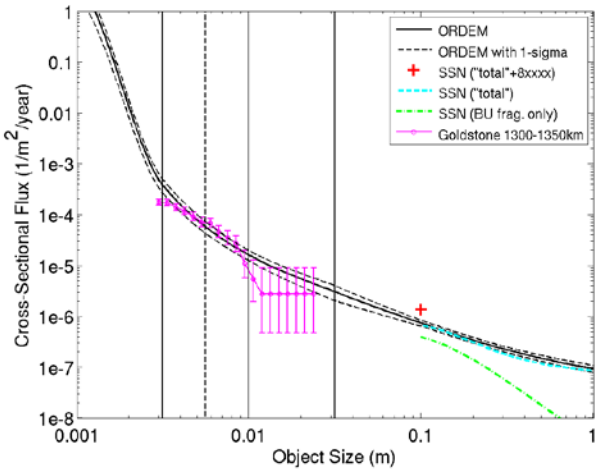

Figure D.2.5.1-8. 2005, KITSAT1 (Hp=1304 km, Ha=1327 km, inc=66.1°.

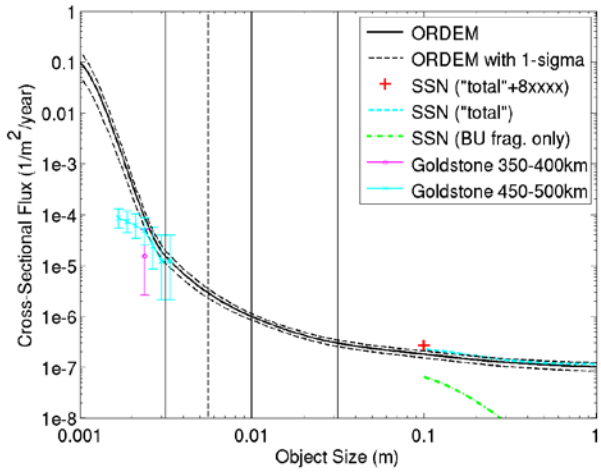

Figure D.2.5.1-9. 2006, ISS (Hp=Ha=400 km, inc=51.6°.

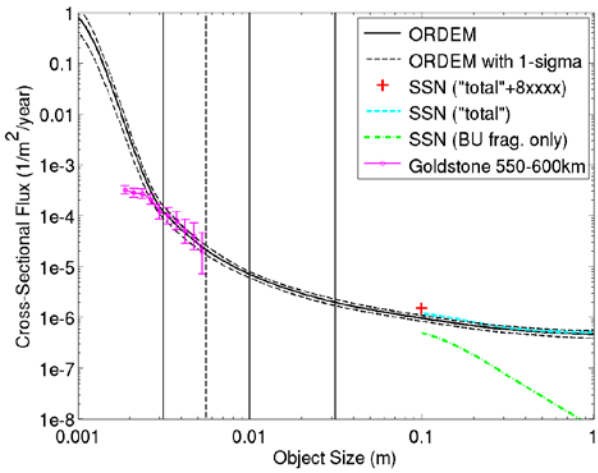

Figure D.2.5.1-10. 2006, HST (Hp=560 km, Ha=565 km, inc=28.5°.

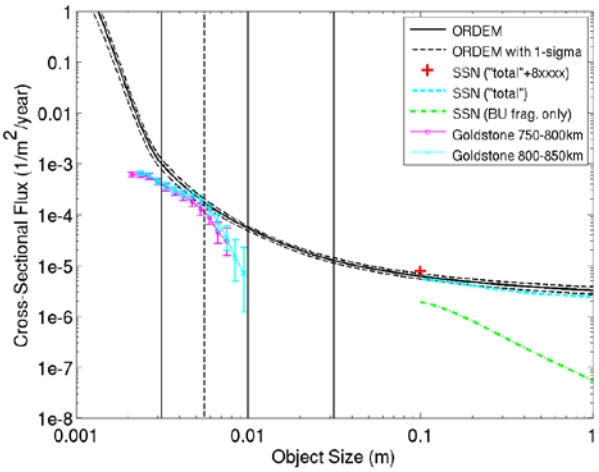

Figure D.2.5.1-11. 2006, RADARSAT2 (Hp=791 km, Ha=792 km, inc=98.6°.

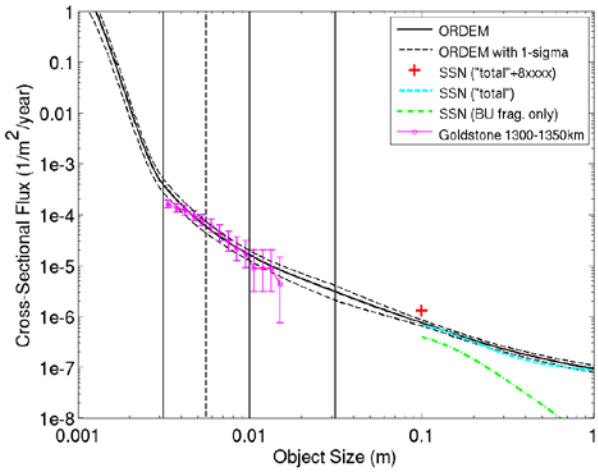

Figure D.2.5.1-12. 2006, KITSAT1 (Hp=1304 km, Ha=1327 km, inc=66.1°.

3.0 GEO Region

The following validation charts show the ORDEM 3.0 population by standard orbital element combinations unique to the GEO region. The sensors available for GEO study are presented below.

TABLE D.3.0-1 – GEO RADAR AND OPTICAL DATASETS

Radar System	Years Accessed	Location &Pointing	Region/ Detection Size Limit
SSN	2000-2013	Multiple Detectors	GEO>1 m
MODEST	2004-2006	30.2˚SLat, 70.8˚WLon, survey	GEO>30 cm

3.1. OPTICAL MEASUREMENTS IN GEO (10 cm and LARGER SIZES)

Validation of ORDEM 3.0 in GEO is challenged by a lack of available data. While the LEO SSN Catalog reliably tracks objects down to about 10 cm, and the Goldstone/Haystack/HAX sensor set contributes over a thousand hours per year of statistical data to a minimum size of about 3 mm, the GEO regions must depend on the SSN Catalog (~ > 1 m) and the MODEST survey data (~ > 30 cm).

The only other resource which may be used for ORDEM 3.0 GEO validation at this time is the ESA 1-m telescope at Tenerife, Canary Islands. This sensor program provides survey data to compare with that of MODEST. However, at present there is no data sharing agreement between NASA and ESA, nor has there been any attempt to correct the ESA populations based on observation biases as was done with the MODEST data. Therefore any validation of ORDEM 3.0 in GEO by the ESA telescope data can only be by gross visual comparison of orbital element mappings.

Validation charts that follow are from the historical period years ending in 2006 and 2013.

Note: As reported in Section 3.1.4 in the main document, it was discovered after the ORDEM 3.0 software release that the GEO population suffers from a double counting of the Titan 3-C Transtage (SSN #3432) fragments. This occurs once in the MODEST and extended MODEST database and again in the LEGEND fragmentation deposit. This results in a 10% population error that will be rectified in the next ORDEM release.

3.2. GEO ORBITAL PARAMETER VALIDATION

The orbital dynamics of satellites in the geosynchronous region shows revealing relationships in orbital parameters. The elements of interest are eccentricity (ECC) and mean motion (MM), and inclination (INC) and right ascension of ascending node (RAAN). Figures D.3.2-1 to D.3.2-4 display the frequency of each element in the GEO region at the end of 2006. The green curves are from the GEO satellites in the TLE set 07001.elm (January 1, 2007). The green represents "truth" for satellites larger than 1 m.

Red curves are ORDEM 3.0 GEO satellites (> 1 m). The comparison between TLEs and ORDEM 3.0 objects is displayed in Figure 3.2-1 below for inclination. The green and red curves follow the same overall trend throughout the inclination range. However, there are obvious discrepancies between the two sets of numbers that are caused by the use of database (DBS) files in LEGEND for the development of ORDEM 3.0.

The DBS files are internal ODPO files. Satellites are tagged at different stages of orbital position by using TLE information (*e.g.*, launch, orbit insertion, maneuver, and end-of-station keeping) as well as satellite size, composition, and bus information from the open literature. The DBS update process is labor intensive and has lagged behind that of the TLEs at various times over the last decade due to budget issues. Even so, all four of the frequency charts included below show good trending between the GEO TLE set, TLE set 07001.elm (green), and the ORDEM 3.0 GEO objects larger than 1 m (red).

The black curves in each figure represent the full ORDEM 3.0 population down to 10 cm. Note that the number of objects between 10 cm and 1 m are far more than the > 1 m sets.

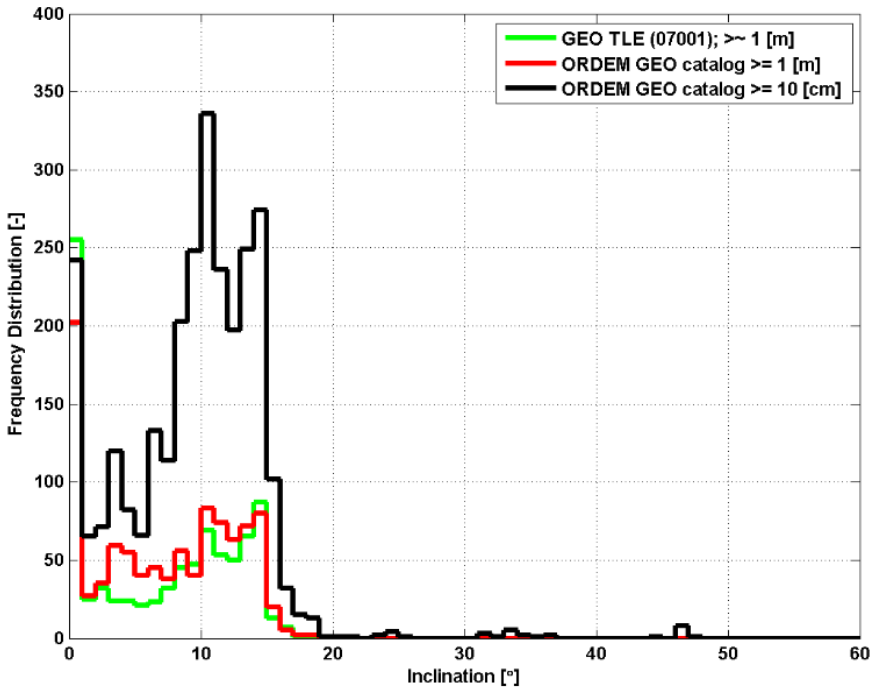

Figure D.3.2-1. Frequency vs. INC at the end of 2006.

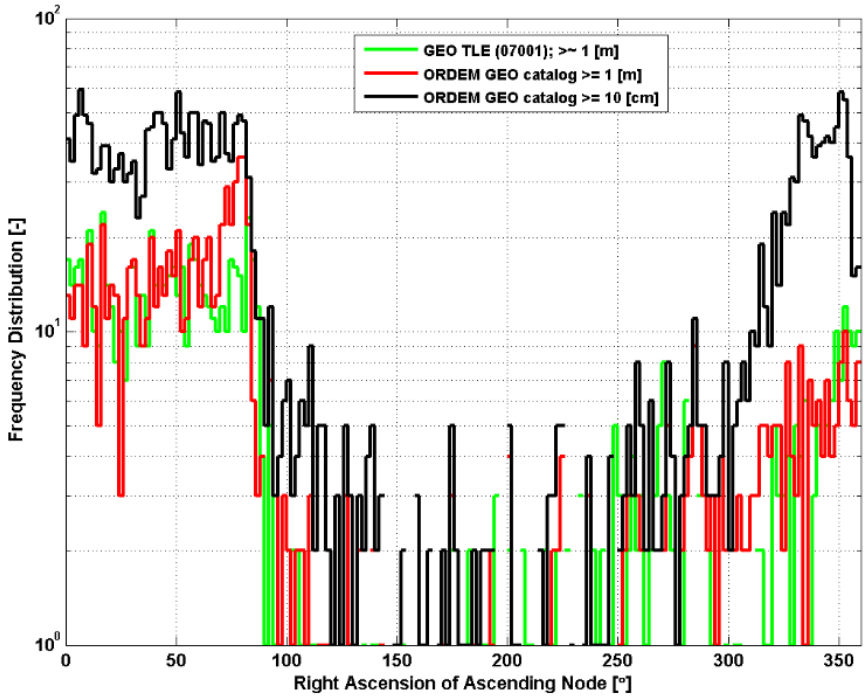

Figure D.3.2-2. Frequency vs. RAAN at the end of 2006.

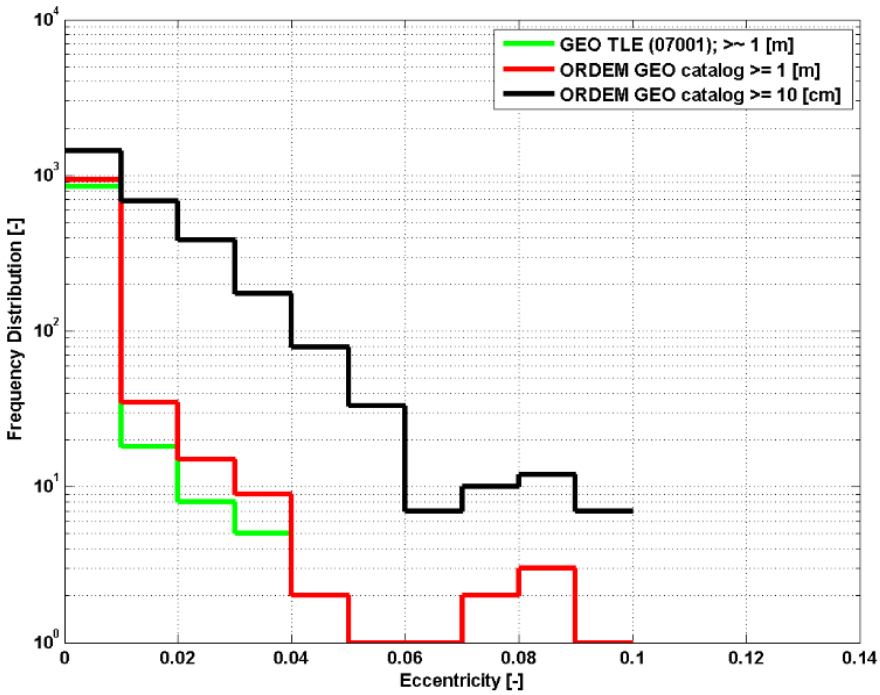

Figure D.3.2-3. Frequency vs. ECC at the end of 2006.

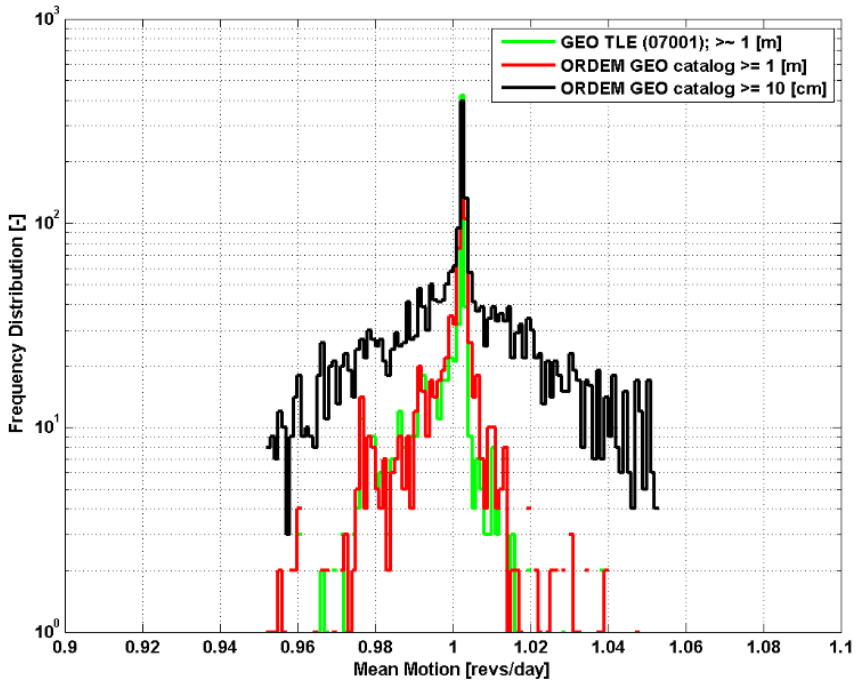

Figure D.3.2-4. Frequency vs. MM at the end of 2006.

As a final test of GEO orbital parameter validation Figure D.3.2-5 presents the Titan 3C Transtage (SSN #3432) breakup in 1992, in INC/RAAN space at the end of 2013. The actual cataloged fragments, shown as open circles, are compared to the LEGEND modeled and propagated fragments to the end of 2013. The cataloged fragments, which must be > 1 m to be tracked, cluster near the modeled largest fragments (> 30 cm), as would be expected.

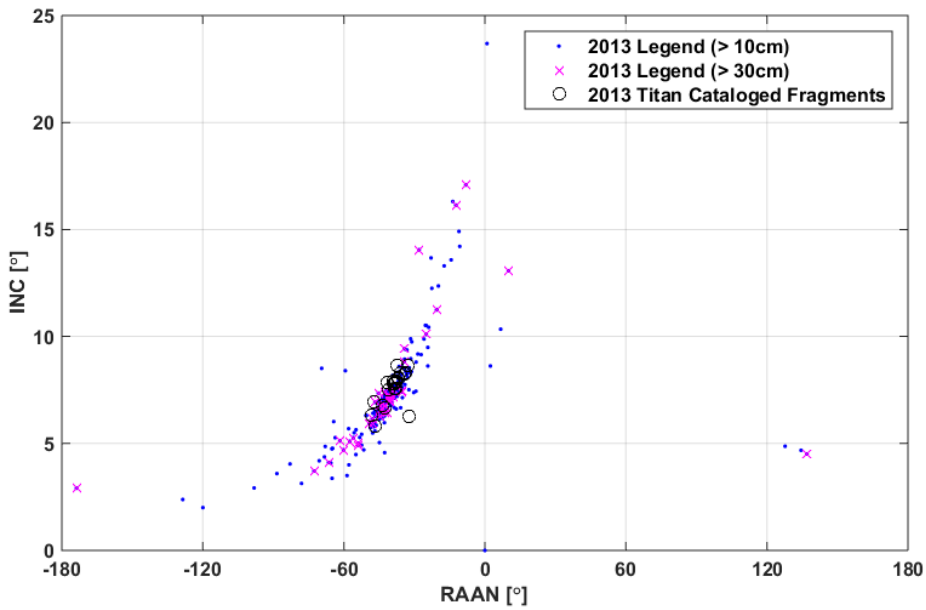

Figure D.3.2-5. Cataloged and LEGEND generated Titan fragments in 2013.

3.3. EFFECTIVE NUMBER VS. ALTITUDE

The TLE set for 07001.elm (January 1, 2007) is again used for the comparison with ORDEM 3.0 at the end of 2006. In this section, the effective number of objects within each 50 km altitude bin surrounding GEO is displayed at the end year 2006 in Figures D.3.3-1 and F.3.3-2. The effective number of satellites is also termed "spatial density." The fraction of time that each satellite spends in a particular 50 km altitude bin in one orbit is summed (the sum for each satellite must total to 1 if it inhabits the altitude region 32,000 to 40,000 km).

The three curves are again displayed below. The green curve represents TLE 07001.elm objects (*i.e.*, "truth"). This curve compares well by inspection with the red ORDEM 3.0 GEO population (> 1 m). Geostationary orbit straddles altitude bin peak 35,750 to 35,800 km. At the bottom of the figures, the spread in altitude range is very similar between the TLEs and ORDEM 3.0 GEO (all > 1 m). Figure D.3.3-2 uses $\log_{10}$ space to highlight that region.

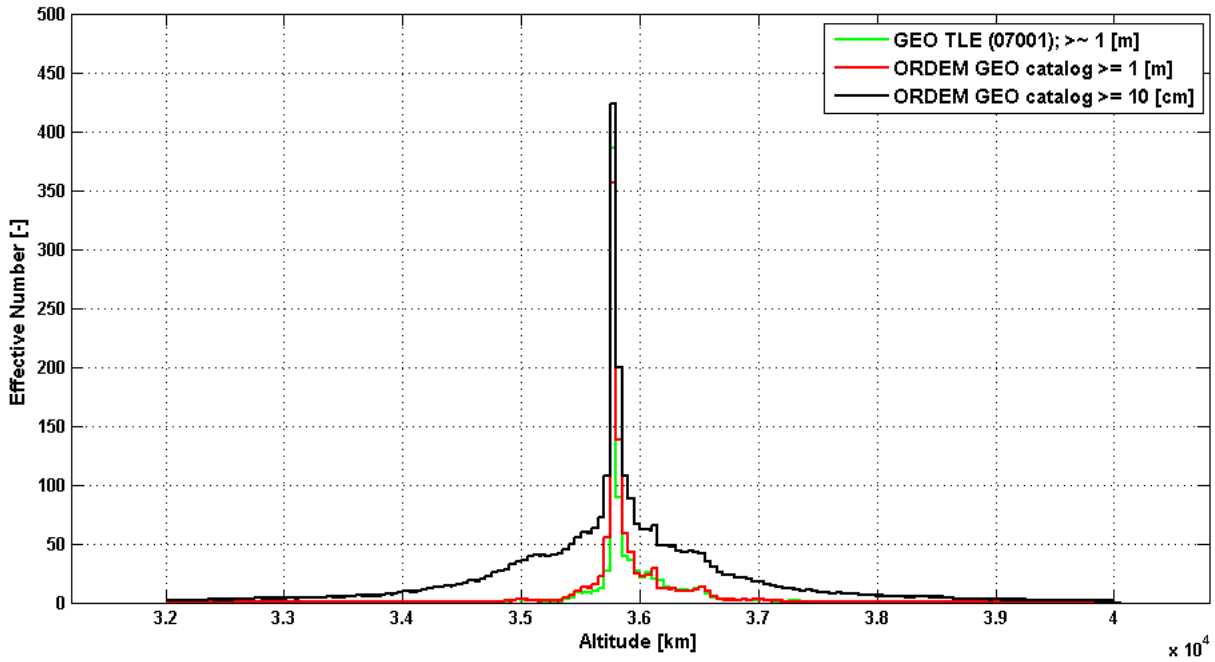

Figure D.3.3-1. Effective number of objects vs. alt, bins=50km, GEO, end of 2006.

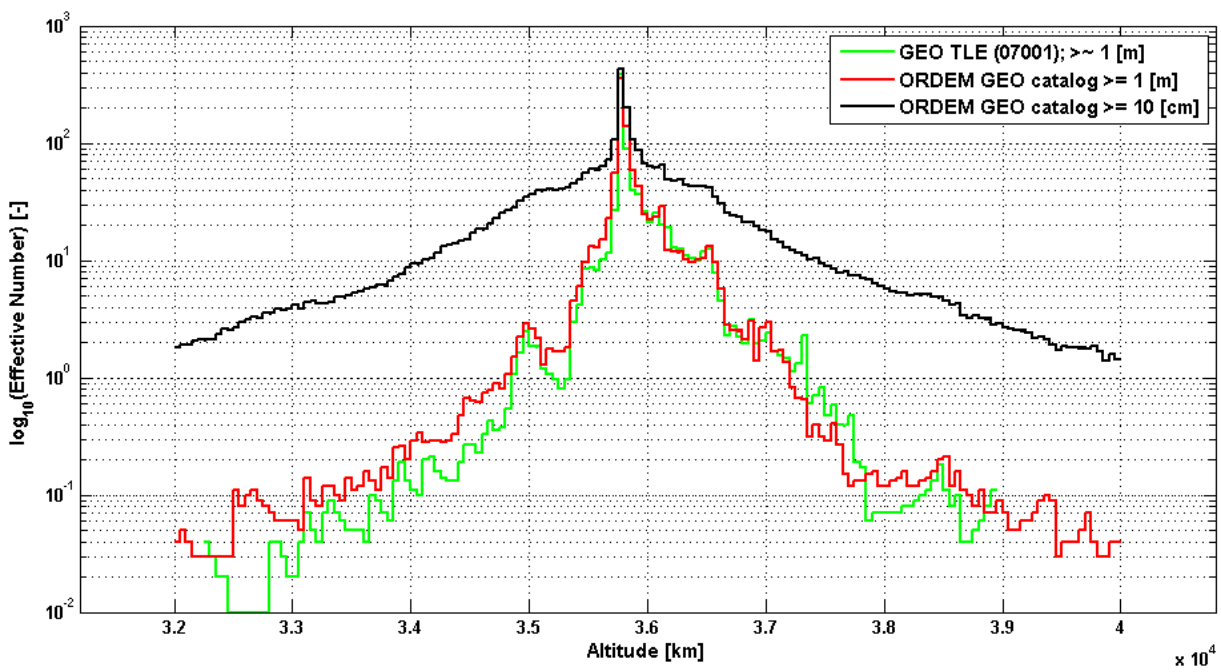

Figure D.3.3-2. Effective number of objects vs. alt, bins=50km, GEO, end of 2006.

3.4. QUALITATIVE GEO SURVEY COMPARISONS BETWEEN NASA AND ESA

Figure D.3.4-1 shows GEO satellites in INC/RAAN space during a survey within one calendar year (2006) with the ESA 1-m telescope at Tenerife, Canary Islands. One purpose of this survey was to identify high area-to-mass objects in elliptical orbits. These are the uncataloged objects (termed "uncorrelated" in red) that are homogenous in INC/RAAN (*i.e.*, they are off the "evolution track" of the true GEO objects). The cataloged objects (termed "correlated" in blue) and uncataloged objects on the evolution track can be clearly observed.

Note that the MODEST survey and analysis was specifically designed to correct for observation biases in order to arrive at an accurate global population in the GEO region. In contrast, the ESA survey did not include any systematized effort to remove observation biases, so it is unclear how complete it is.

The clumping of the uncataloged objects straddling RAAN = 0° is indicative of the ESA assertion that there are nine, possibly ten, uncataloged major explosive breakups in GEO. The ESA choice of running RAAN from -180° to 180° in survey figures, like that below, is emulated by the NASA ODPO in Figure D.3.4-2.

Unlike the ESA 1-year survey, the NASA 2-year survey has included cataloged, station-kept satellites, as evidenced by the visible blue objects near 0° inclination. The clumping of uncataloged objects straddling RAAN = 0° is also visible, since ORDEM 3.0 GEO was designed to include ~6 additional GEO breakups. MODEST is not capable of distinguishing many objects in highly elliptical orbits. Thus, there are very few objects off the evolution track in Figure D.3.4-2.

Figure D.3.4-3 shows GEO objects in ECC/MM space during a survey within four calendar years (2002-2006) with the ESA 1-m telescope. The survey highlights the high area-to-mass objects in elliptical orbits. ESA also identified 6-parameter orbits of over 700 of these objects and added them to its internal catalog (the objects in blue in Figure D.3.4-3). Overlaid in the chart are colored smooth curves that represent the progression of velocity at apogee curves with changes in eccentricity and mean motion.

In the companion Figure D.3.4-4, it is reiterated that ORDEM 3.0 GEO excludes those high area-to-mass objects in elliptical orbits.

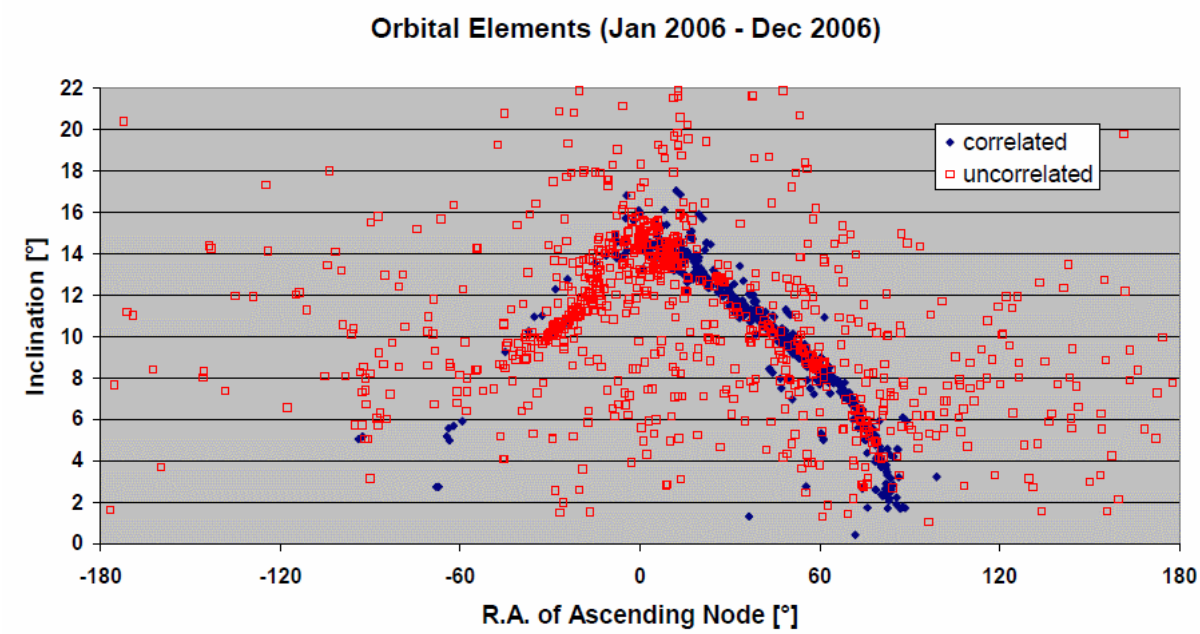

Figure D.3.4-1. INC vs. RAAN, 2006 survey of GEO objects (Schildknecht).

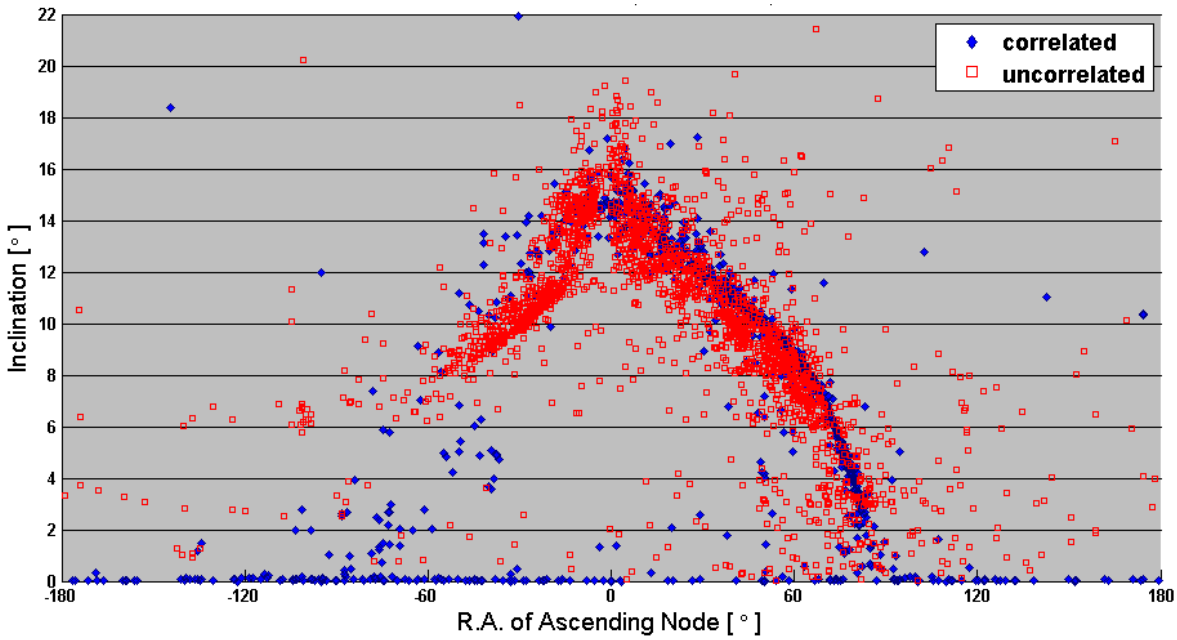

Figure D.3.4-2. INC vs. RAAN, ORDEM 3.0, 2004-2006 survey of GEO objects.

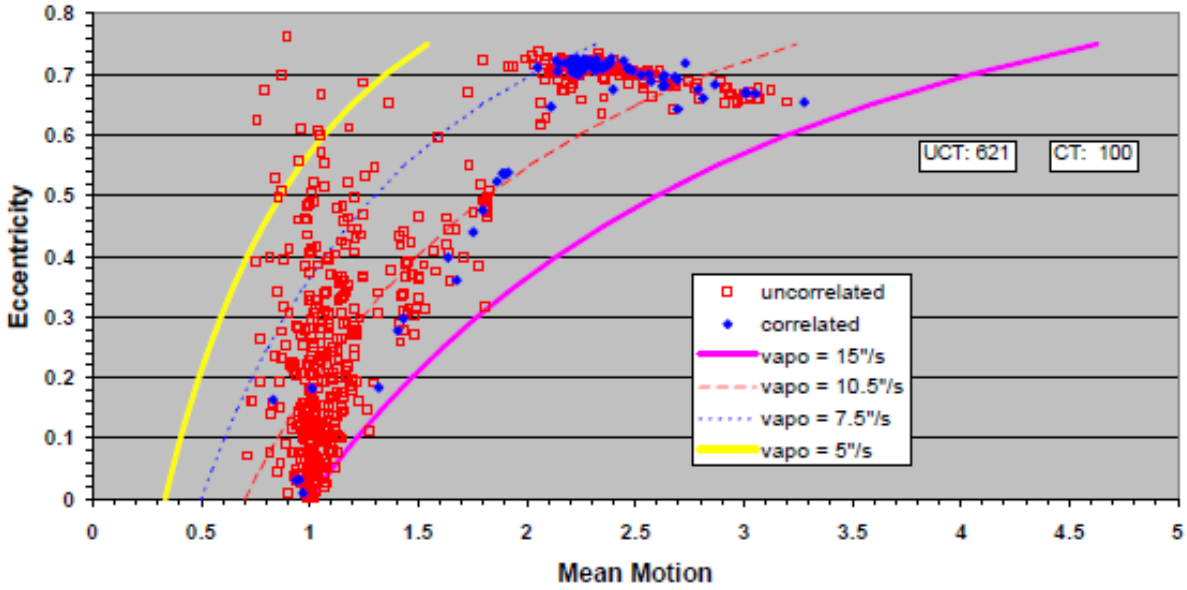

Figure D.3.4-3. ECC vs. MM, 2002-2006 survey of GEO objects (Schildknecht)..

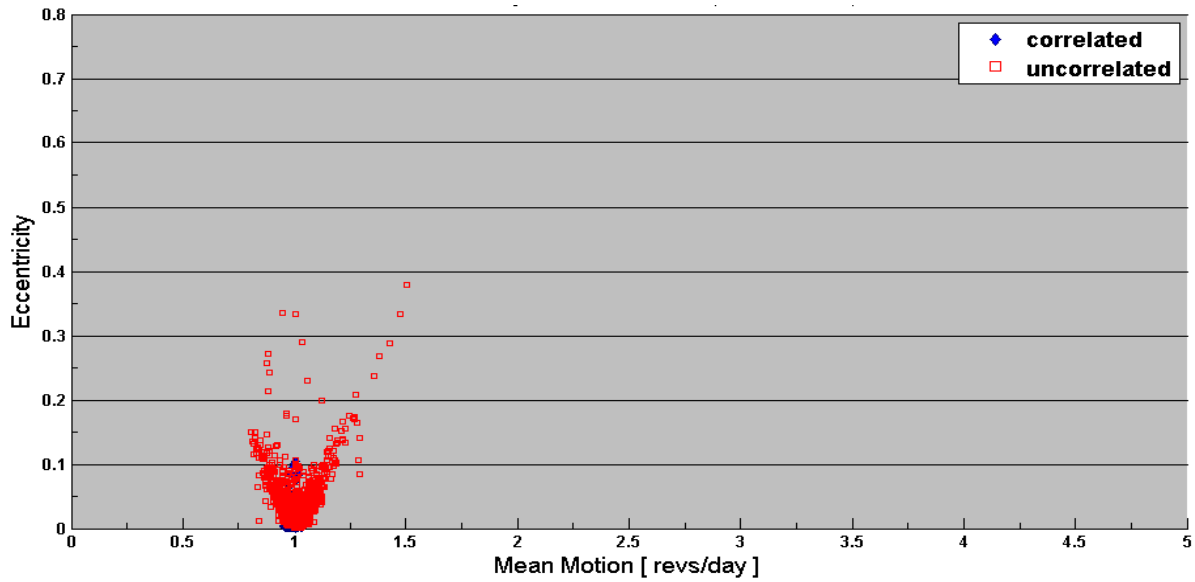

Figure D.3.4-4. ECC vs. MM, ORDEM 3.0, 2004-2006 survey of GEO objects

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13. ABSTRACT *(Maximum 200 words)*
This report documents the verification and validation (V&V) of the ORDEM 3.0 software package. These processes determine whether all phases of product software development perform as intended (verification) and whether the final model populations match the actual debris environment, as surmised from available data sources (validation). The ORDEM debris and intact population files encompass a very large and disparate set of sizes (10 µm –1 m), orbit types (LEO, MEO, Molniya, GTO, and GEO), dates (2010 through 2035) and observation methods (remote sensors, returned surfaces). The ODPO chose to rely on the IEEE V&V standards to organize the assessments. For verification assessments comparisons are made between the ORDEM 3.0 software and ODPO legacy software. For validation assessments the comparisons are between ORDEM 3.0 software and statistically viable observations. Each metric assessment lists an outcome as pass/fail. Tables of outcomes with detailed statistical information are included throughout the text and appendices. Charts in the appendices provide more detail on the assessments.

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