# JWST Structural Test Monitoring, Instrumentation and Data Acquisition

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## ABSTRACT

The use of an optical measurement system for structural proof testing which measures deflection and strain data can save valuable schedule time. In structural proof testing, traditional deflection measurements use physical contact Linear Variable Differential Transformers (LVDTs) which require labor-intensive mounting fixture fabrication that is set up around the test article to hold the sensors. It also requires an operator to adjust and validate each sensor. The major disadvantages of LVDTs are that each sensor measures in a single axis and requires additional fixtures and sensors to acquire data in orthogonal axes. A measuring technique that uses high resolution video cameras, 3D tracking/Data Acquisition System (DAS) software, and tracking targets for measuring deflection is an innovative solution to acquire 3-dimensional displacement information with reduced setup time. This video measuring deflection technique is "non-contact" where tracking targets are placed at key locations on the structural test article and the cameras are focused at the desired field of view (FOV). These tracking targets allow collection of data in three axes versus a single axis. The output is real-time data recorded in a display of load versus deflection for the structural analyst to view during the mechanical proof testing process. Significant cost savings were realized during a JWST bus structures test where an optical measurement system augmented the use of LVDTs to reduce test schedule time. These deflection measurements characterized the structures deformation and validated the theoretical finite element model.

## KEYWORDS

James Webb Space Telescope (JWST), Linear Variable Differential Transformer (LVDT), Digital Image Correlation (DIC), Data Acquisition System (DAS), Real-Time Display, Photogrammetry

## INTRODUCTION

It was realized that the JWST spacecraft bus structure test was going to require many deflection measurement sensors to characterize the structure's deformation and validate its theoretical finite element model (see Figure 1). A trade study was conducted to evaluate various deflection measuring techniques that could save significant instrumentation setup time during structural proof testing. It was observed that the traditional method of using contact type deflection measuring sensors (e.g., LVDTs) required labor intensive mounting fixture fabrication and setup around the test article to hold each sensor. Each test operation requires the test performer to adjust, calibrate and validate the sensors prior to the start of a test. The major disadvantages are that each measurement is only one direction and requires extra fixturing for additional directions. Traditionally, the applied load was displayed along with the deflection against the same time reference. In the trade study, several displacement measuring methods were evaluated such as single-point industrial lasers and alignment tools such as laser trackers and photogrammetry techniques. The optical measurement system (ARAMIS using advanced photogrammetry method) was selected because it was quick to set up, easy to use and met the program accuracy requirements.

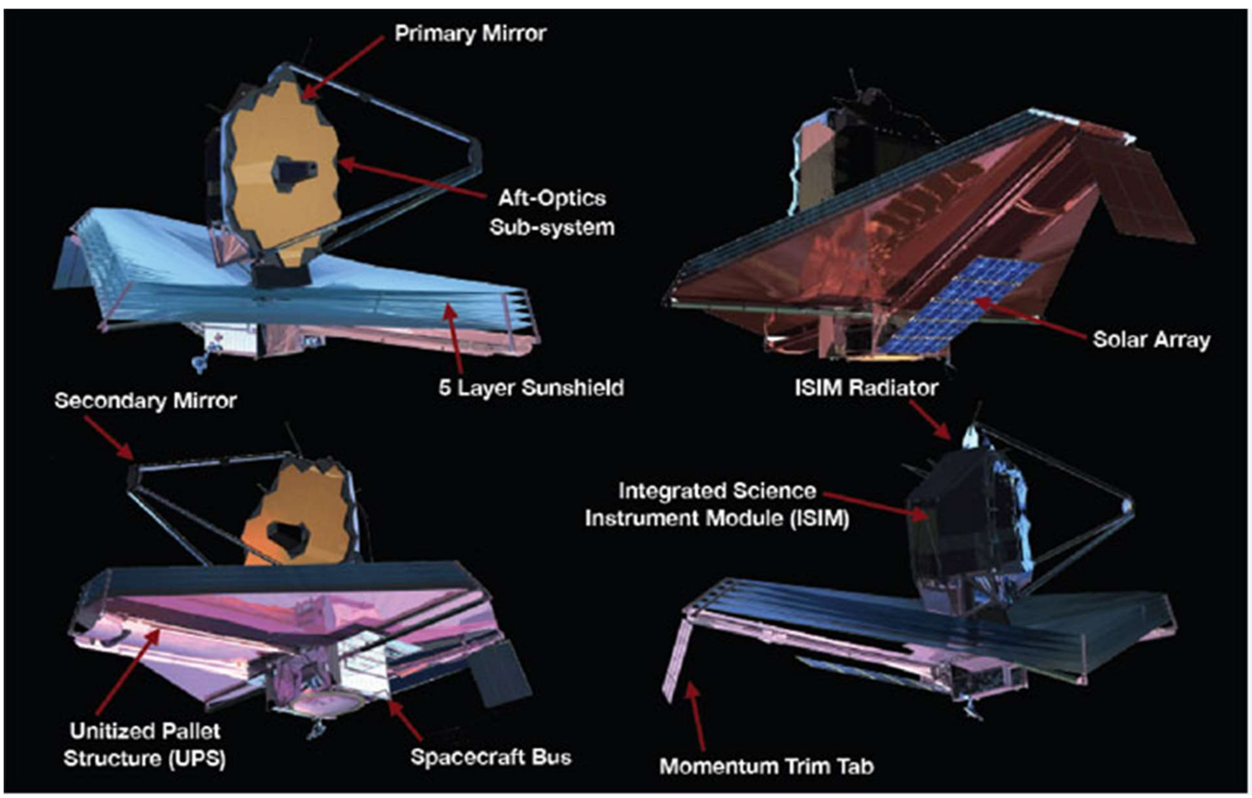


Figure 1. JWST Sub-Systems

# DISCUSSION

## The Trade Study Selection Process

A series of demonstrations evaluating different measurement techniques was performed in the lab. Each method was reviewed against the baseline using the traditional LVDT measurement method. A mock-up structure was used to evaluate the measurement techniques where LVDTs were installed as a comparison. The ability to use the systems in real-time to quickly collect and merge the load and deflection data was reviewed for each method. The strategy was to determine the most efficient way to collect the deflection data and correlate that data with the load data coming in from a different data system.

Hence, a trade study began with various candidates. Industrial lasers were considered and had the required accuracy, but they had the same laborious fixturing requirements as the LVDT. Another selection was the laser tracker. It functions by tracking a laser beam to a spherical mounted retro-reflective mirrored target (e.g., SMR) through a scanning feature where each point takes about one to three seconds to record. This scanning feature even though accurate at collecting the target point data, was not quick enough to record 50-100 points continuously and took some processing time. It also became evident that it would be a little challenging breaking into the laser trackers proprietary data acquisition hardware to capture the 3D deflection data and synchronize it with the load data. In similar fashion, using photogrammetric techniques and electronic flash cameras had its challenges. The low sample rate of the camera was limited but was capable of collecting real-time deflection data. The ability to extract the 3D deflection data and merge it with the load data to one clock reference was not impossible but would take some in-house programming work. Finally, we reviewed the ability of using video cameras which is popularly being used in the materials testing industry for recording strain in material samples. This showed the most promise since the deflection data output was easily obtained from the system. The ability to video record and replay the measurement had a lot of merit and each point was non-contact and three dimensional. This method was also used by NASA for the Shuttle Return-to-Flight and is being used for advanced Orion studies.

## Optical Video Measurement Description

The Optical Video Measurement technology is primarily used in the materials and process and quality inspection industries. There have not been many structural monitoring applications used in aerospace. The technology employs tracking and image techniques for three-dimensional deflection measurements. It is more commonly called Digital Image Correlation (DIC) and also uses photogrammetry techniques. It is not the purpose of this paper to describe the technical details of DIC or Photogrammetry principals. A rudimentary view of its application is discussed.

The solution for the system used a pair of 12 mega-pixel digital video cameras to obtain 3D measurements by recording changes in the gray scale values of the digital pixels (see Figure 2).

The camera sensor pair looking from two different positions at an object, similar to human vision, provides enough information to perceive the object in 3D space. The system combines image correlation (optical method to track sub-pixel changes in images) with photogrammetry principals. The advent of fast processing computers also makes this technology work rapidly. Photogrammetry requires triangulation (determine the location of a point), resection (knowing camera positions) and self-calibration (ability to remove errors) to work properly.


Figure 2: Optical Measurement System (12 mega-pixel camera pair)

The video measurement system requires the operator to calibrate for the FOV and a bundle adjustment is made. The bundle adjustment takes triangulation, resection, and self-calibration and bundles them together to find a solution of the final XYZ points. The matching accuracy of the correlation algorithm software compares two images to get the resulting displacement.

By merging the load data taken from an independent data acquisition system and the video recorded deflection, a plot of the multiple deflections with its associate loads is displayed. The raw data is stored, as well as the video image recording. The novel features of using it for

structural test monitoring is taking an existing video displacement measurement system and merging load data into one data set. The merging of the two data sets is accomplished by the addition of a real-time module for display which consists of data acquisition hardware and custom software provided by the vendor for Northrop Grumman's use. The real-time software has unique features that support the multiple displays, 3D displacements, filtering, math functions and limit alarms needed to support structural test monitoring.
The use of self-adhesive tracking targets can be placed strategically on the test article where the measurement points are desired. It would also work with painted-on tracking targets which would provide permanent 3D measurement points on the structure. This would allow it to be monitored throughout the structures life. The micro view of the tracking target area would amount to about 100 pixels, and the centroid would be found by the tracking software. The tracking software can resolve the centroid of an ellipse down to 1/30 of a pixel. The targets would displace as the test article is loaded. A pair of cameras would capture the measurements during the loading event. The cameras are mounted on a bar held rigid on a tripod such that their relative position and orientation with respect to one another are fixed and known. This non-contact use of targeting was very convenient for a structural analyst to direct the technician staff where to locate the target points, as many as desired, and not restrained by budget. The real measurement data nominally matched the analytical model.

In addition, this non-contact technology allows synchronous measurements of all targeted points in 3D rather than a single point. The technology offers full-field wide-area coverage of the complete test article surface in the FOV. It eliminates the need for the labor intensive instrumentation mounting fixtures which saves substantial schedule time. In addition, the images are digitally recorded for advanced post-processing where all point data and video can be reused for future review. The system is networkable where four camera sensor pairs surrounded the complete JWST bus structure from all four sides during the entire test sequence which allowed real-time understanding of the structural integrity of the large bus structure's hardware.

**Real-Time Software**

In order to meet the standard requirements for displaying quasi-static test data, a new piece of software was needed. In addition, a real-time module for display which consists of data acquisition hardware was used with the vendor supplied software (see Figure 3). The vendor designed the software to merge the analog stream of data coming from the load cell DAS and the digital stream of the tracking XYZ target data from the optical measurement system. The software provided the ability to plot the real-time XYZ data against the load data in a format that is traditionally used at Northrop Grumman's -Space Park facility. The software also allowed computational abilities. With any of the data streams coming into the real-time module and software (analog, digital, etc.), it was able to use their values in mathematical computations to derive critical measurements for the structural analysts to use. A discussion in later sections will explain how we used this function to meet requirements and make unique measurements with the optical measurement system.

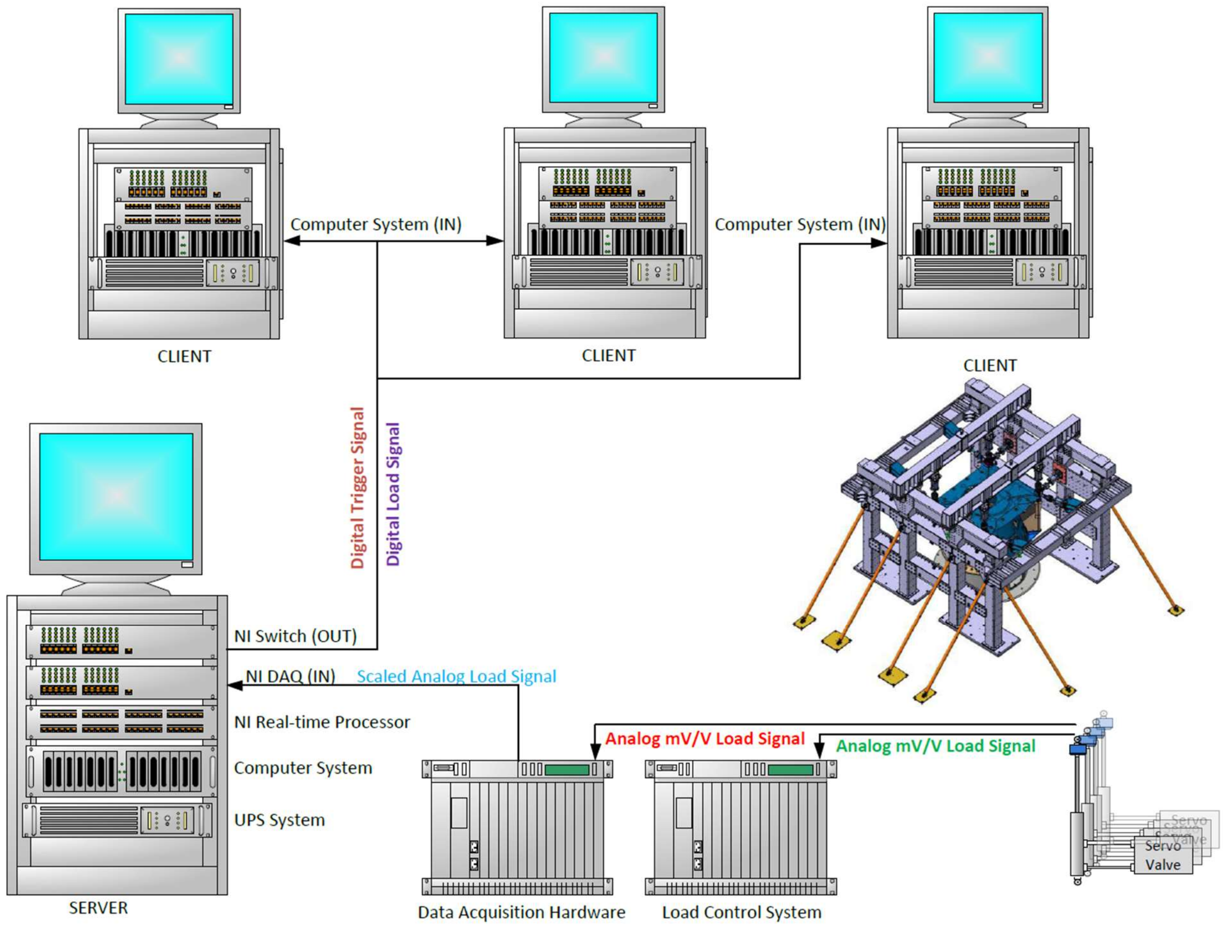


Figure 3: Real-Time Module & Hardware Connections

# APPLICATIONS

## Evaluating and Observations While Using the Optical Measurement System

A calibrated digital micrometer and targets at the measurement points were used to validate the method and to gain confidence with the technology. By adjusting the micrometer across an expected working displacement range, providing a known displacement, it validated the video measurement process. In addition, during some non-flight structure mock up testing, several

LVDTs and redundant targets were used until the video method was refined and confidence was achieved. It allowed for specific setup observations to be made.

To obtain the best accuracy, the cameras needed to be approximately normal to the test article. The sample rate of the cameras should be approximately 30 times greater than the frequency of the test movement on the article to avoid data aliasing and allow for temporal averaging. By placing the test article at the center of the calibrated depth ensures that the targets are in focus and to minimize the FOV provides the best accuracy. It is best practice to keep the camera system mechanically isolated from the test article and the reaction structure. It was also best to avoid load trains, tethers, rods, and cables from crossing in between the camera system and blocking the view of the tracking targets. To gain even more experience and confidence in using the video system, early measurements of some of the JWST Spacecraft bus panels were performed. They consisted of manufacturing repairs, proof tests, and panel deflection tests.

**JWST +J3 Panel Insert Repair Test**

Usage of the optical measurement system was required on the +J3 panel (approximately 8'x8' composite panel) to monitor critical deflection measurements. This test was a type of tensile test performed on panel mounted inserts in multiple areas of the +J3 panel to validate the strength of a manufacturing repair in certain areas. The panel was configured with a LVDT and a number of tracking targets positioned closely to each of the inserts to be proof loaded. Each insert was required to be pull-tested to 170 pounds and each insert was tested individually. In order to measure vertical deflections in close proximity to the insert repairs, placing several tracking targets in a small area was a much more feasible approach than using multiple LVDTs. The ability to place 60 tracking targets in close proximity made it extremely advantageous to monitor the deflection vector fields as opposed to attempting to interpolate from a few LVDTs. This allowed the analyst to visualize 3D deflections of the panel while it was being loaded in tension. The measurements from the optical system matched the LVDTs exactly (see Table 1).

| Deflection (m-Inch) | | |
|---|---|---|
| Test | LVDT | Optical |
| 1 | 16 | 16 |
| 2 | 16 | 16 |
| 3 | 7.4 | 7.4 |
| 4 | 24 | 24 |

Table 1: LVDT verses Optical Measurements

## JWST Radiator Latch Fitting Bond Proof

The JWST radiator latch fittings are bonded into the +J2 panel (approximately 4'x8' composite panel). Proof testing was performed by applying offset weights to introduce proof level moments. The weight was applied using sealed bags with lead shot and a load cell to record the load applied to each fitting location. By using the optical measurement system (one pair of cameras), we were able to record the in-plane and out-of-plane deflection of the +J2 panel during the test in real-time. The load versus deflection was displayed during the entire duration of the test. Table 2 shows the comparison of the LVDT and optical data against the predicted.

| Test | Location | Predicted | LVDT | Optical |
|---|---|---|---|---|
| 1 | 9 - 12 | 11 - 16 | 13-18 | 12 - 17 |
| 2 | 5 - 8 | 5 - 10 | 4 - 10 | 6 - 9 |
| 3 | 1 - 4 | 7 - 20 | 13 - 26 | 14 - 22 |
| | | | | |

Table 2: Radiator Latch Fitting, LVDT versus Optical Data, mils

## Bus Lift Measurement

The first spacecraft bus primary structure testing performed with the optical measurement system was during the initial lift of the bus structure off of the manufacturing platform on which it was built. To confirm analysts' predictions that the bus was structurally sound for further crane lift operations, the optical measurement system was used in a unique fashion. Two tracking targets were placed on each of the upper outer edges of the shear wall panels, near the cruciform fittings of the structure. Two additional tracking targets were placed on each of the lower outer edges of the shear wall panel, near the location where the launch vehicle interface ring is mounted to the structure. The bus was offloaded using lift slings and a crane system until it was lifted off the manufacturing stand such that a visual gap was observed or the target data showed significant lift (the bus was touching support stand at three locations in case the bus began to fall). After the bus was in the lift position described above, the relative distance between the top and bottom shear wall tracking targets was recorded and monitored by analysts to verify that excessive separation of the structure was not occurring. The relative distance between the top and bottom of the structure was recorded by the optical measurement system for duration of five minutes. At the end of the five minute hold period, the system showed that no excessive separation of the tracking targets had occurred in any axis and therefore proving that it was safe to lift the structure from the manufacturing stand to the transport vehicle (see Figures 4, 5, and 6).

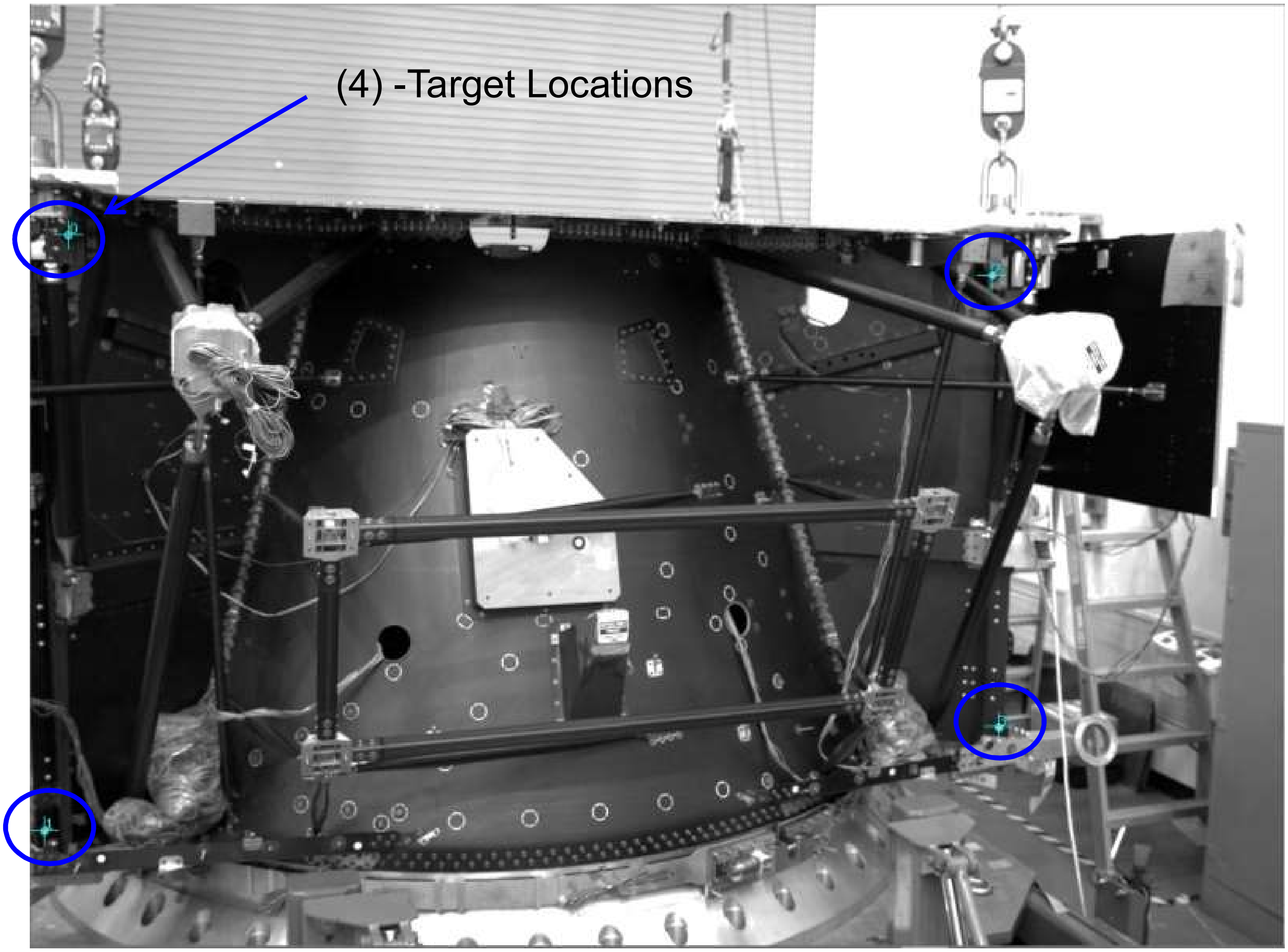


Figure 4: Bus Lift Target Locations

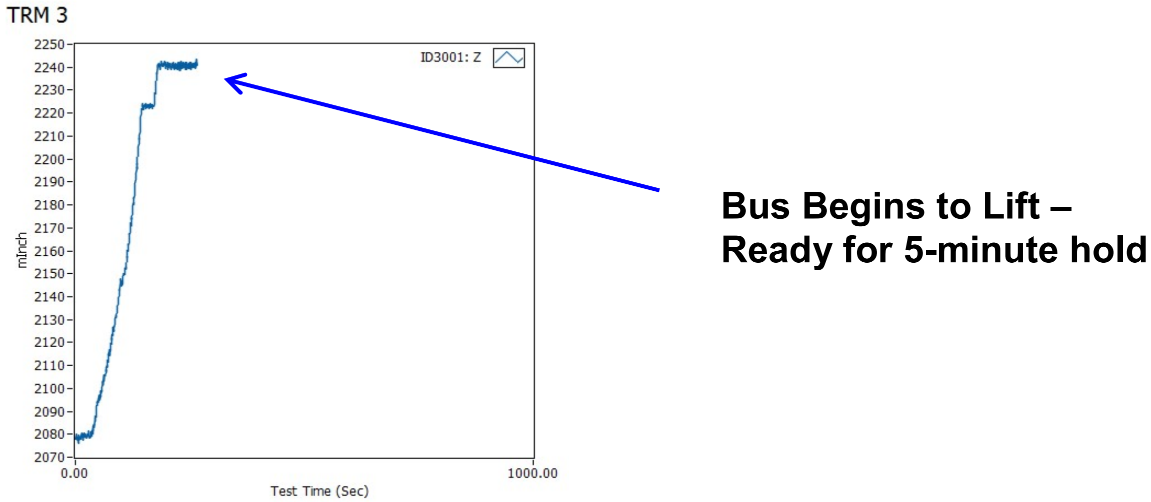


Figure 5: Bus Lift Travel versus Time with Hold

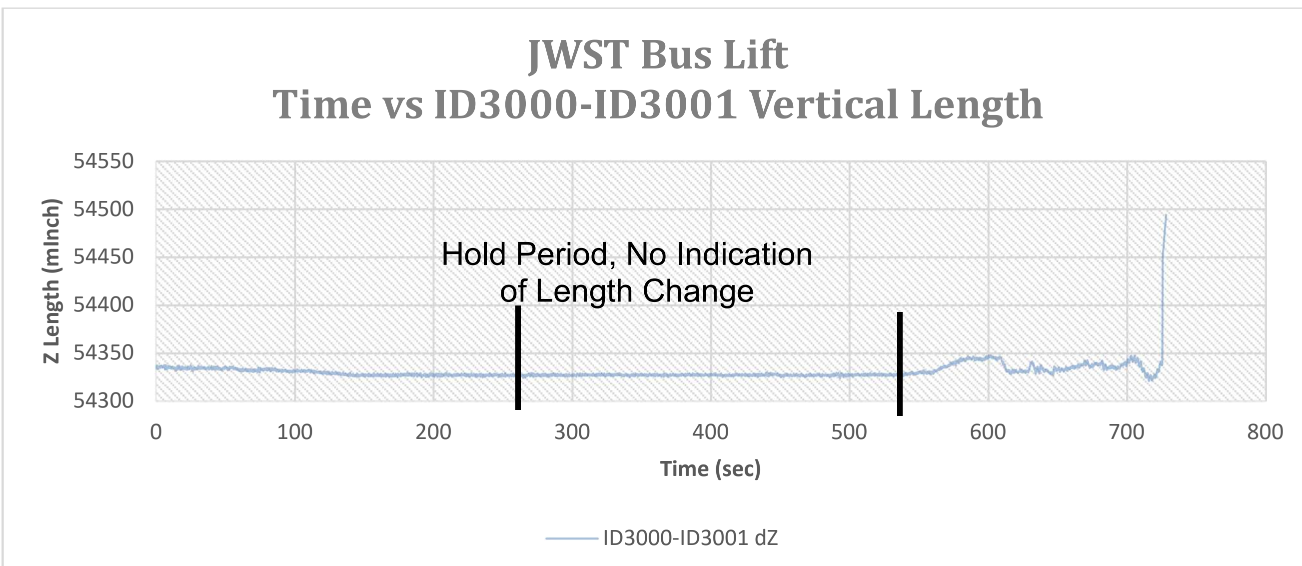


Figure 6: Bus Lift Hold Period

**JWST Bus Structure Proof Test Measurements**

A large-scale proof test of the complete JWST spacecraft bus structure was performed while being monitored by a network of optical measurement systems for highly critical deflection data. At each upper corner of the bus' +J3 panel structure, special fittings were installed to allow computer controlled hydraulic actuators to apply compressive and tensile loads in the XYZ axes. Altogether, twelve load actuators could be applied, either individually or simultaneously, as required by the test specifications in order to meet the load case requirement per the structural analyst (see Figures 7, 8 and 9).

A network of optical measurement systems surrounded the bus structure and provided deflection data to structural analyst for both the bus structure and the load actuators. Due to the high sensitivity of the angle at which the load actuators applied the load into the bus structure, the optical measurement system was used to monitor and calculate angle change down to a very small value during all loading conditions of the JWST bus structure proof test. In order to calculate this value, the hardware vendor supplied software and real-time module was used. With the software program, it gave the ability to take any individual component of the tracking targets XYZ location in space and use it to perform mathematical calculations. Using the values of the targets attached to the load actuators allowed the structural analyst to calculate the angle at which the load actuators should be and also how much they had changed during each of the tests. These critical measurements allowed the analysts to maintain the safety of the hardware under very high proof load conditions.


Figure 7: Bus Structural Test with Monitor Displays

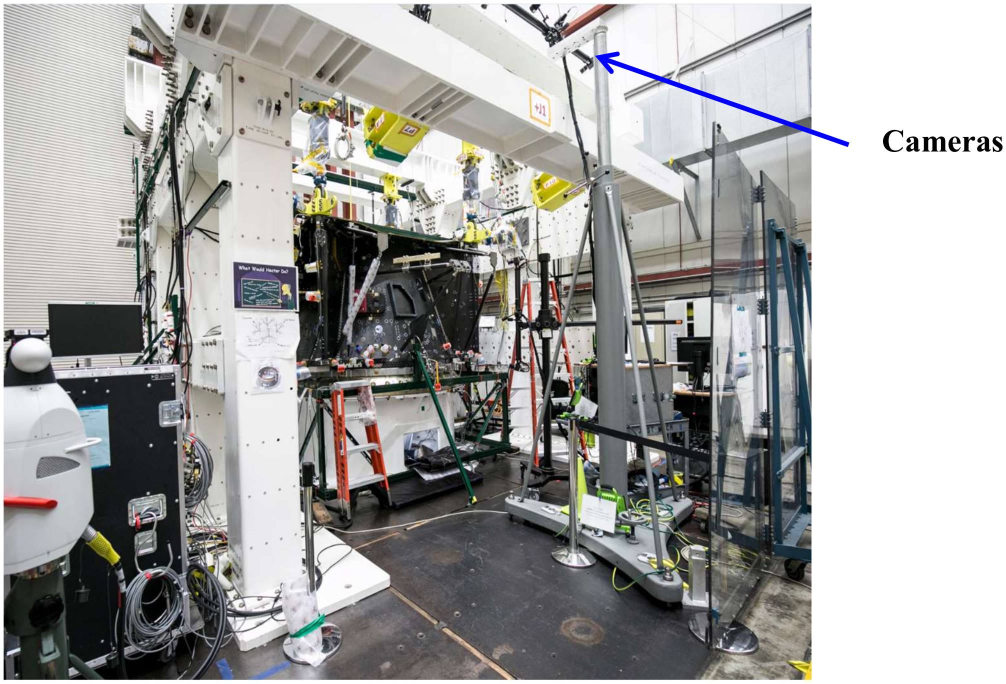


Figure 8: Bus Structural Test Setup

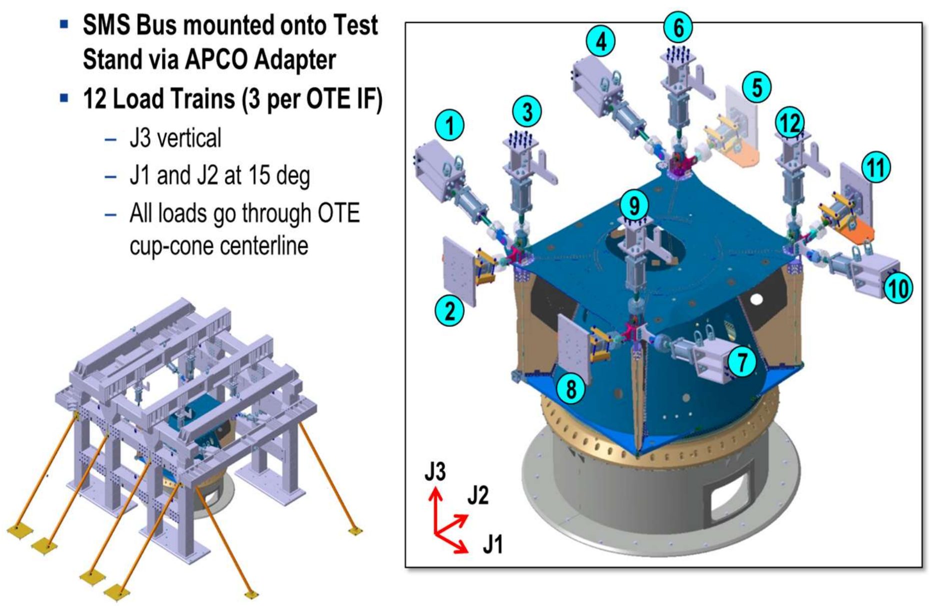


Figure 9: Structural Mechanical Subsystem (SMS) Bus Test Load Trains

# CONCLUSION

The optical measurement system displacement data was found to be equivalent to the LVDT data for the 10-foot FOV. For the primary use on the bus testing, a 25% schedule savings was realized using this technology. The additional off-bus panel and other associated tests added additional substantial cost savings. The targets being reusable throughout the test process and of minimal cost just added to the cost savings for the JWST project. The elimination of the majority of the LVDTs was considered cost avoidance for the setup time and avoided any risk to having LVDT fixturing around the bus. The well planned target strategy revealed deflections not anticipated. The merging of load versus deflection data along with display saved the analyst time and allowed more time for review. Since optical measurement is non-contact and relies on an unobstructed view, it works in certain situations where LVDTs do not work; for example, where LVDT fixturing is challenging or over extension may occur. The attractiveness of the non-contact capability allows for no applied force effect on the measurement area. The ability to replay a recording is an excellent visual tool for showing deflection envelops or vector fields across an area. For example, the system provides 3D coordinates and 3D deformation with in-plane and out-of-plane deflection vectors. With the 12 mega-pixel cameras, accuracies were between a 0.5 and 1.5 mils depending on the FOV. Overall, the system provided a very rapid measurements process that has full-field, real-time results, and a wide area coverage. The more the system was used, the more lessons learned steps became realized to produce good measurements.

### Lessons Learned to Make a Good Optical Measurement

1. A successful calibration prior to starting a measurement series can be used for several measurement tasks.
2. A pre-test of the software initialization is recommended prior to performing any measurement and will require some warm up (~10 minutes).
3. Video measurements are limited by the FOV. If you have an unobstructed view, then you can measure it. Avoid having anyone or anything pass in front of the cameras during recording.
4. Measurements during real-time operations can see up to +/- 1.5 mil of noise band due the environment with a 10-foot FOV.
5. Good lighting is an important aspect in assuring the capture of good data.
6. The ability to video record allows post process view of hardware displacement which is not available for LVDTs and includes the ability to replay the entire test.
7. Strategically placed targets are the key in making good measurements and obtaining deformation information about your structure. For precise target locations, CAD can be imported.
8. Vector field view is very handy to visualize 3D displacements and good for model tuning. It confirms that you are measuring what you think you are measuring versus single point sensors.

# ACKNOWLEDGEMENTS

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# REFERENCES

Tyson, J., Schmidt, T., Galanulis, K. (2002). “Advanced Photogrammetry for Robust Deformation and Strain Measurement,” *SEM 2002 Annual Conference*, Milwaukee, WI

# BIOGRAPHIES

**Andy Pokk**

Andy has a Bachelor of Science degree in mechanical engineering from California State University Northridge.  Currently, he is the assistant department manager for the Environmental, Structures Labs, and Operations at Northrop Grumman Corporation, Redondo Beach, CA.  For over 10 years, he was the Measurements Engineering department manager at Northrop Grumman Corporation.  From 1993 to 1994, he was an IEST chapter president in Northridge, CA.  He also worked for over 10 years at Barry Controls as the Test Engineering Manager in Burbank, CA.  He acquired one patent in 1993 as a co-inventor of a shock absorbing linkage rod for a commercial aircraft application.

**Chris Gurden**

Chris graduated from California State University, Long Beach with a Bachelor of Science degree in electrical engineering in 2008. After graduating from college, he was hired by Raytheon as a systems engineer on a battlefield radar program for five years. In 2014, he was hired by Northrop Grumman to join the Measurements Engineering department. Since then he has worked on many different air and space programs, providing support for static, dynamic, mechanical structural tests, operational tests, and functional tests as well as transportation monitoring of flight hardware. His role as a measurements engineer has lately been introducing the optical measurement system to the corporation. It has broadened his understanding of the possible applications of the technology and where the technology is best suited as a new measurements tool for the department.