Using 3D-DIC on Space Flight Hardware

Nathaniel W. Gardner[1]
Sotiris Kellas[2], David S. Dawicke[1], Michael P. McNeill[3]
William M. Johnston[3]

[1]Analytical Services & Materials, Inc.
[2]Structural Materials and Concepts Branch, NASA Langley Research Center
[3]Science and Technology Corporation

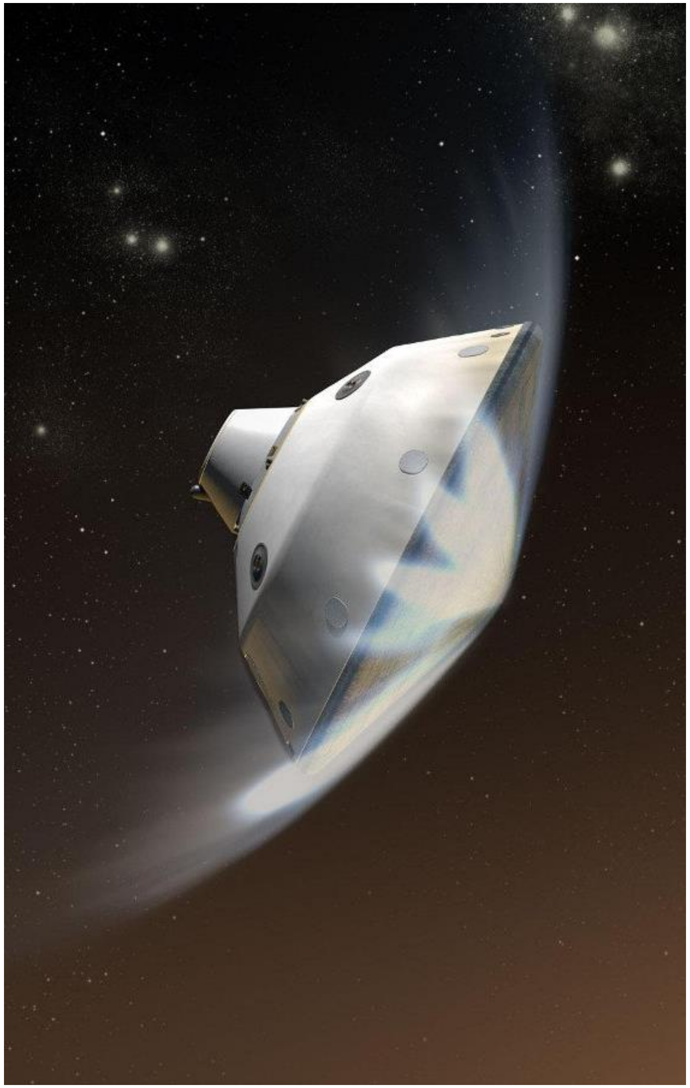
2019 International Digital Image Correlation Society (iDICs)
Conference and Workshop
Portland, OR, October 14 - 17, 2019

Outline

- Background
- Test Objectives
- Proof of Concept Testing
- Mock-up Build and Testing
- Experimental set-up
- DIC Objectives
- VIC-3D^{TM} processing and Data Assembly
- Summary and Conclusions
- Acknowledgements

Background

- When the Mars 2020 spacecraft reaches the Red Planet, it will face the most dangerous phase of the mission – hitting the atmosphere at interplanetary speeds.
- Sealed inside its protective aeroshell, the probe will be traveling at 12,000 mph as it plunges into the thin Martian atmosphere, piling up the air in front of it in a shockwave that will slow it down to supersonic speeds.
- The aeroshell's phenolic plastic structure protects the vehicle by carrying off the heat (~ 3,800° F) as the shield burns away layer by layer.



www.space.com

Problem / Solution

- This mission uses a similar architecture to the previous science mission to Mars, the Mars Science Laboratory (MSL).
  - Initial plan was that Mars 2020 would use the spare MSL heat shield (HS) structure (HS#1).
  - During structural proof testing, HS#1 developed an unexpected fracture near its outer edge that spanned the entire circumference (only visible during post-test inspection).
- In order to maintain launch schedule, HS#3 was redesigned, built and tested (acceptance) in April, 2019.
  - To guard against failure, and observe the HS response in real-time, full-field photogrammetry was implemented and monitored over the entire outer surface.
  - Any failure in proof test would likely cause a 2-year delay in launch and a loss of about 2 billion dollars

Problem / Solution

- **The test article was the actual flight hardware that would have the thermal protection system bonded to the surface post-test and flown to Mars.**
  - **This required that HS#3 be returned in pristine condition and a very limited list of materials was allowed to contact the surface.**

- **Thus, typical methods of applying a contrasting speckle pattern could not be used.**
  - **A removable vinyl-vehicle wrap with a printed speckle pattern was evaluated and approved for use in this test.**
    - **3M Wrap Film Series 1080**

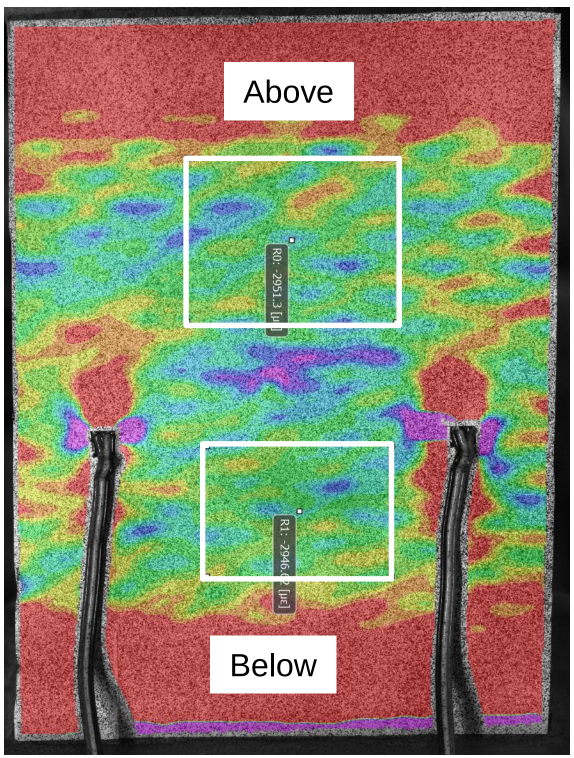
Test Objectives

- **To verify the aeroshell structure can survive entry pressure load, descent and landing (EDL) loads**
  - **Launch G Loading: 5-6 G's**
  - **Entry Pressure: 11-12 G's**

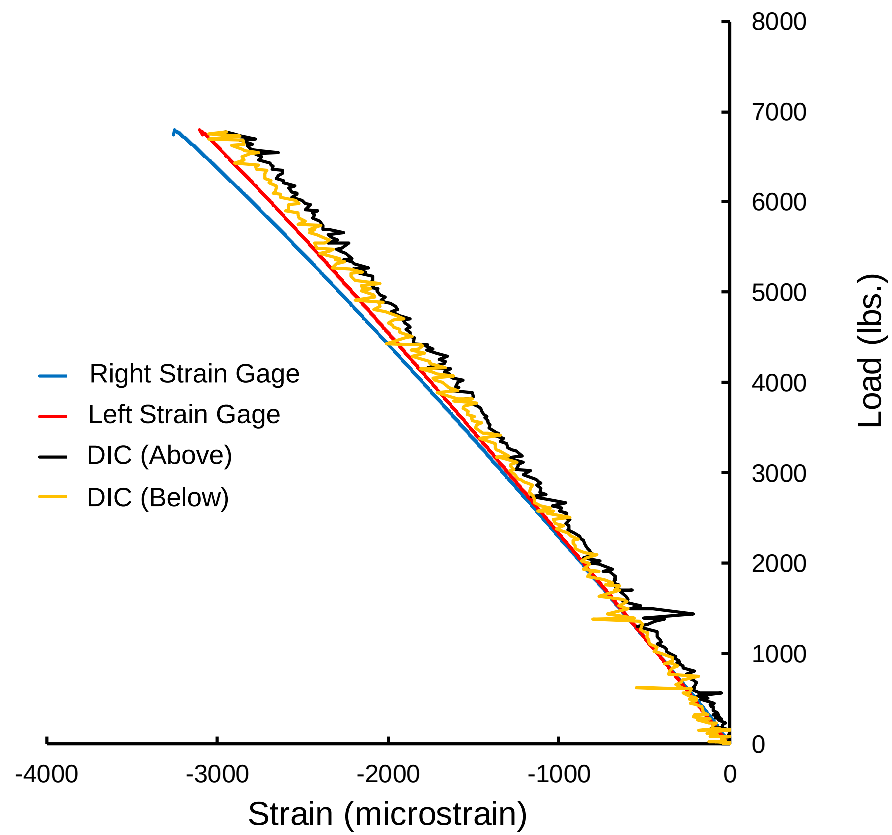
- **Obtain test data to develop and validate high-fidelity structural simulations.**

Proof of Concept Testing - Wrap

- **Validate that the vinyl-vehicle wrap would sufficiently adhere to the surface of the aeroshell (using surrogate panel) by comparing DIC data to strain gage data.**

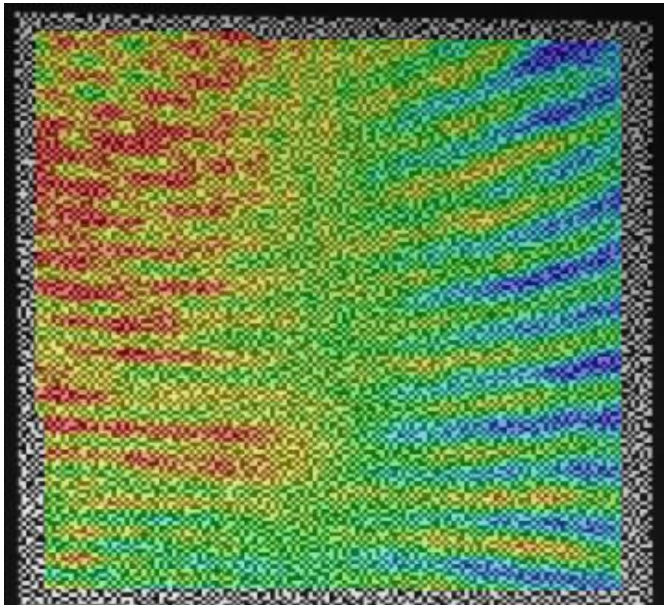


Surrogate panel with vehicle wrap applied to surface

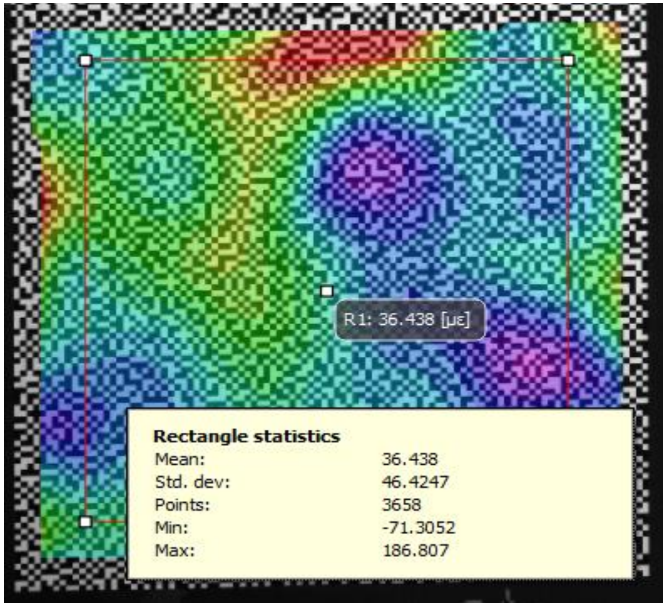


Proof of Concept Testing - Pattern

- **Optimized Speckle Pattern**
  - Four different speckle sizes (0.06in, 0.08in, 0.10in, 0.12in) were selected based upon the field-of-view (~173in x 118in) and the resolution of the cameras (6576 x 4384)
  - Optimized speckle pattern (Bomarito, Hochhalter, Ruggles, and Cannon, "Increasing Accuracy and Precision of Digital Image Correlation Through Pattern Optimization," Optics and Lasers in Engineering, Vol. 91, PP 73-85, April 2017)



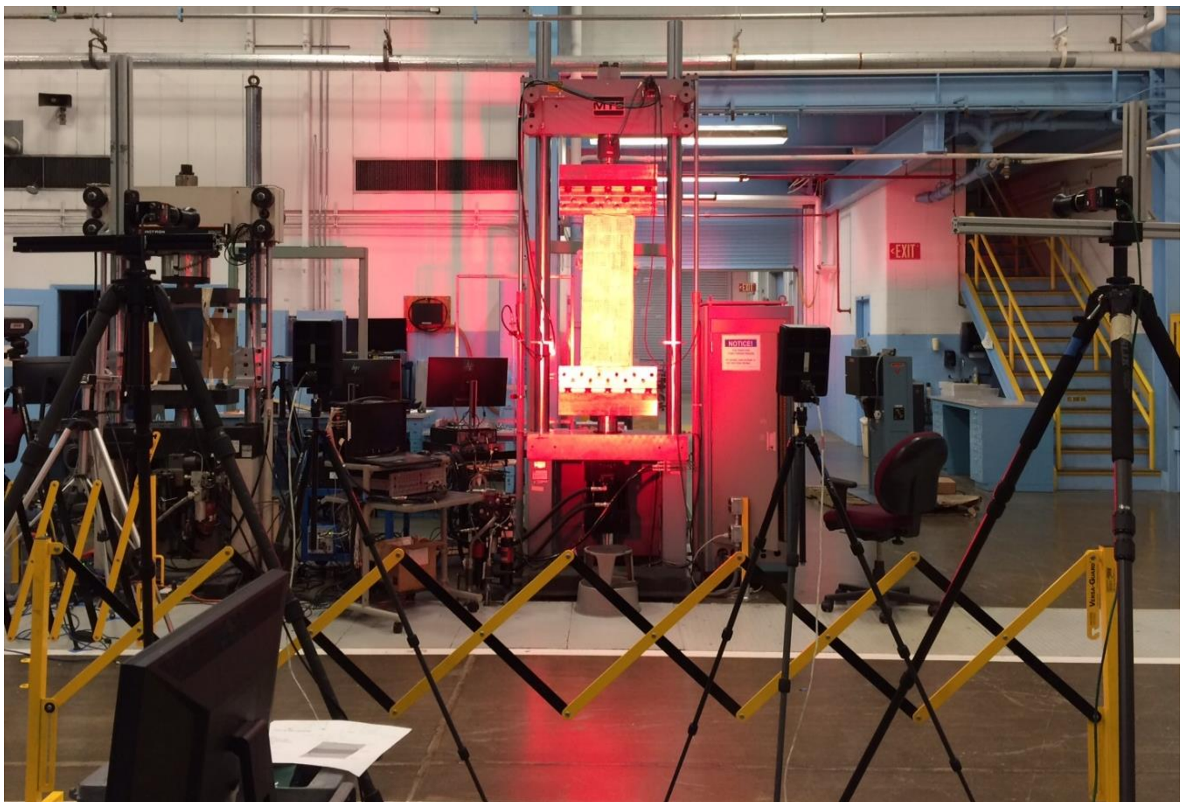
Typical response of smaller speckle pattern showing moiré effect



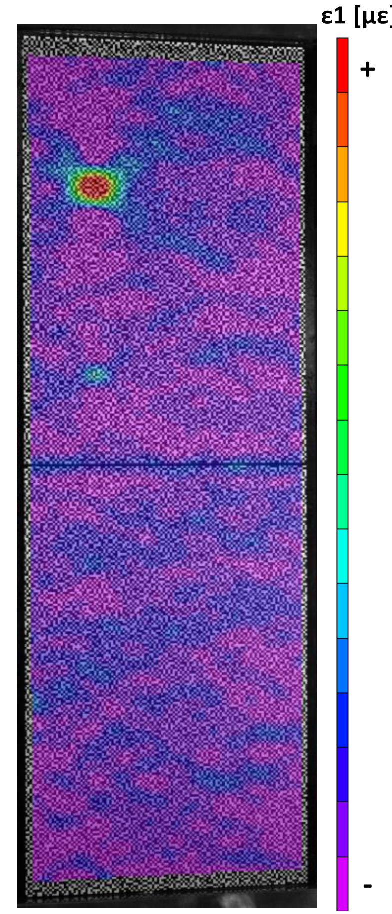
Typical response of larger speckle pattern showing lower noise floor

Proof of Concept Testing – Localized Strain

- **Ensure that localized elevated strain behaviors of a specific size (on the scale of ½”) could be detected using the vinyl wrap.**



Test set-up with field of view and speckle size set to same test parameters as the Heat Shield Testing to ensure localized strain behavior can be observed



Localized strain observed over ½” and ¼” circular cut-outs

Proof of Concept Testing – Results

- Vinyl-vehicle wrap: Results indicated that wrap showed excellent correlation with the strain gage data.

- Speckle pattern: Results indicated that the 0.06in and 0.08in speckle pattern caused moiré effects and higher-strain values (noise), while the 0.10in and 0.12in speckle pattern showed lower strain values (noise), no moiré effects, and an overall better correlation.
  - Speckle pattern was chosen to be 0.10in, since the 0.12in pattern was larger than the "ideal" pixel/speckle

- Localized strain behavior: The wrap was able to detect localized strain behavior on the size scale of ½".

Mock-up Testing - Build

- **Build a to-scale mock-up model of the aeroshell to validate camera set-up and location, as well as ensure full-field coverage is possible given the camera positions and geometry of the test article.**

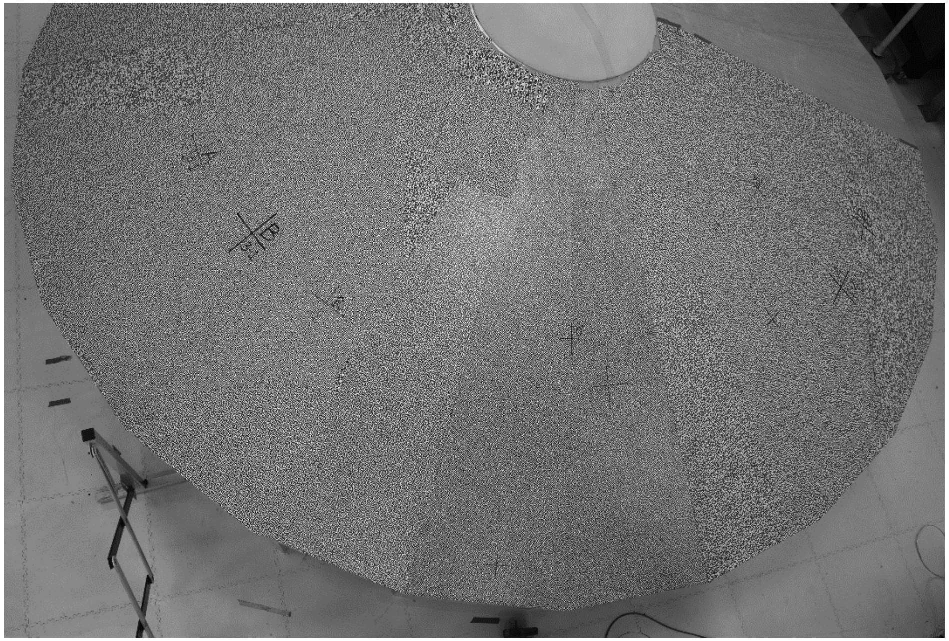
Mock-up Heat Shield Framing

Mock-up Heat Shield with Laminate surface

Mock-up Testing – Set-up

- **Apply same pattern and speckle size to OML surface of aeroshell.**

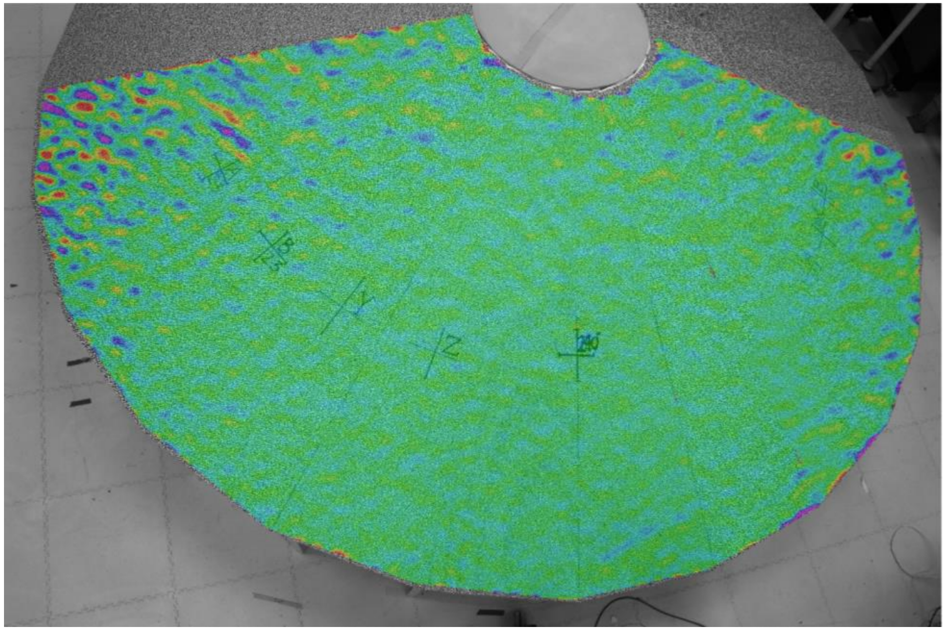
Mock-up Heat Shield with printed speckle pattern applied (printed on paper)



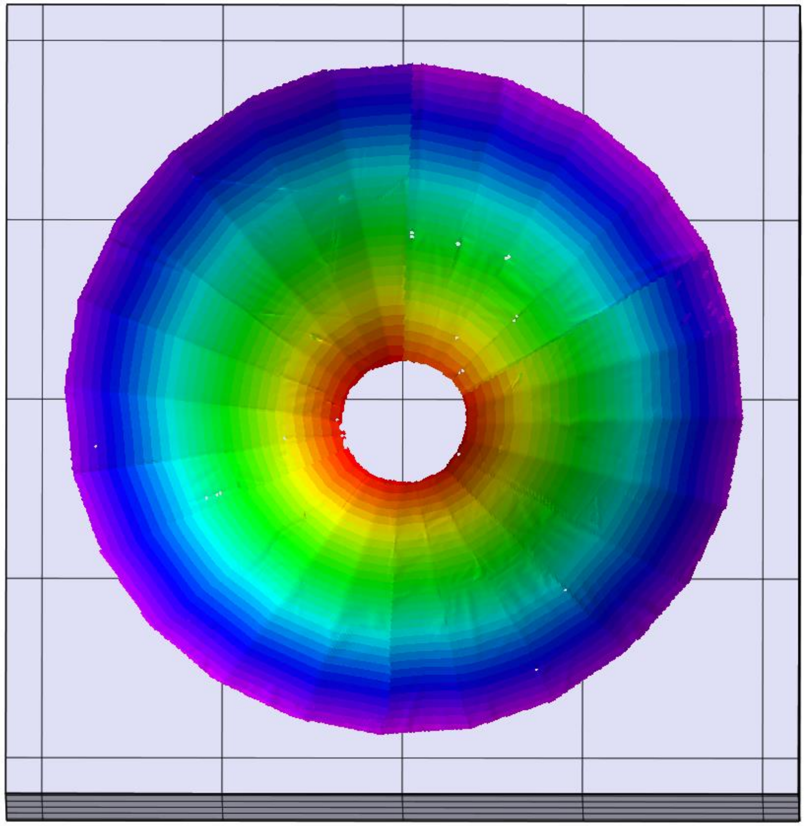
3D DIC camera view of surface of Mock-up Heat Shield

Mock-up Testing – Results

- To save time and provide complete coverage, one 29MP camera system was used and the aeroshell was rotated 120degrees (data taken at each location).

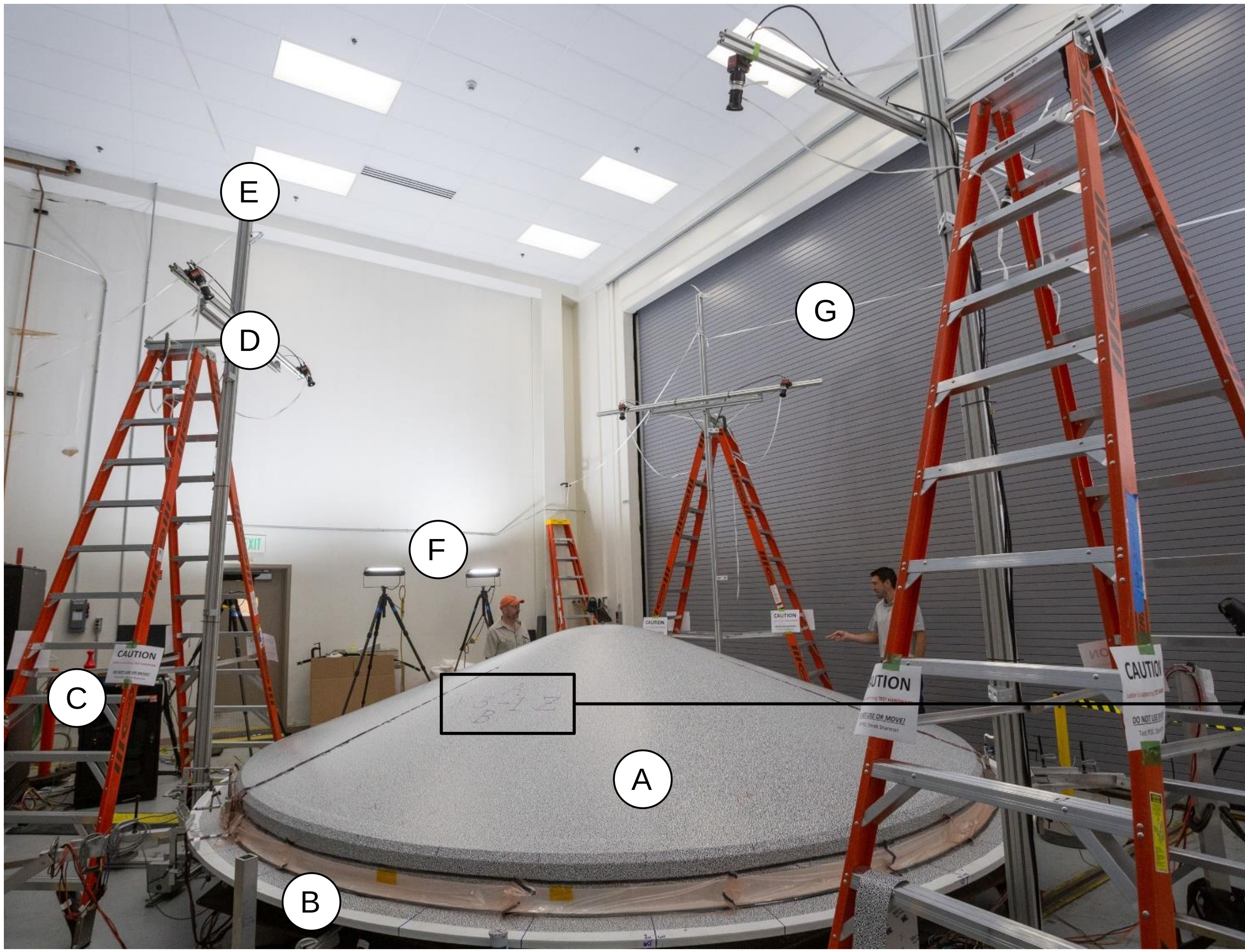


Correlated area of surface of Mock-up Heat Shield



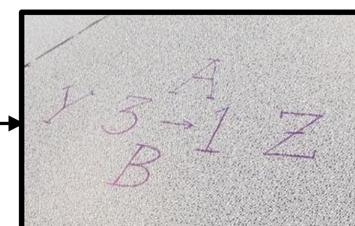
Full-field Stitched data of surface of Mock-up Heat Shield

Experimental Set-up



Experimental test set-up for Mars 2020 Heat Shield at Lockheed Martin

- (a) Test Article, HS#3
- (b) Test Frame
- (c) Twin Step Ladders
- (d) 29MP Cameras
- (e) 80-20 Frames
- (f) 5000K Lights
- (g) Tethers



Fiducial Marks for Merging Adjacent Systems

DIC Objectives

- **Implement low-speed three-dimensional Digital Image Correlation (3D-DIC) to characterize the full-field strain and displacement behavior of the aeroshell.**
  - **Traditional instrumentation, such as linear variable displacement transducers (LVDTs) and electrical-resistance strain gages, only allow for data to be recorded at a select number of point locations.**
- **Monitor behavior in real-time using Real-Time module of VIC-3D™ to ensure localized strain behavior does not exceed critical/failure levels.**
- **Obtain test data through commercially available VIC-3D™ software and other post-processing techniques to:**
  - **Verify measured test data obtained from other instrumentation**
  - **Enhance test and analysis correlation**

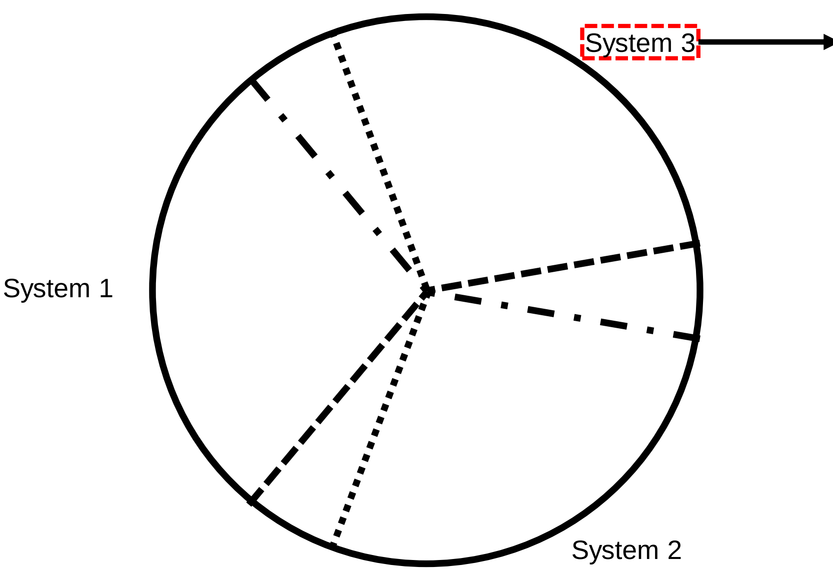
DIC System Set-up

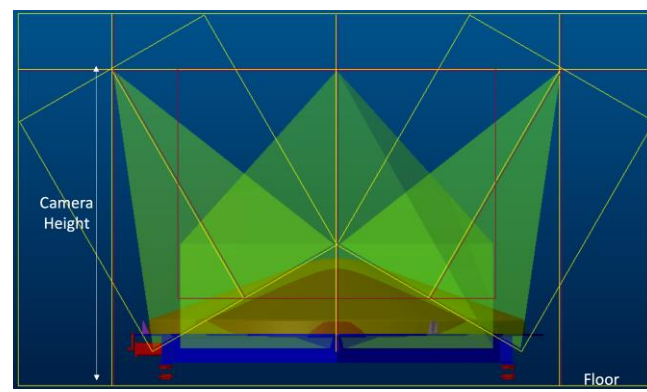
Hardware/Software:

- Three pairs of cameras located every 120°
  - 29MP [6576 x 4384] AVT Prosillica GT6600 cameras
  - 28mm Schneider Xenon-Emerald lenses, f-stop: 11
  - Min. Overlap between adjacent systems: 20°
- Cameras mounted on 80/20 supported by twin step ladders
- Hardware synced systems
- VIC3D-8^{TM} with Real-Time
- Lighting and exposure time optimized

DIC Configuration:

- Area of Interest: 176 inch x 117 inch
- Pixel Resolution: ~38 pixels/inch
- Speckle Size: ~0.1 inch (printed on vinyl)
- Subset Size: 29 pixels [0.77 in]
- Step Size: 7 pixels [0.19 in]
- Standoff Distance: ~ 12 feet
- Distance Between Cameras: ~5 feet
- Camera Angle: ~22°
- Calibration grid: 12 x 9: 70 mm

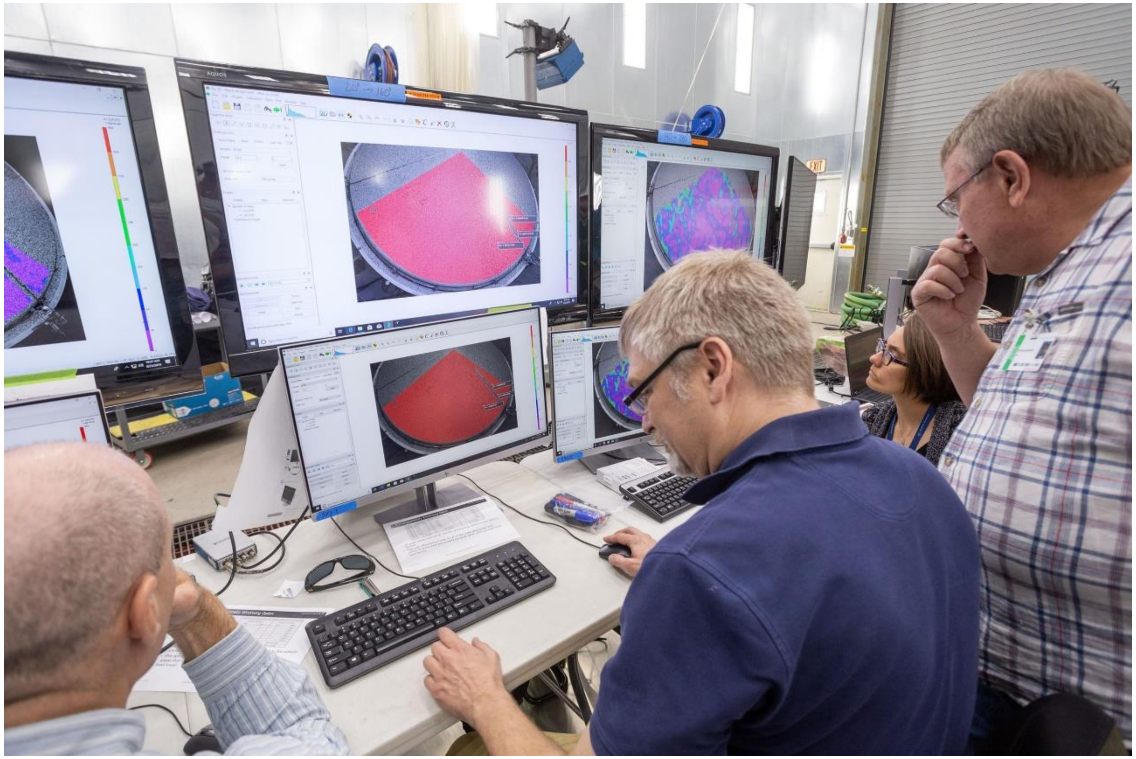




CAD representation of the 3 DIC systems viewing HS#3

DIC System Operation

- **Images acquired at 1Hz during loading and 2Hz during holds**
  - **Load holds every 20% of peak flight load**
- **Set of images acquired at tare load for noise estimates**
  - **~ 50 images**
- **Pressure data recorded by DIC to synchronize with data acquisition system**
- **VIC-3D™ Real-time module used during testing**
  - **Monitors available for each system**



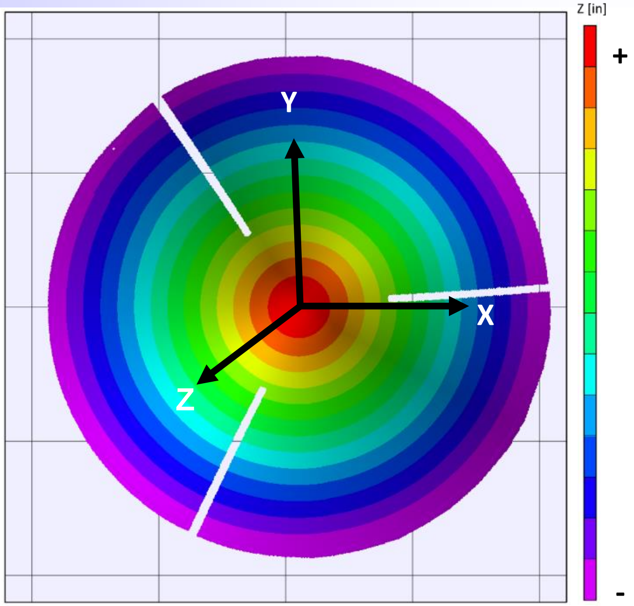
Control Room with VIC-3D™ Real-time Monitoring of each system

DIC Data Processing Methods and Results

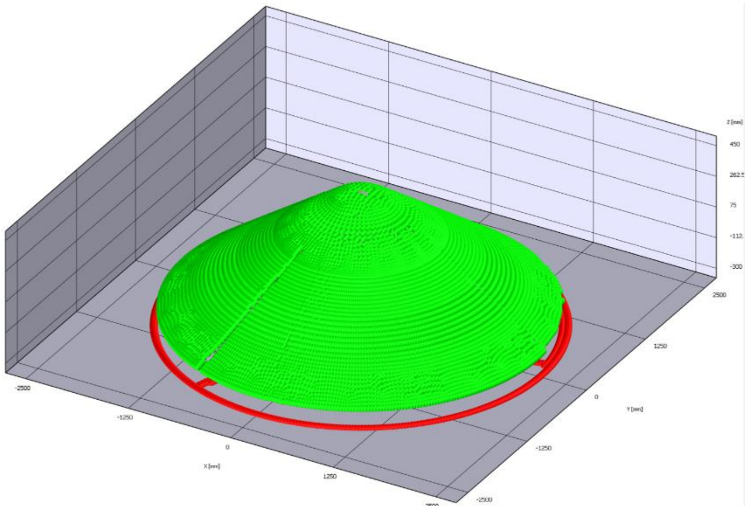
- **Initial DIC Processing**
- **Data Assembly**
  - Merging Multiple Data Sets
  - Coordinate Transformation
- **Importing Nodal Mesh values**
- **Results**
  - Stitched DIC data vs Finite-Element-Model (FEM) predictions

DIC Processing and Data Assembly

- Choose AOI
- Specify spatial resolution
- Process the data
- Merge individual data sets into global data set
- Process of merging data set involves 3 basic steps;
  - (1) Calculate the geometric transformation between systems.
  - (2) Calculate the shape/deformation fields for each system separately.
  - (3) Use the transform from step 1 to combine the data files from step 2.
- Set System 3 (centered at 300deg) as Primary Coordinate System
- Rotate global data set by 60deg to align coordinate system with FEM coordinate system
- Import x,y coordinates for nodal mesh values using .csv file
- Export nodal mesh values to import into FEM mesh



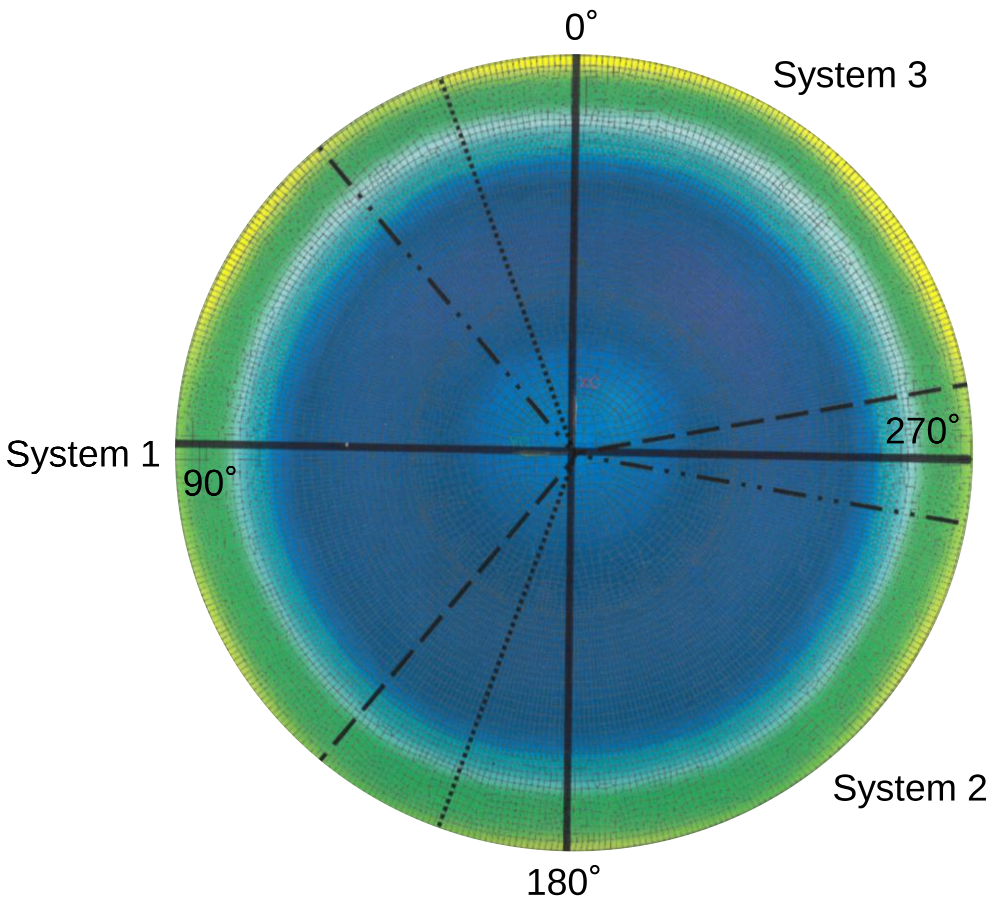
Stitched 3D-DIC global data set



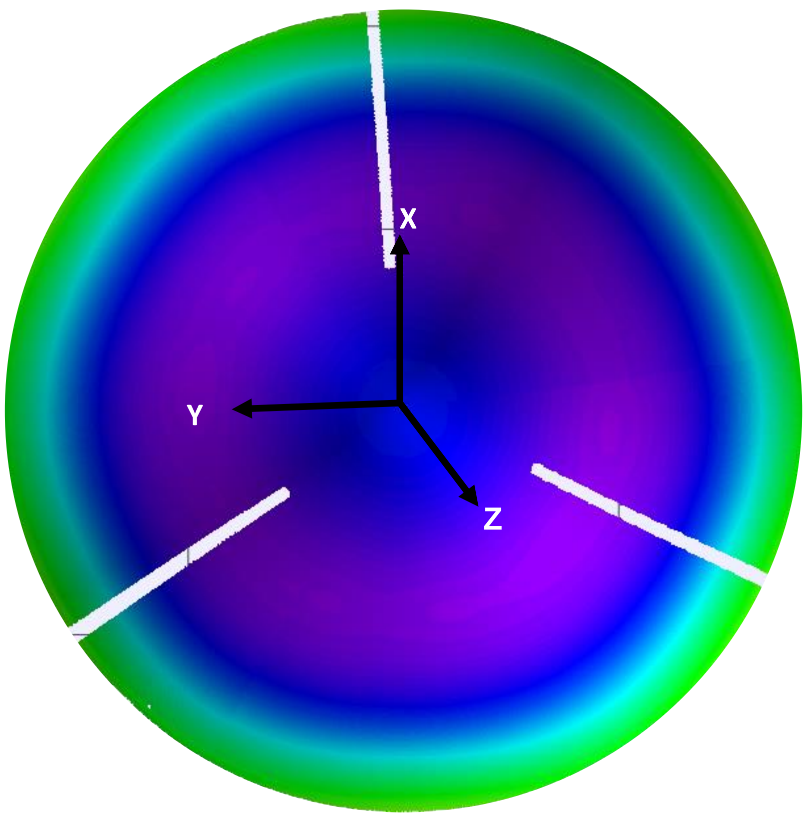
3D plot in VIC-3D showing FEM nodal mesh overlay

FEM Prediction vs Stitched DIC

Analysis W-displacement

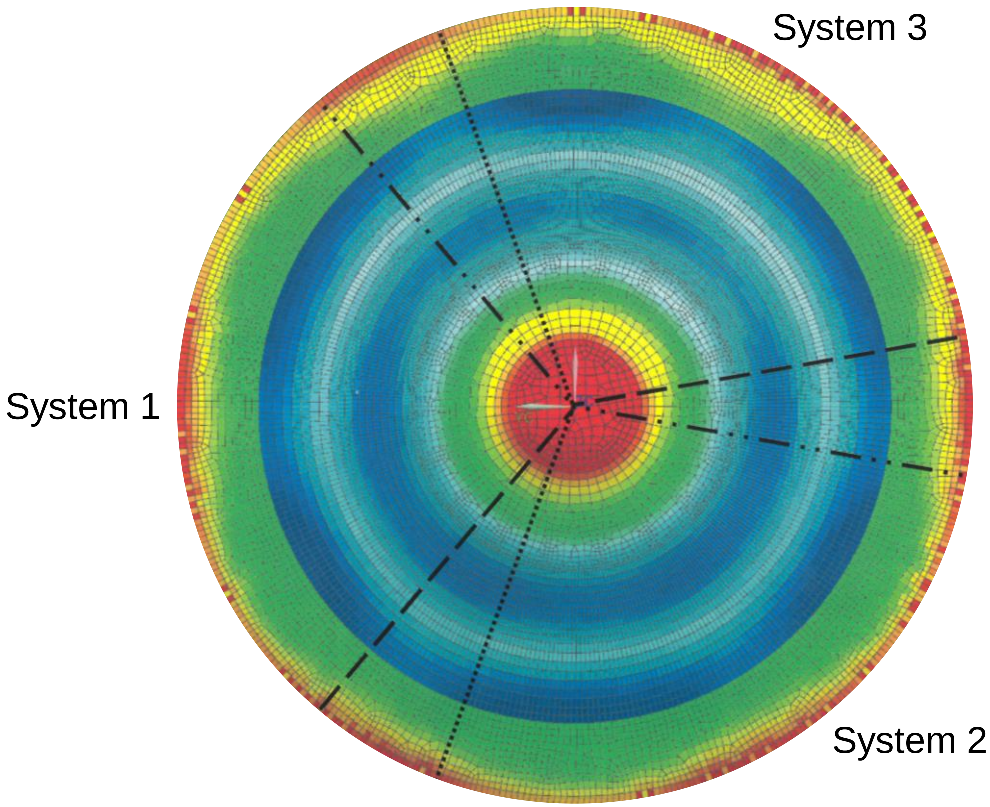


DIC W-displacement

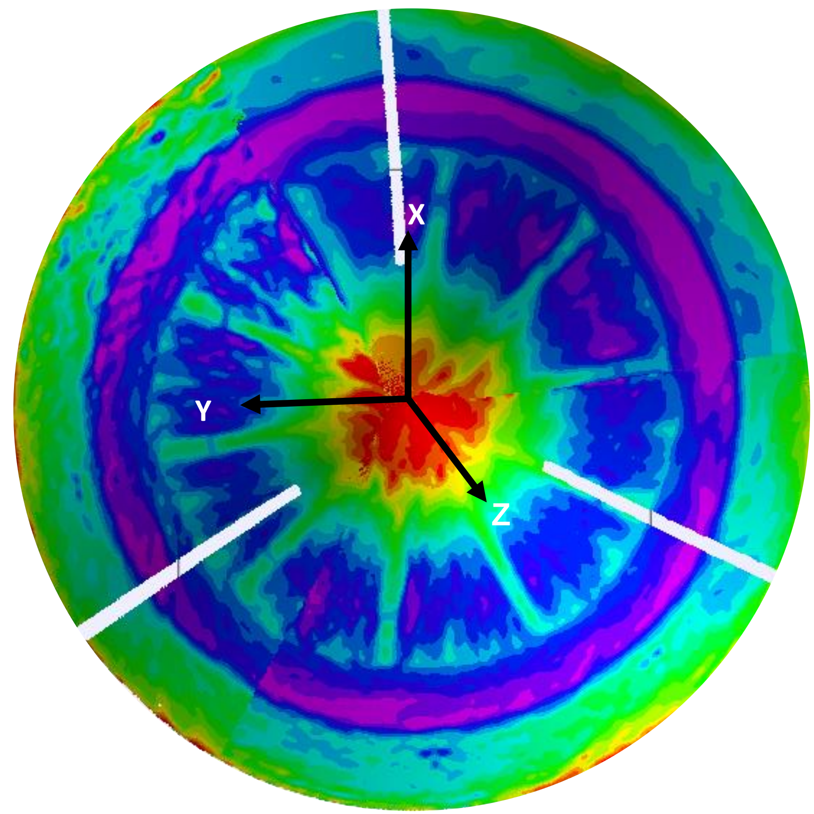


FEM Prediction vs Stitched DIC

Analysis Minimum Principal Strains

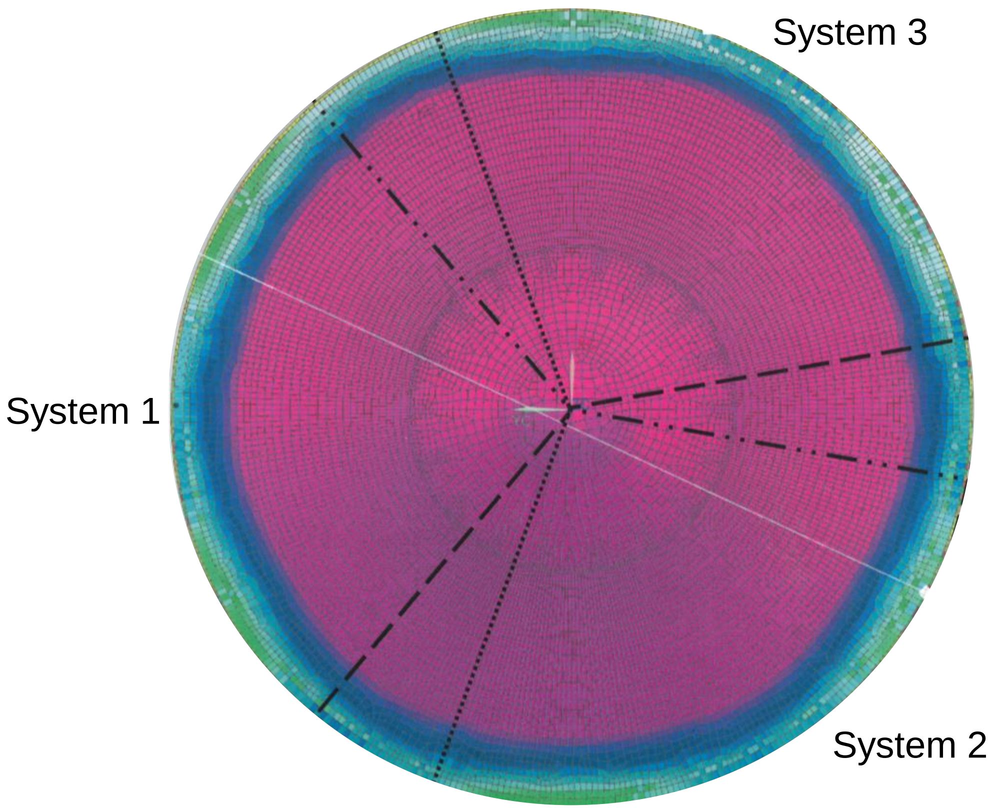


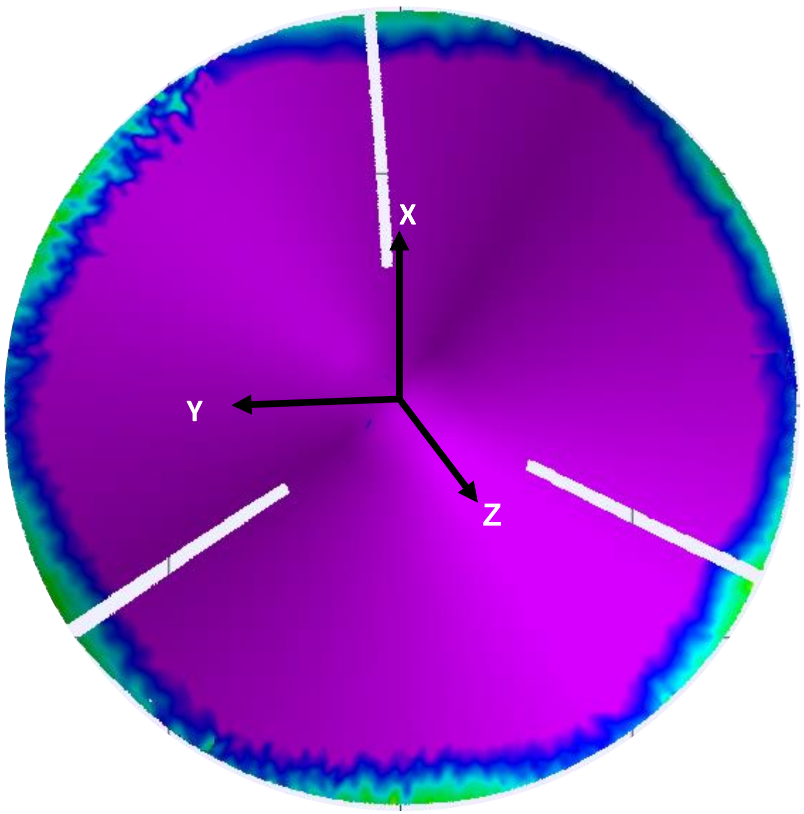
DIC Minimum Principal Strains



FEM Prediction vs Stitched DIC

Analysis Minimum Principal Strains **DIC Minimum Principal Strains**





Summary and Conclusions

- **DIC was successfully implemented on large-scale space-flight hardware**
  - **Mars 2020 Heat Shield passed the 120% qualification test without fracture or strains that exceed prediction limits**
  - **"While we have used this full-field photogrammetry technique on test articles in the past, this is the first successful implementation on official flight hardware“ – Sotiris Kellas, NASA Lead for Technical Demonstration**
- **The full-field strain and displacement measurements that were extracted at FEA nodal points showed excellent agreement with the analytical predictions.**

☰ POPULAR MECHANICS TECHNOLOGY CARS TOOLS DEFENSE CAMPING GUIDE SUBSCRIBE NEWSLETTER

NASA’s Mars 2020 Mission Passes Critical Heat Shield Test

This is how engineers recreate the hellish conditions of Martian reentry to test components that will go up against the real thing.

By Joe Pappalardo May 2, 2019


LOCKHEED MARTIN