GLAST LAT SUBSYSTEM TECHNICAL DOCUMENT	LAT Document # **LAT-TD-01122-1**	Date Effective 11/06/02
	Prepared by(s) Dave Thompson	Supersedes None
	Subsystem/Office Anticoincidence Detector Subsystem	
Document Title **ACD Micrometeoroid Shield Analysis and Design**		

Gamma-ray Large Area Space Telescope (GLAST)

Large Area Telescope (LAT)

ACD Micrometeoroid Shield Analysis and Design

Prepared by
Hypervelocity Impact Technology Facility Group
NASA Johnson Space Center

GLAST ACD Meteoroid/Debris Shielding

Test and Analysis Results

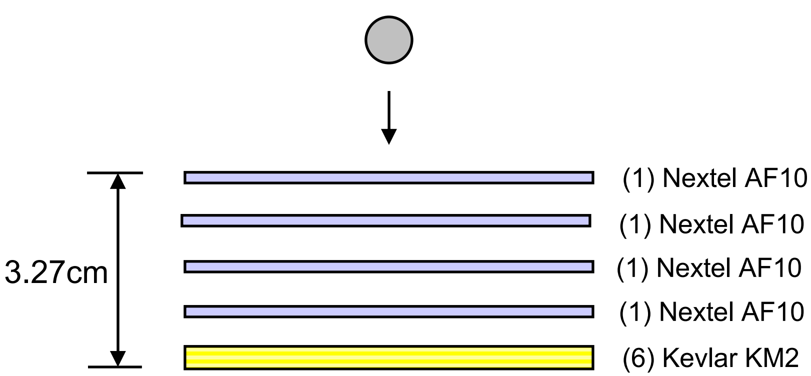
NASA JSC/Eric Christiansen and Jeanne Crews
Lockheed/Dana Lear, GB-Tech/Frankel Lyons

18 September 2002

- Objective: Meet or exceed GLAST Anti-Coincidence Detector (ACD) Meteoroid/Debris requirements established by ACD Project Office: 0.95 probability of no penetration (PNP) of the ACD shielding over 5 year exposure period
  - Requirement established in FY01
  - Design based on environment models current at time: NASA standard meteoroid model and NASA ORDEM96 debris model
- Shielding Design Constraints:
  - Mass per unit area of shielding not to exceed 0.3 g/cm^2
  - Total shield standoff not to exceed 3.27cm (desire 2cm)
- A combined hypervelocity impact test and analysis approach used to develop & verify GLAST ACD meteoroid/debris shielding
  - Hypervelocity impact testing used to assess various shielding options, determine particle size at threshold of shield failure for a limited set of impact conditions, and certify final shielding configuration
  - Ballistic limit equations developed from test data and analysis. Equations used to predict threshold particle size resulting in shield failure at all potential meteoroid/debris impact velocities, angles and particle densities.
  - BUMPER code used to assess GLAST ACD Probability of No Penetration (PNP) for a variety of operational attitudes

GLAST Meteoroid/Debris Risk Assessment Status (Continued)

- Baseline shield concept evaluated by hypervelocity impact tests is a Nextel/Kevlar multi-shock shield.
  - Nextel ceramic cloth bumpers are effective at projectile breakup (4 layers of Nextel 312, style AF10 fabric)
  - Kevlar (high strength to weight) rear wall provides final barrier to penetration high (6 layers of Kevlar KM2, style CS-705 fabric)
  - Open cell, solimide foam spacers used between bumper layers to maintain separation (hypervelocity impact tests conducted without foam)
- Tests indicate shield will provide protection from a 1.8mm diameter aluminum sphere at 7km/s, and 0° impact angle normal to shield (i.e. light-tight)



Component	**Number in Shield**	**Thickness each (cm)**	**Mass per Unit Area each (g/cm^2)**	**Total thickness (cm)**	**Total Mass per Unit Area (g/cm^2)**
Nextel AF10	4	0.0254	0.025	0.102	0.100
Solimide Foam Spacer	4	0.66	0.0051	2.640	0.020
Thermal Blanket	1	0.32	0.0368	0.320	0.037
Kevlar KM2	6	0.0254	0.023	0.152	0.138
Overall Shield				3.21	0.295

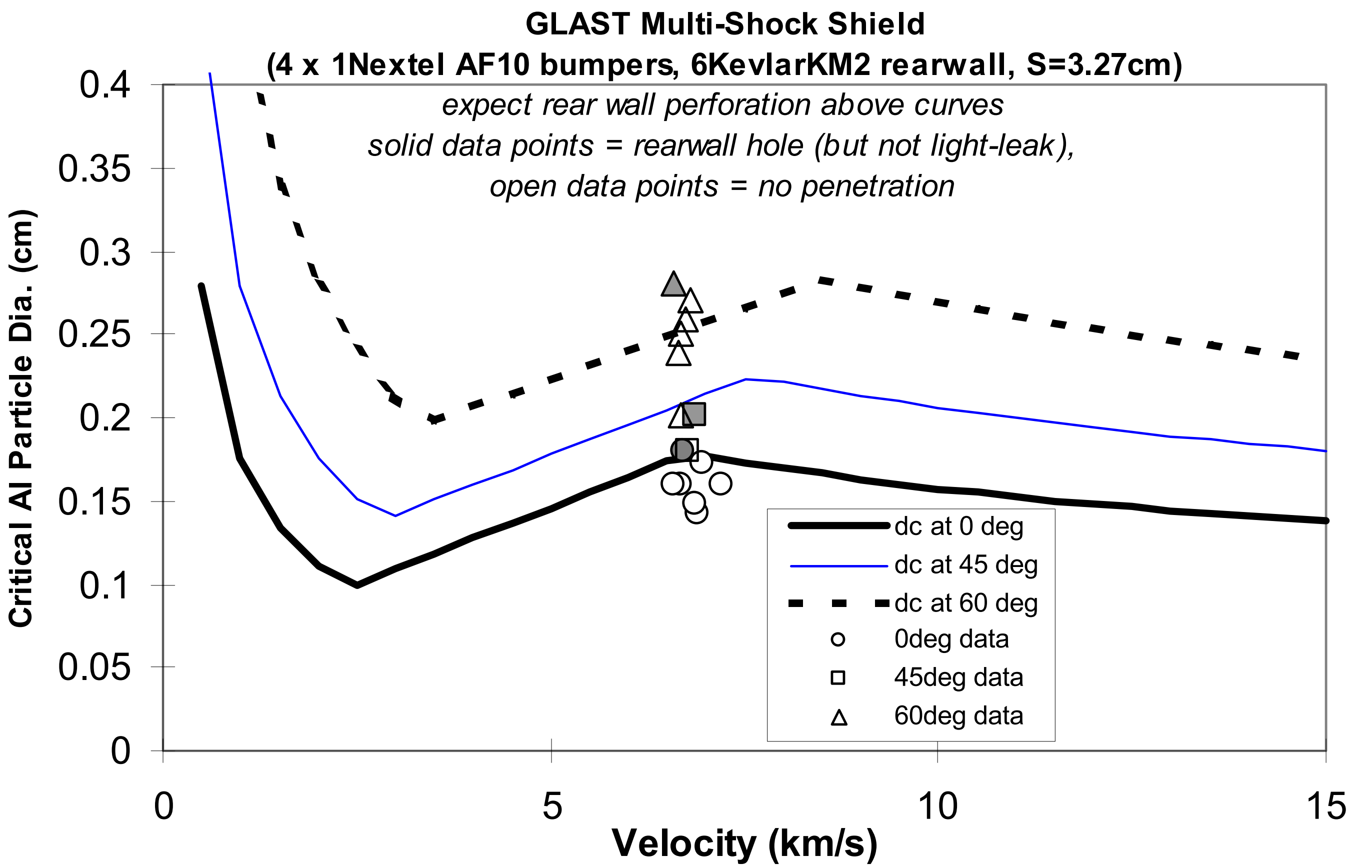
- BUMPER code program used to perform PNP assessments
  - NASA standard code for PNP assessments
  - BUMPER finite element model (FEM) based on GLAST geometry model provided by GLAST project office
- BUMPER assessments indicate assessed PNP exceeds requirement for the 3.27cm standoff, marginally below at 2.6cm, and will not meet requirement at 2cm standoff

Standoff	5-yr PNP
3.27cm	0.966
2.6 cm	0.934
2.0 cm	0.898

- PNP results conservative
  - MLI thermal blanket and solimide foam not included in HVI tests or ballistic limit equations

Baseline GLAST shield ballistic limits

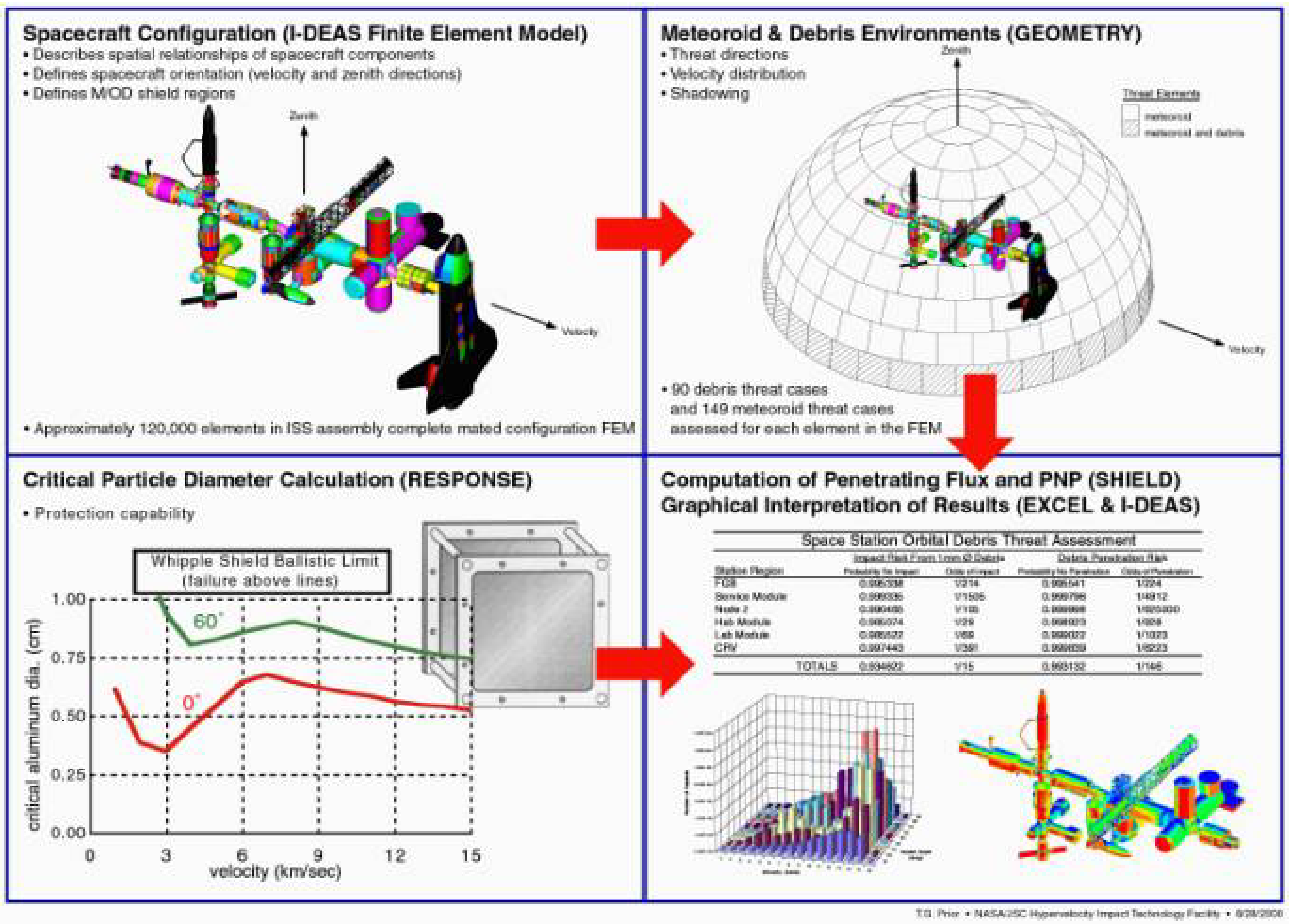
- Ballistic limit equations developed for GLAST shielding based on HVI test results
  - Documented in "Ballistic limit equations for Nextel/Kevlar multi-shock shields, version E", E.L. Christiansen, 15 September 2002
- Equations coded into BUMPER



BUMPER Code for GLAST Meteoroid/Debris Assessment

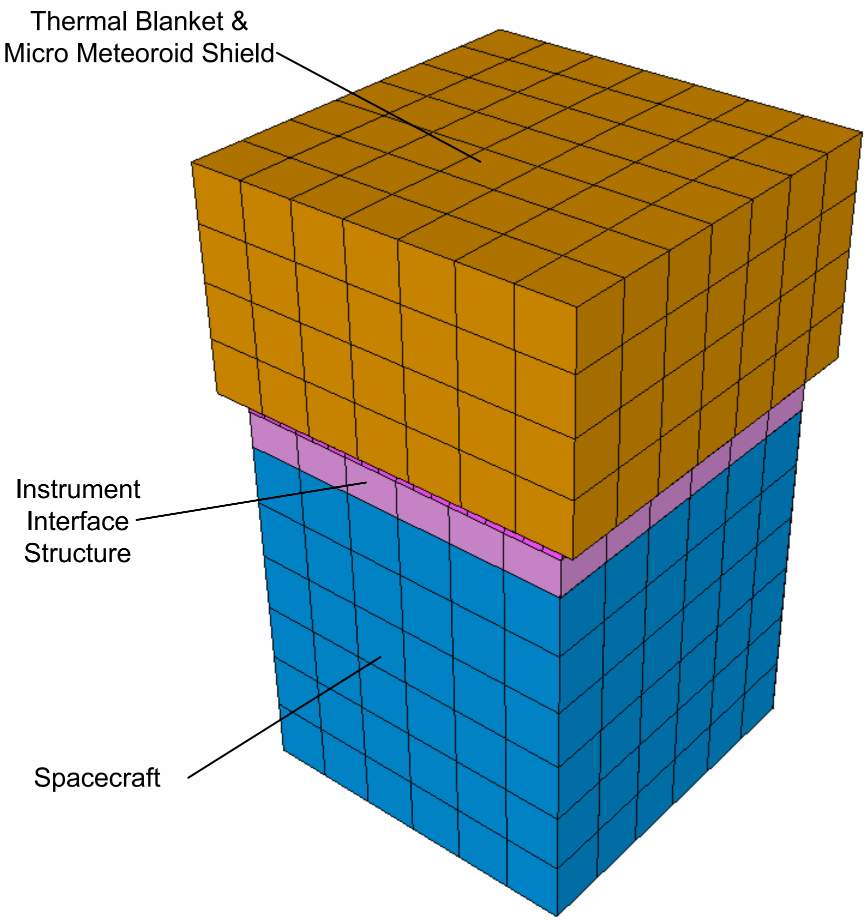
NASA/Industry Standard for Meteoroid/Debris Risk Assessments

- BUMPER Code is NASA approved code for performing meteoroid/debris risk calculations for Shuttle, ISS and EVA

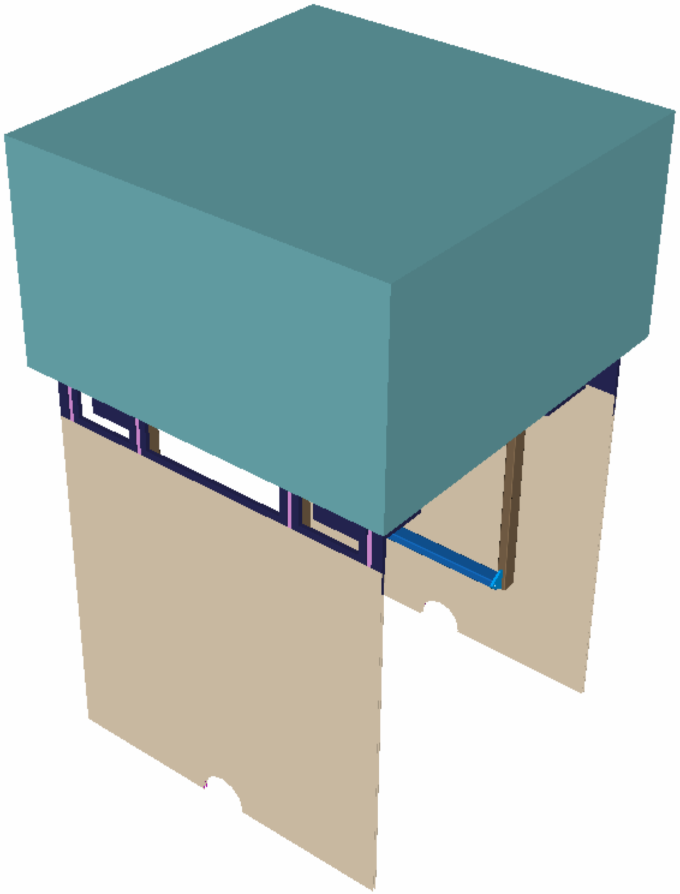


Comparison of Finite Element Model and Original Geometry Model

BUMPER Finite Element Model

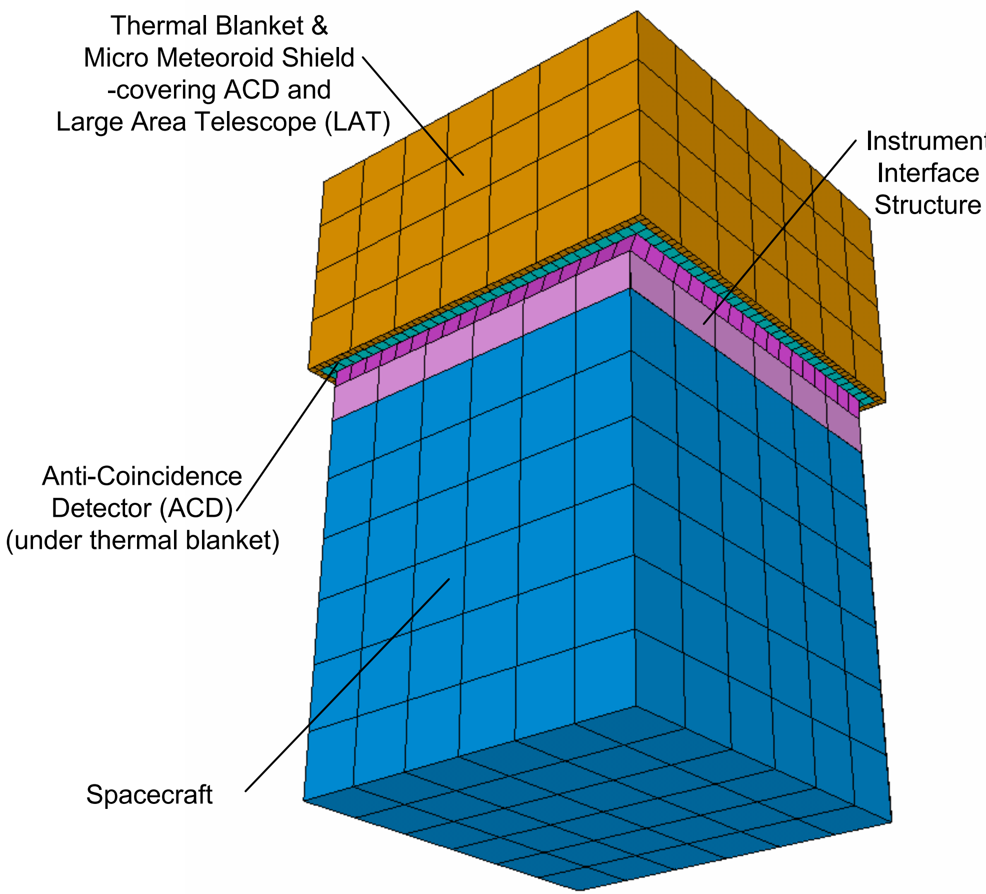


GLAST Geometry Model

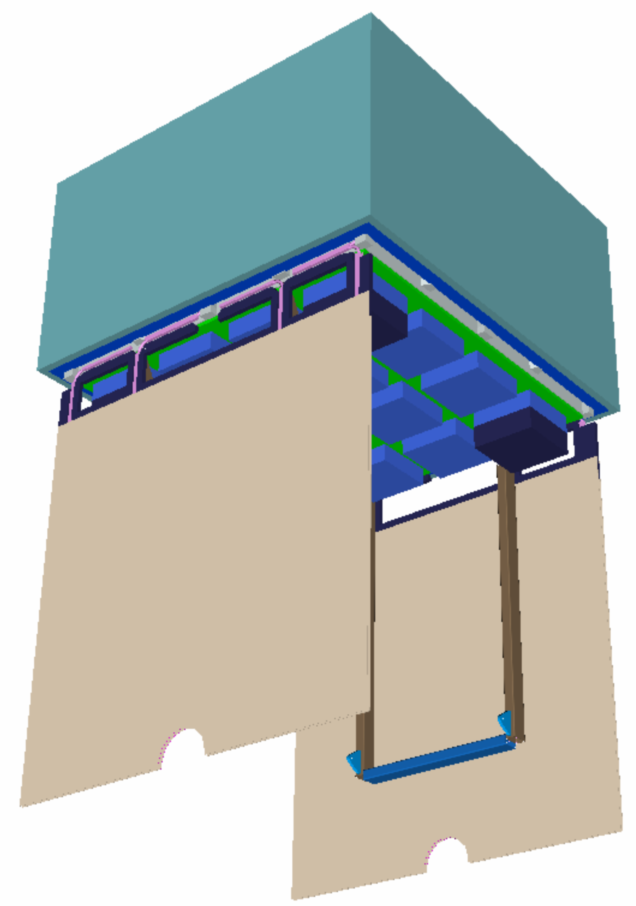


Comparison of Finite Element Model and Original Geometry Model

BUMPER Finite Element Model

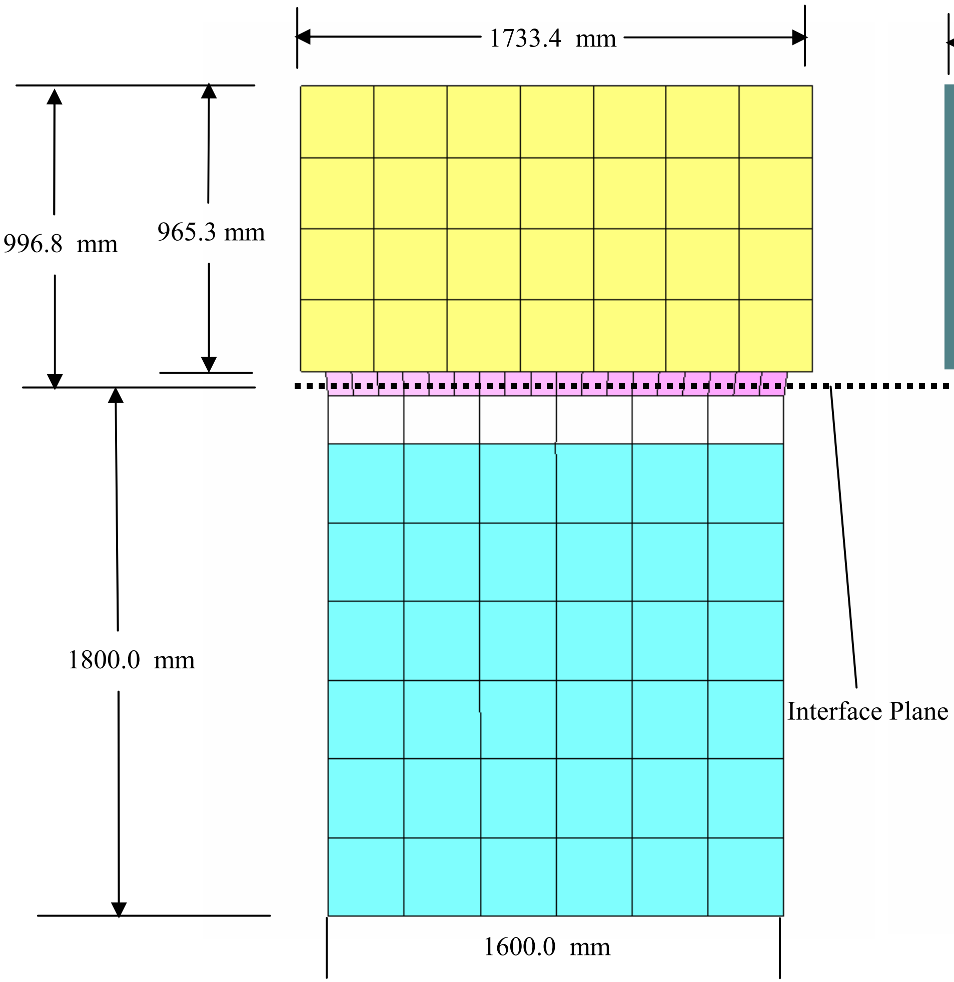


GLAST Geometry Model

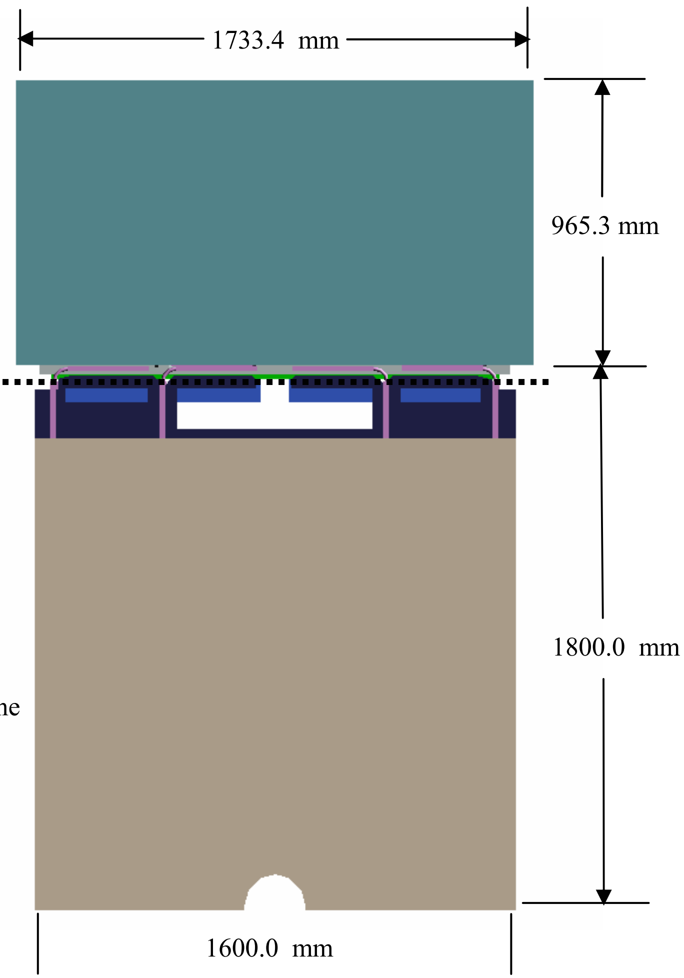


Comparison of Finite Element Model and Original Geometry Model (Side View)

BUMPER Finite Element Model

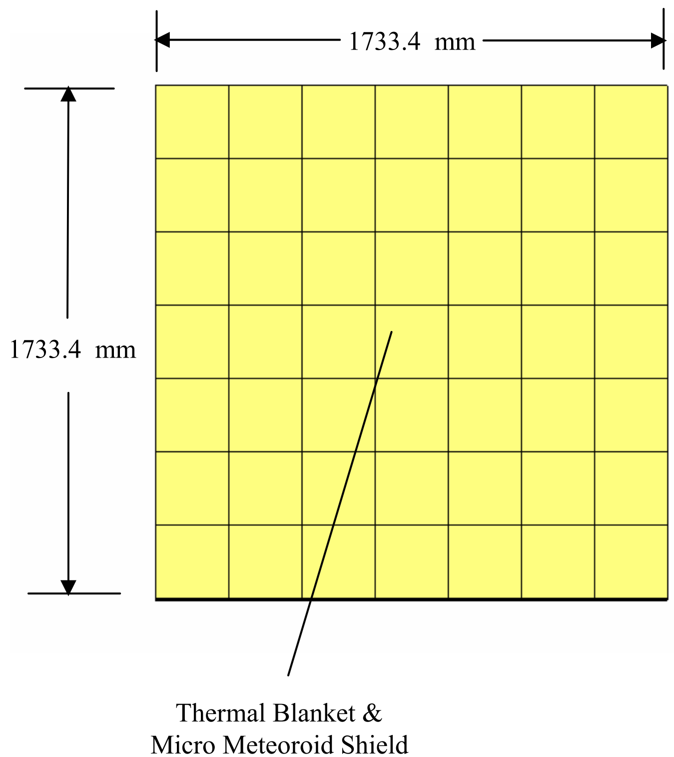


GLAST Geometry Model

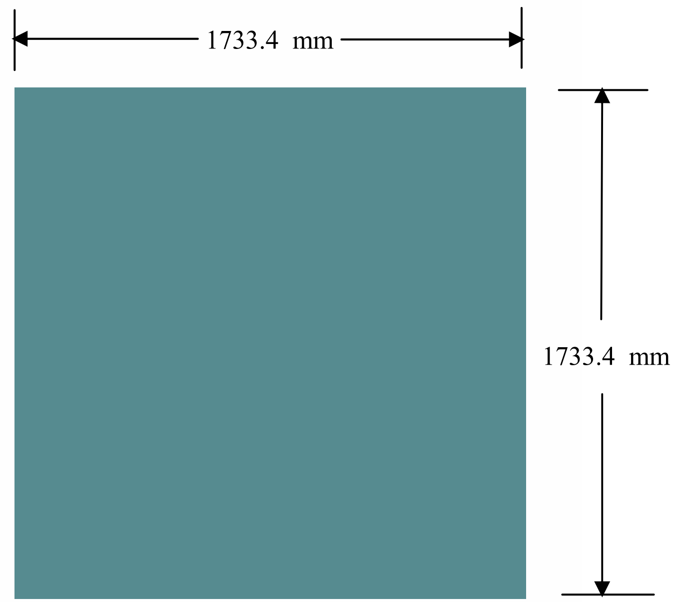


Comparison of Finite Element Model and Original Geometry Model (Top View)

BUMPER Finite Element Model

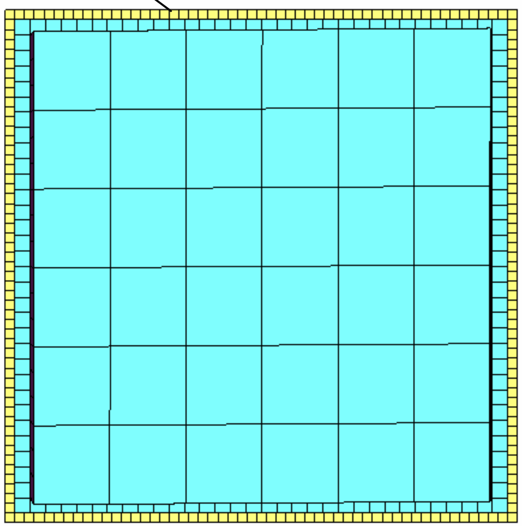


GLAST Geometry Model

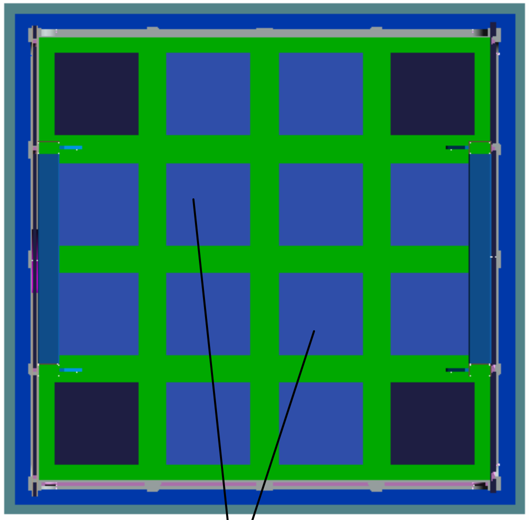


Comparison of Finite Element Model and Original Geometry Model (Bottom View)

BUMPER Finite Element Model

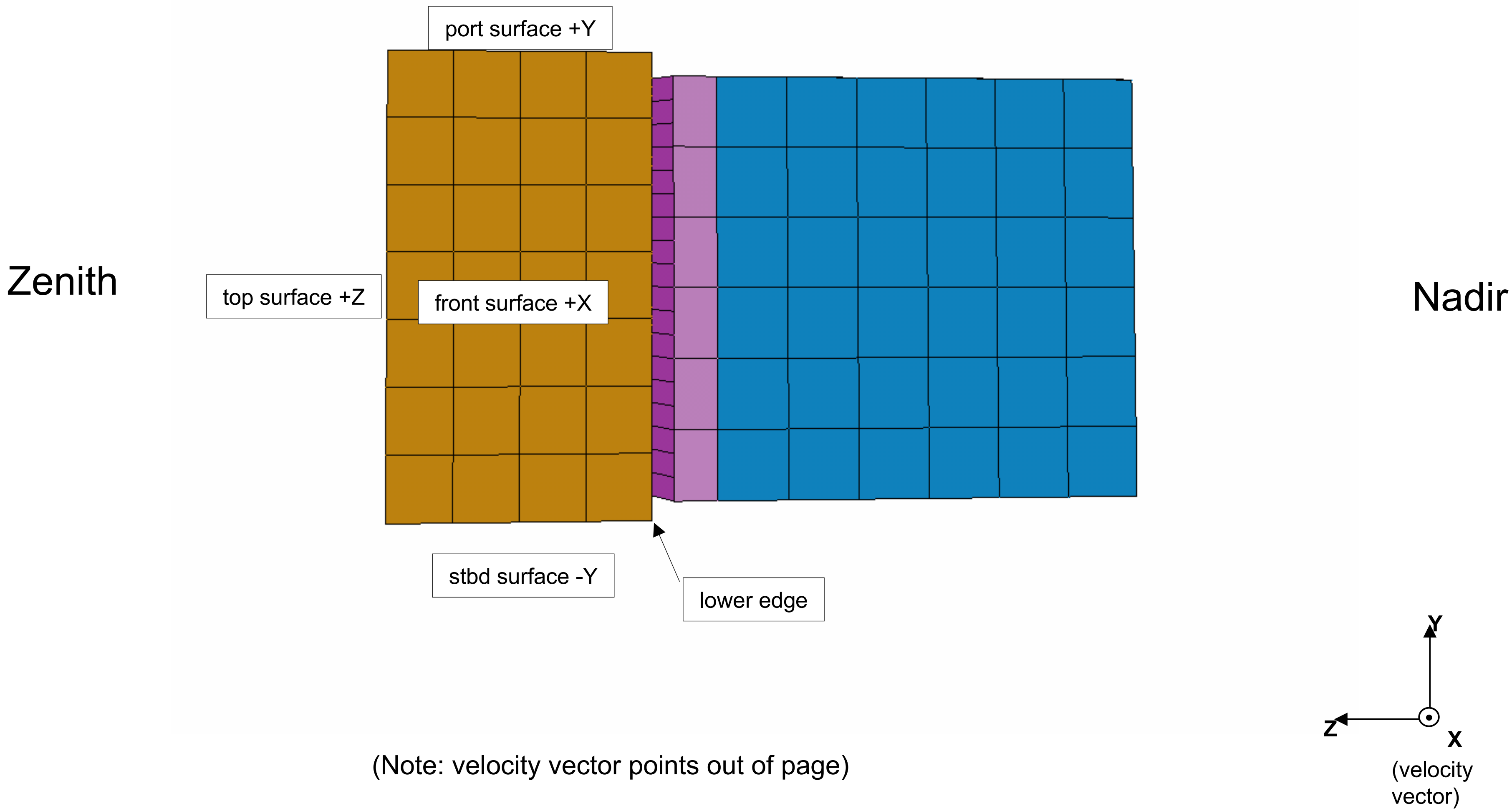


GLAST Geometry Model



GLAST Attitude 1B1 (37.50 % of mission duration)

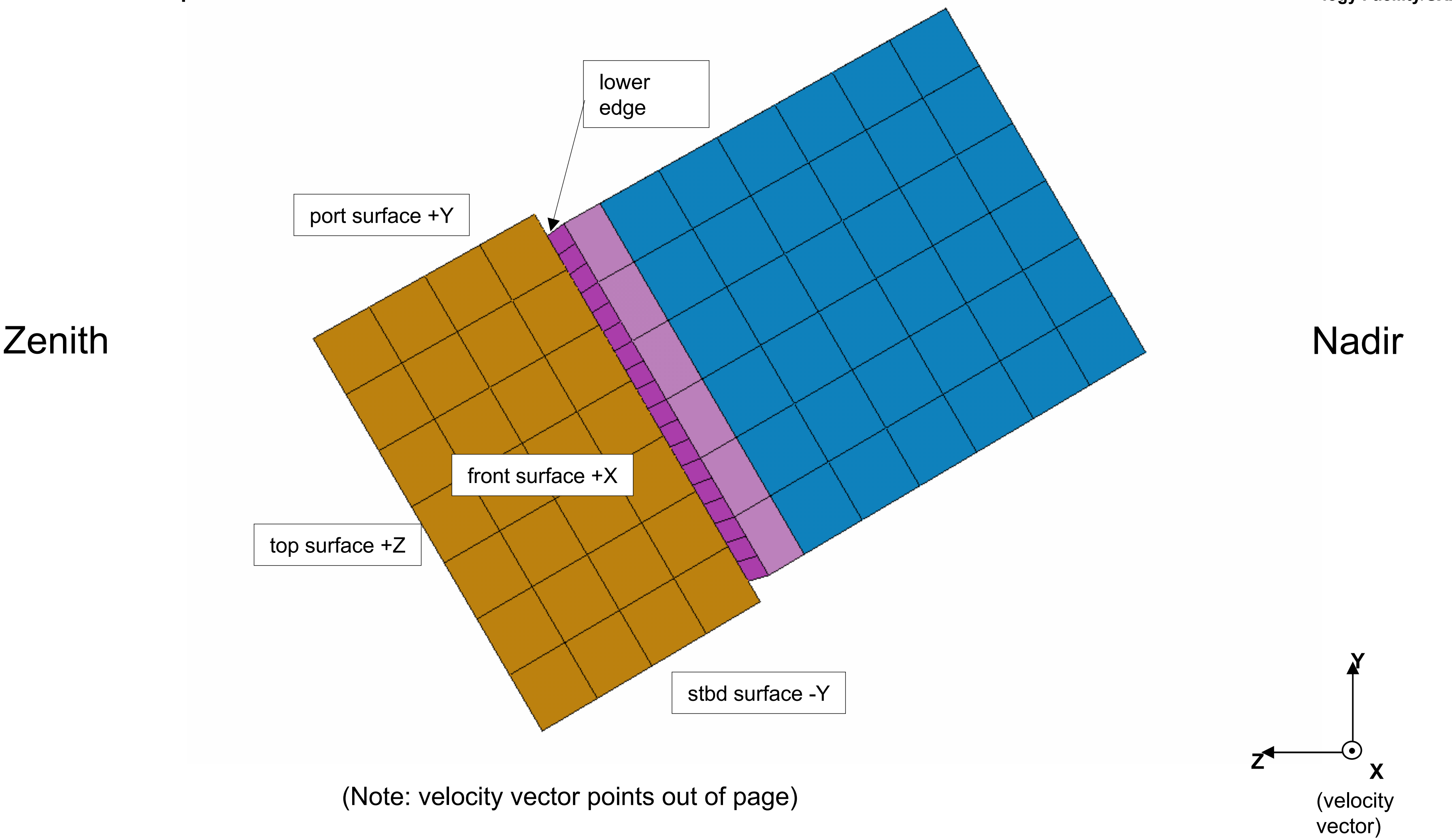
Mode: Sky Survey (75% of mission) & Sub-Mode: Non-Step Rocking (50% of mode)



(Note: velocity vector points out of page)

GLAST Attitude 1A1 (18.75 % of mission duration)

Mode: Sky Survey (75% of mission) & Sub-Mode: Step Rocking (25% of mode)



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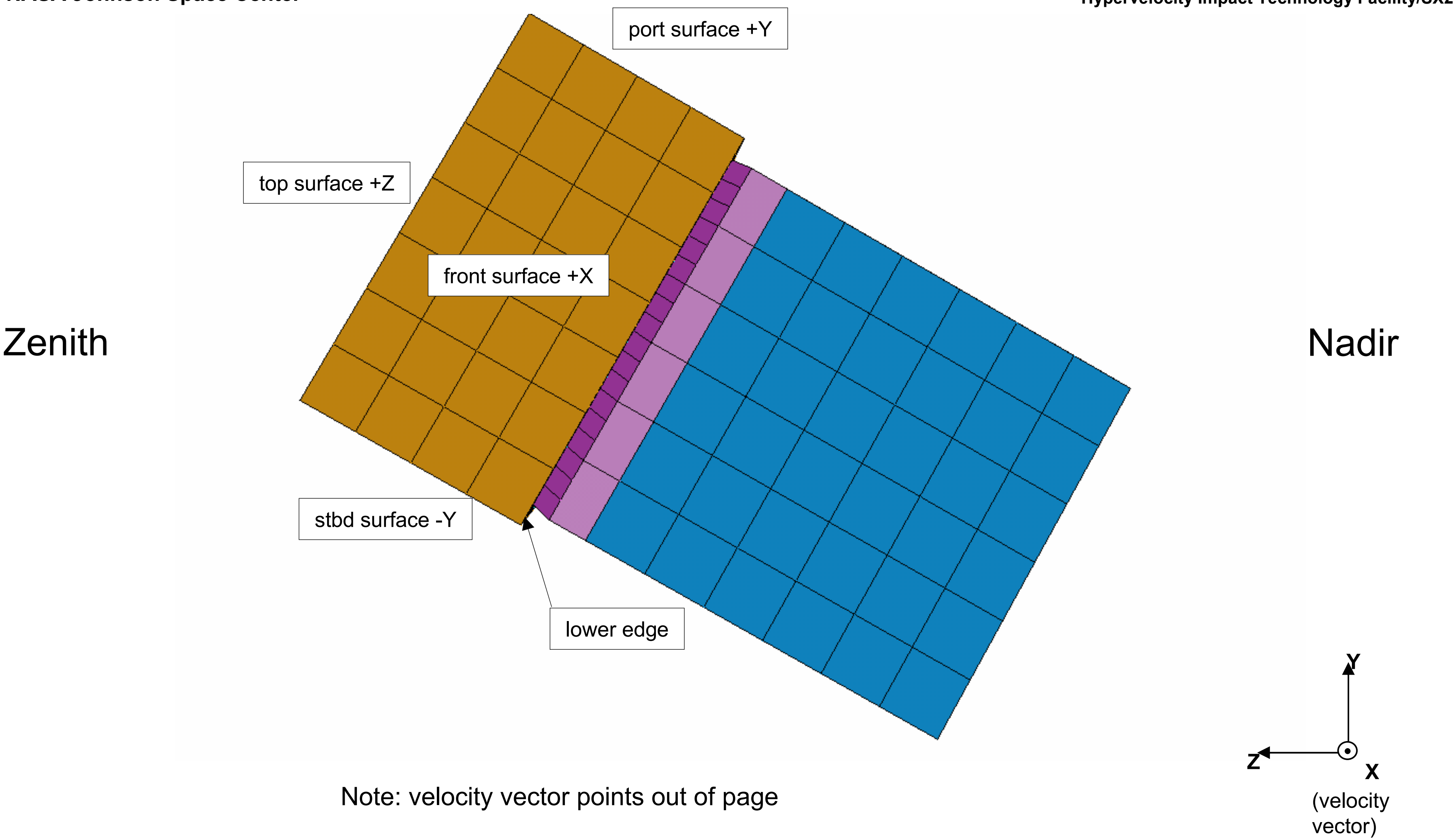
GLAST Attitude 1A2 (18.75 % of mission duration)

Mode: Sky Survey (75% of mission) & Sub-Mode: Step Rocking (25% of mode)



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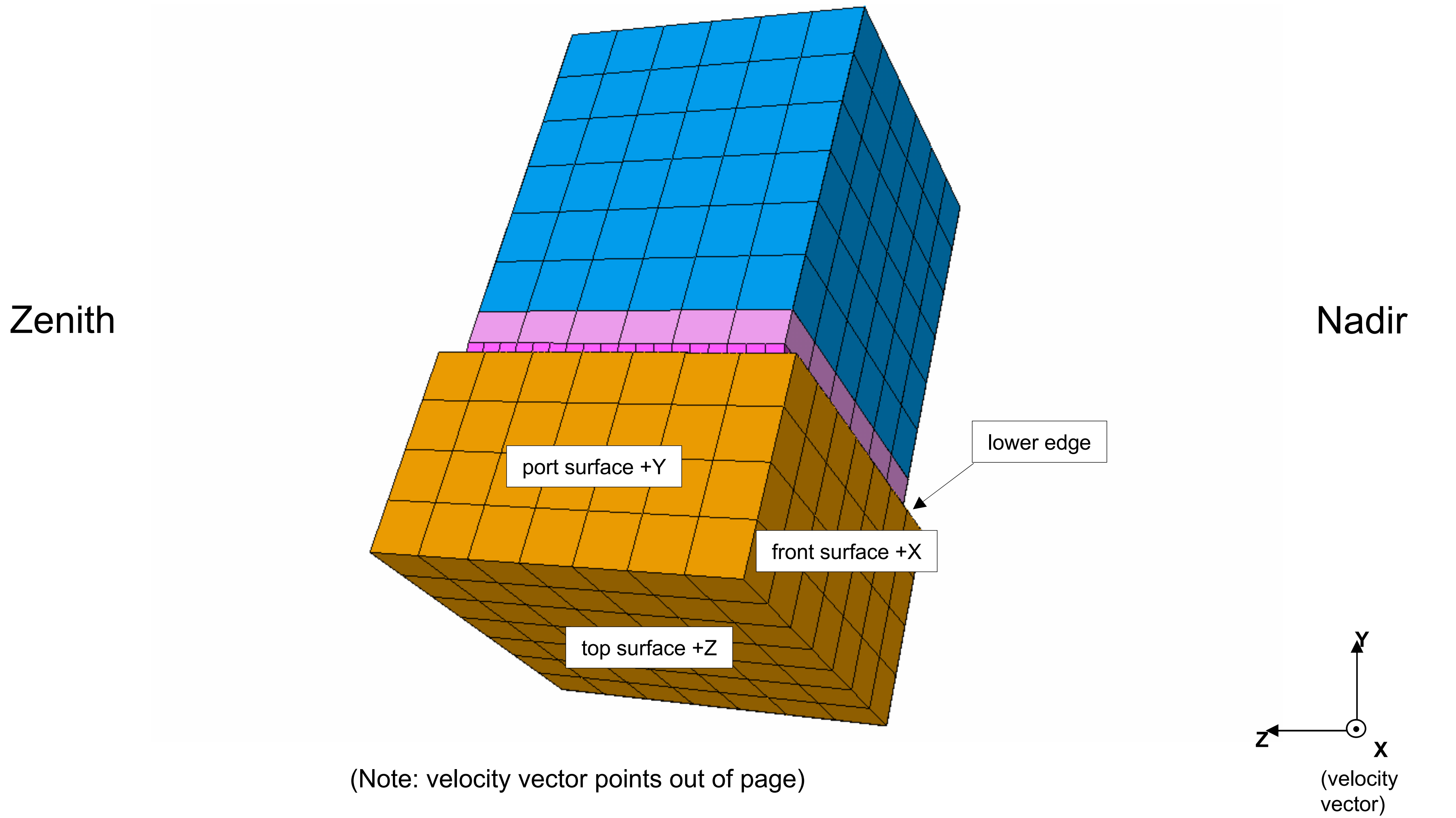
GLAST Attitude 2A1 (6.25 % of mission duration)

Mode: Pointed Observation (25% of mission) & Sub-Mode: Target Tracking (25% of mode)



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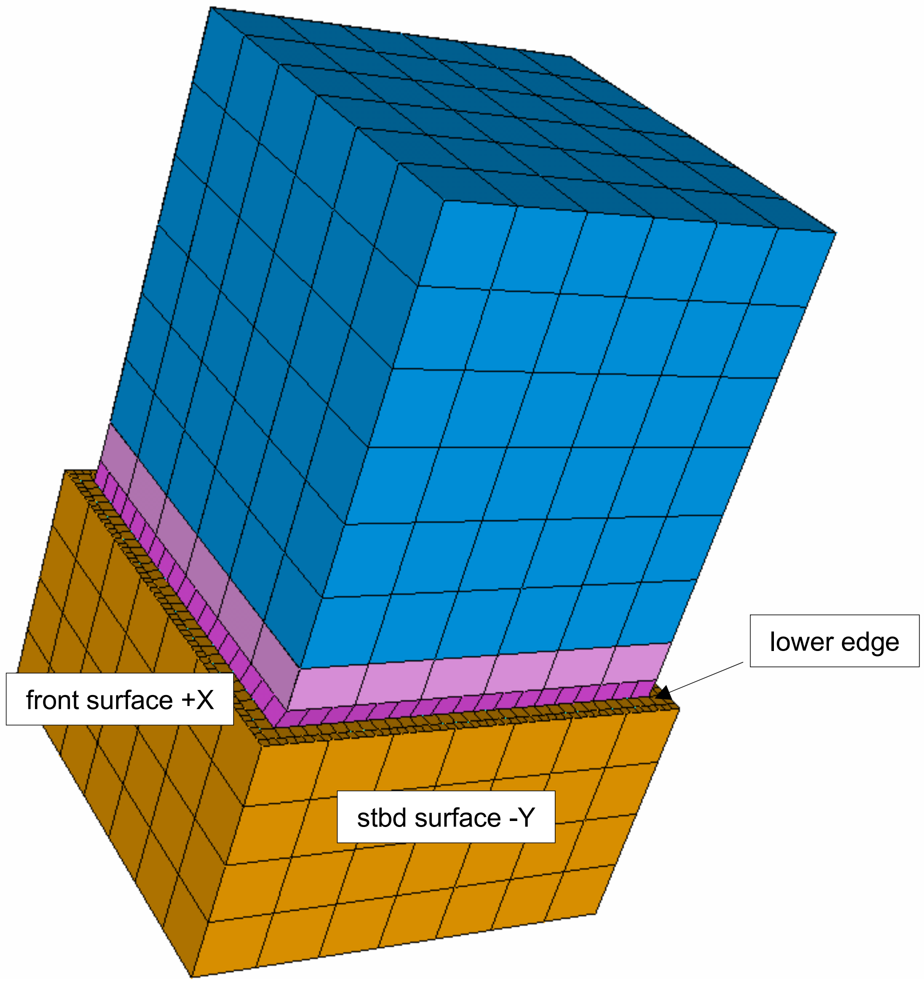
GLAST Attitude 2A2 (6.25 % of mission duration)

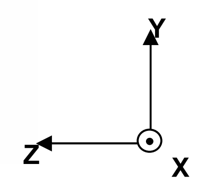
Mode: Pointed Observation (25% of mission) & Sub-Mode: Target Tracking (25% of mode)

Zenith



Nadir

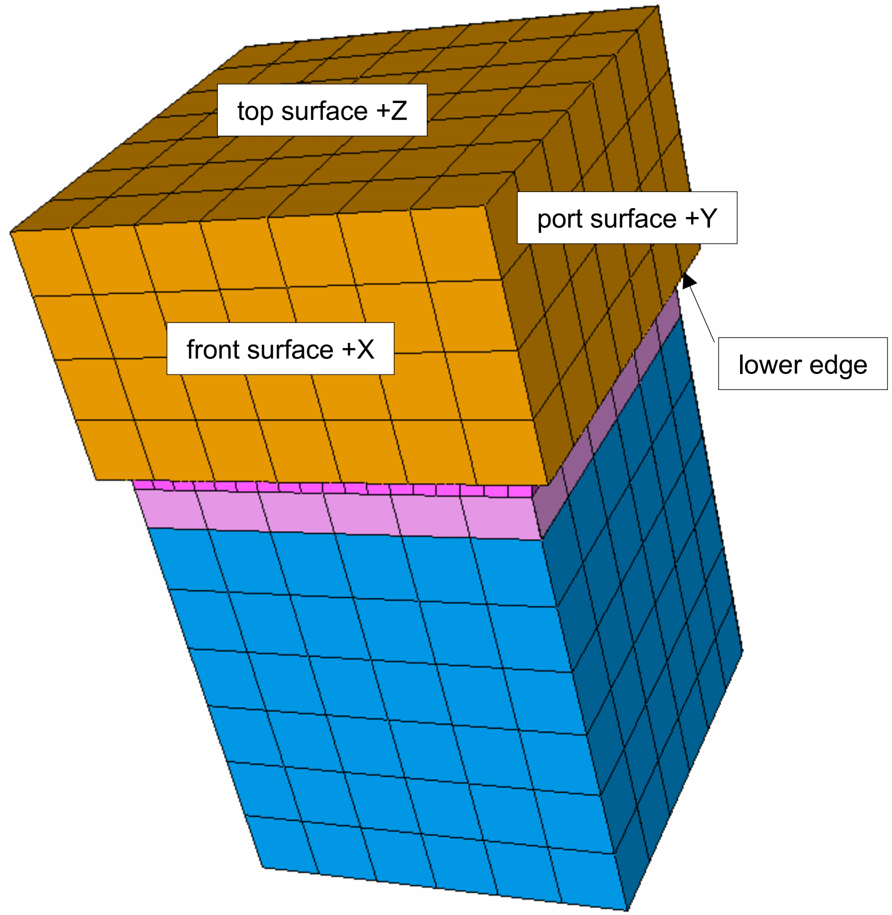
(Note: velocity vector points out of page)



GLAST Attitude 2A3 (6.25 % of mission duration)

Mode: Pointed Observation (25% of mission) & Sub-Mode: Target Tracking (25% of mode)

Zenith



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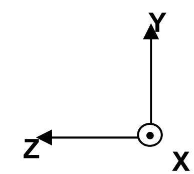
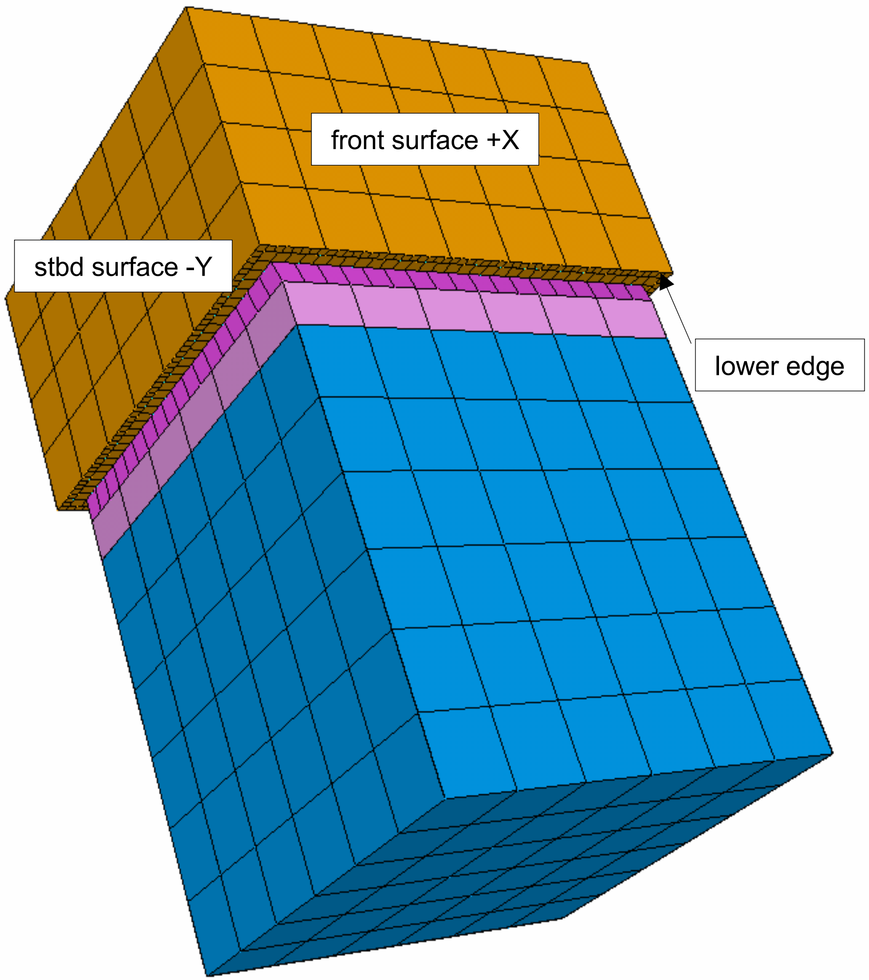
(Note: velocity vector points out of page)



Zenith



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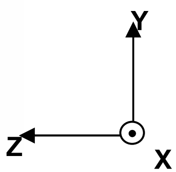
(Note: velocity vector points out of page)



(velocity vector)

BUMPER GLAST Meteoroid/Debris Risk Assessment: Input Parameters

DEBRIS PERFORMANCE ASSESSMENT

BUMPERII VERSION 1.92b
TM 104825 DEBRIS FLUX EQUATIONS
SPACECRAFT ORBIT INCLINATION (DEG) = 28.5000
NUMBER OF THREATS = 90
SPACECRAFT ALTITUDE (KM) = 515.000
BEGINNING EXPOSURE DATE = 2005.5000
CURRENT SOLAR RADIO FLUX DATA, UPDATED 08/01
SPACECRAFT EXPOSURE TIME (YEARS) = 5.0000
MAN-MADE DEBRIS CONSTANT DENSITY (2.8 g/cm^3)
TM 104825 (ORDEM96) DEBRIS PRODUCTION RATE RATIO DATA

METEOROIDS PERFORMANCE ASSESSMENT

BUMPERII VERSION 1.92b
SSP 30425 FLUX EQUATIONS
NUMBER OF THREATS = 145
SPACECRAFT ALTITUDE (KM) = 515.000
SPACECRAFT EXPOSURE TIME (YEARS) = 5.0000
METEOROID VELOCITIES IN SSP 30425 REV. A
METEOROID VARIABLE DENSITY

ORIENTATIONS:

FINITE ELEMENT MODEL: glast_v01.unv

#	MODE	ATTITUDES (S123)			% of Mode	Mode % of Mission	% of Mission
		ROLL	PITCH	YAW			
1A1	SKY SURV/STEP ROCKING	30.0	0.0	0.0	25.00%	75.00%	18.75%
1A2	SKY SURV/STEP ROCKING	-30.0	0.0	0.0	25.00%		18.75%
1B1	SKY SURV/NO STEP ROCKING	0.0	0.0	0.0	50.00%		37.50%
2A1	POINTED OBSERVATION	60.0	60.0	0.0	25.00%	25.00%	6.25%
2A2	POINTED OBSERVATION	60.0	-60.0	0.0	25.00%		6.25%
2A3	POINTED OBSERVATION	-60.0	60.0	0.0	25.00%		6.25%
2A4	POINTED OBSERVATION	-60.0	-60.0	0.0	25.00%		6.25%
						Total:	100.00%

BUMPER Predicted Meteoroid/Debris Risk Breakdown for GLAST Shielding with 3.27cm standoff

	PNP (2005.5 + 5-years)				Risk to Area Ratio				
Gamma-ray Large Area Space Telescope (GLAST)	Meteoroid	Debris	Combined	%	Risk (1-PNP)	% of Total Risk	Area (m^2)	% of Total Area	Risk to Area Ratio
Large Area Telescope (LAT) M/OD Blanket:	0.99491	0.97140	0.96645	100.0%	3.4%	100%	10.26	100%	1.00
top surface (+Z)	0.99858	0.99656	0.99514	14.3%	0.5%	14%	3.01	29%	0.49
front surface (+X)	0.99783	0.99738	0.99521	14.1%	0.5%	14%	1.67	16%	0.87
port surface (+Y)	0.99933	0.99461	0.99394	17.8%	0.6%	18%	1.67	16%	1.11
stbd surface (-Y)	0.99933	0.99461	0.99394	17.8%	0.6%	18%	1.67	16%	1.11
aft surface (-X)	0.99987	0.98829	0.98817	34.9%	1.2%	35%	1.67	16%	2.16
lower edge	0.99996	0.99965	0.99961	1.1%	0.0%	1%	0.56	5%	0.21

GLAST Shield Properties for BUMPER Analysis

ISS M&D Critical Item	Surface Area	Shield		"Analysis" Shield Configuration						Critical Particle Dia
				Bumper		s.o.	inter.	Rear Wall		
Gamma-ray Large Area Space Telescope (GLAST)	(m^2)	PID	Type	(cm)	material	(cm)	layers	(cm)	material	@7 km/s (cm)
Large Area Telescope (LAT) M/OD Blanket:	**24.342**	-	-	-	-	-	-	-	-	-
top surface (+Z)	3.005	2	M	0.102	(4) Nextel AF10 (b=0.110)	3.27	-	0.152	(6) Kevlar KM2 (b=0.139)	0.1778
front surface (+X)	1.673	2	M	0.102	(4) Nextel AF10 (b=0.110)	3.27	-	0.152	(6) Kevlar KM2 (b=0.139)	0.1778
port surface (+Y)	1.673	2	M	0.102	(4) Nextel AF10 (b=0.110)	3.27	-	0.152	(6) Kevlar KM2 (b=0.139)	0.1778
stbd surface (-Y)	1.673	2	M	0.102	(4) Nextel AF10 (b=0.110)	3.27	-	0.152	(6) Kevlar KM2 (b=0.139)	0.1778
aft surface (-X)	1.673	2	M	0.102	(4) Nextel AF10 (b=0.110)	3.27	-	0.152	(6) Kevlar KM2 (b=0.139)	0.1778
lower edge	0.559	2	M	0.102	(4) Nextel AF10 (b=0.110)	3.27	-	0.152	(6) Kevlar KM2 (b=0.139)	0.1778
Instrument Interface Structure Region 1	0.531	3	S	shadowing						20.0000
Instrument Interface Structure Region 2	1.025	4	S	shadowing						20.0000
Spacecraft	12.530	5	S	shadowing						20.0000

BACKUP SLIDES

Effect on GLAST ACD penetration probabilities from latest NASA update in debris environment models (ORDEM2000)

Note: GLAST design based on ORDEM96 and NASA Standard Meteoroid model (design specification)

ORDEM2000 BACKGROUND

- Latest Orbital Debris Engineering Model (ORDEM2000) released Nov.01 and implemented in BUMPER code for meteoroid/debris risk assessments (Dec.01/Shuttle - Mar.02/ISS)
- At Shuttle/ISS altitudes, ORDEM2000 predicts higher numbers of particles from 0.01mm to 4mm diameter than previous debris model (ORDEM96) and fewer numbers of particles from 4mm to 10cm diameter
    - 1mm particles are 7-10x more numerous and 1cm particles are 2-3x less numerous with ORDEM2000

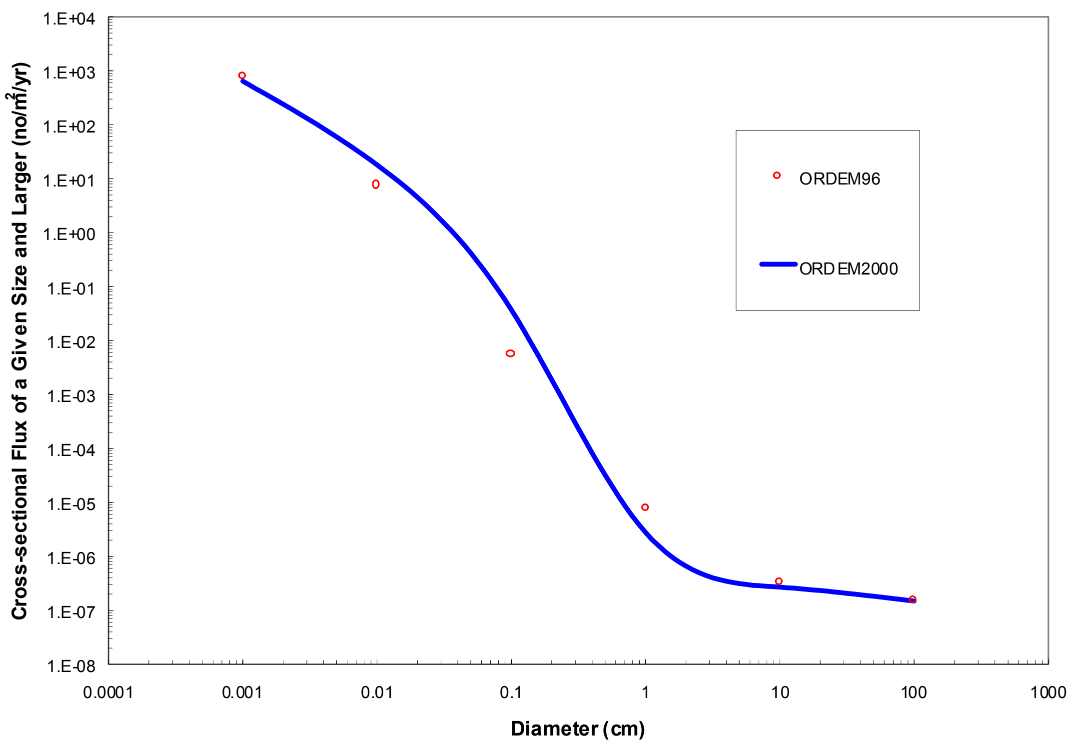


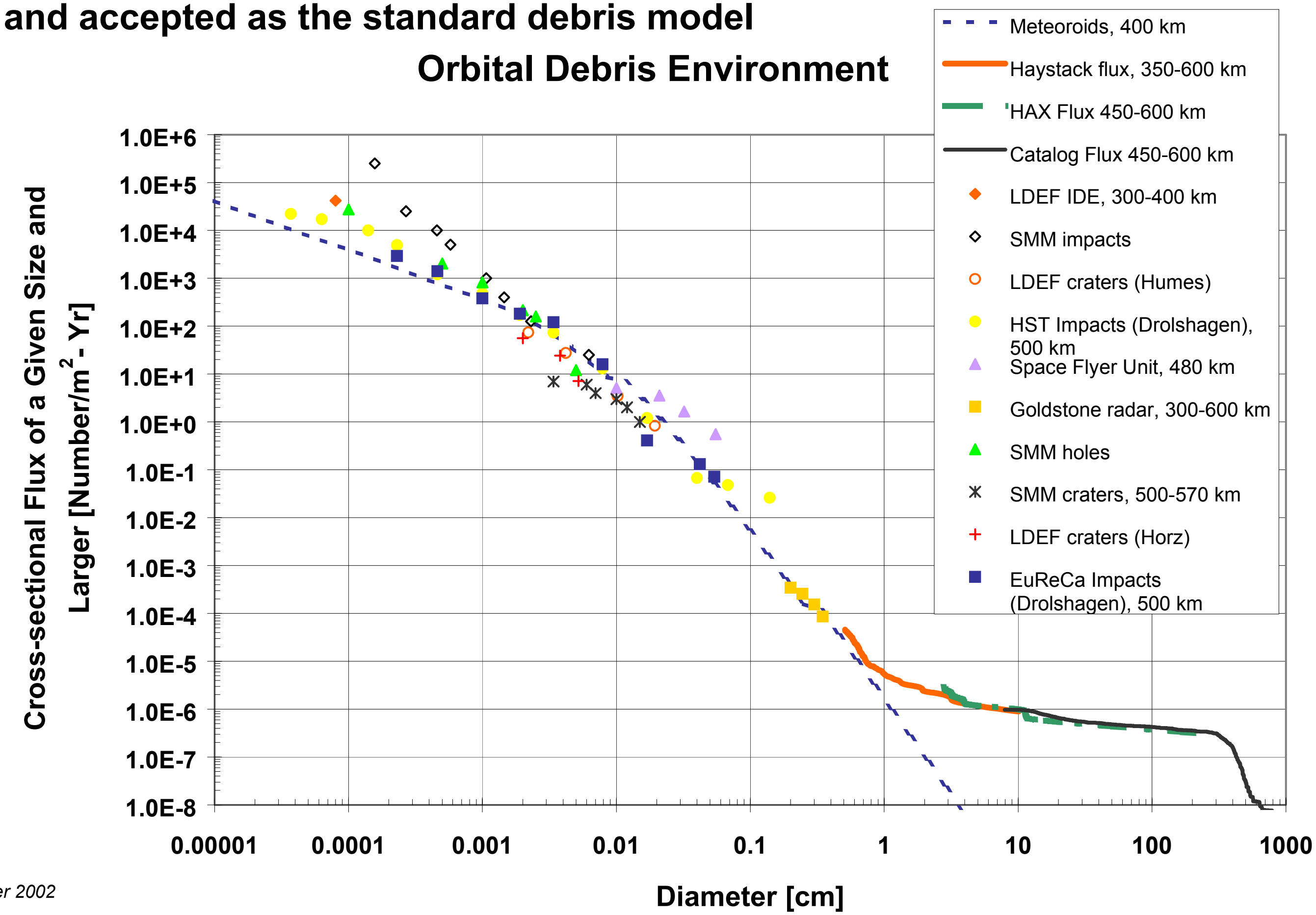
Figure B-2: Debris flux on ISS in 2005.

ORDEM2000 Verification & Validation

Reference: NASA TP-2001 “The New NASA Orbital Debris Engineering Model ORDEM2000”

- ORDEM2000 update based on availability of new data, new analytical techniques and assessment of debris evolution in time (EVOLVE)
- Necessary update to reflect debris environment changes over the last 5 years, and because more data has become available (new sources & larger quantity of data for a broad range of particle sizes)
- **ORDEM2000 has been peer-reviewed by the International Interagency Debris Coordination Committee, and accepted as the standard debris model**

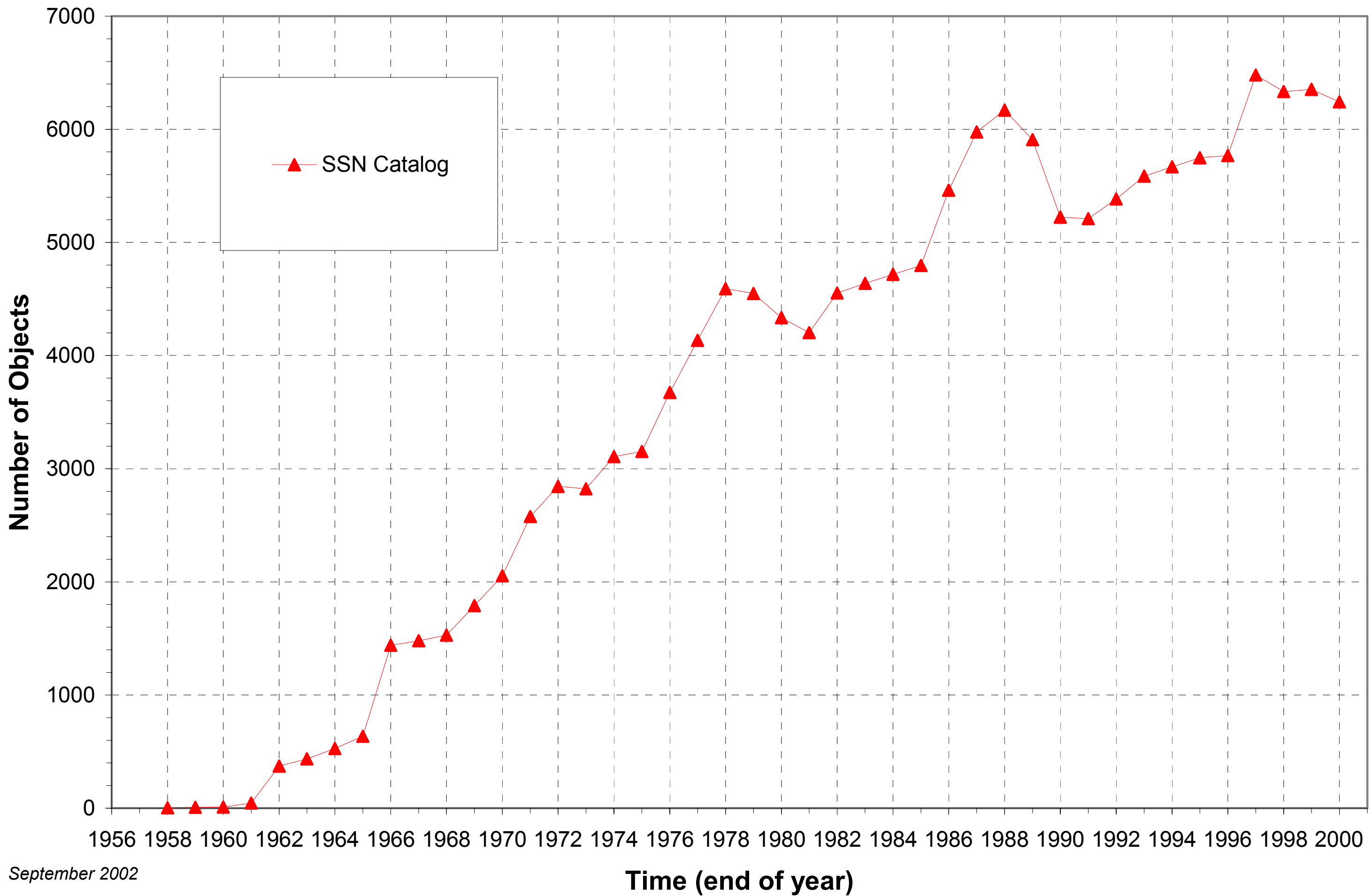
Orbital Debris Environment



Change in Orbital Debris

- Debris environment is changing
- Knowledge of environment is changing

Debris objects (size > 10 cm) tracked in Low Earth Orbit as given in Space Surveillance Network (SSN) catalog



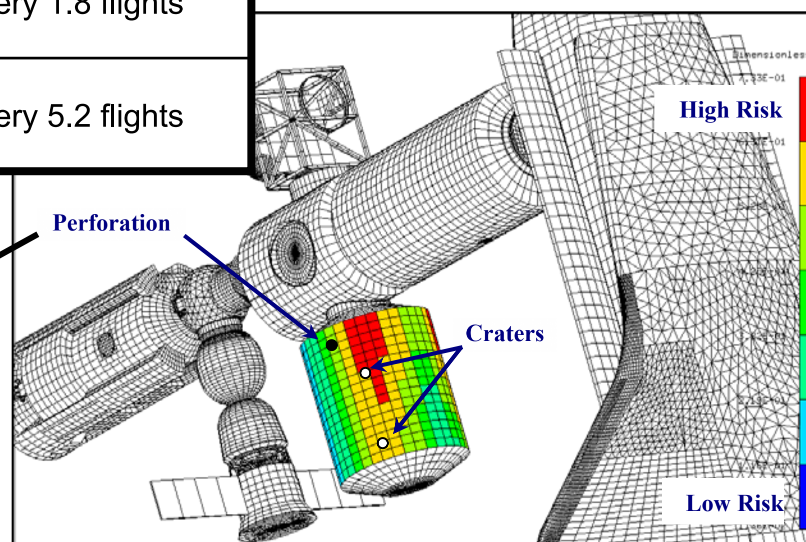
Per SX/J. Pawlowski

ORDEM2000 matches ISS impact experience

- MPLM is inspected for meteoroid/debris damage post-flight
  - 2 craters & 1 complete penetration of outer bumper observed after flight 1 (5A.1)
  - 7 craters & 1 complete penetration of outer bumper observed after flight 4 (UF1)
- Observed damage to MPLM (i.e., 1 bumper perforation every 2 flights) matches predictions using ORDEM2000 in BUMPER. Damage is underestimated with ORDEM96.

PREDICTIONS	Risk of MPLM bumper perforation each flight	Frequency of bumper perforations
ORDEM2000 & std. Meteoroids	55%	1 every 1.8 flights
ORDEM96 & std. Meteoroids	19%	1 every 5.2 flights

5A.1: 1.4mm diameter through-hole, 2.5mm diameter exterior crater



MPLM bumper perforation risk plot, with impact locations noted

Impact damage occurred near predicted high-risk area

Effect on GLAST ACD Penetration Probabilities

- Risk of ACD shield penetration from meteoroid/debris impact increases from 3.4% to 14% with ORDEM2000 over 5-years
- If it occurs, a penetration would degrade one experimental cell of ACD
- But due to redundancy, science return from the entire ACD payload will not be seriously degraded if one cell is lost due to a meteoroid/debris penetration

Environment	Meteoroid	ORDEM96 Debris	Total "Design" Case	Meteoroid	ORDEM2K Debris	Total with ORDEM2K
5-year PNP	0.9949	0.9714	**0.9665**	0.9949	0.8655	**0.8611**

Ballistic Limit Equations for Nextel/Kevlar Multi-Shock Shields used in GLAST

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Summary--NASA has developed enhanced performance shields to improve the protection of spacecraft from orbital debris and meteoroid impacts. One of these shields is a flexible multi-shock shield consisting of Nextel™ ceramic fabric bumpers and Kevlar™ high strength rear wall. This paper provides preliminary ballistic limit equations for the GLAST spacecraft shield. These equations have been updated from Version D, issued November 2001, based on hypervelocity impact tests performed in FY01-02. The equations are subject to further revision based on additional testing and/or analysis.

Nomenclature

d	projectile diameter (cm)
D	hole or crater diameter (cm)
ρ	density (g/cm^3)
m_b	areal density of bumpers (g/cm^2)
m_w	areal density of rear wall (g/cm^2)
M	projectile mass (g)
P	penetration depth (cm)
t	thickness (cm)
θ	impact angle from surface normal (deg)
V	projectile velocity (km/s)
V_n	normal component of projectile velocity (km/s) = $V \cos\theta$

Subscripts:

c	crater/cavity
h	hole
n	normal component (of velocity vector)
p	projectile
s	surface spall
t	target

Flexible Multi-Shock Shield for GLAST

Design equations for a flexible multi-shock shield for GLAST are given in Equations 1-2 (for $V_n > 6.4$ km/s). The areal density of all 4 ceramic bumpers is given by Equation 1.

$$m_b = 0.22\ d\ \rho_p \qquad (1)$$

The areal density of the Kevlar rear wall is estimated from Equation 2.

$$m_w = 26\ M\ V_n / S^2 \qquad (2)$$

Based on Equation 1, the areal density of the bumpers should be 0.11 g/cm^2 for an impact of a 0.18cm diameter aluminum spherical particle with a density of 2.8 g/cm^3 at 7 km/s with normal impact angle. The bumpers of the baseline shield will consist of 4 layers of Nextel AF10 fabric (0.025 g/cm^2 each, total of 0.1 g/cm^2).

Based on Equation 2, the rear wall areal density should be 0.144 g/cm^2 given a total shield standoff of 3.27cm to stop a 0.18cm diameter Aluminum sphere impacting at 7 km/s normal impact. This would require 6 layers of Kevlar KM2 style CS-705 cloth in the rear wall (0.023 g/cm^2 each).

Hypervelocity Impact Test Results

Hypervelocity impact testing was conducted on GLAST shielding without multi-layer insulation (MLI) and between-bumper open-cell foam spacers present. Test results are conservative without MLI and foam present.

Test No.	Proj. Mass (g)	Proj. Dia. (cm)	Vel. (km/s)	Impact Angle (deg)	Bumper Mat'ls	Total standoff (cm)	Rearwall Mat'ls	Total Areal Dens. (g/cm2)	Rearwall results
HD0120189	0.00421	0.142	6.90	0	4 NextelAF10	3.27	(6) Kevlar KM2 CS705	0.246	No Pen.
HD0120332	0.00481	0.149	6.86	0	4 NextelAF10	3.27	(6) Kevlar KM2 CS705	0.246	No Pen.
HITF02072	0.00596	0.160	6.67	0	4 NextelAF10	3.27	(6) Kevlar KM2 CS705	0.246	No Pen.
HD0120329	0.00594	0.159	6.58	0	4 NextelAF10	3.27	(6) Kevlar KM2 CS705	0.246	No Pen.
HITF02043	0.00597	0.160	7.21	0	4 NextelAF10	3.27	(6) Kevlar KM2 CS705	0.246	No Pen.
HD0120245	0.00763	0.173	6.96	0	4 NextelAF10	3.27	(6) Kevlar KM2 CS705	0.246	No Pen., fibers broke on Kev.back
HITF02007	0.00858	0.180	6.71	0	4 NextelAF10	3.27	(6) Kevlar KM2 CS705	0.246	BL, 0.5mm "hole", light-tight, no damage to witness
HITF02048	0.00857	0.180	6.77	45	4 NextelAF10	3.27	(6) Kevlar KM2 CS705	0.246	No Pen.
HITF02047	0.01199	0.202	6.87	45	4 NextelAF10	3.27	(6) Kevlar KM2 CS705	0.246	BL, 1mm "hole", light-tight, soot & no craters on witness
HD0120257	0.01188	0.201	6.69	60	4 NextelAF10	3.27	(6) Kevlar KM2 CS705	0.246	No Pen.
HD0120258	0.01988	0.239	6.65	60	4 NextelAF10	3.27	(6) Kevlar KM2 CS705	0.246	No Pen.
HITF02046	0.02293	0.250	6.68	60	4 NextelAF10	3.27	(6) Kevlar KM2 CS705	0.246	No Pen.
HITF02071	0.02554	0.259	6.73	60	4 NextelAF10	3.27	(6) Kevlar KM2 CS705	0.246	No Pen.
HITF02049	0.02911	0.271	6.80	60	4 NextelAF10	3.27	(6) Kevlar KM2 CS705	0.246	No Pen.
HITF02073	0.03234	0.281	6.58	60	4 NextelAF10	3.27	(6) Kevlar KM2 CS705	0.246	BL, 3mm "hole", light-tight, soot & no craters on witness

Failure Mode

The criterion for failure of the shield is a hole in the last layer of the rear wall allowing light to pass through all 6 layers of Kevlar. A microscope (at 6x to 40x magnification) with a strong (intense) backlight stage was used to assess light transmission of the shield's rear wall. In some cases, a hypervelocity impact test would result in perforation of the last layer (with a small hole 2-3 millimeters diameter at most) but due to fluffing of the Kevlar, no light was transmitted through all 6 layers of Kevlar.

BALLISTIC LIMIT EQUATIONS FOR BUMPER CODE

Preliminary performance equations for the GLAST flexible multi-shock shield are given in equations 3-5:

High-Velocity: when $V \geq 6.8/(\cos\theta)^{1/3}$,

$$d_c = 0.42\ m_w^{1/3}\ \rho_p^{-1/3}\ V^{-1/3}\ (\cos\theta)^{-7/9}\ S^{2/3} \tag{3}$$

Intermediate-Velocity: when $2.4/(\cos\theta)^{0.5} < V < 6.8/(\cos\theta)^{1/3}$,

$$d_c = 0.222\ m_w^{1/3}\ \rho_p^{-1/3}\ (\cos\theta)^{-2/3}\ S^{2/3}\ [(V - 2.4/(\cos\theta)^{0.5})/\ (6.8/(\cos\theta)^{1/3} - 2.4/(\cos\theta)^{0.5})]$$
$$+\ 1.506\ \rho_p^{-1/2}\ [0.5\ m_w + 0.37\ m_b]\ (\cos\theta)^{-1}\ [[(6.8/(\cos\theta)^{1/3} - V)/(6.8/(\cos\theta)^{1/3} - 2.4/(\cos\theta)^{0.5})] \tag{4}$$

Low-Velocity: when $V \leq 2.4/(\cos\theta)^{0.5}$,

$$d_c = 2.7\ V^{-2/3}\ (\cos\theta)^{-4/3}\ \rho_p^{-1/2}\ [0.5\ m_w + 0.37\ m_b] \tag{5}$$

The ballistic limit equations (3-5) above result in the performance curves given in Figure 1 for a projectile with density 2.8 g/cm^3. Figure 2 illustrates the baseline GLAST shield.

Note the equations provided in this paper are subject to change. Updates are possible after further analysis of hypervelocity impact test results.

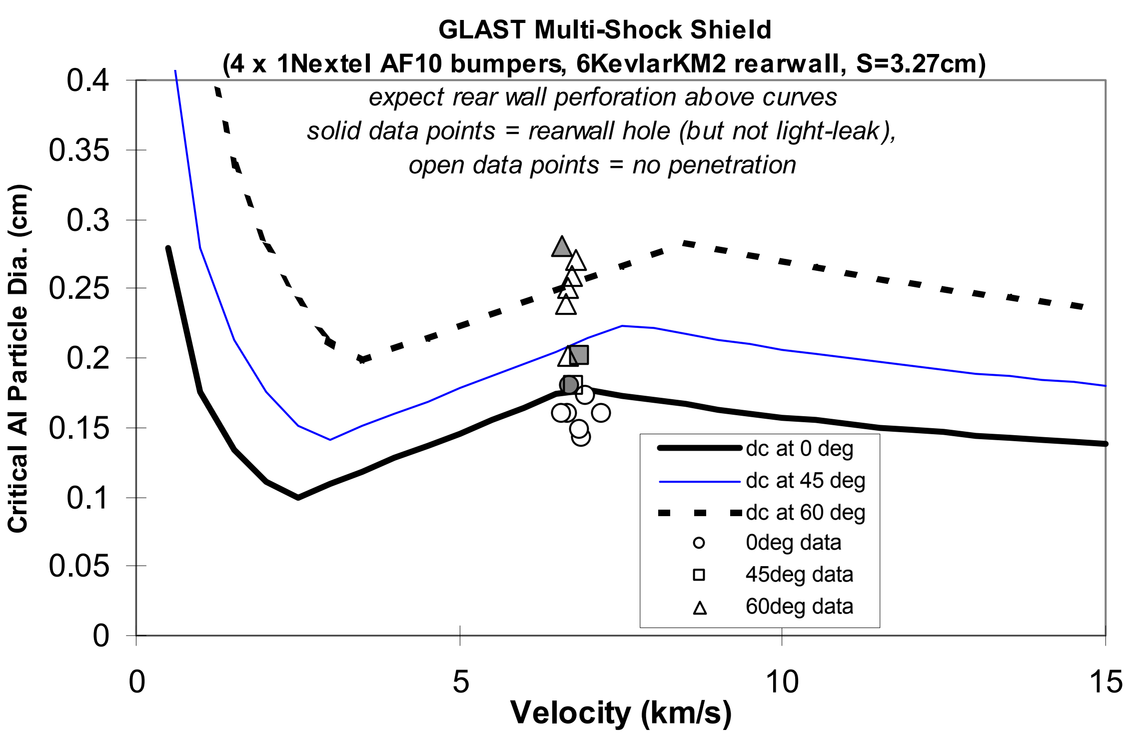

Fig. 1. Predicted Ballistic Limits for GLAST Multi-Shock Shield (preliminary)
4 bumpers (4Nextel AF10 layers total), total Standoff of 3.27cm, 6 layers Kevlar KM2 cloth rear wall

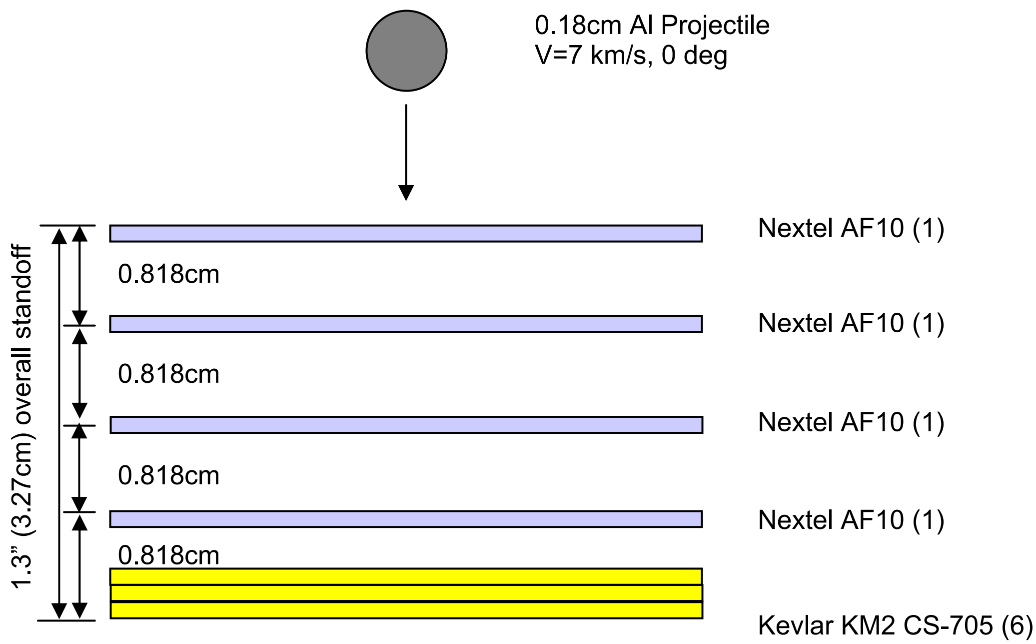

Figure 2. Baseline GLAST Shield Cross-Section