Cryogenic Thermal Distortion Model Validation for the JWST ISIM Structure

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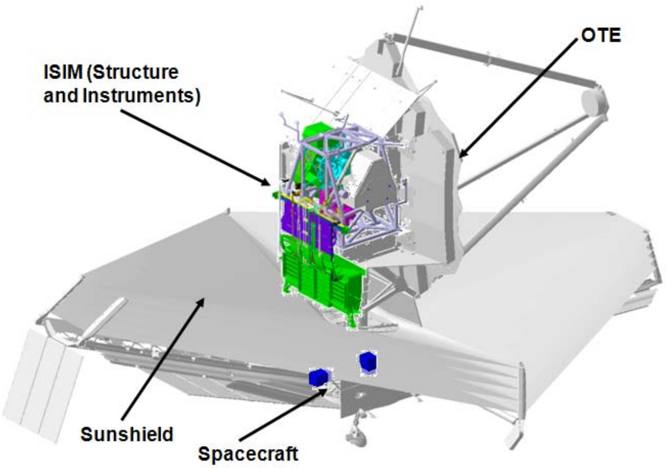
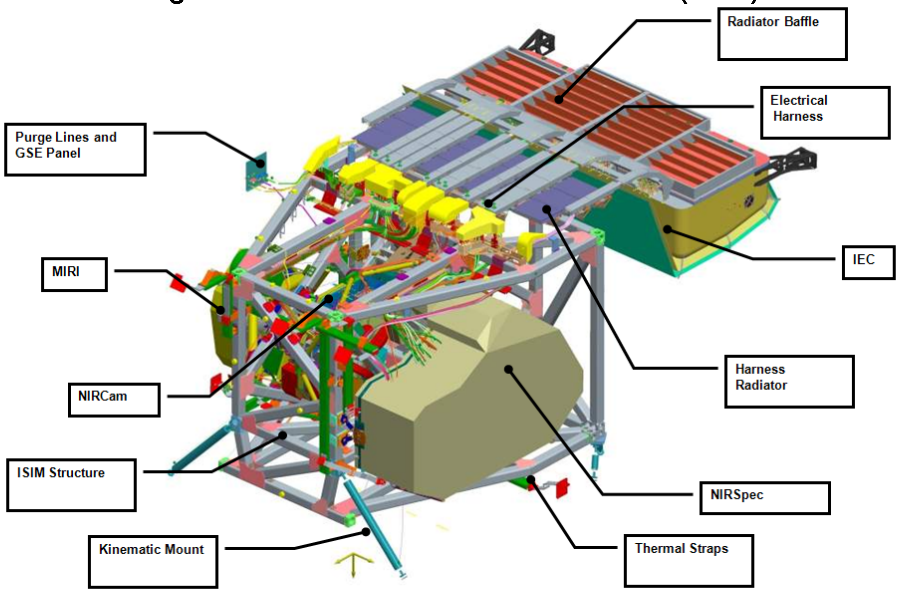
JWST/ISIM Overview

- The James Webb Space Telescope (JWST) is a large, infrared-optimized space telescope consisting an Optical telescope element (OTE), Integrated science instrument module (ISIM), a Spacecraft, and a Sunshield.
- The Integrated Science Instrument Module (ISIM) consists of the JWST science instruments (NIRCam, MIRI, NIRSpec), a fine guidance sensor (FGS), the ISIM Structure, and thermal and electrical subsystems.
- JWST's instruments are designed to work primarily in the infrared range of the electromagnetic spectrum, and the instruments and telescope operate at cryogenic temperatures (~35 K for the instruments).

James Webb Space Telescope (JWST)

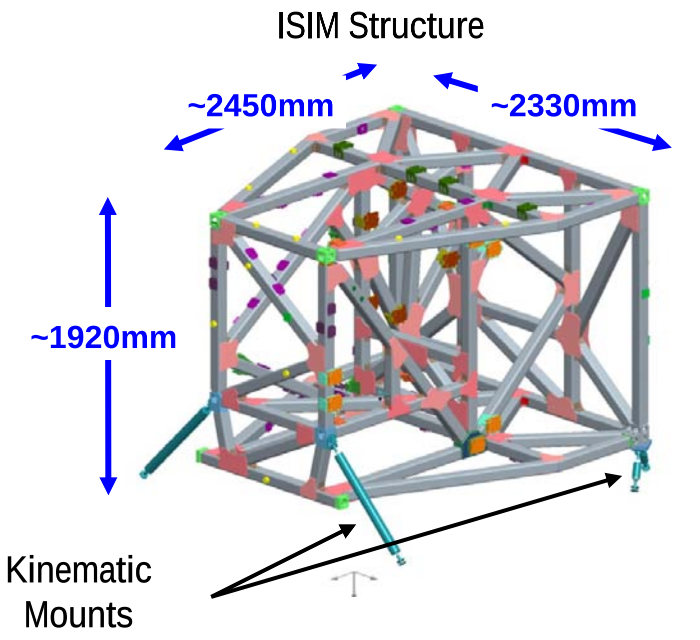


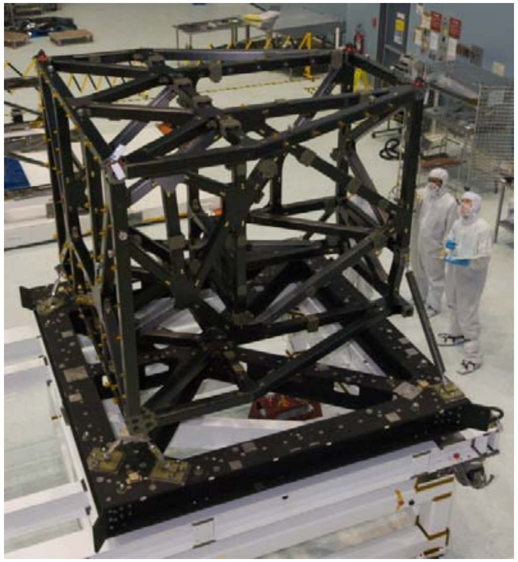
Integrated Science Instrument Module (ISIM)



ISIM Structure Overview

- The ISIM Structure is a large, bonded composite frame that serves as the metering structure between the instruments/guider and the telescope.
  - The ISIM Structure interfaces to the OTE via a kinematic mount (KM) system consisting of two bipods and two monopods.
  - Science instruments interface to the ISIM Structure via instrument kinematic mounts attached to ISIM Structure saddle joints.
- The ISIM Structure and the supported instruments are designed to operate at cryogenic temperatures (~35 K), and thermal distortion performance is critical to maintaining the alignment of the instruments.
- Significant effort has been expended on the development of capabilities to predict and measure cryogenic thermal distortion in order to ensure that the requirements are met and to provide validated models for prediction of on-orbit performance.

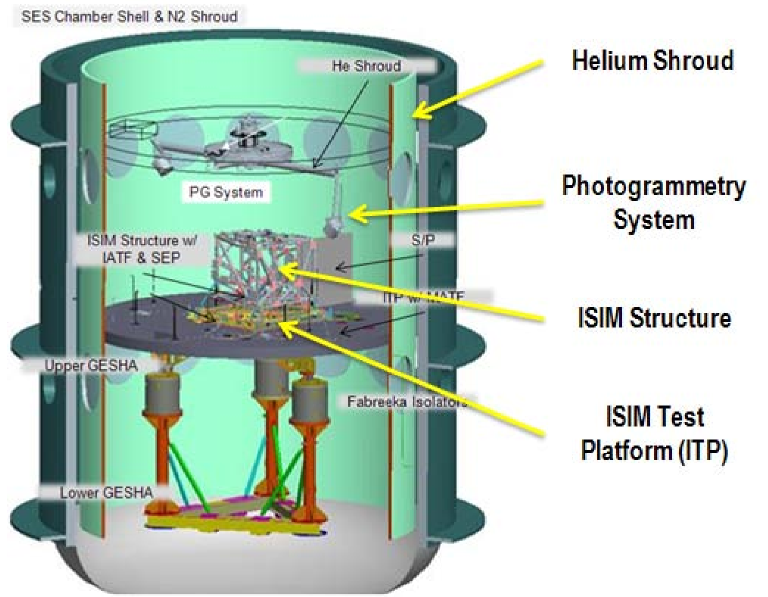


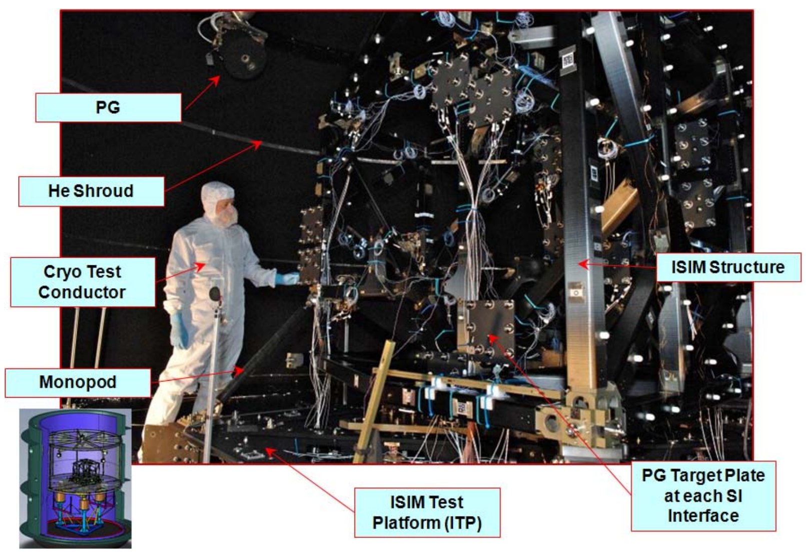


ISIM Structure Thermal Distortion Tests

- ISIM Structure development and verification followed a building blocks approach starting with the development and testing of material samples, followed by bonded joint and subassembly level activities, and culminating with the structural verification program for the flight hardware.
- Two major cryogenic environmental tests were then completed as part of the protoflight ISIM Structure verification program:
  - The Cryoset Test was completed in May 2010 for thermal distortion performance characterization.
  - The Cryoproof Test was completed in October 2010 for demonstration of cryogenic strength.
  - During each of these tests, the hardware under test was thermal cycled between ambient and cryogenic temperatures with metrology performed via photogrammetry at the warm and cold states.
- This presentation focuses on thermal distortion model validation completed using results from the Cryoset and Cryoproof tests.

ISIM Structure Cryoset Test Configuration

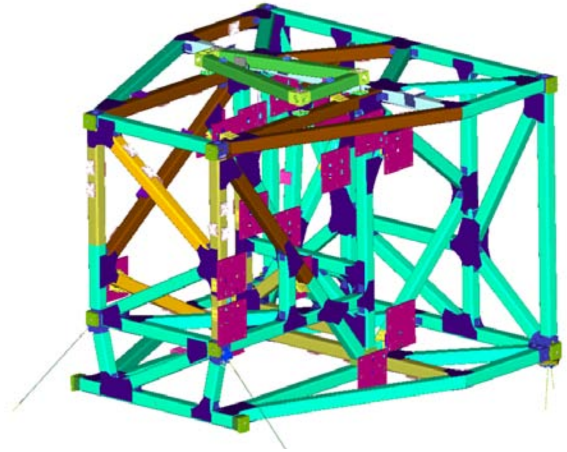


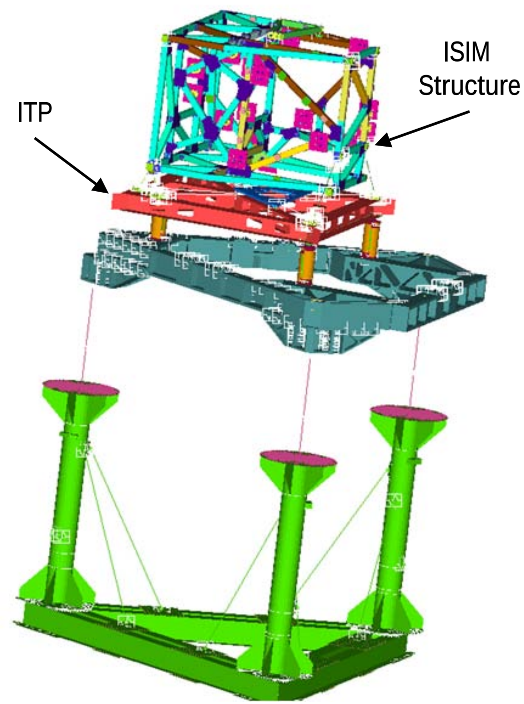


Thermal Distortion Modeling and Analysis

- Thermal distortion analysis was completed using NASTRAN finite element analysis software.
- Detailed structural models were completed for both the flight hardware and associated mechanical ground support equipment in the test setup.
- The ISIM Structure models used for thermal distortion analysis are high fidelity (>2 million degrees of freedom) structural models:
  - Composite frame modeled using solid elements with sufficient fidelity to capture details such as bond lines and shapes.
  - Material properties are all tied to test data specifically generated for the program, in particular temperature-dependent CTE and stiffness properties.
- The MGSE included in the test configuration models includes all of the hardware in the structural load path from the chamber floor interface up to the flight hardware.
  - MGSE structural models were of sufficient fidelity to predict the influence of the supporting hardware on the flight HW.
  - Model validation was completed for the ISIM Test Platform which directly interfaces to the flight hardware to confirm the adequacy of this model.

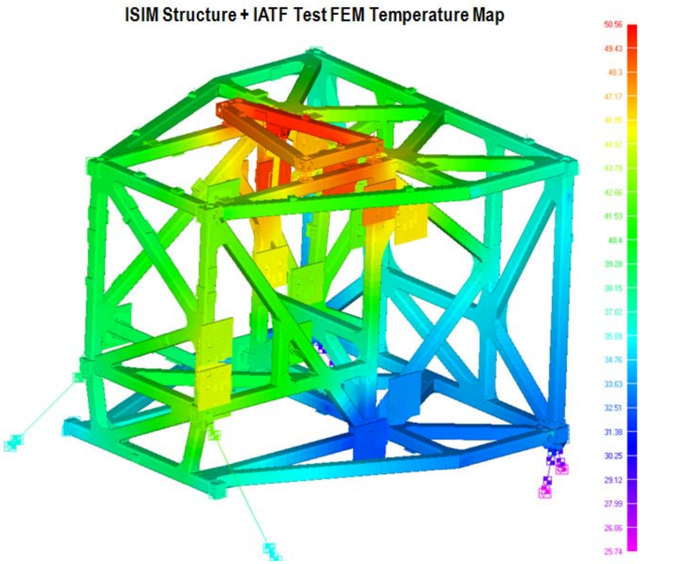
Cryo Set Test
ISIM Structure FEM

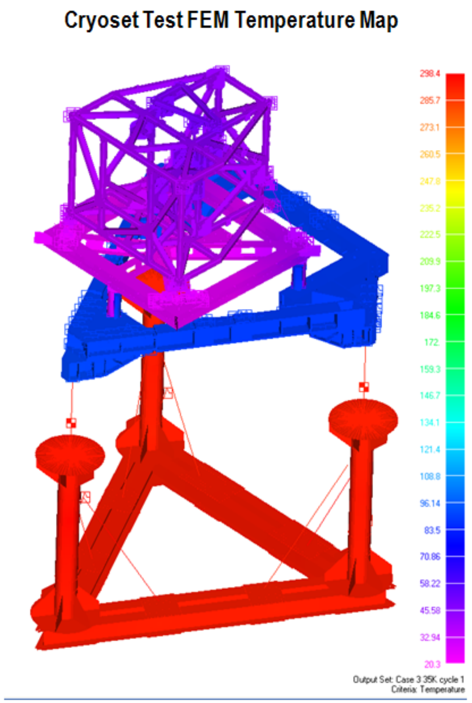




Thermal Distortion Modeling and Analysis – cont.

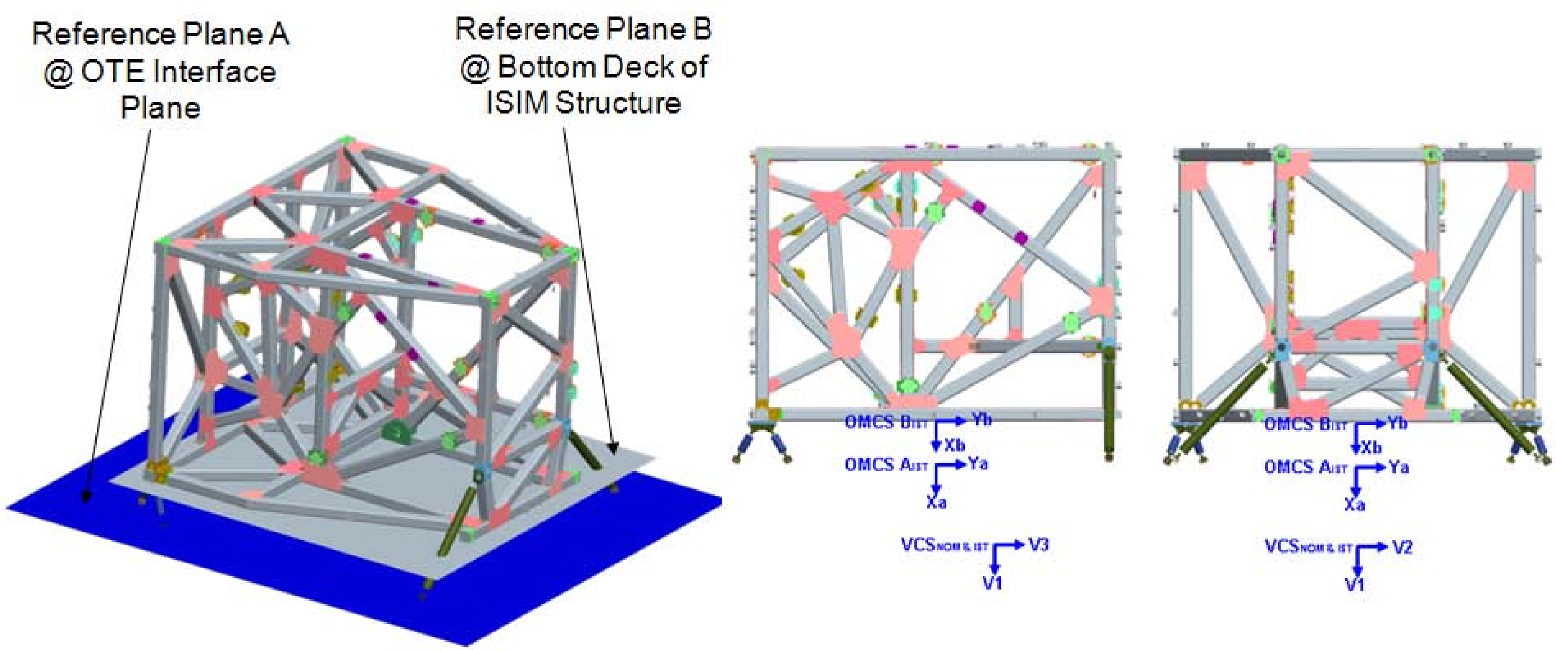
- Temperature mapping:
  - Temperature sensor measurements are used to generate a temperature value for each node in the flight hardware and MGSE structural models via temperature mapping.
  - Temperature maps were created for each ambient and cryo state at which metrology data was taken.
- Modeling and analysis approaches:
  - Nominal model approach is used for basic analysis
  - Stochastic model approach is used to predict the model uncertainty due to factors such as material property and geometric variability. Provides a mean prediction and an uncertainty band determined by multiplying the 95% confidence interval by a modeling uncertainty factor (MUF).
- Modeling uncertainty factors and model validation criteria:
  - Model validation criteria are tied to these analysis approaches and their associated modeling uncertainty factors.
  - For nominal model predictions, the model validation goal is for predictions multiplied by the 1.6 MUF to bound the measured performance.
  - For stochastic model predictions, the model validation goal is for the predicted uncertainty bandwidth to envelop measured performance including measurement error.





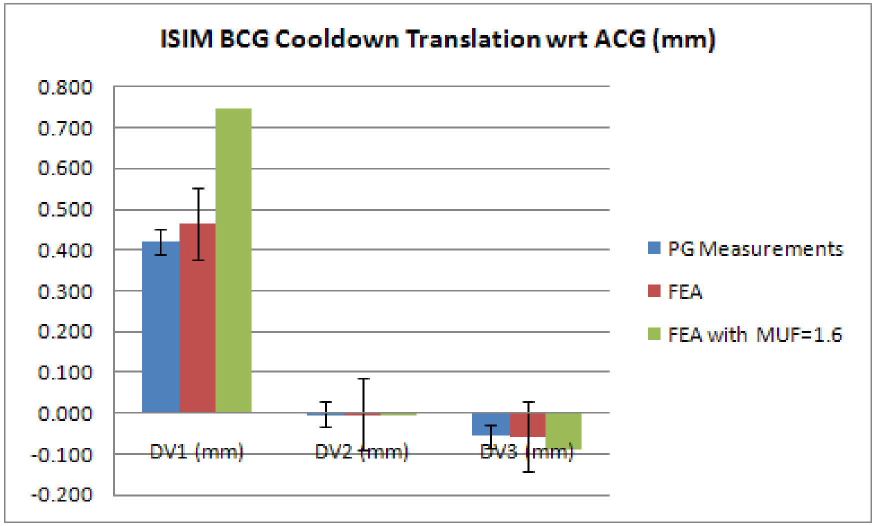
Optomechanical Coordinate Systems

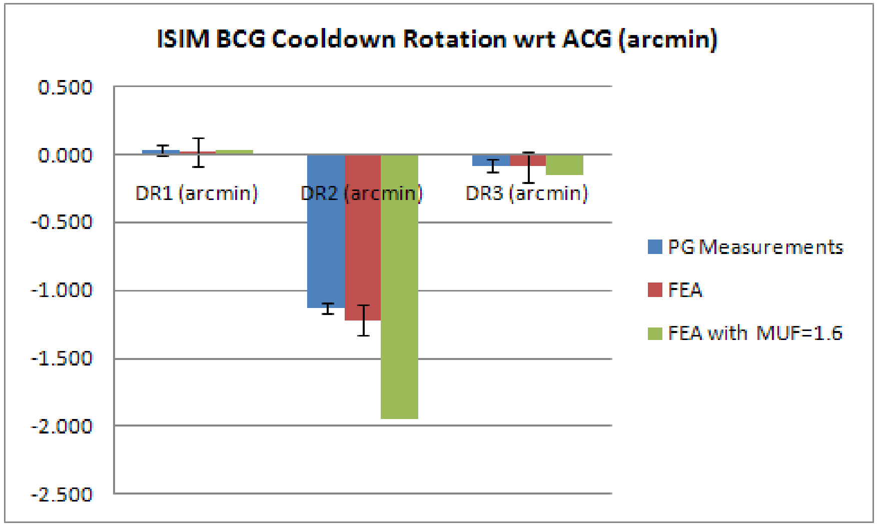
- Optomechanical coordinate systems and references used in thermal distortion analysis:
  - V Coordinate System: Primary coordinate system for the JWST observatory
  - Optomechanical coordinate system A represents the ISIM-to-OTE interface, with Reference Plane A at the bottom of the ISIM kinematic mounts. There are 18 A targets on the ITP that represent the ISIM-to-OTE interface. Reference ACG motions are calculated based on motions of the 18 A targets on the ITP.
  - Optomechanical coordinate system B represents the ISIM Structure, with Reference Plane B at the top of the ISIM kinematic mounts. The 8 B targets on the ISIM Structure at the kinematic mount interfaces that represent the ISIM Structure's rigid body motion. Reference BCG motions are calculated based on motions of the 8 B targets on the Structure.



Cryoset Test Model Validation: BCG-to-ACG

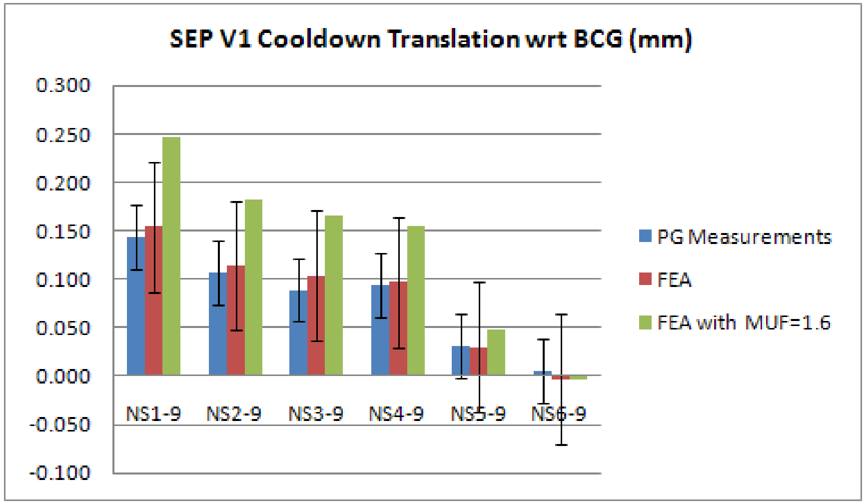
- Compared measured and predicted performance for rigid body motion of the ISIM Structure on its kinematic mounts (BCG to ACG motions):
  - Translations are primarily in the V1 direction due to axial cooldown distortion of the kinematic mount struts. V1 translation predictions show excellent agreement with translation measurements (45 micron difference out of 421 microns or ~10% difference).
  - Rotations are primarily about the V2 axis due in large part to differences in axial length change of the bipod and monopod mount struts. R2 rotation predictions also show excellent agreement with rotation measurements (0.1 arcmin difference out of 1.1 arcmin or ~10% difference).
- Model validation criteria satisfied:
  - Nominal predictions with MUF=1.6 bound the measured performance
  - Stochastic model predictions including 2-sigma uncertainty bandwidth with MUF=1.4 envelop measured performance

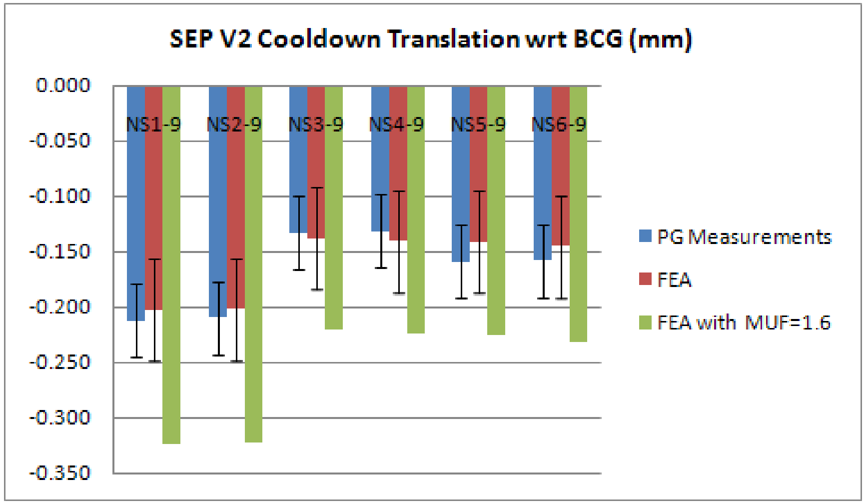




Cryoset Test Model Validation: SI Pads-to-BCG Translations

- Compared measured and predicted performance for internal distortion of the ISIM Structure in terms of translations of the science instrument interfaces with respect to BCG (SI Pads to BCG translations):
  - Maximum cooldown translations with respect to BCG are on the order of 200 microns
  - Significant translations defined as >50 microns (3-sigma photogrammetry error bar).
  - For significant translations, the nominal model predictions without modeling uncertainty factor agree with test measurements to within 50 microns.
- Model validation criteria satisfied for significant translations:
  - Nominal predictions with MUF=1.6 bound the measured performance
  - Stochastic model predictions including 2-sigma uncertainty bandwidth with MUF=1.4 envelop measured performance





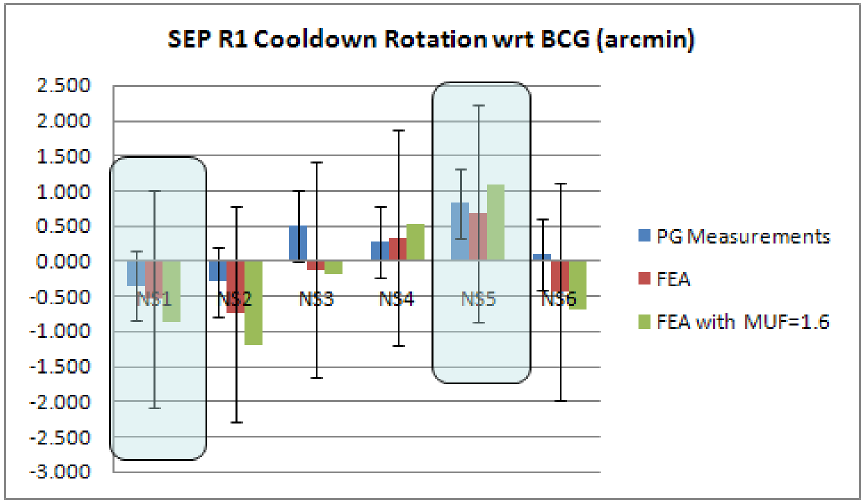
Cryoset Test Model Validation: SI Pads-to-BCG Translations

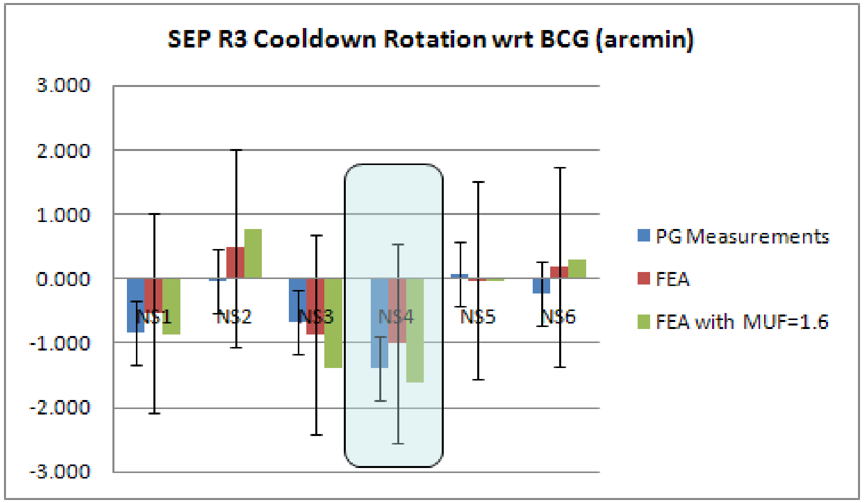
- Table below provides values for measured and predicted cooldown translations in the V1, V2, V3 directions at all nineteen science instrument interface locations.
  - In all cases, the measured performance meets requirements (200 microns max versus 500 micron rqmt)
  - Significant motions were defined as translation greater than the 3-sigma photogrammetry error bar of 50 microns (see values in bold in the table).
  - For significant motions, the nominal model predictions without modeling uncertainty factor agree with test measurements to within 50 microns.

		Significant motion tol =		0.05 3-sigma PG error										
		(Values > tol highlighted)		-0.05 3-sigma PG error										
Node	FEM Node Name	PG TGT Name	PG Measurements[1] (Cycle 1, 39 K - Ambient)			FEA with No MUF[2]			FEA with MUF=1.6[3]			Difference (PG - FEA w/o MUF)		
			ΔV1 (mm)	ΔV2 (mm)	ΔV3 (mm)	ΔV1 (mm)	ΔV2 (mm)	ΔV3 (mm)	ΔV1 (mm)	ΔV2 (mm)	ΔV3 (mm)	ΔV1 (mm)	ΔV2 (mm)	ΔV3 (mm)
13139	MIR1-9	MIR1-9	0.003	**0.237**	0.025	0.032	0.246	0.022	0.052	0.394	0.035		-0.009	
13129	MIR2-9	MIR2-9	0.023	**0.206**	0.049	0.006	0.190	0.044	0.009	0.305	0.071		0.016	
13119	MIR3-9	MIR3-9	**-0.057**	**0.186**	0.039	-0.060	0.200	0.032	-0.096	0.320	0.051	0.003	-0.014	
13219	NC1-9	NC1-9	**0.104**	**0.195**	**0.095**	0.128	0.184	0.102	0.204	0.295	0.164	-0.024	0.011	-0.007
13229	NC2-9	NC2-9	**0.105**	**0.114**	**-0.055**	0.100	0.094	-0.080	0.159	0.151	-0.128	0.005	0.020	0.025
13239	NC3-9	NC3-9	**0.070**	**0.059**	-0.022	0.064	0.049	-0.028	0.102	0.078	-0.045	0.006	0.010	
13249	NC4-9	NC4-9	**0.091**	**0.202**	0.015	0.103	0.173	0.048	0.166	0.277	0.077	-0.013	0.029	
13319	NS1-9	NS1-9	**0.144**	**-0.212**	**-0.077**	0.155	-0.203	-0.103	0.247	-0.324	-0.165	-0.010	-0.009	0.026
13329	NS2-9	NS2-9	**0.107**	**-0.210**	**-0.105**	0.114	-0.202	-0.119	0.183	-0.322	-0.190	-0.008	-0.008	0.014
13339	NS3-9	NS3-9	**0.089**	**-0.133**	**0.053**	0.104	-0.138	0.051	0.166	-0.221	0.081	-0.015	0.005	0.002
13349	NS4-9	NS4-9	**0.095**	**-0.131**	**0.116**	0.097	-0.140	0.131	0.155	-0.224	0.210	-0.003	0.009	-0.015
13359	NS5-9	NS5-9	0.031	**-0.159**	0.046	0.030	-0.141	0.045	0.048	-0.225	0.072		-0.018	
13369	NS6-9	NS6-9	0.005	**-0.158**	-0.031	-0.003	-0.145	-0.027	-0.005	-0.232	-0.043		-0.013	
13419	FGS1-9	FGS1-9	**0.120**	**-0.085**	**0.146**	0.139	-0.067	0.161	0.222	-0.106	0.258	-0.018	-0.019	-0.015
13429	FGS2-9	FGS2-9	**0.077**	**-0.063**	**0.084**	0.080	-0.055	0.083	0.128	-0.088	0.134	-0.003	-0.008	0.000
13439	FGS3-9	FGS3-9	**0.074**	**-0.109**	**0.083**	0.083	-0.063	0.045	0.133	-0.101	0.072	-0.008	-0.046	0.038
13449	FGS4-9	FGS4-9	**0.092**	**-0.088**	**0.077**	0.059	-0.075	0.080	0.094	-0.121	0.128	0.033	-0.013	-0.003
13459	FGS5-9	FGS5-9	**0.150**	**-0.102**	**0.140**	0.120	-0.075	0.152	0.191	-0.119	0.243	0.030	-0.027	-0.012
13469	FGS6-9	FGS6-9	**0.064**	**-0.113**	**0.128**	0.048	-0.104	0.126	0.076	-0.166	0.201	0.016	-0.009	0.002
		max	0.1499	0.2368	0.1457	0.1546	0.2460	0.1610			*max*	*0.033*	*0.029*	*0.038*
		min	-0.0568	-0.2120	-0.1051	-0.0600	-0.2026	-0.1189			*min*	*-0.024*	*-0.046*	*-0.015*
											RMS	*0.016*	*0.017*	*0.017*

Cryoset Test Model Validation: SI Pads-to-BCG Rotations

- Compared measured and predicted performance for internal distortion of the ISIM Structure in terms of rotations of the science instrument interfaces with respect to BCG (SI Pads to BCG rotations):
  - Maximum cooldown rotations with respect to BCG are on the order of 1.3 arcmin
  - Significant rotations defined as >0.7 arcmin (3-sigma photogrammetry error bar).
  - In general, measured rotations were small compared to performance requirements (<5 arcmin required) and only 11 SEP rotation DOFs (out of 57) greater than 0.7 arcmin threshold.
  - For significant rotations, the nominal model predictions without modeling uncertainty factor agree with test measurements to within 0.6 arcmin (about the PG measurement error).
- Model validation criteria partially satisfied for significant rotations:
  - Nominal model meets criteria in some cases and is partially validated.
  - Stochastic model meets criteria in all cases and is fully validated.





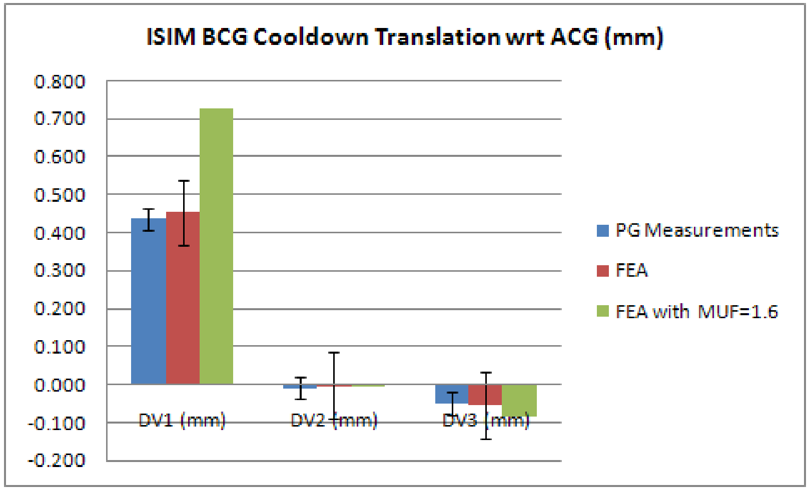
Cryoset Test Model Validation: SI Pads-to-BCG Rotations

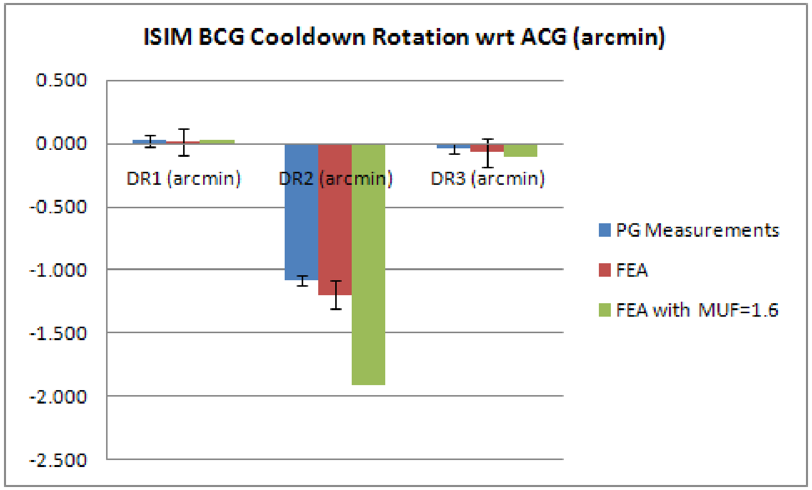
- Table below provides values for measured and predicted cooldown rotations about the V1, V2, V3 axes at all nineteen science instrument interface locations:
  - In all cases, the measured performance meets requirements (1.4 arcmin microns max versus 5 arcmin rqmt)
  - Significant rotations were defined as greater than the 3-sigma photogrammetry error bar of 0.7 arcmin (see values in bold in the table). Note that measured SEP rotations were small relative to the measurement error and cooldown performance requirements. Only 11 SEP rotation DOFs (out of 57) showed cooldown rotations > 0.7 arcmin validation threshold
  - For significant motions, the nominal model predictions without modeling uncertainty factor agree with test measurements to within 0.6 arcmin.

		Significant motion tol =		0.71	3-sigma PG error									
		(Values > tol highlighted)		-0.71	3-sigma PG error									
			PG Measurements[1] (Cycle 1, 39 K - Ambient)			FEA with No MUF[2]			FEA with MUF=1.6[3]			Difference (PG - FEA w/o MUF)		
Node	FEM Node Name	PG TGT Name	ΔR1 (arcmin)	ΔR2 (arcmin)	ΔR3 (arcmin)	ΔR1 (arcmin)	ΔR2 (arcmin)	ΔR3 (arcmin)	ΔR1 (arcmin)	ΔR2 (arcmin)	ΔR3 (arcmin)	ΔR1 (arcmin)	ΔR2 (arcmin)	ΔR3 (arcmin)
13130	MIR1-Avg(1-9)	MIR1	**-1.173**	-0.517	**-1.019**	-0.601	0.331	-0.455	-0.962	0.529	-0.728	-0.572		-0.564
13120	MIR2-Avg(1-9)	MIR2	0.035	-0.091	-0.233	0.001	-0.659	0.378	0.002	-1.054	0.605			
13110	MIR3-Avg(1-9)	MIR3	-0.578	**0.924**	**-0.720**	-0.105	1.495	-0.987	-0.167	2.392	-1.579		-0.571	0.267
13210	NC1-Avg(1-9)	NC1	-0.074	0.472	0.055	0.067	0.868	0.379	0.107	1.388	0.607			
13220	NC2-Avg(1-9)	NC2	-0.061	0.448	0.459	-0.262	1.011	1.254	-0.420	1.617	2.007			
13230	NC3-Avg(1-9)	NC3	**0.841**	0.218	-0.168	0.713	0.541	0.003	1.141	0.865	0.005	0.127		
13240	NC4-Avg(1-9)	NC4	0.529	-0.113	0.568	0.022	0.702	0.000	0.035	1.123	0.000			
13310	NS1-Avg(1-9)	NS1	-0.346	0.621	**-0.840**	-0.532	-0.197	-0.536	-0.852	-0.316	-0.857			-0.304
13320	NS2-Avg(1-9)	NS2	-0.290	0.294	-0.039	-0.750	-0.094	0.487	-1.199	-0.151	0.779			
13330	NS3-Avg(1-9)	NS3	0.504	-0.076	-0.681	-0.120	-0.691	-0.861	-0.192	-1.105	-1.378			
13340	NS4-Avg(1-9)	NS4	0.274	0.023	**-1.388**	0.338	-0.426	-1.002	0.541	-0.682	-1.604			-0.386
13350	NS5-Avg(1-9)	NS5	**0.823**	0.483	0.068	0.682	0.085	-0.030	1.091	0.136	-0.047	0.142		
13360	NS6-Avg(1-9)	NS6	0.096	0.572	-0.234	-0.432	0.252	0.190	-0.691	0.403	0.303			
13410	FGS1-Avg(1-9)	FGS1	0.044	-0.030	-0.660	0.150	0.117	-0.553	0.240	0.187	-0.885			
13420	FGS2-Avg(1-9)	FGS2	0.507	-0.165	0.170	0.740	0.868	0.238	1.185	1.388	0.381			
13430	FGS4-Avg(1-9)	FGS3	0.382	0.333	-0.203	0.975	0.602	-0.168	1.560	0.964	-0.268			
13440	FGS3-Avg(1-9)	FGS4	**1.291**	-0.005	-0.187	0.834	0.796	-0.051	1.334	1.273	-0.081	0.457		
13450	FGS5-Avg(1-9)	FGS5	0.018	0.374	**-0.778**	0.310	0.656	-0.515	0.497	1.050	-0.824			-0.263
13460	FGS6-avg(1-9)	FGS6	0.328	-0.373	**-0.932**	-0.331	0.129	-1.470	-0.530	0.207	-2.353			0.538
		max	1.2910	0.9245	0.5683	0.9752	1.4951	1.2545			*max*	*0.457*	*-0.571*	*0.538*
		min	-1.1729	-0.5174	-1.3883	-0.7496	-0.6905	-1.4703			*min*	*-0.572*	*-0.571*	*-0.564*
											RMS	*0.376*	*0.000*	*0.388*

Cryoproof Test Model Validation

- The Cryoproof Test provided additional data on ISIM Structure cryogenic distortion in a mass loaded configuration for a subset of the targets measured during the Cryoset Test:
  - Ambient to cryo cooldown motions for the ISIM BCG-to-Reference ACG and ISIM Structure general targets-to-Reference BCG.
  - Science instrument interfaces could not be measured due to the presence of the science instrument mass simulators.
- Compared measured and predicted performance for BCG to ACG motions:
  - V1 translation predictions show excellent agreement with translation measurements agreeing to within 18 microns out of a total motion of 435 microns or about 5% difference.
  - R2 rotation predictions show excellent agreement with rotation measurements agreeing to 0.1 arcmin out of a total rotation of 1.1 arcmin or about 10% difference.
  - Model validation criteria are satisfied for both the nominal and stochastic analyses.





Comparison of Cryoset and Cryoproof Test Results

- Comparison was made between the ISIM Structure cooldown performance measured and predicted in the Cryoset Test (bare ISIM Structure) and Cryoproof Test (mass-loaded ISIM Structure) configurations for the following metrics:
  - BCG-to-ACG motion indicative of rigid body motion of the ISIM Structure on its kinematic mounts.
  - ITOR CG-to-BCG motion indicative of general target motion on the "top" (-V1) deck of the ISIM Structure relative to Reference BCG.
- The differences in measured and predicted cooldown performance between the two tests are less than 14 microns for both metrics.
- This demonstrates that the influence of differences in thermal environment on the order of <10K and the presence of mass loading did not appreciably change thermal distortion performance as predicted.

Test	Target Centroid	Reference	PG Measurements			FEA with No MUF			Difference (PG - FEA)		
			ΔV1 (mm)	ΔV2 (mm)	ΔV3 (mm)	ΔV1 (mm)	ΔV2 (mm)	ΔV3 (mm)	ΔV1 (mm)	ΔV2 (mm)	ΔV3 (mm)
Cryoset	BCG	ACG	**0.421**	-0.001	-0.055	**0.466**	-0.001	-0.057	-0.045	0.000	0.002
Cryoproof	BCG	ACG	**0.435**	-0.008	-0.050	**0.454**	-0.001	-0.053	-0.018	-0.007	0.003
Difference (CS-CP)	*BCG*	*ACG*	*-0.014*	*0.007*	*-0.005*	*0.013*	*0.000*	*-0.004*			
Cryoset	ITOR CG	BCG	**0.142**	0.057	**0.097**	**0.129**	0.055	**0.114**	0.013	0.002	-0.017
Cryoproof	ITOR CG	BCG	**0.147**	0.058	**0.085**	**0.127**	0.054	**0.111**	0.020	0.003	-0.027
Difference (CS-CP)	ITOR CG	BCG	*-0.006*	*0.000*	*0.012*	*0.002*	*0.001*	*0.003*			

Summary

- Cryogenic testing and associated thermal distortion model validation for the JWST ISIM Structure were successfully completed in 2010.
  - Detailed comparisons were made between test measurements and analytical predictions from nominal and stochastic analyses for the cooldown performance of the protoflight ISIM Structure and critical MGSE.
  - Results from these comparisons demonstrate that the models accurately predict thermal distortion performance and meet model validation goals tied to the type of analysis and associated model uncertainty factors.
  - The validated models will be used for the analysis of both future test configurations and on-orbit performance.
- Future cryogenic thermal vacuum testing of the integrated ISIM Element, consisting of the science instruments and associated subsystems mounted to the ISIM Structure, will build on the success of the ISIM Structure cryogenic testing and associated model validation to verify integrated ISIM performance requirements.
- At the JWST level, a final cryo thermal vacuum test of the combined ISIM and OTE (telescope) system will be performed to characterize optical and thermal performance for the observatory.