Metrology for trending alignment of the James Webb Space Telescope before and after ambient environmental testing

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Introduction

- **James Webb Space Telescope (JWST)**
  - NASA mission developed in conjunction with the European Space Agency and the Canadian Space Agency
  - Large infrared space telescope with a 6.5m diameter primary mirror
  - The observatory consists of two primary structures
    - Spacecraft (SC) bus
    - OTIS- Optical Telescope Element (OTE) and Integrated Science Instrument Module (ISIM)
- **The telescope must survive:**
  - unforgiving launch conditions
  - space environment
  - handling and transportation during the integration and test phase of the program
- **Pre/Post alignment subsystem checks**
  - Secondary Mirror to Mount
  - ISIM to JWST coordinate system
  - Aft optical system (AOS) to OTIS backplane
  - Gaps between segmented mirrors

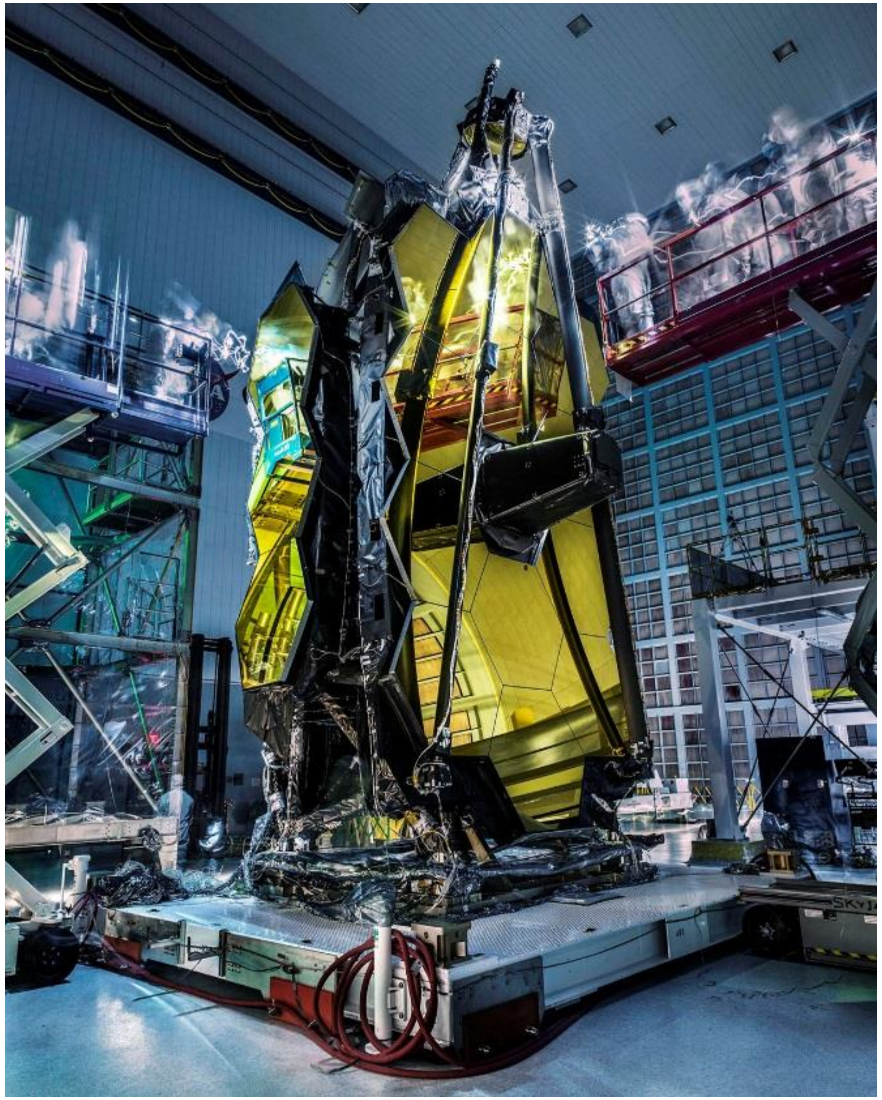


Photo credit: Chris Gunn GSFC

Instrumentation

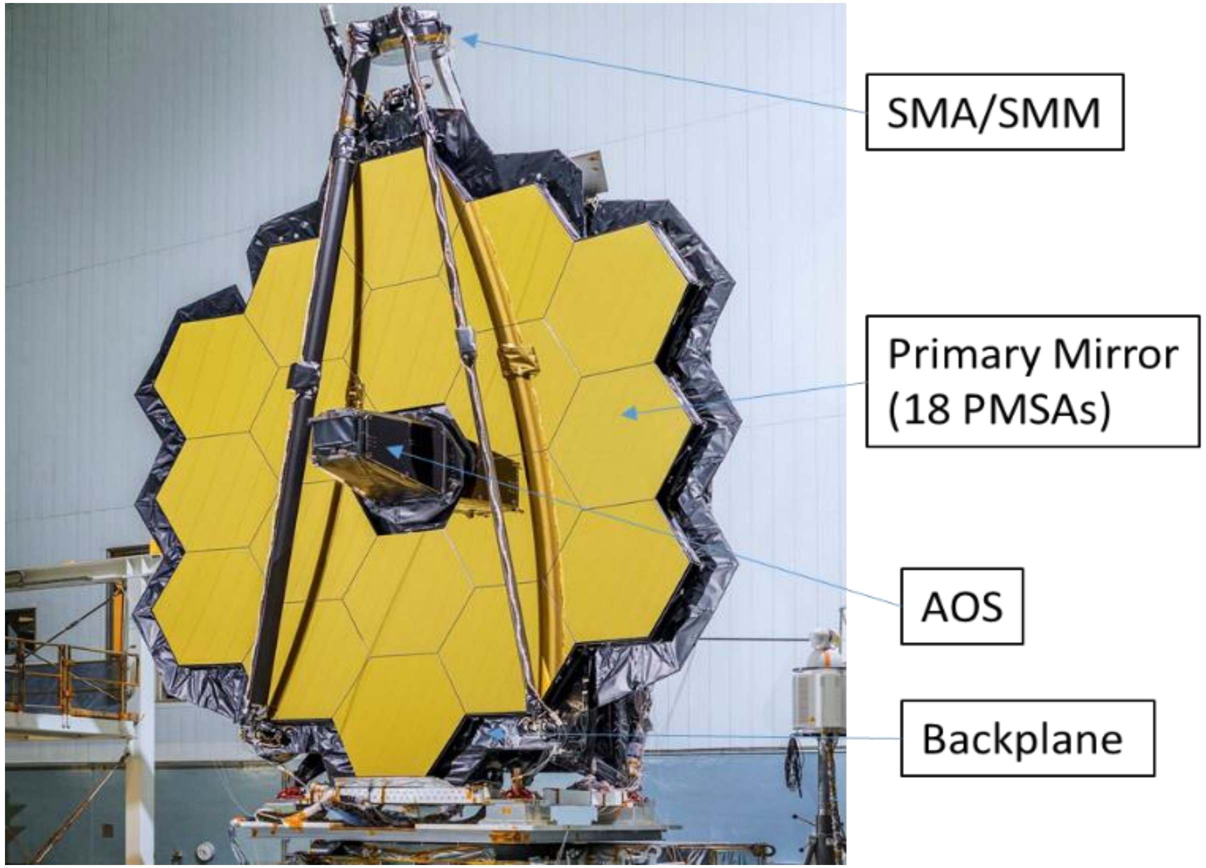
Nikon MV-224:
- High precision tooling balls
- High fidelity non-contact surface scaning

Leica Laser tracker
- Spherically mounted retro-reflectors (SMR)
- Tramming using SMR (not utilized)
- Tracking single and rigid body using SMRs
    - very useful during I&T

METROLOGY TARGET AND SUBSYSTEM DESCRIPTIONS

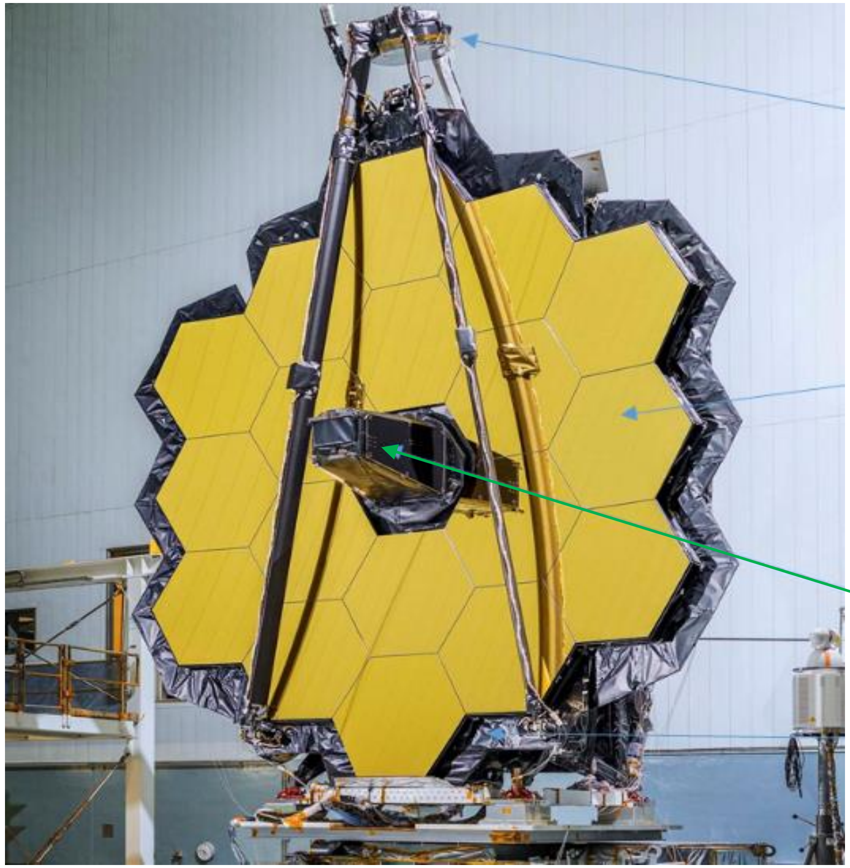
Subsystems

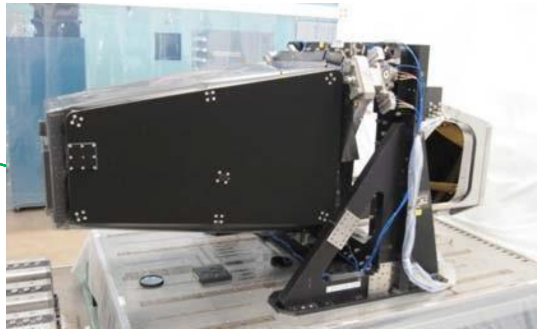
1. Secondary Mirror to Mount (SMA to SMM)
2. ISIM to JWST coordinate system
   - Master references on back of telescope structure
   - Aft Optical system
3. Aft optical system to OTIS backplane
4. Gaps between 18 Primary segmented mirrors



The AOS and Targets

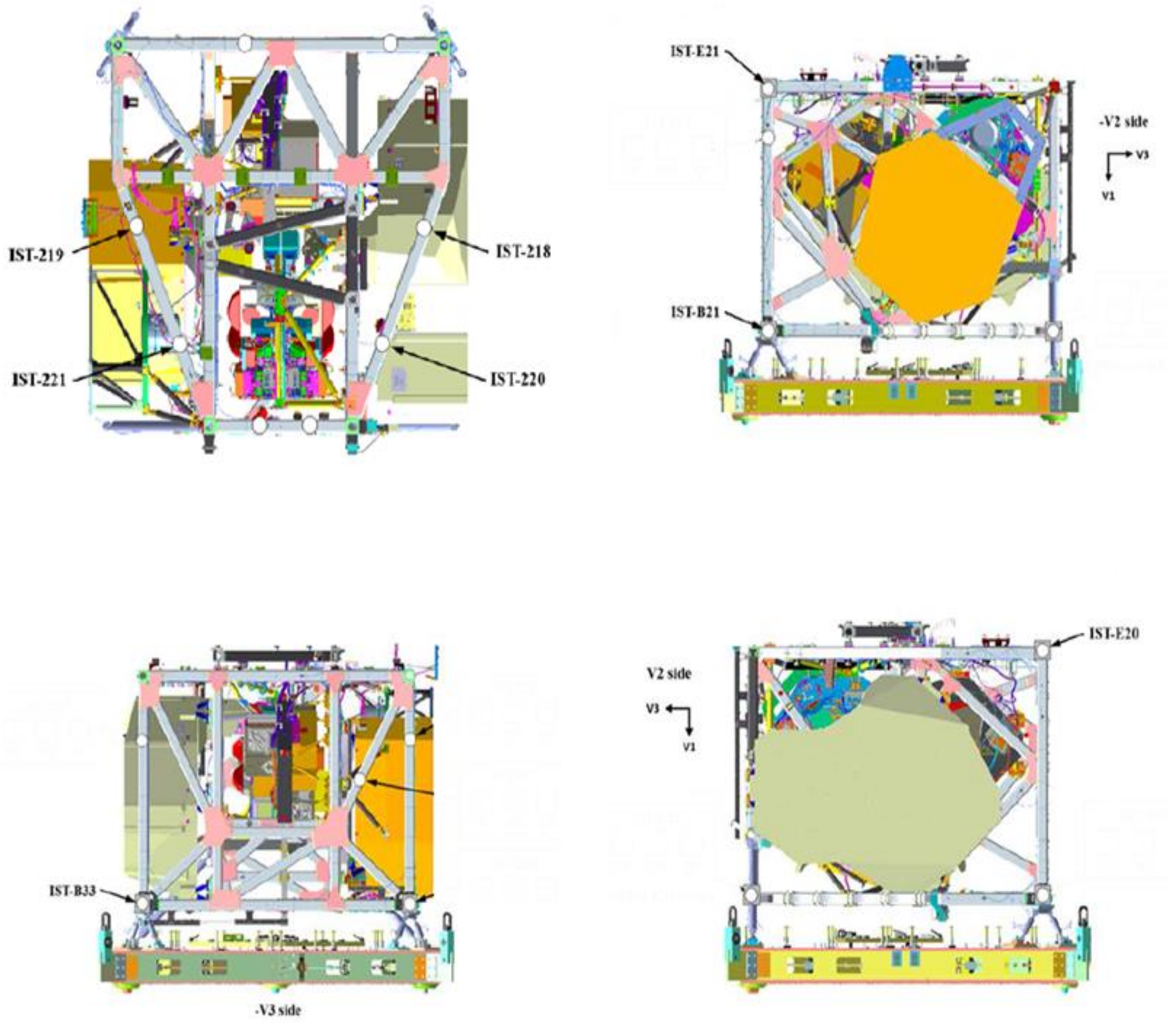
- The AOS holds the OTE’s fine steering mirror (FSM) and tertiary mirror.
- Installed in the center of the telescope backplane, it directs light from the secondary mirror into the instruments on the ISIM.
- The AOS also defines the telescope coordinate system.
- Located on the front bulkhead of the AOS are four, 12.7mm diameter SMR targets (with lanyards for drop safety).
- On the base of AOS are six, 12.7 mm diameter SMR targets (with lanyards for safety). These SMR targets are pointed towards the LTs and away from the LRs during testing.





ISIM Targets

- Integrated to the OTE behind the primary mirror, houses the science instruments.
- Eight integral, monolithic, 12.7mm diameter TB targets with magnetic bases were used on the ISIM.
- Due to blanketing and OTIS structure a subset of original ISIM targets were used.
- Compromise with blanketing team provided necessary lines of sight for validation of pre/post rigid body position checks of the ISIM.

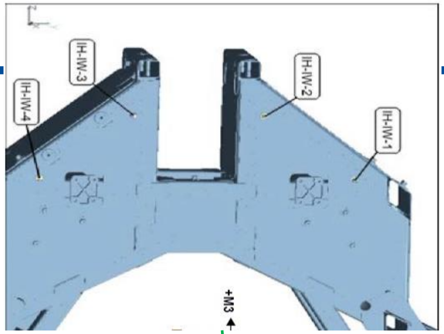


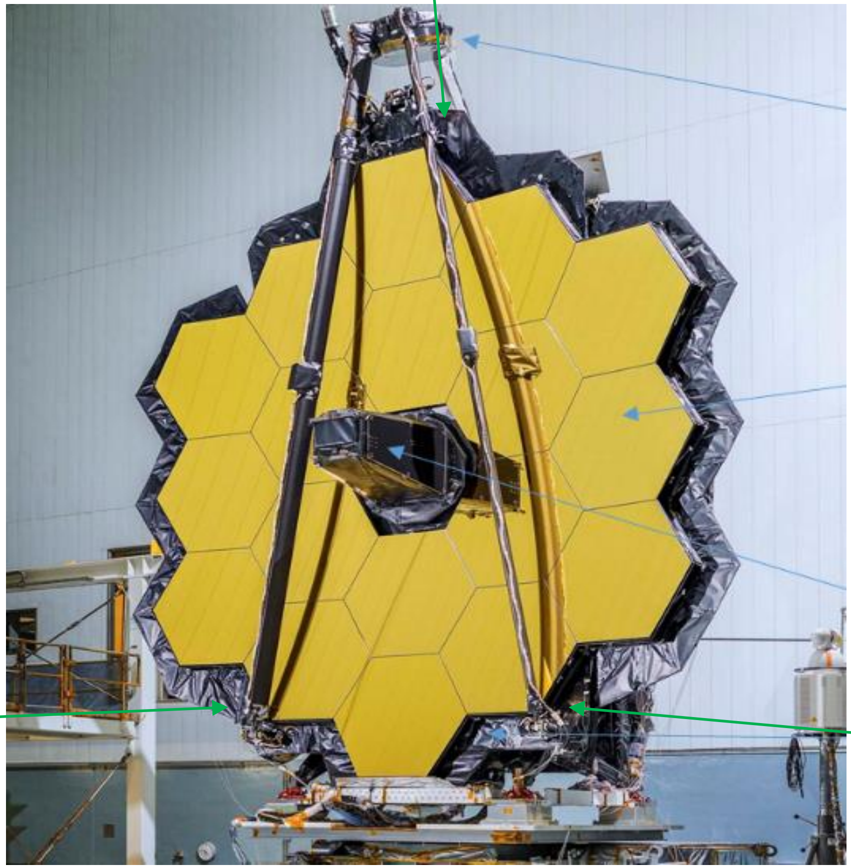
OTIS Backplane Targets

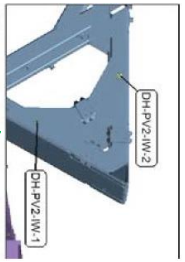
- The backplane targets, Inboard Hinge (IH) and Dual Hinge (DH), are located at the top and bottom of the primary mirror sections on the primary mirror backplane support structure (PMBSS).

- They are 12.7mm diameter SMR targets (with lanyards) and located near the Secondary Mirror Support Structure (SMSS) leg attachment/hinge points on the PMBSS.

- These targets use nests attached magnetically to Invar “washers” on the PMBSS. The SMR targets also attached magnetically to the nests

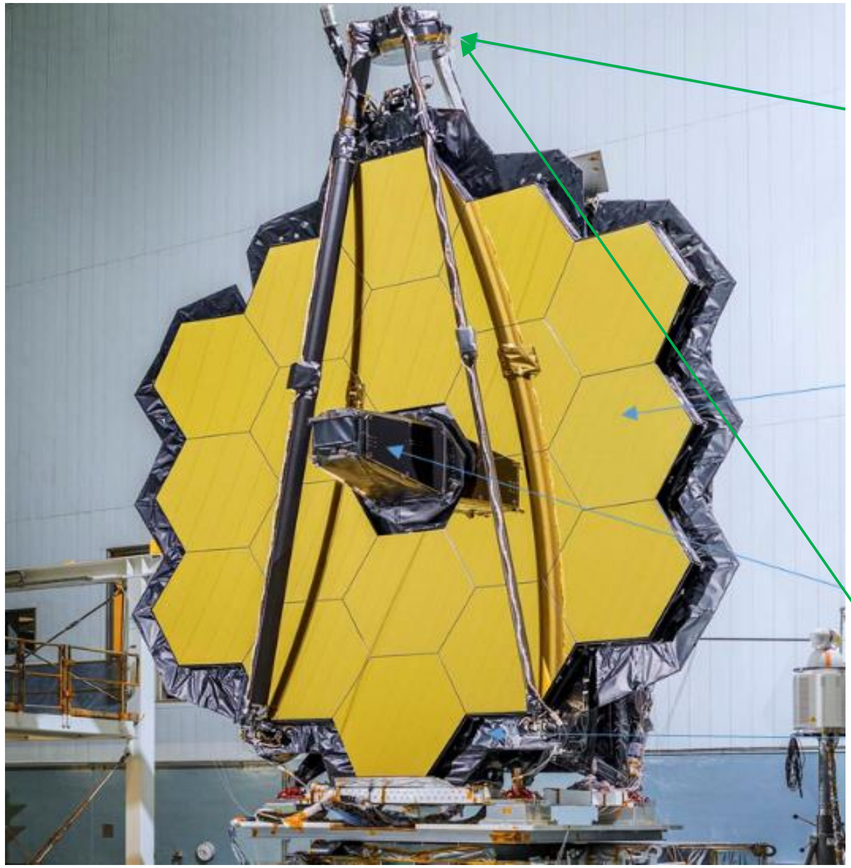




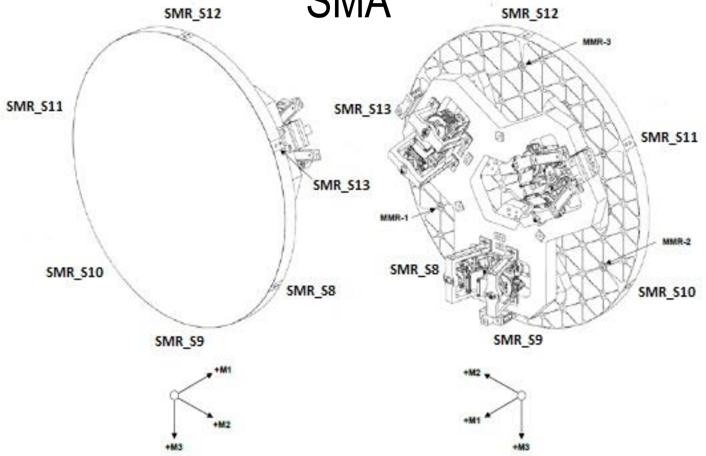


Secondary Mirror Assembly Targets

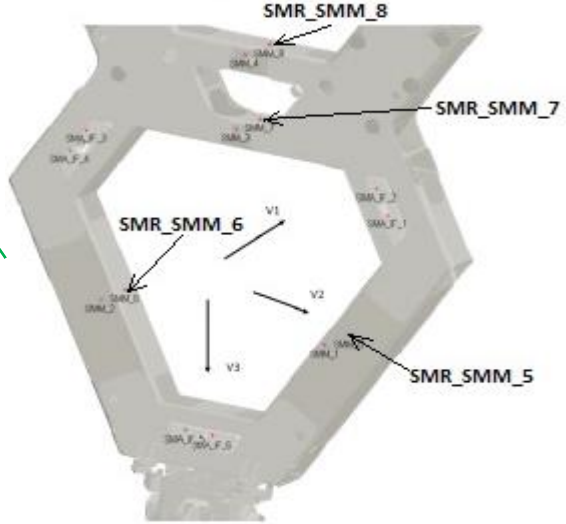
- Five secondary mirror assembly (SMA) target locations
- Four secondary mirror mount (SMM) targets were used during this metrology.
- These are all 12.7mm SMR targets with lanyards and separate nests.
- The targets attached magnetically to the nests.



SMA



SMM



METROLOGY OPERATIONS

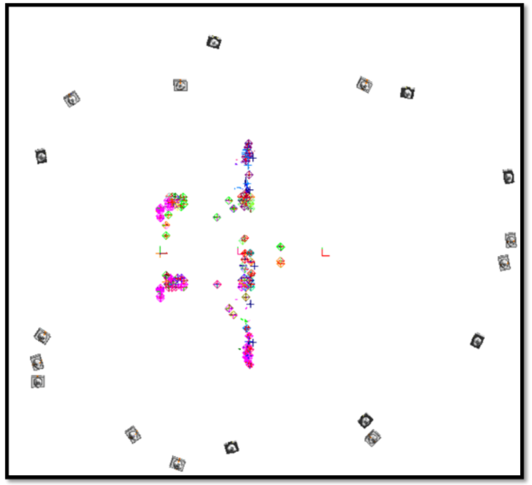
Each subsystem was measured during both pre- and post-environmental metrology operations.

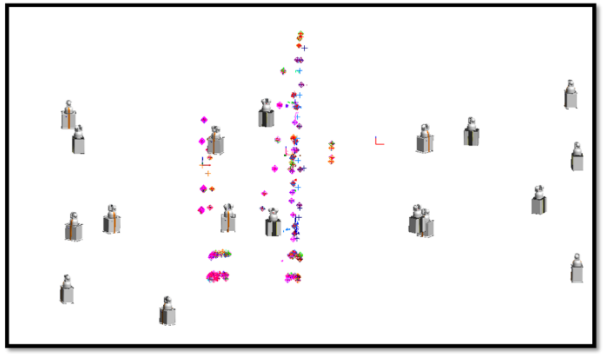
Each group was assigned a local coordinate system parallel to the telescope coordinate system, but with an origin centered on one of the two subsystems being measured.

1. ISIM-to-BSF master reference
2. AOS-to-Backplane
   - The ISIM to BSF master reference and AOS to backplane was measured during one operation.
3. SMA-to-SMM
   - Line of sign limitations moved us to perform the SMA to SMM measurement in a second configuration with the telescope rotated with optical axis down.
4. delta PMSA Gap metrology
   - The PMSA gap measurements were measured in yet another configuration with the OTIS wings stowed

ISIM and AOS Metrology

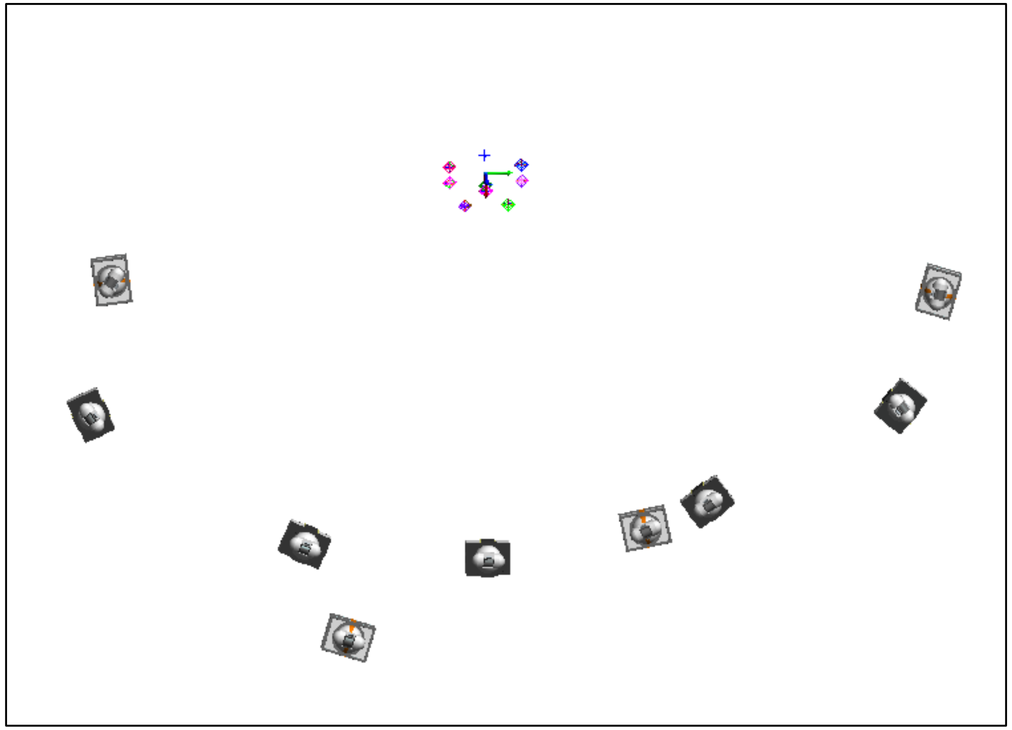
- OTIS mounted onto a handling and integration fixture (HIF) attached at the spacecraft interfaces and supported on a roll-over table.
- The primary mirror “wings” were in the deployed state
- SMA was in the stowed position.
- Instrument stations were established to fully sweep 360 degrees around the OTIS to capture and bundle all targets.
- LRs and LTs were mounted to metrology stands in a height range of 3 m to approximately 9 m in height.

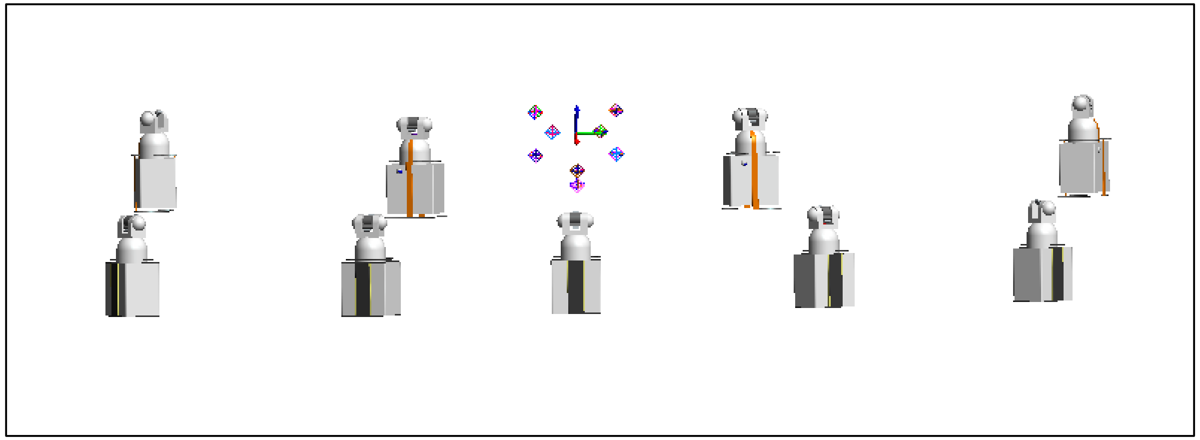




SMA-SMM Metrology

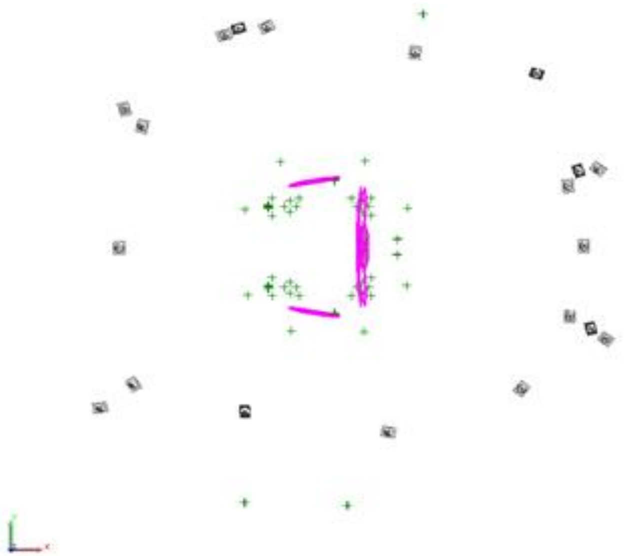
- OTIS was mounted onto the HIF/rotary table and rotated 90 degrees such that the primary mirror surface was approximately parallel with the SSDIF floor (i.e., optical axis down).
- This provided access to install the SMA-SMM targets and suitable lines of sight for multi-station metrology.
- PMSA wings remained in the "deployed" configuration.
- Approximately 10 stations were needed to fully characterize the SMA to SMM configuration pre- and post-environmental testing.

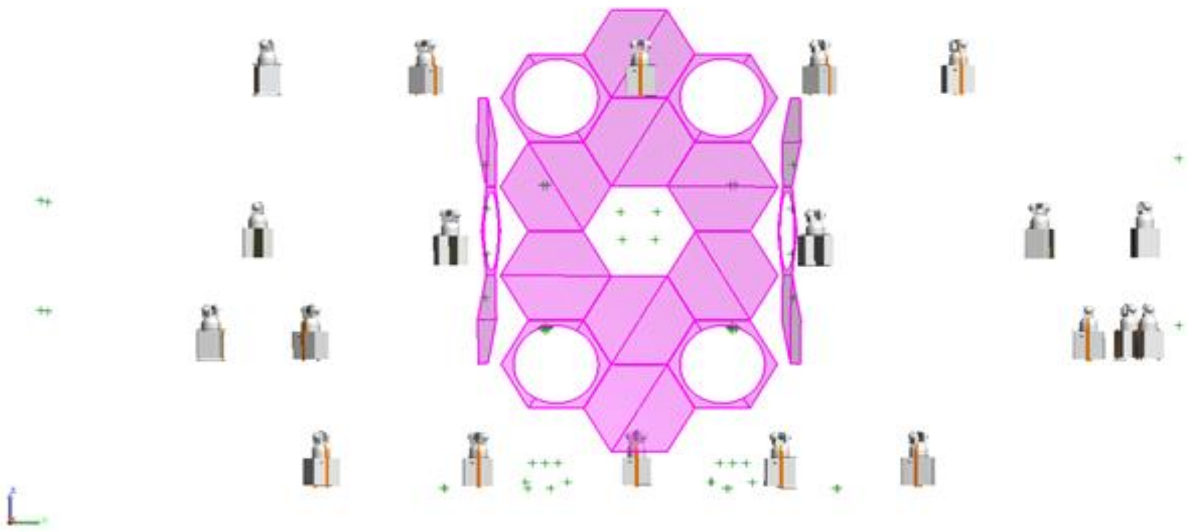




PMSA Stowed Gap Metrology

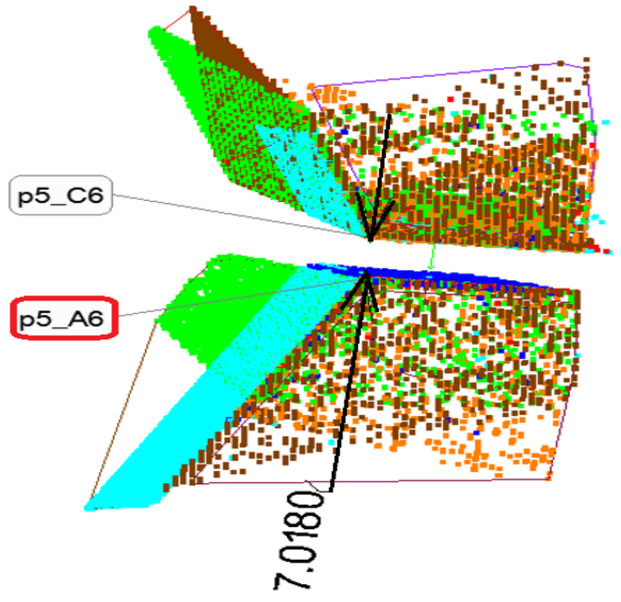
- The PMSA gap is defined as the distance between two adjacent PMSA mirror aperture “vertices,” where a vertex is the tip of each hexagon-shaped aperture.
- OTIS was mounted onto another fixture, the vibe fixture (VF), and supported on a large dolly leveled at three points with high capacity jacks on the floor
- PMSA wings and the SMA were in the “stowed” configuration
- Approximately 20 stations were needed to fully wrap around the entire OTIS bundling targets front to back
- BSF and AOS targets for coordinate system definition
- Additional targets were placed around the base of the telescope on the dolly and VF as well as some PMSA wing targets which provided height to assist an acceptable LR station bundle

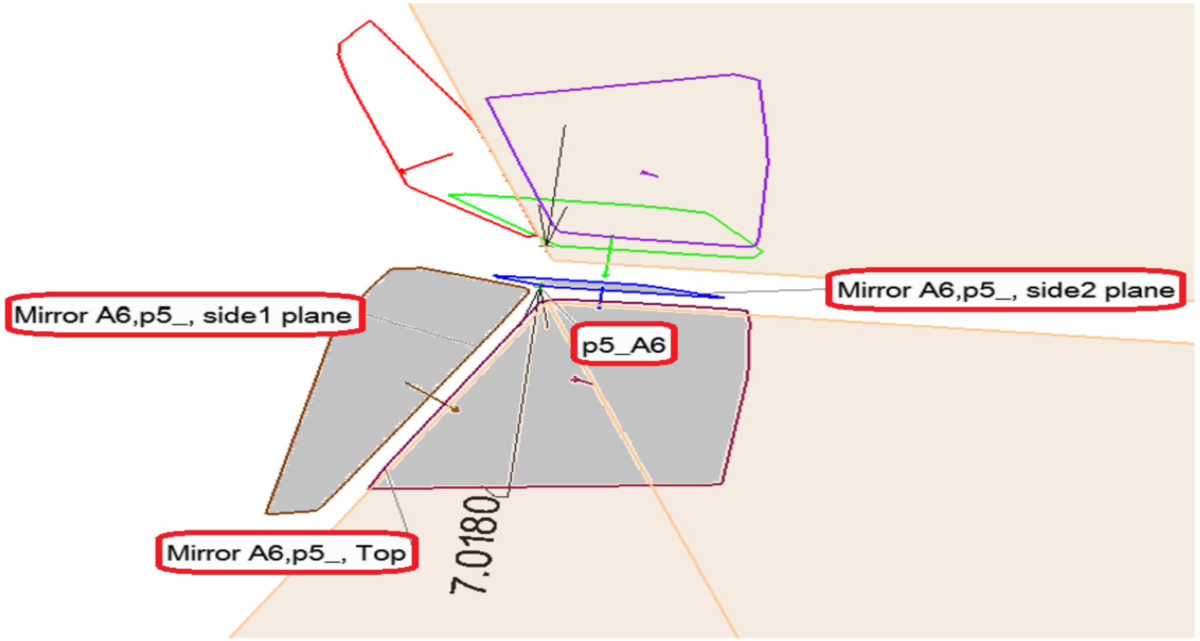




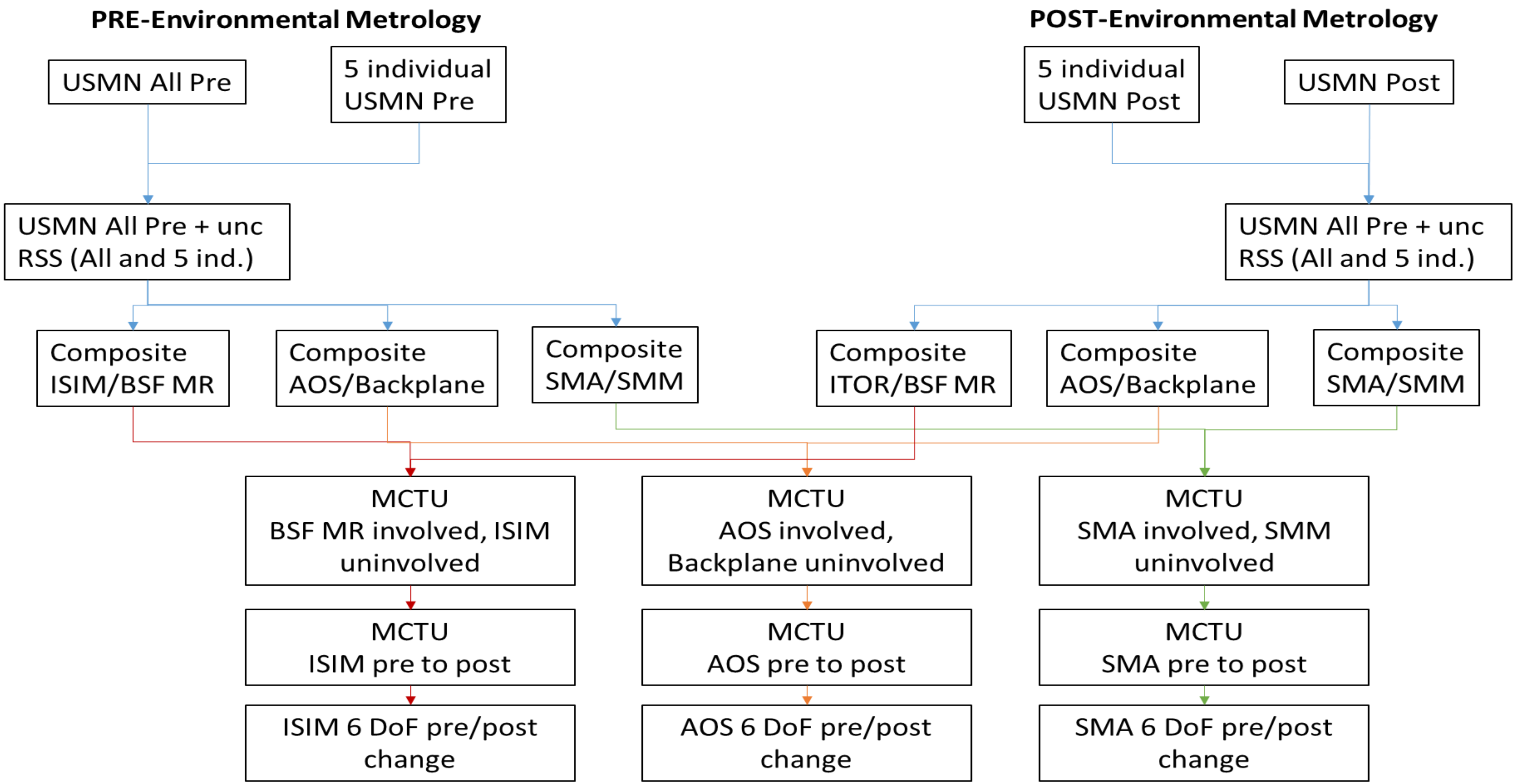
PMSA Stowed Gap Metrology

- PMSAs themselves had no targets on their substrates or elsewhere.
- LR vision scans were analyzed at each PMSA vertex
- Gaps between each mirror were on the order of millimeters,
    - approximate LR station locations were based on a line of sight study using a simulation using metrology software associated with Spatial Analyzer
- Each scan (in totality after station bundle) needed to acquire three planes, two on the sides of the mirror and the mirror's optical surface, to define a mirror vertex point

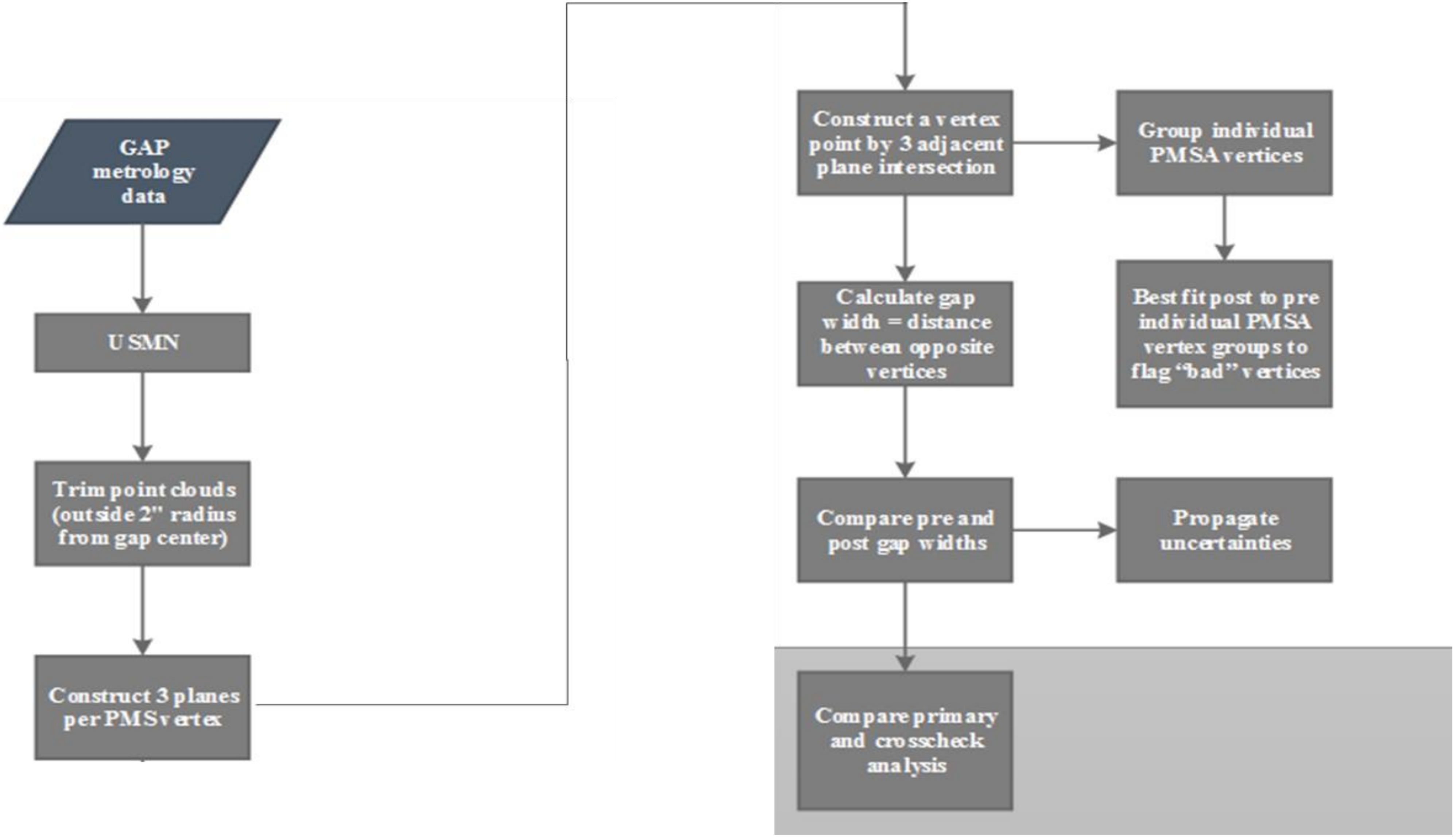




METROLOGY DATA ANALYSIS



GAP Metrology Analysis Flow



METROLOGY PRE VS POST ENVIRONMENTAL TESTING RESULTS

AOS Motion About the Backplane

The AOS-to-Backplane has a small V1 change though the statistical significance is debatable. There are no observable V2/V3 translations or rotations.

MCTU 1

RMS of involved target transformation residuals:

	u1 (mm)	u2 (mm)	u3 (mm)	Mag(mm)
Nominal	0.01740	0.02620	0.01840	0.03640
MC	0.01700	0.02580	0.01860	0.03600

MCTU 2

0.1 mrad = 20 arcsec

	Nominal (mm)	MC Ave (mm)	U95 (mm)	Nu
Translation V1	-0.0232	-0.0232	0.0077	60
Translation V2	-0.0114	-0.0114	0.0110	20
Translation V3	-0.0124	-0.0123	0.0093	27

	Nominal (Arc Sec)	MC Ave (Arc Sec)	U95 (Arc Sec)	Nu
Rotation R1	-4.9000	-4.9000	3.9000	50
Rotation R2	-1.4000	-1.4000	2.7000	18
Rotation R3	-0.6000	-0.7000	2.7000	60

	Nominal	MC Ave	U95	Nu
Scale	1.0	1.0	0.0	0

RMS of involved target transformation residuals:

	u1 (mm)	u2 (mm)	u3 (mm)	Mag(mm)
Nominal	0.00570	0.01160	0.01410	0.01920
MC	0.00580	0.01160	0.01400	0.01910

ISIM motion about BSF

The ISIM-to-BSF MR has a small V1&V3 change though the statistical significance is debatable. There are no observable V2 translations and no observable rotations.

MCTU 1

RMS of involved target transformation residuals:

	u1 (mm)	u2 (mm)	u3 (mm)	Mag(mm)
Nominal	0.00900	0.02050	0.02340	0.03230
MC	0.00900	0.02050	0.02340	0.03230

MCTU 2

	Nominal (mm)	MC Ave (mm)	U95 (mm)	Nu
Translation V1	0.0378	0.0378	0.0126	60
Translation V2	0.0033	0.0034	0.0141	10
Translation V3	0.0460	0.0465	0.0143	59

	Nominal (Arc Sec)	MC Ave (Arc Sec)	U95 (Arc Sec)	Nu
Rotation R1	-2.8000	-2.8000	2.0000	12
Rotation R2	5.8000	5.8000	2.2000	60
Rotation R3	3.6000	3.6000	1.8000	27

	Nominal	MC Ave	U95	Nu
Scale	1.0	1.0	0.0	0

RMS of involved target transformation residuals:

	u1 (mm)	u2 (mm)	u3 (mm)	Mag(mm)
Nominal	0.03260	0.02480	0.00900	0.04190
MC	0.03220	0.02450	0.00890	0.04150

SMA Motion about SMM

There are no observable translations or rotations.

MCTU 1

RMS of involved target transformation residuals:

	u1 (mm)	u2 (mm)	u3 (mm)	Mag(mm)
Nominal	0.00420	0.00860	0.01240	0.01570
MC	0.00380	0.00870	0.01270	0.01590

MCTU 2

	Nominal (mm)	MC Ave (mm)	U95 (mm)	Nu
Translation V1	-0.0022	-0.0023	0.0163	14
Translation V2	0.0081	0.0083	0.0313	18
Translation V3	0.0270	0.0270	0.0246	43

	Nominal (Arc Sec)	MC Ave (Arc Sec)	U95 (Arc Sec)	Nu
Rotation R1	10.9000	11.1000	9.8000	29
Rotation R2	4.2000	4.2000	15.4000	36
Rotation R3	-10.9000	-11.3000	22.6000	12

	Nominal	MC Ave	U95	Nu
Scale	1.0	1.0	0.0	0

RMS of involved target transformation residuals:

	u1 (mm)	u2 (mm)	u3 (mm)	Mag(mm)
Nominal	0.00510	0.01090	0.02720	0.02970
MC	0.00490	0.01060	0.02690	0.02930

Extra Credit: ISIM motion about AOS

Though there seems to be a measureable change, it is well below the optically acceptable motion and may be due to the fact that the AOS has a small base and the ISIM is relatively far from the local coordinate system at the base of the AOS thus a large lever arm. If we move the coordinate system to a more favorable place with a larger base, say the ISIM targets this observed translation changes.

MCTU 1

RMS of involved target transformation residuals:

	u1 (mm)	u2 (mm)	u3 (mm)	Mag(mm)
Nominal	0.00570	0.01160	0.01410	0.01920
MC	0.00570	0.01160	0.01420	0.01920

MCTU 2

	Nominal (mm)	MC Ave (mm)	U95 (mm)	Nu
Translation V1	-0.0274	-0.0274	0.0174	22
Translation V2	0.0881	0.0882	0.0313	60
Translation V3	0.0111	0.0113	0.0276	60

	Nominal (Arc Sec)	MC Ave (Arc Sec)	U95 (Arc Sec)	Nu
Rotation R1	2.2000	2.2000	2.9000	60
Rotation R2	4.3000	4.3000	2.7000	60
Rotation R3	2.2000	2.2000	2.4000	60

	Nominal	MC Ave	U95	Nu
Scale	1.0	1.0	0.0	0

RMS of involved target transformation residuals:

	u1 (mm)	u2 (mm)	u3 (mm)	Mag(mm)
Nominal	0.03260	0.02480	0.00900	0.04190
MC	0.03270	0.02500	0.00890	0.04210

- The average Gap measurements are within 60um average uncertainty with gap uncertainties >60 um attributed to the following.
  - Point cloud offset,
  - Differences in cloud trimming,
  - point selection,
  - plane fitting approach among analysts. “Pre” and “Post”
  - Measured gap absolute delta pre-to-post environmental change results show Ave = 74 μm with a max = 209 μm.

		"Pre" center section gaps		"Post" center section gaps			(Post-Pre)		
Point1	Point2	Average	U	Average	U		Δ	|Δ|	U
wp1_B2	wp1_C2	7.497	0.042	7.450	0.051		-0.047	0.047	0.066
wp2_B2	wp2_C2	7.019	0.046	7.009	0.053		-0.010	0.010	0.070
wp3_B3	wp3_C2	7.113	0.043	7.015	0.052		-0.097	0.097	0.068
wp4_B3	wp4_C2	7.039	0.040	6.917	0.057		-0.122	0.122	0.070
		"Pre" center section gaps		"Post" center section gaps			(Post-Pre)		
Point1	Point2	Average	U	Average	U		Δ	|Δ|	U
wp5_B6	wp5_C5	6.997	0.042	7.052	0.051		0.054	0.054	0.067
wp6_B6	wp6_C5	7.012	0.041	7.032	0.050		0.020	0.020	0.065
wp7_B5	wp7_C5	7.114	0.040	7.126	0.054		0.012	0.012	0.067
wp8_B5	wp8_C5	7.067	0.040	7.040	0.057		-0.027	0.027	0.069
		Ave	0.047	Ave	0.054	Ave	-0.044	0.074	0.072
		Max	0.087	Max	0.065	Max	0.107	0.209	0.104
		min	0.040	min	0.050	min	-0.209	0.000	0.065

Unit = (mm)		"Pre" center section gaps		"Post" center section gaps		(Post-Pre)		
Point1	Point2	Average	U	Average	U	Δ	|Δ|	U
p2_B1	p2_C1	7.030	0.041	6.824	0.052	-0.205	0.205	0.066
p3_A1	p3_B1	6.817	0.058	6.650	0.050	-0.166	0.166	0.077
p3_A1	p3_C6	7.020	0.041	7.084	0.050	0.063	0.063	0.065
p3_B1	p3_C6	7.010	0.046	7.061	0.065	0.050	0.050	0.080
p4_A1	p4_B1	7.083	0.041	6.988	0.051	-0.095	0.095	0.065
p4_A1	p4_C1	7.083	0.042	7.183	0.061	0.100	0.100	0.075
p4_B1	p4_C1	7.670	0.043	7.654	0.056	-0.016	0.016	0.071
p5_A6	p5_C6	7.004	0.044	6.804	0.053	-0.200	0.200	0.069
p6_A1	p6_A6	7.028	0.053	6.972	0.057	-0.056	0.056	0.078
p6_A1	p6_C6	7.050	0.045	6.908	0.052	-0.143	0.143	0.069
p6_A6	p6_C6	7.062	0.041	6.991	0.051	-0.071	0.071	0.066
p7_A1	p7_A2	7.173	0.043	7.278	0.051	0.105	0.105	0.066
p7_A1	p7_C1	6.992	0.044	7.045	0.051	0.053	0.053	0.067
p7_A2	p7_C1	7.125	0.042	7.024	0.058	-0.100	0.100	0.072
p8_A2	p8_C1	7.109	0.061	7.098	0.051	-0.011	0.011	0.080
p9_A1	p9_A6	7.180	0.057	6.971	0.052	-0.209	0.209	0.077
p10_A1	p10_A2	7.151	0.047	7.130	0.050	-0.021	0.021	0.069
p11_A5	p11_A6	6.978	0.042	6.978	0.051	0.000	0.000	0.066
p12_A5	p12_A6	7.075	0.083	6.921	0.050	-0.154	0.154	0.097
p13_A2	p13_A3	6.938	0.043	6.952	0.050	0.014	0.014	0.066
p14_A2	p14_A3	7.028	0.052	7.092	0.053	0.064	0.064	0.074
p15_A4	p15_A5	7.129	0.042	7.026	0.054	-0.103	0.103	0.068
p16_A3	p16_A4	7.109	0.052	7.003	0.054	-0.107	0.107	0.075
p17_A5	p17_C4	7.128	0.040	7.144	0.051	0.016	0.016	0.065
p18_A4	p18_A5	7.228	0.053	7.069	0.052	-0.159	0.159	0.074
p18_A4	p18_C4	7.058	0.087	6.923	0.056	-0.135	0.135	0.104
p18_A5	p18_C4	7.077	0.044	7.043	0.065	-0.035	0.035	0.078

Unit = (mm)		"Pre" center section gaps		"Post" center section gaps			(Post-Pre)		
Point1	Point2	Average	U	Average	U		Δ	|Δ|	U
p19_A3	p19_A4	7.026	0.054	6.898	0.057		-0.128	0.128	0.079
p19_A3	p19_C3	7.079	0.040	7.114	0.057		0.035	0.035	0.069
p19_A4	p19_C3	7.135	0.042	7.139	0.054		0.004	0.004	0.069
p20_A3	p20_C3	6.955	0.043	7.061	0.052		0.107	0.107	0.068
p21_A4	p21_B4	6.830	0.042	6.801	0.051		-0.029	0.029	0.066
p21_A4	p21_C4	7.153	0.041	7.081	0.052		-0.072	0.072	0.067
p21_B4	p21_C4	6.956	0.044	6.924	0.052		-0.032	0.032	0.068
p22_A4	p22_B4	6.967	0.040	6.950	0.054		-0.017	0.017	0.068
p22_A4	p22_C3	7.124	0.043	7.141	0.053		0.017	0.017	0.068
p22_B4	p22_C3	7.068	0.043	7.007	0.059		-0.061	0.061	0.073
p23_B4	p23_C4	6.985	0.064	6.881	0.052		-0.104	0.104	0.082
p24_B4	p24_C3	7.201	0.047	7.158	0.050		-0.044	0.044	0.069
		"Pre" center section gaps		"Post" center section gaps			(Post-Pre)		
Point1	Point2	Average	U	Average	U		Δ	|Δ|	U
wp1_B2	wp1_C2	7.497	0.042	7.450	0.051		-0.047	0.047	0.066
wp2_B2	wp2_C2	7.019	0.046	7.009	0.053		-0.010	0.010	0.070
wp3_B3	wp3_C2	7.113	0.043	7.015	0.052		-0.097	0.097	0.068
wp4_B3	wp4_C2	7.039	0.040	6.917	0.057		-0.122	0.122	0.070
		"Pre" center section gaps		"Post" center section gaps			(Post-Pre)		
Point1	Point2	Average	U	Average	U		Δ	|Δ|	U
wp5_B6	wp5_C5	6.997	0.042	7.052	0.051		0.054	0.054	0.067
wp6_B6	wp6_C5	7.012	0.041	7.032	0.050		0.020	0.020	0.065
wp7_B5	wp7_C5	7.114	0.040	7.126	0.054		0.012	0.012	0.067
wp8_B5	wp8_C5	7.067	0.040	7.040	0.057		-0.027	0.027	0.069
		Ave	0.047	Ave	0.054	Ave	-0.044	0.074	0.072
		Max	0.087	Max	0.065	Max	0.107	0.209	0.104
		min	0.040	min	0.050	min	-0.209	0.000	0.065

SUMMARY

We successfully performed pre and post environmental metrology on the OTIS subsystems in local coordinates. The results of this metrology showed minimal to no relative rigid body motions between subsystems as well as no individual PMSA gap deltas as a result of vibration and acoustic testing. To within uncertainty of the measurements the OTIS passed the testing of survivability of launch for both physical and optical performance.