Optical Measurement Techniques for Rocket Engine Testing and Component Applications

7 June 2016

Digital Image Correlation and Dynamic Photogrammetry

Paul Gradl

NASA MSFC
256.544.2455
Paul.R.Gradl@nasa.gov

National Aeronautics and Space Administration

NASA

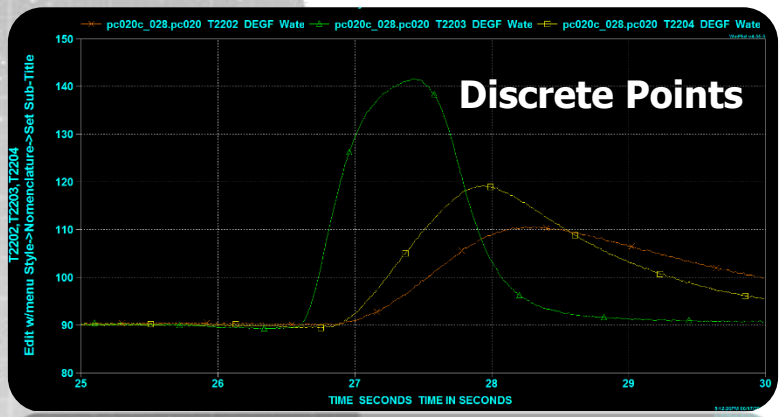
MARSHALL SPACE FLIGHT CENTER

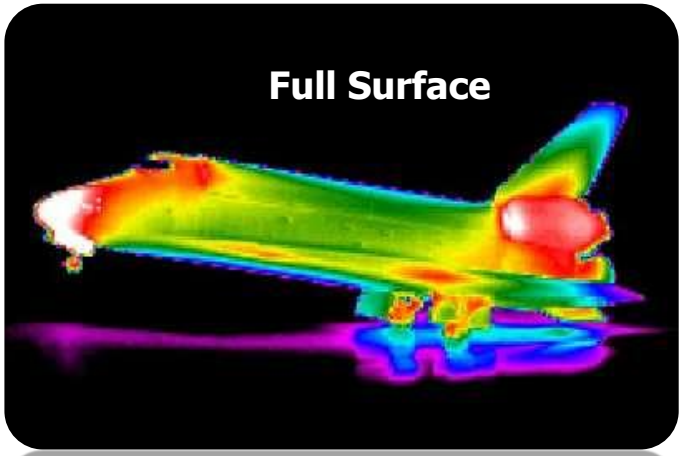
Motivation for Technology

- Subscale and Full-scale testing requires expensive and labor intensive instrumentation to better understand hardware performance
  - Design Modifications and Performance Predictions based on “discrete” point instrumentation
    - Thermocouples, Pressure Transducers, Accelerometers, Strain Gages

Full Surface **>** Point
IR **>** Thermocouple
D.I.C. **>** Strain Gage

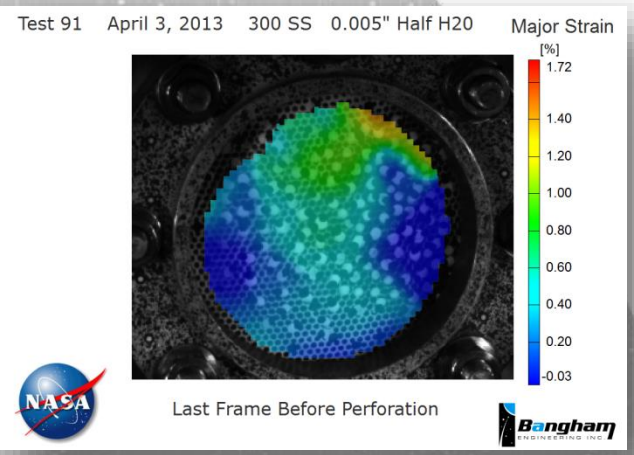
D.I.C. = Digital Image Correlation



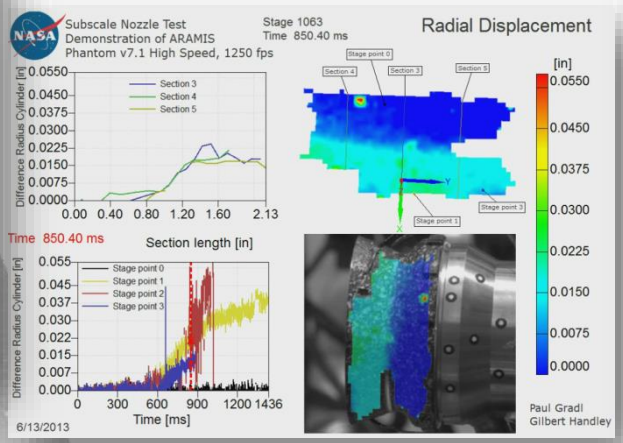


Goal: Augment Traditional Gages to gain a better understanding of hardware and environment loads to design more efficient components and systems

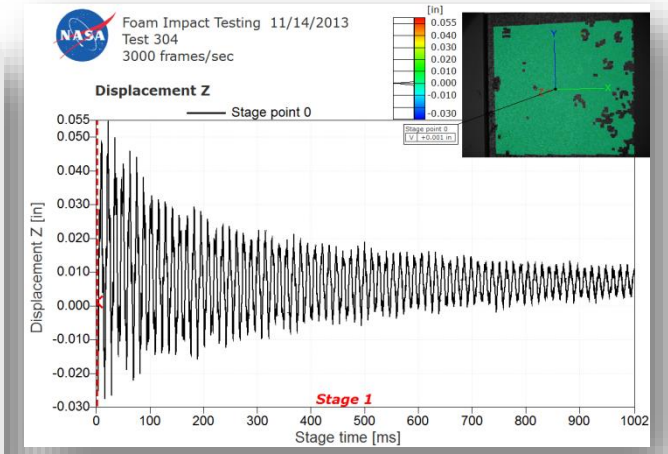
Applications and Development work for Digital Image Correlation at NASA



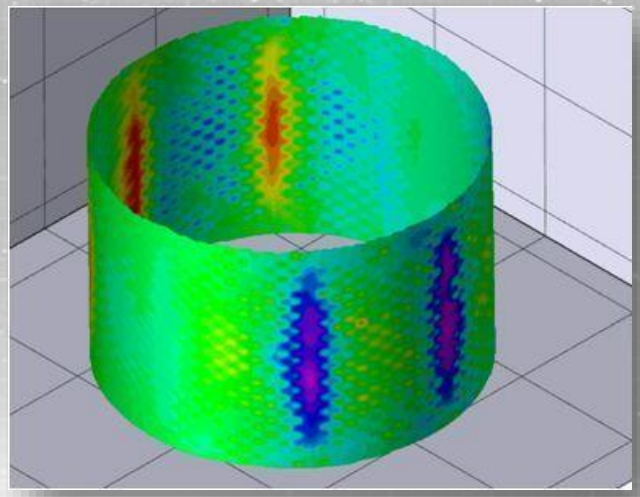
Blast Pressure Wave Tracking at 70,000 fps



Subscale Nozzle Displacements at 1700F

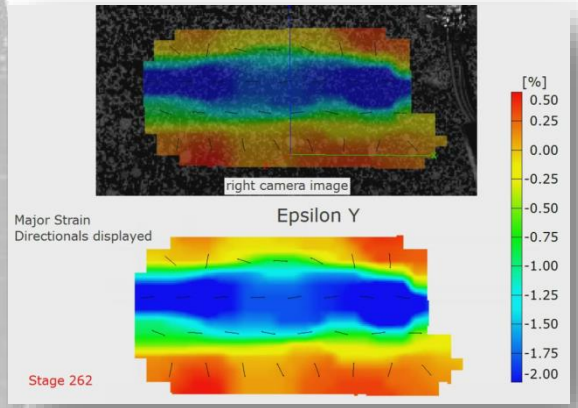


Debris Impact Testing – Eliminated Strain Gages

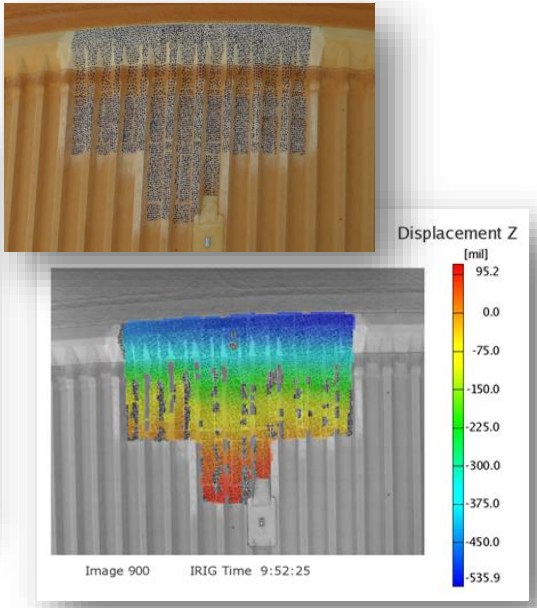


Full-Field Strain and Displacements of 18-ft Dia Tank

Ref: Todd Boles, MSFC/ET30



High Speed Composite Compression – Direct Application of Major Strain

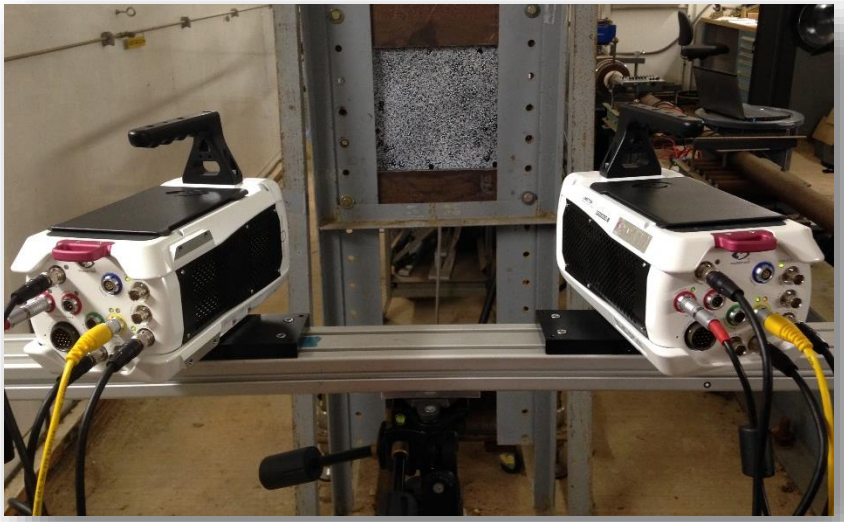


ET (on Pad) Cryo tanking test to observe stringer displacement

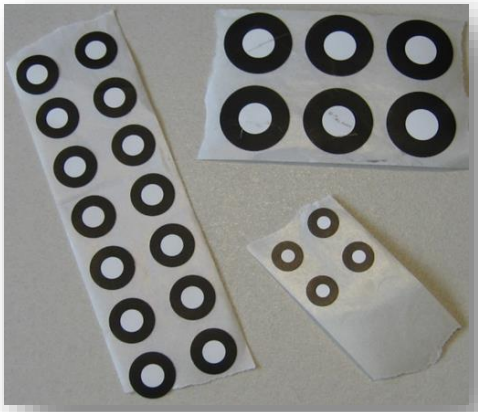
Digital Image Correlation - Overview of Technology

- Uses paired high speed video cameras calibrated to a volume to full field surface data
- Post-processing of paired images to determine **Displacement of surface, strains, acceleration, velocity**
- High Speed cameras can provide high frame rate although frame rate limited by duration of test and current post-processing techniques (tremendous amounts of data)

Photos by: Paul Gradl and Gilbert Handley

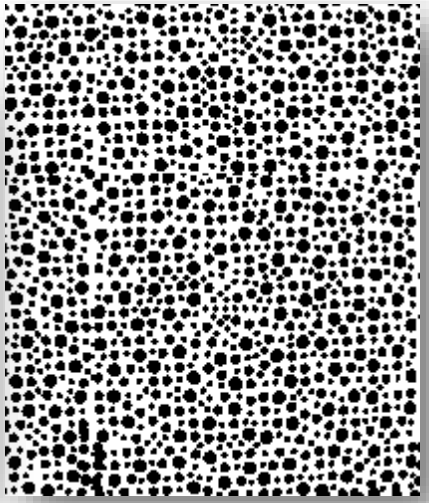


PONTOS



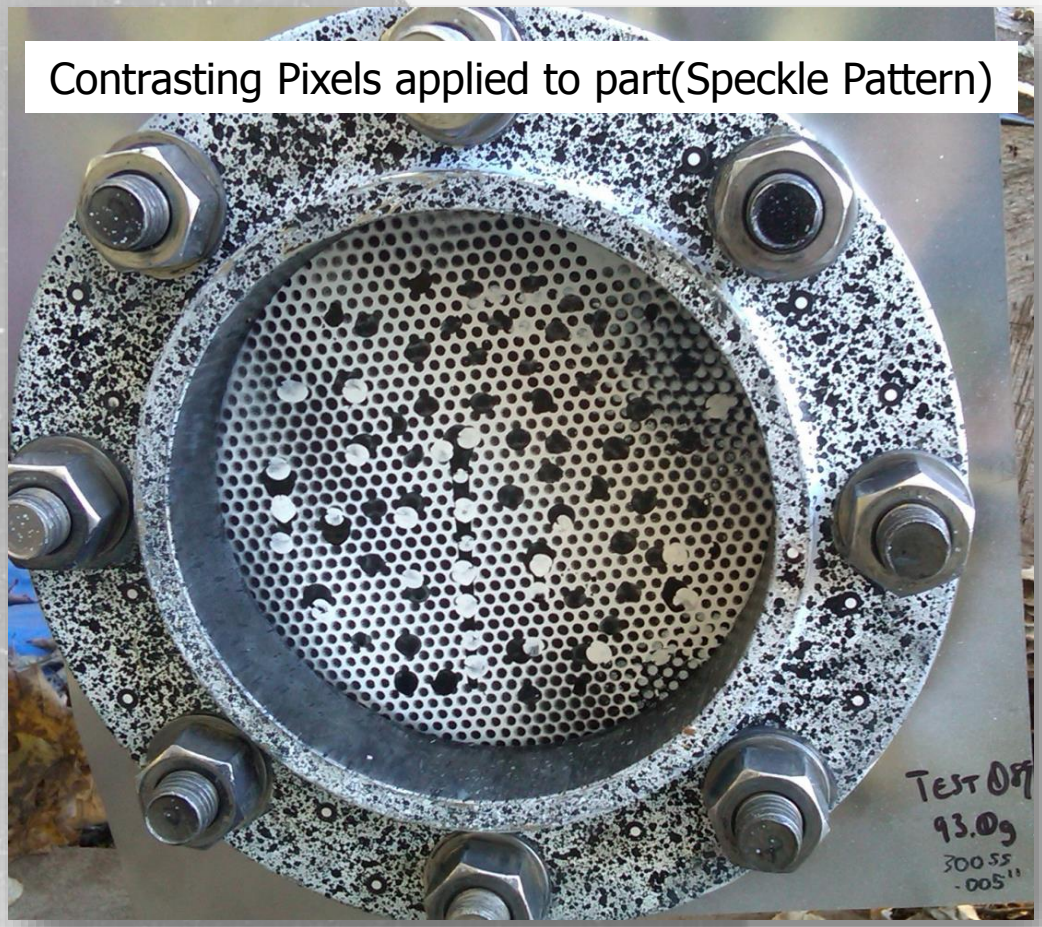
Discrete Point Setup

ARAMIS



Full Surface Setup

What is Digital Image Correlation?



+

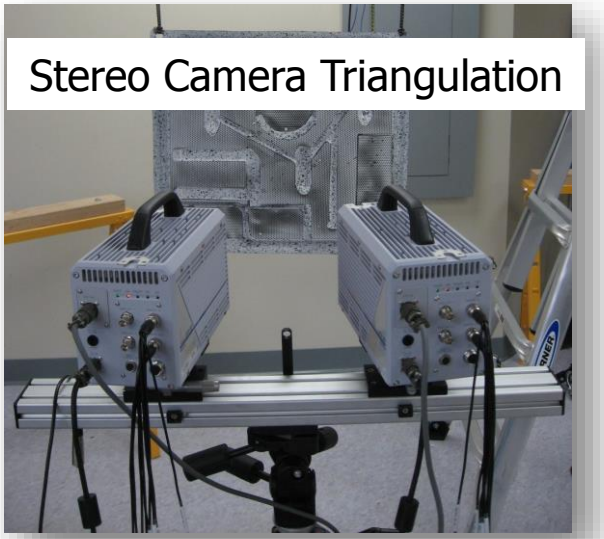
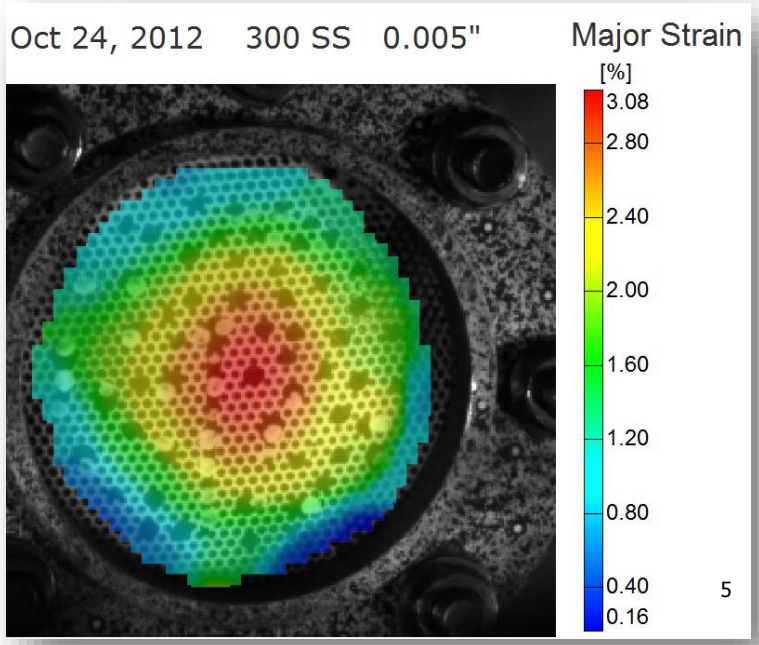
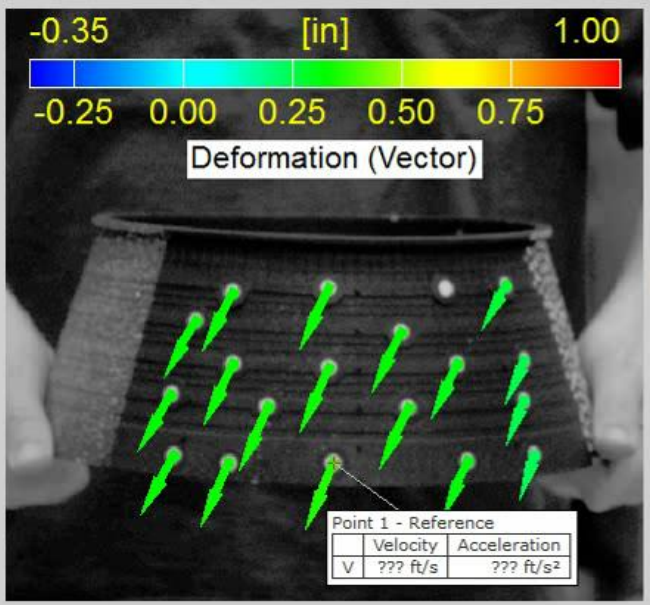


Photo Provided by: Tim Schmidt / Trilion

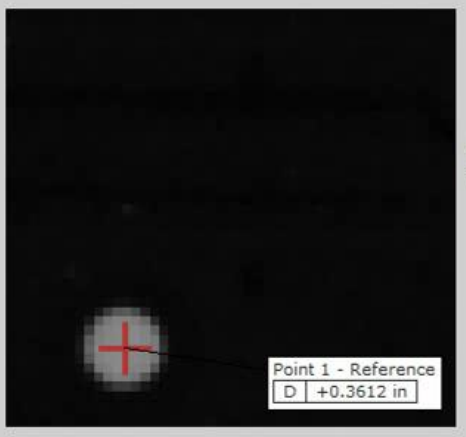
= Full Field Displacement and Strain Measurements

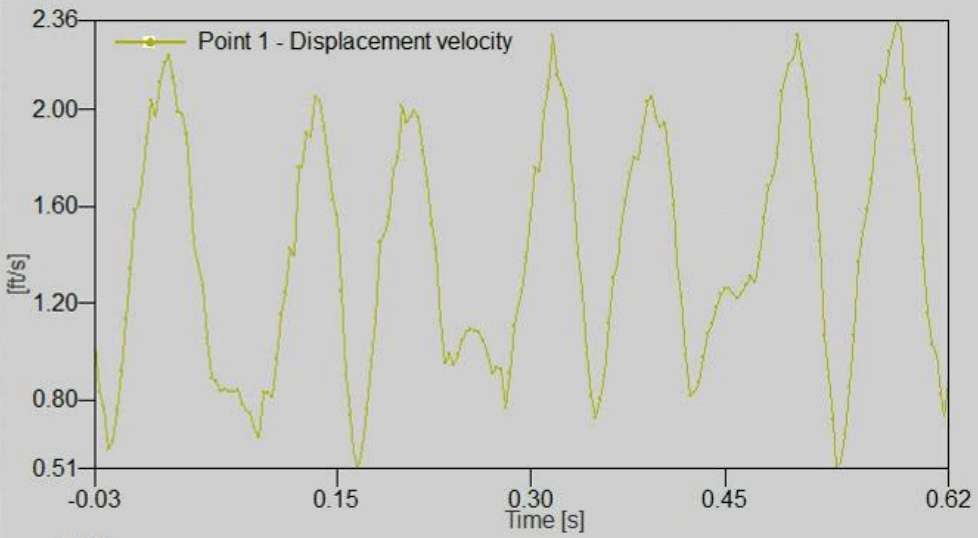


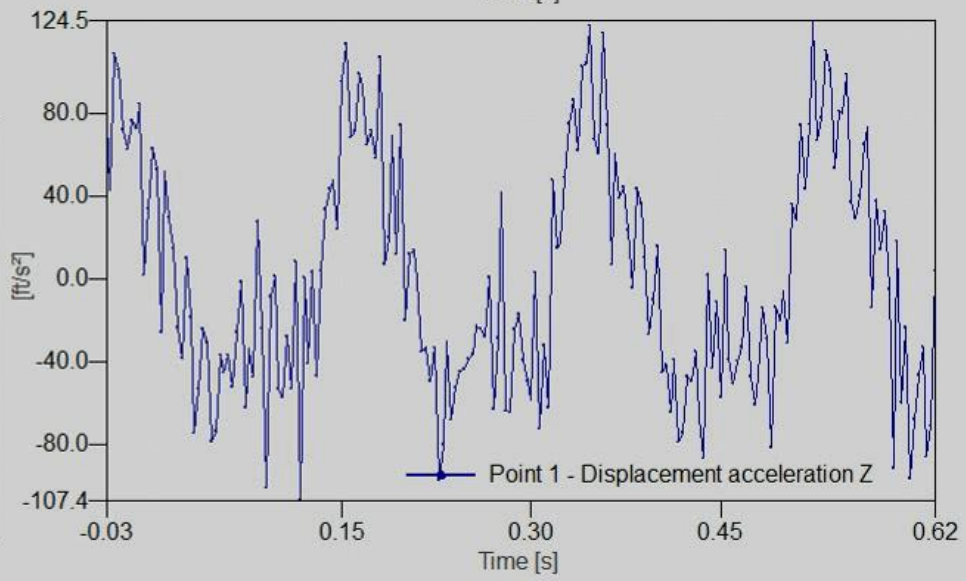
PONTOS Lab Experiments



Nozzle Deformation
Date: 4/2/2013
0.000000 sec
Phantom 7.1M HS
50mm lenses



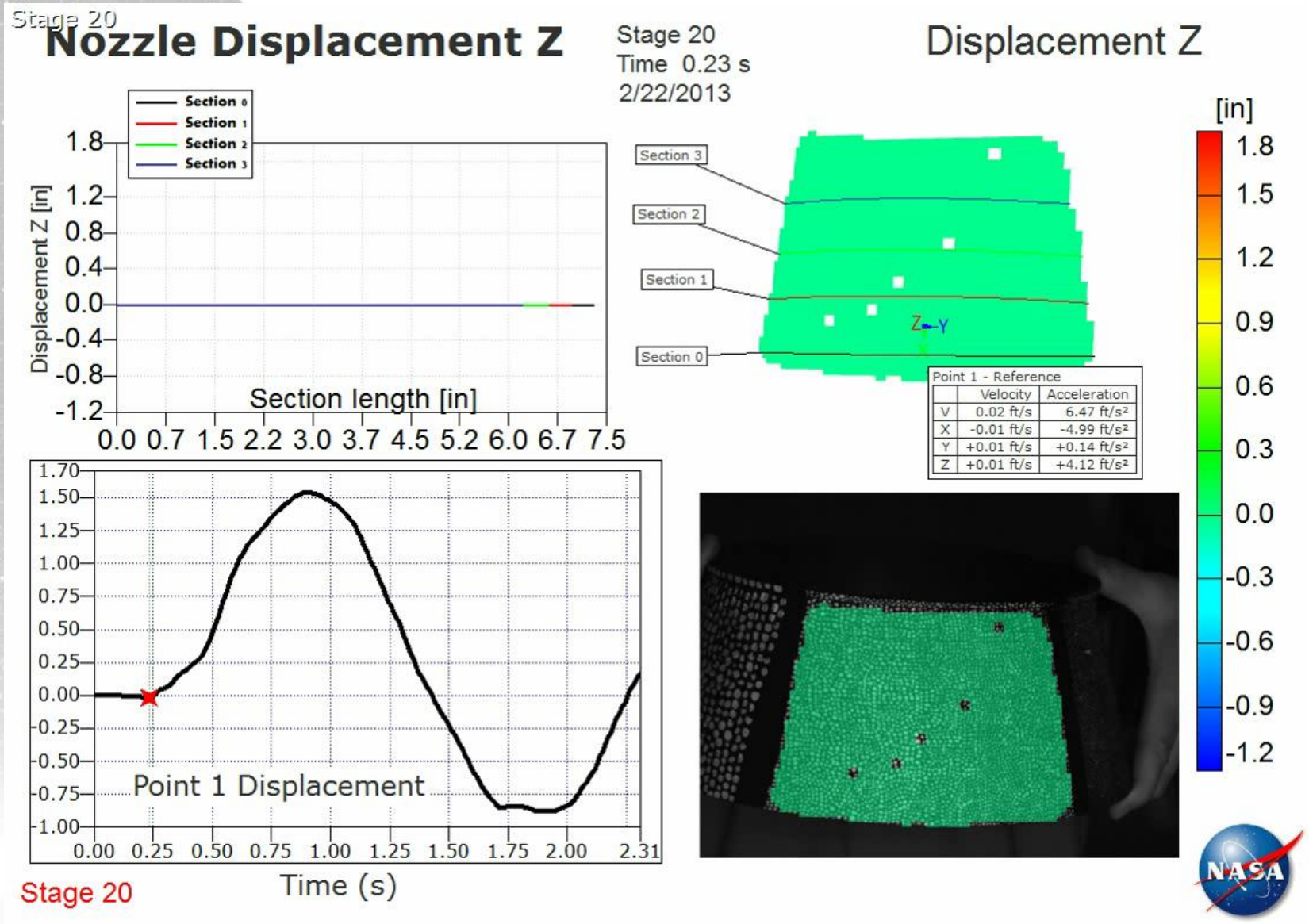




Paul Gradl
Gilbert Handley

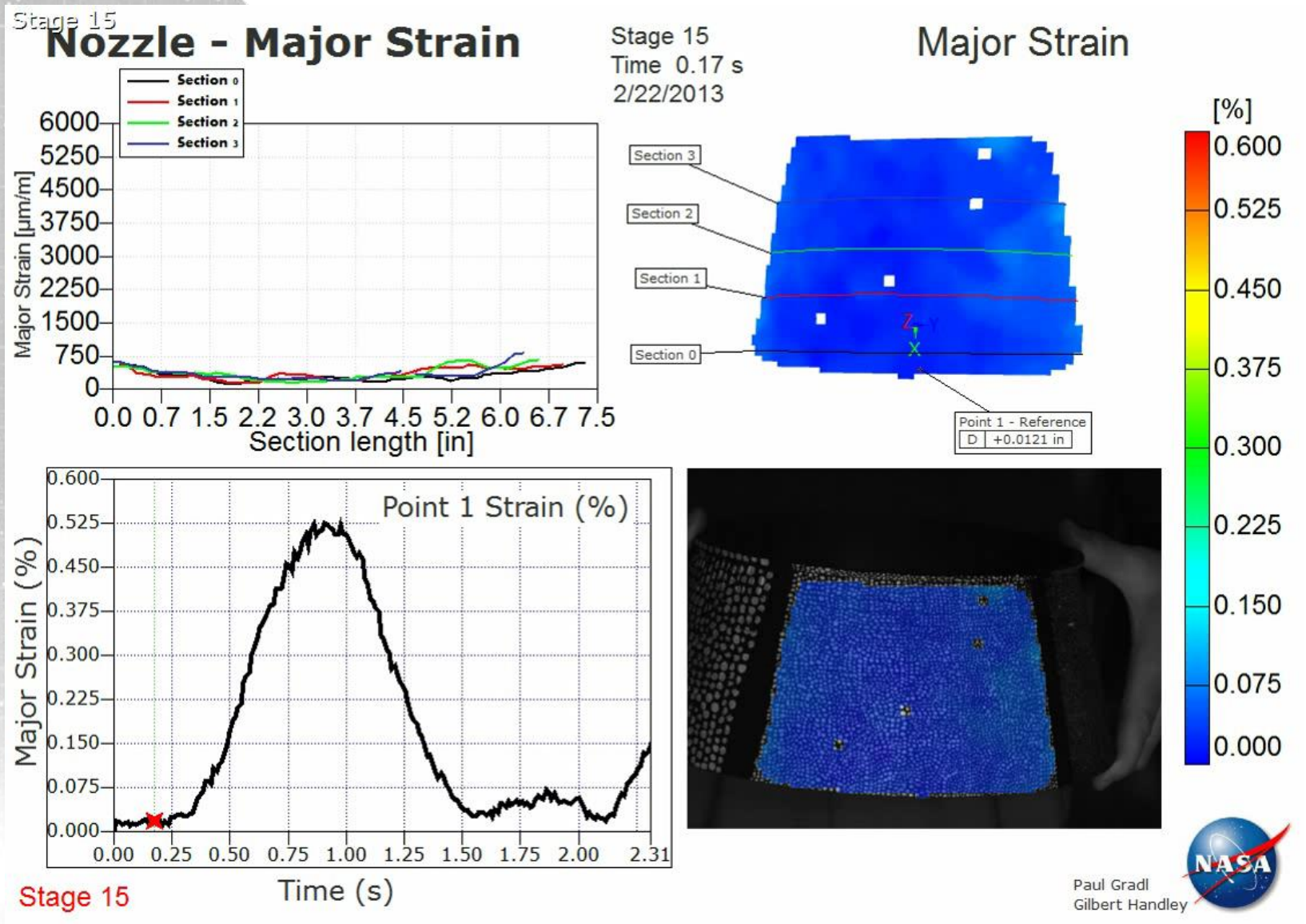
VIDEO

ARAMIS Lab Experiments – Displacement



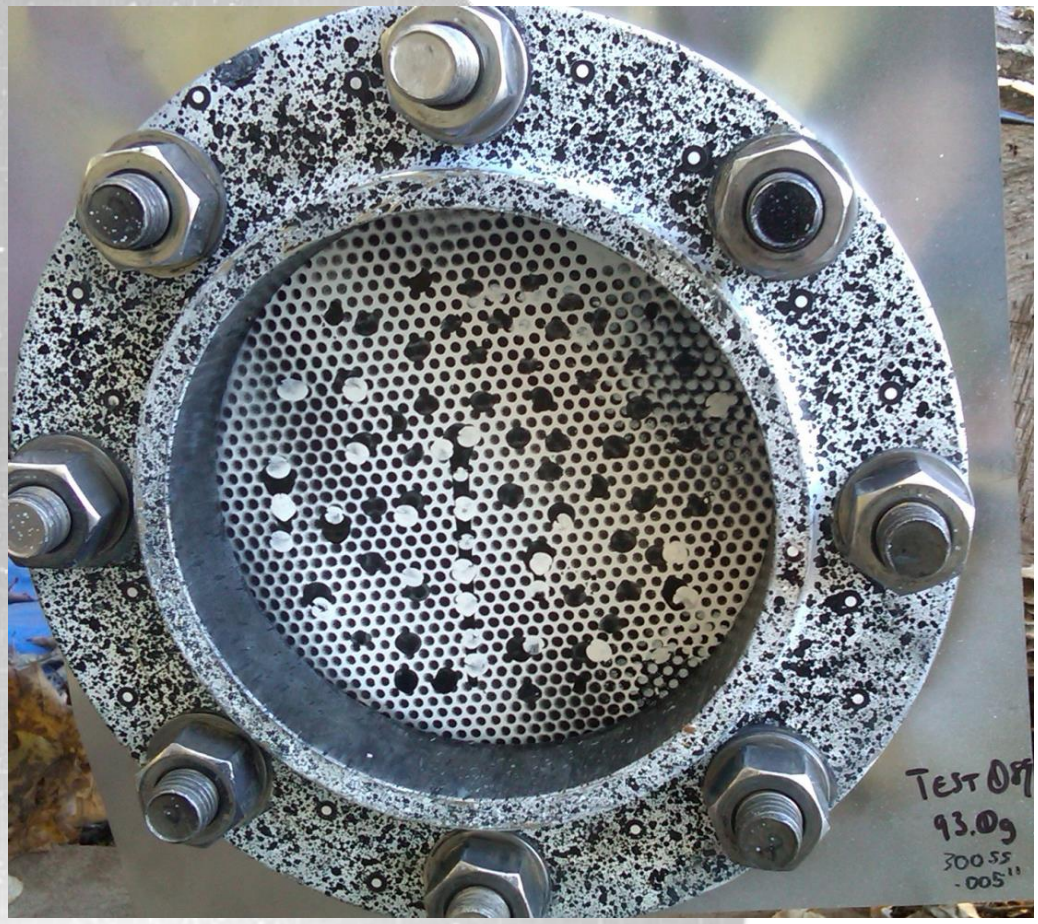
VIDEO

ARAMIS Lab Experiments – Principal Strain

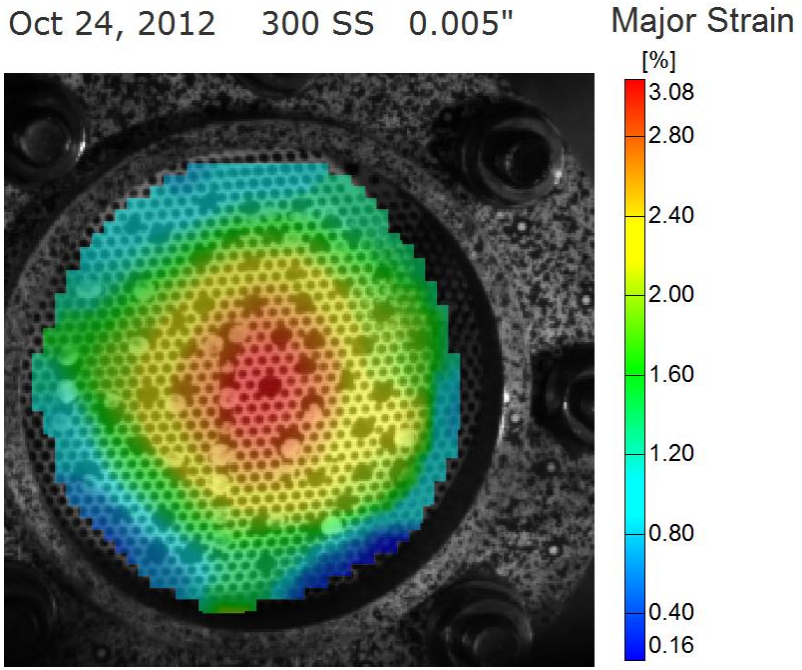


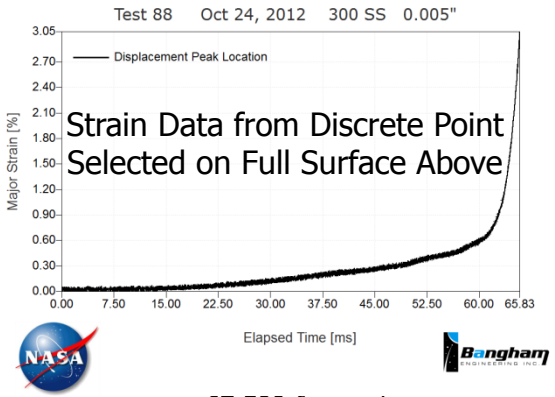
VIDEO

Blast Testing High Speed Example



Speckle pattern applied to component using Rustoluem 1976 Black

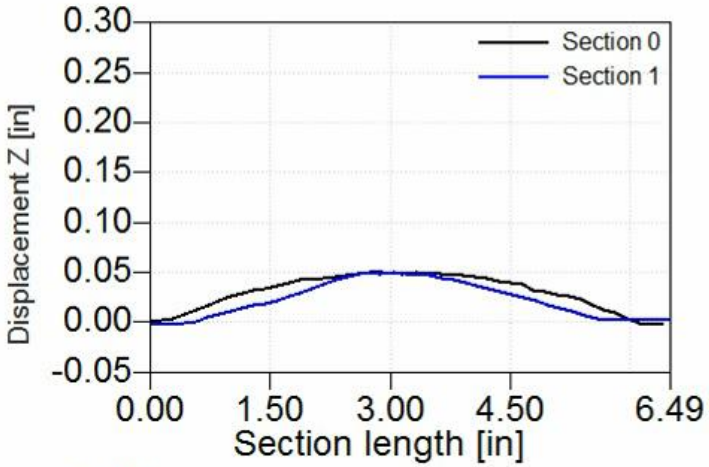


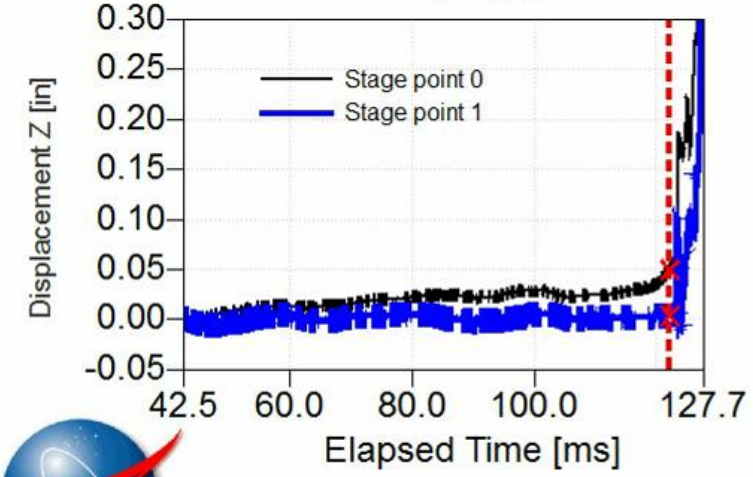


67,500 frames/sec

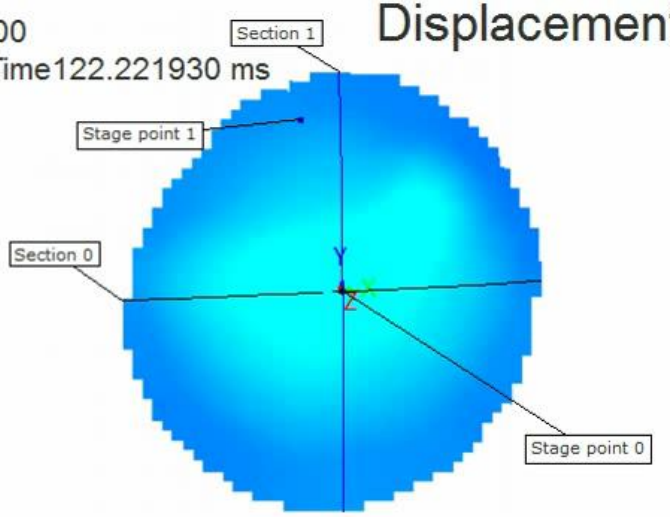
High Speed Fragmentation Testing

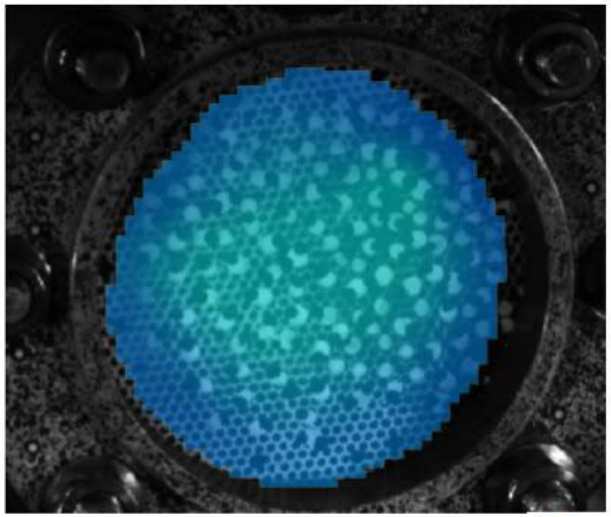
Test 91 April 3, 2013
300 SS 0.005" Half H20





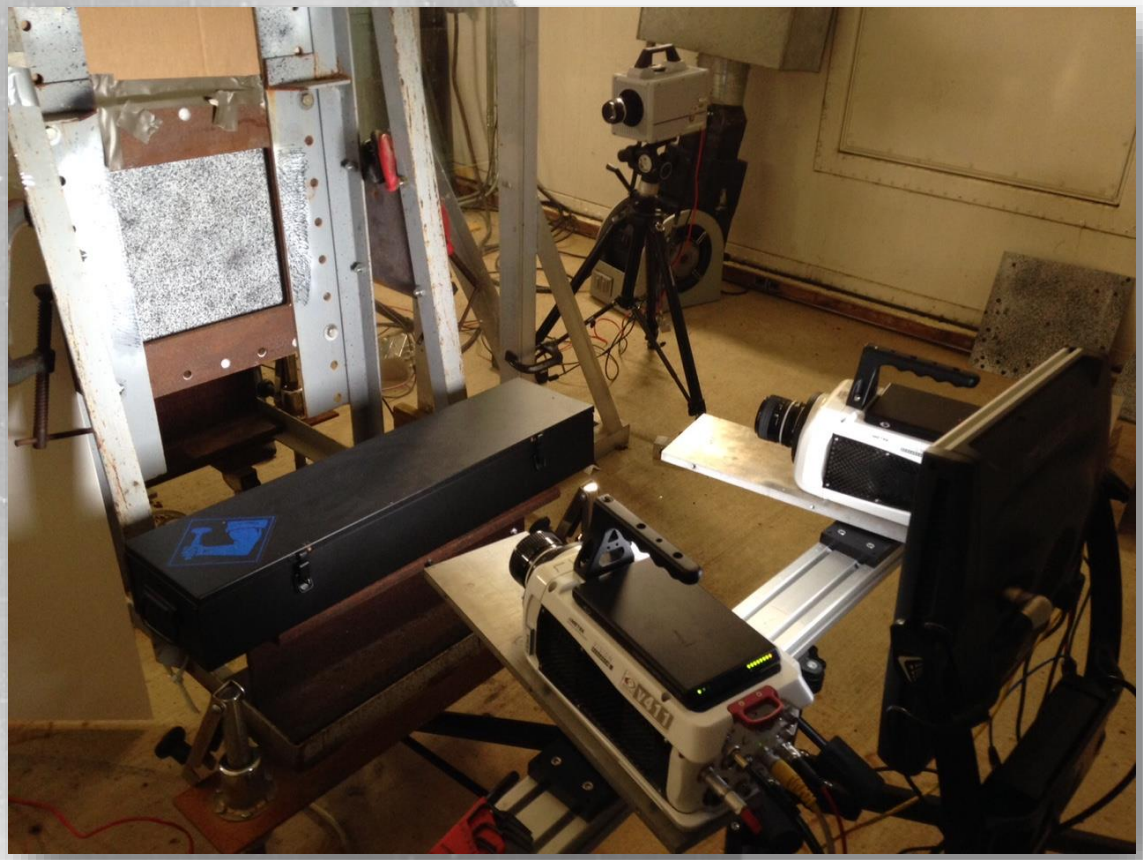
Stage 4300
Elapsed Time122.221930 ms

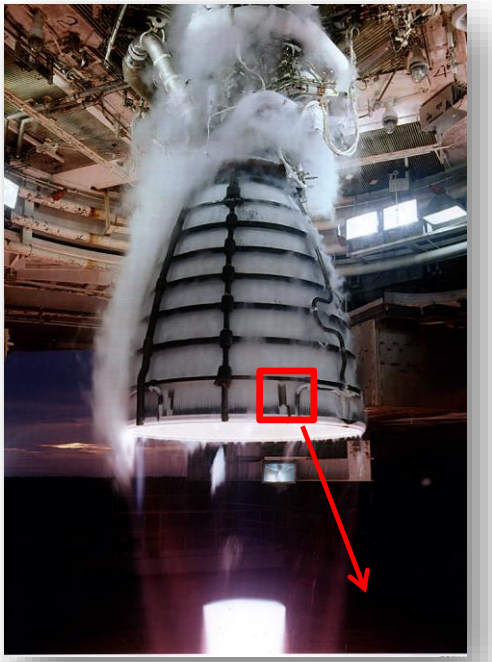


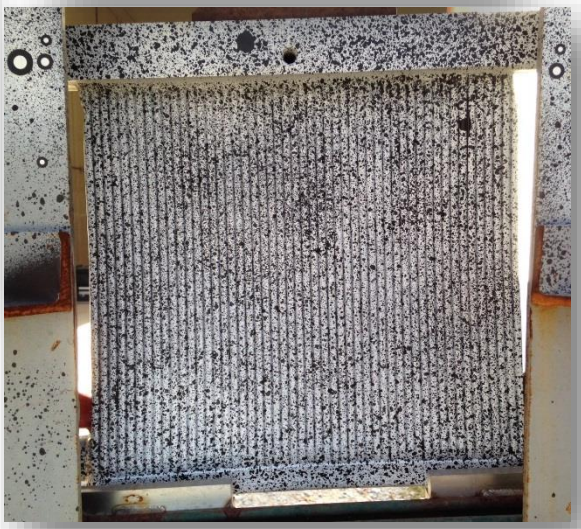


VIDEO

Space Launch System (SLS) Debris Impact Testing



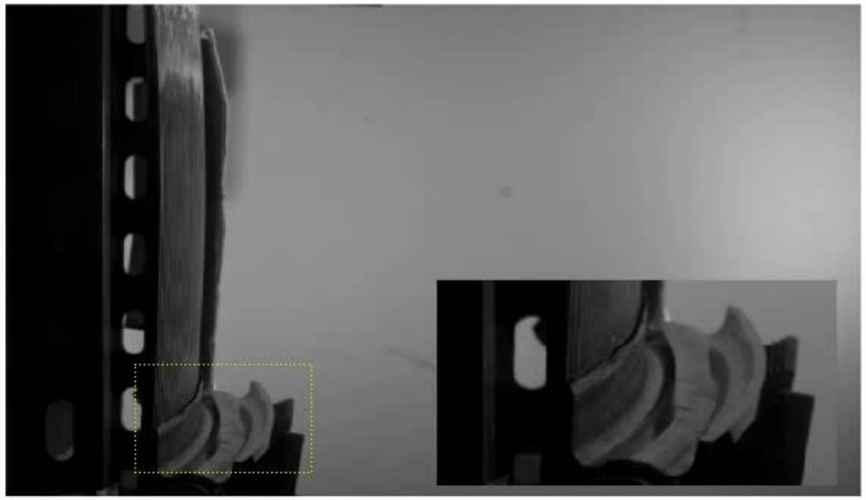


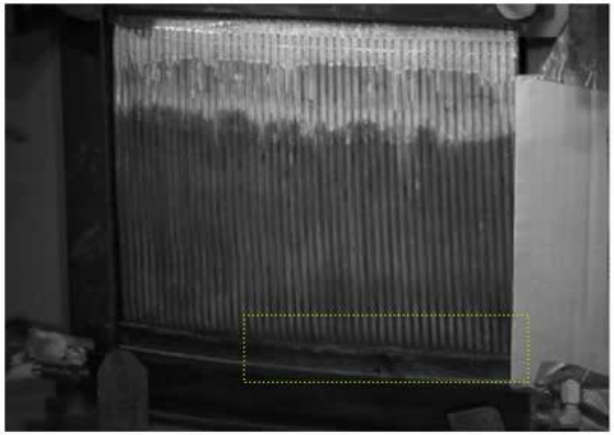


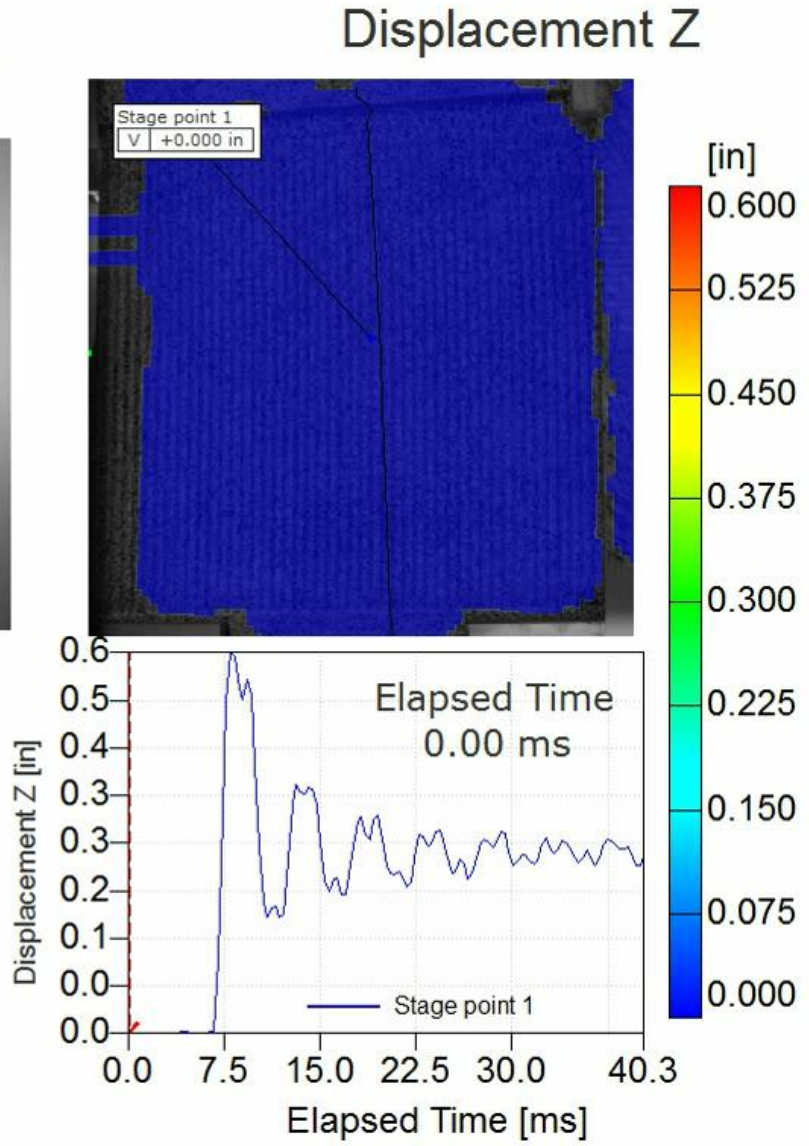
Test provided by: Paul Gradl and Cory Medina
Chip Kopicz, Perry Gray, Bart Suggs

SLS RS25 Nozzle Pressurized Panel

SLS RS25 Pressurized Panel Testing
13 Nov 2015; 6# Foam





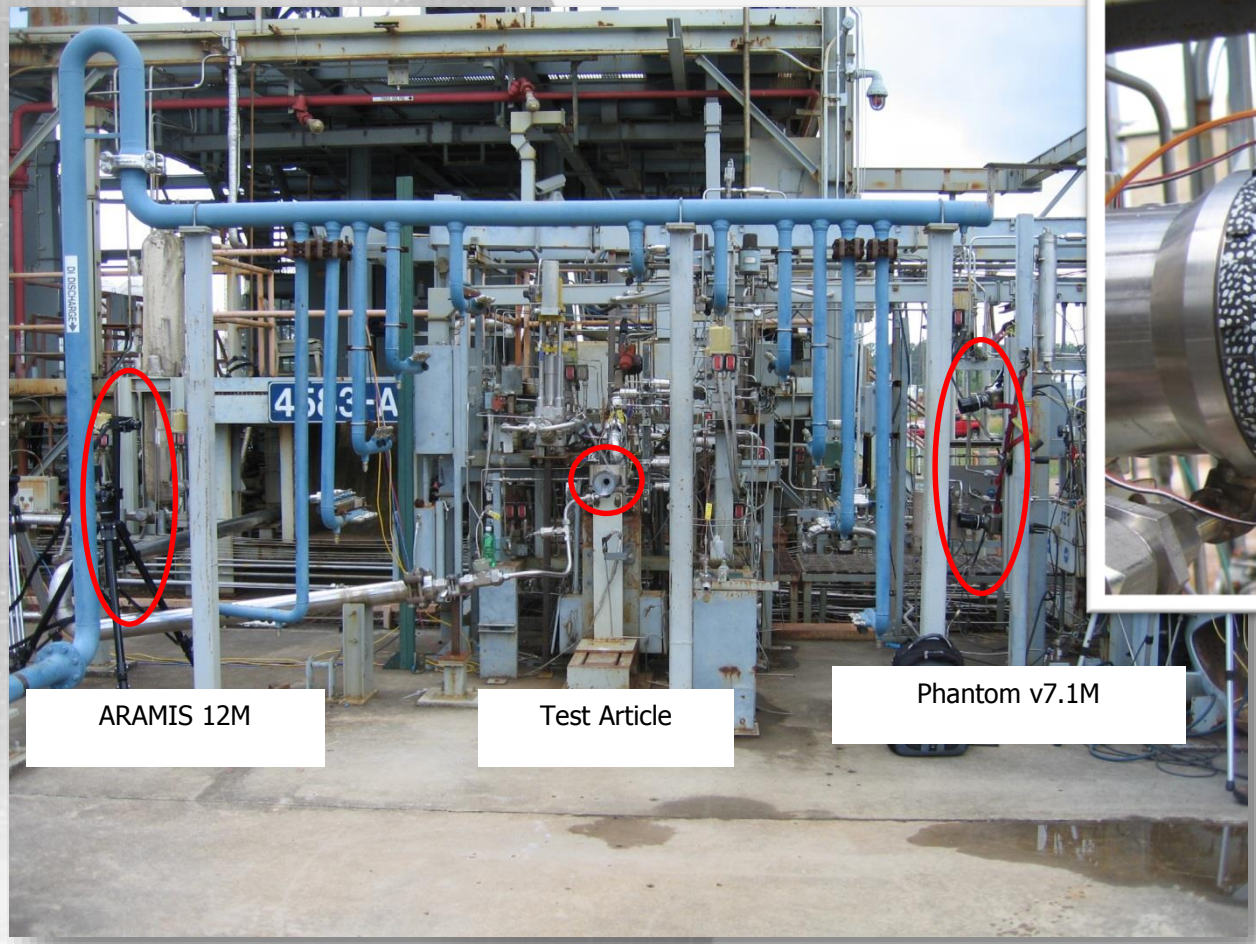


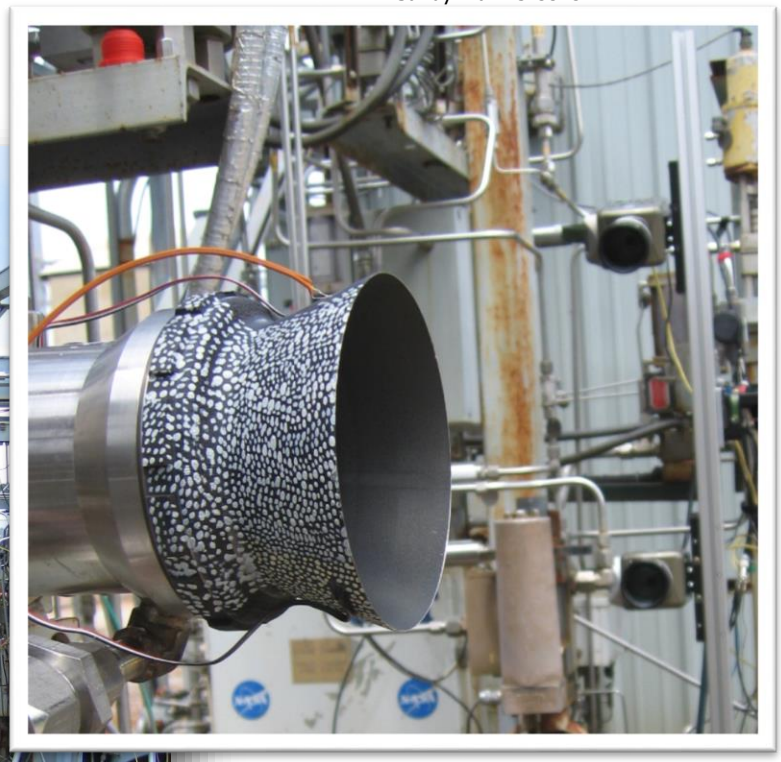
Paul Gradl Cory Medina Chip Kopicz

VIDEO

Subscale Hotfire Nozzle Testing

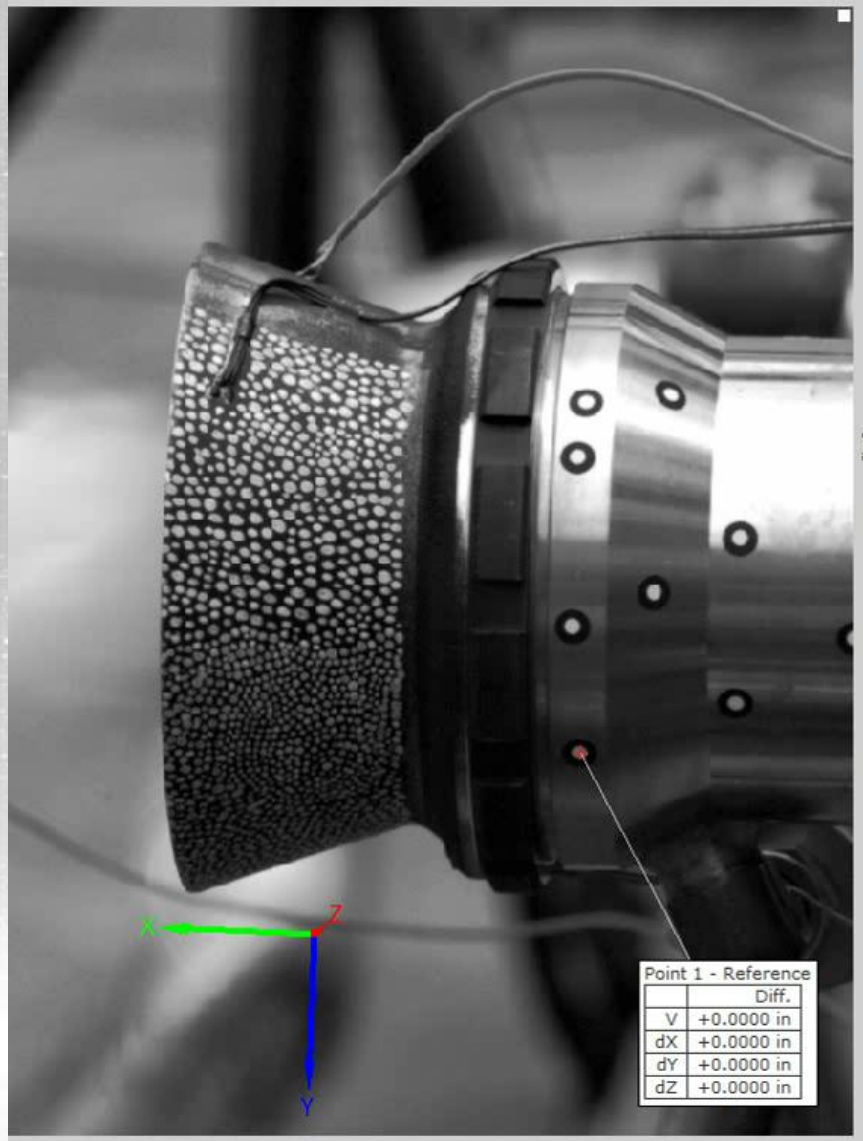
Test Photos and Data Collection:
Paul Gradl
Gilbert Handley
Sandy Elam Greene

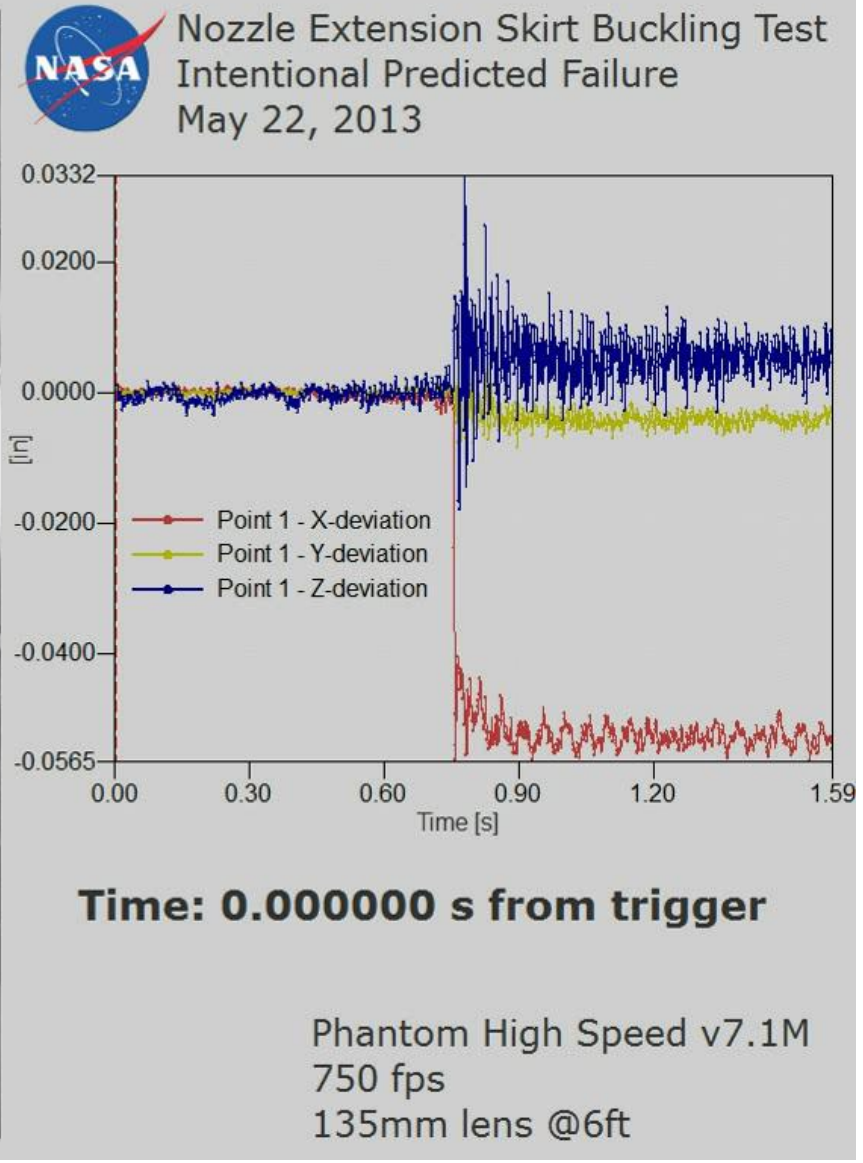




Additively Manufactured Nozzle Extension

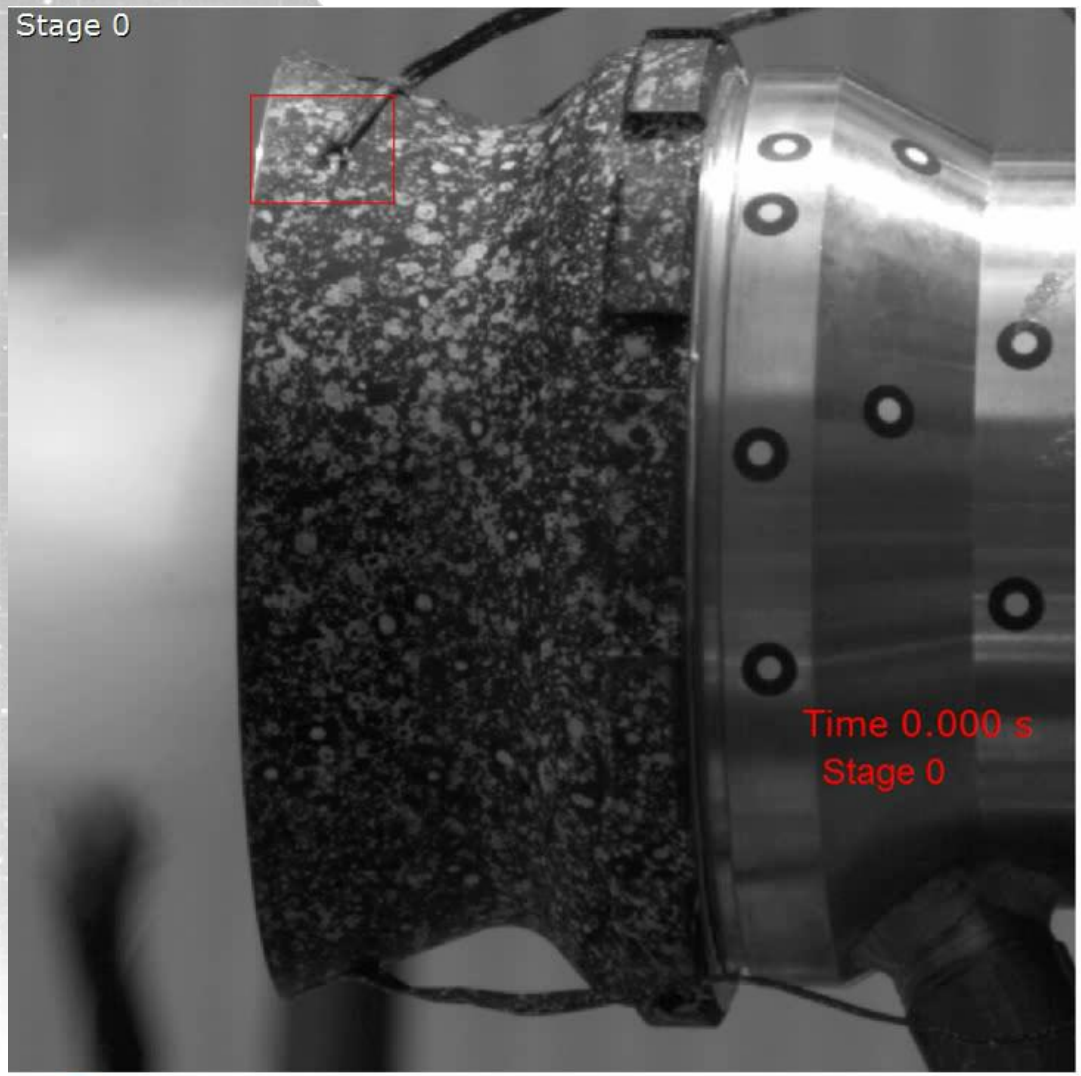
Bench Testing Doesn't Always Translate into the Field…

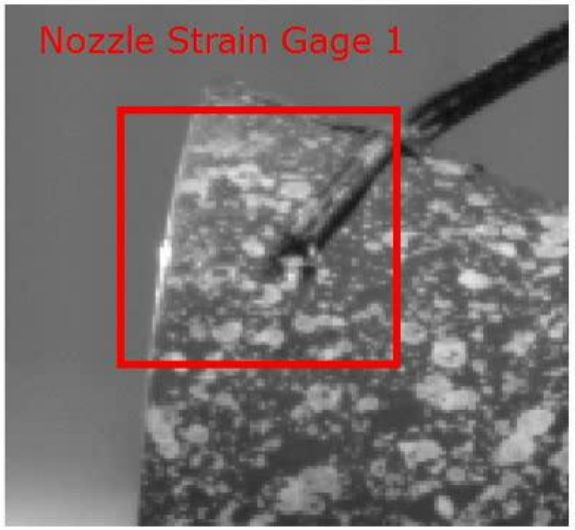


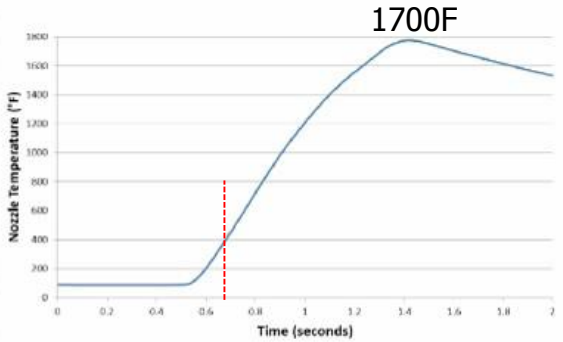


VIDEO

Motivation to Develop Technique







Strain Gage Failure at ~400F

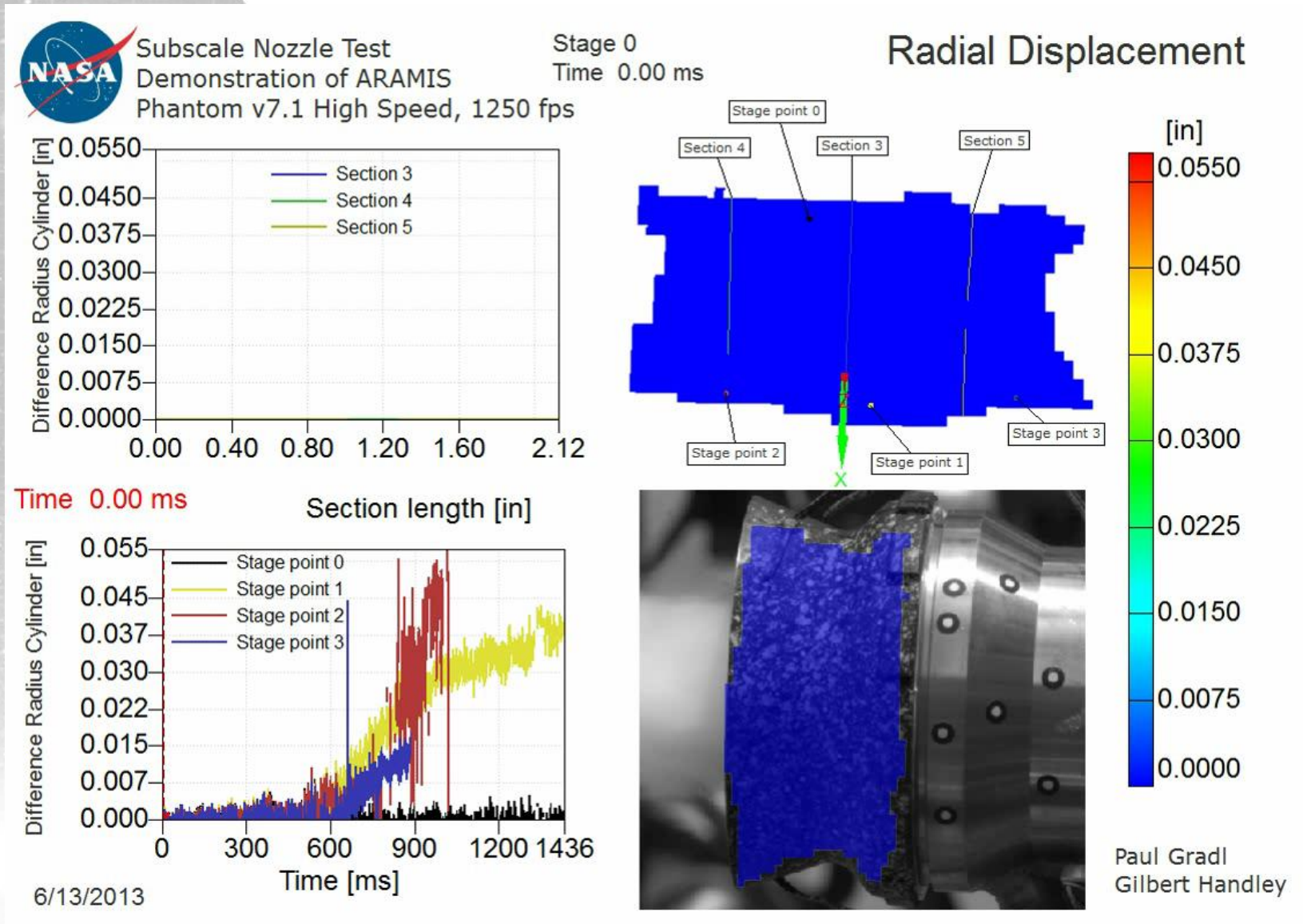
Subscale Nozzle Hotfire Demonstration
Phantom v7.1 M, 1250 fps

6/13/2013

Paul Gradl
Gilbert Handley

VIDEO

Subscale Hotfire Testing on Nozzle



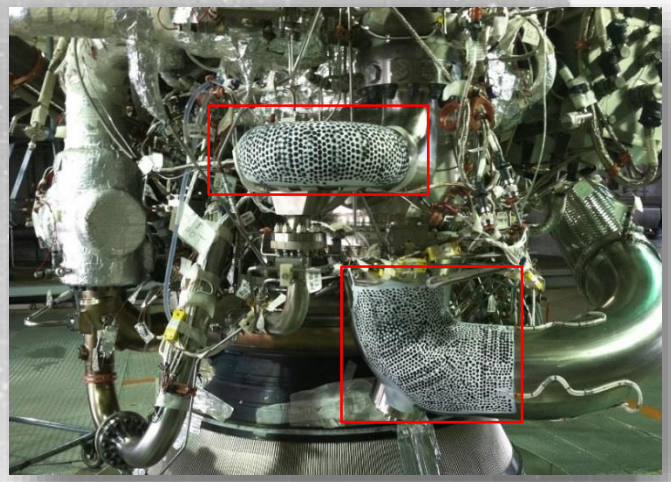
VIDEO

Large Scale D.I.C. for Engine Hotfire Testing

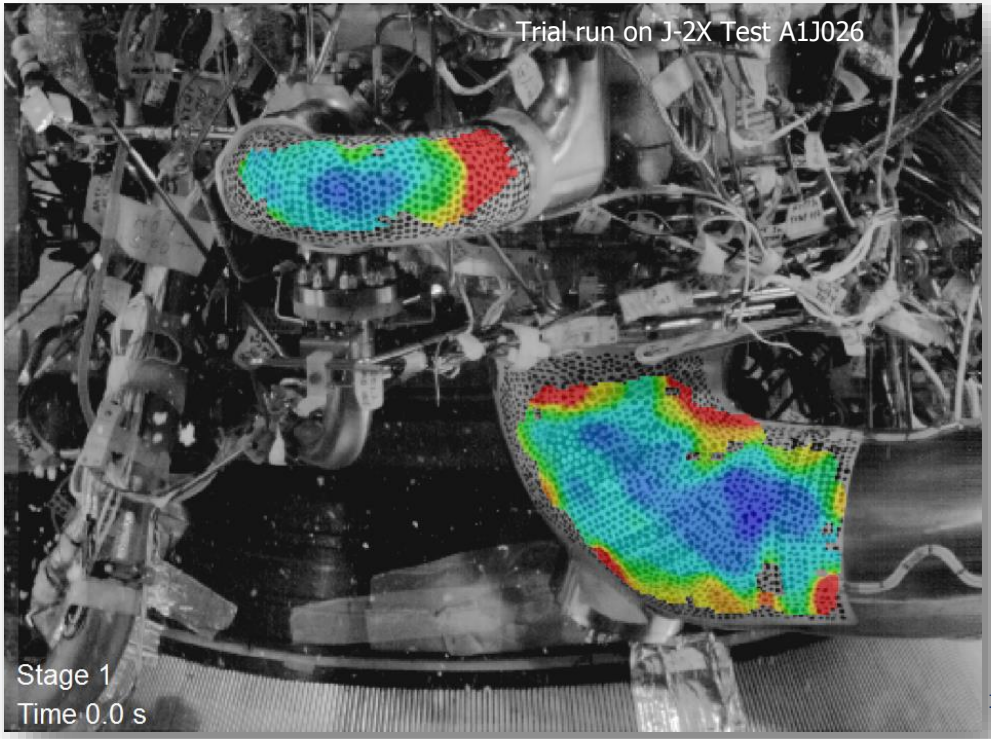
MSFC has developed new optical measurement techniques to augment or replace traditional gages in harsh environment engine testing or manufacturing operations

Stereo high-speed cameras measure full-surface displacements and strains using "speckle pattern" (calibrated triangulation)

- Leveraged basic techniques from NESC Shell Buckling Test and NASA & industry experts
- Developed speckle pattern and initial vibration damping in subscale hotfire testing at MSFC
- J-2X provided the test-bed environment to develop camera stability damping
- Industry-first attempt for high temperature, high vibration environments where traditional gages do not operate reliably



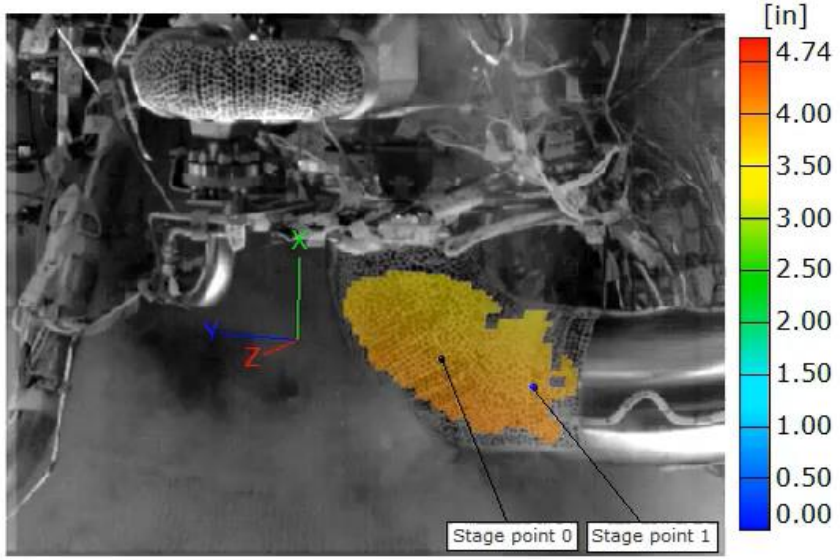
Stereo Cameras installed and Speckle Pattern Applied at Stennis A1 Stand

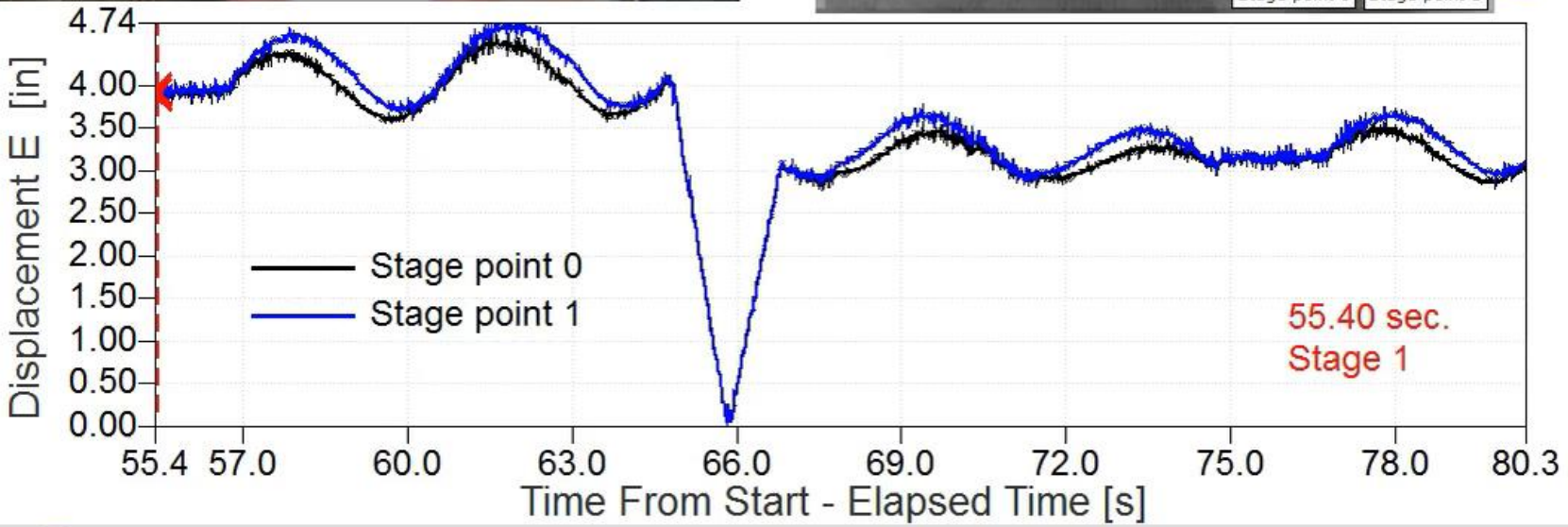


ARAMIS high speed cameras

Test Data Collection:
Paul Gradl, Gilbert Handley, Brian West

ARAMIS Full Surface Strain Measurement Proof of Concept
Displacement during A1J028 Test





ARAMIS Trial on J-2X A1J028

Paul Gradl
Gilbert Handley

Displacement E (Total X, Y, Z)

VIDEO

2.75” Hydra Testing Demo

Test Support: Paul Gradl/MSFC, Cory Medina/MSFC, John Tyson/Trilion, John “*Yanni*” Psilopolous/Trilion

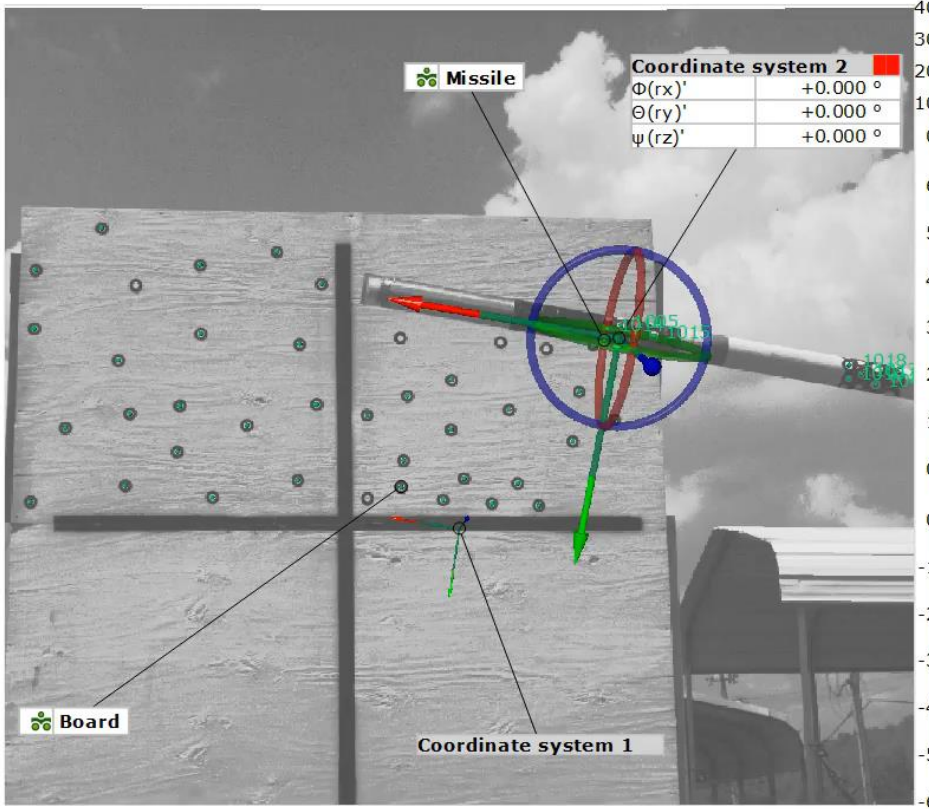
Demonstrated initial feasibility of using photogrammetry and digital image correlation for range testing of missile burst testing.

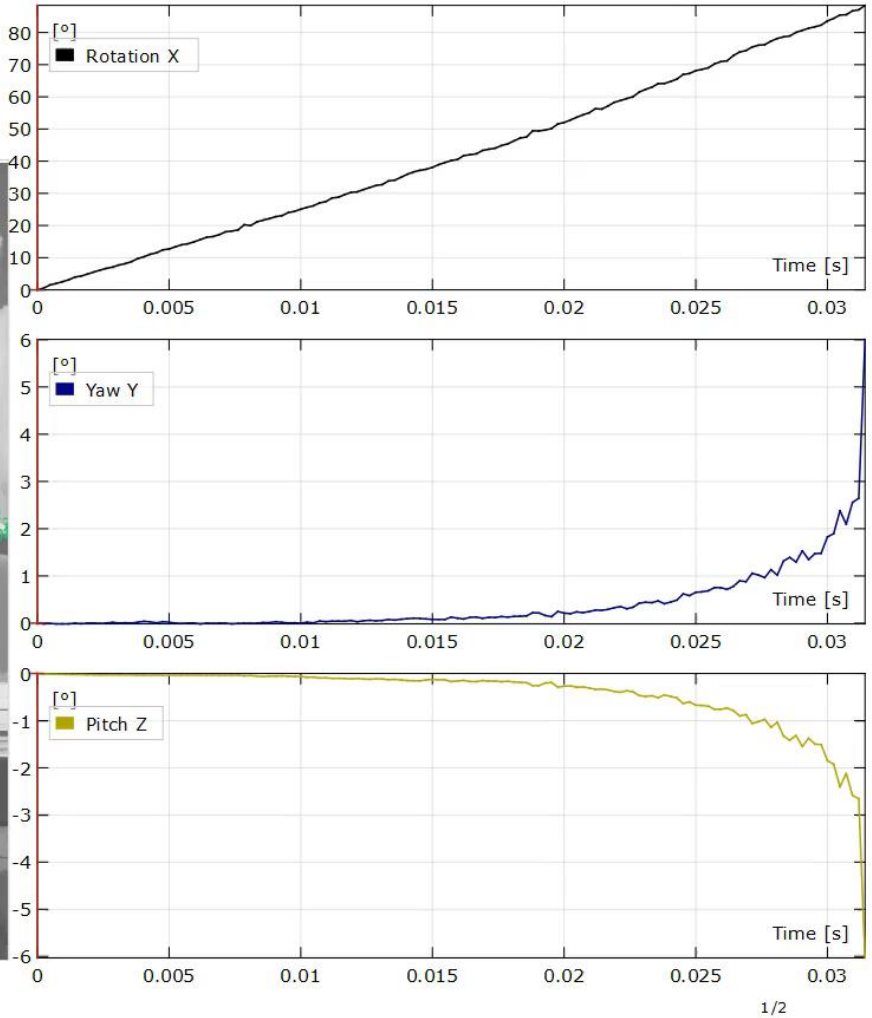
Feasibility of 6-dof Analysis of Missile Testing

Report - PONTOS Testing

Test 62 - TM1 Hydra Missile Testing

Test Data provided:
Paul Gradl and Cory Medina





VIDEO

Where are we going with this technology?

NASA will continue to advance this technology for rocket engine testing, subscale testing, component testing and bench top testing

- Replace traditional measurement systems
- Integrate with modern analysis tools
- Combine advanced techniques such as IR thermography and digital image correlation

NASA and AMRDEC have signed agreements to advance and develop the technology further

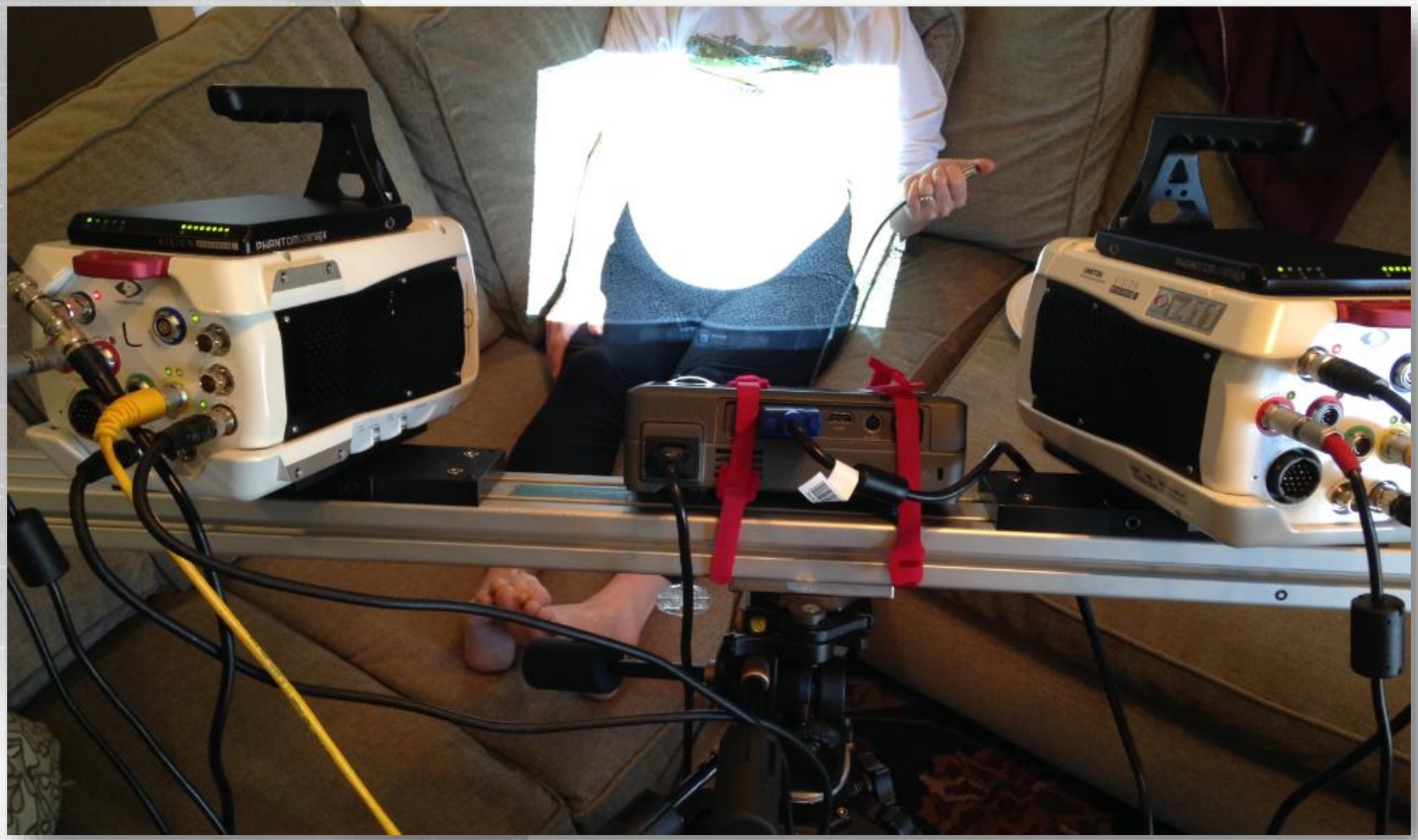
- Further develop techniques for harsh environments
  - Liquid rocket engine testing
  - Missile range testing
  - Static solid motor testing
- Lab environment, modal and dynamic testing

Share lessons learned with industry and government through technical papers and presentations

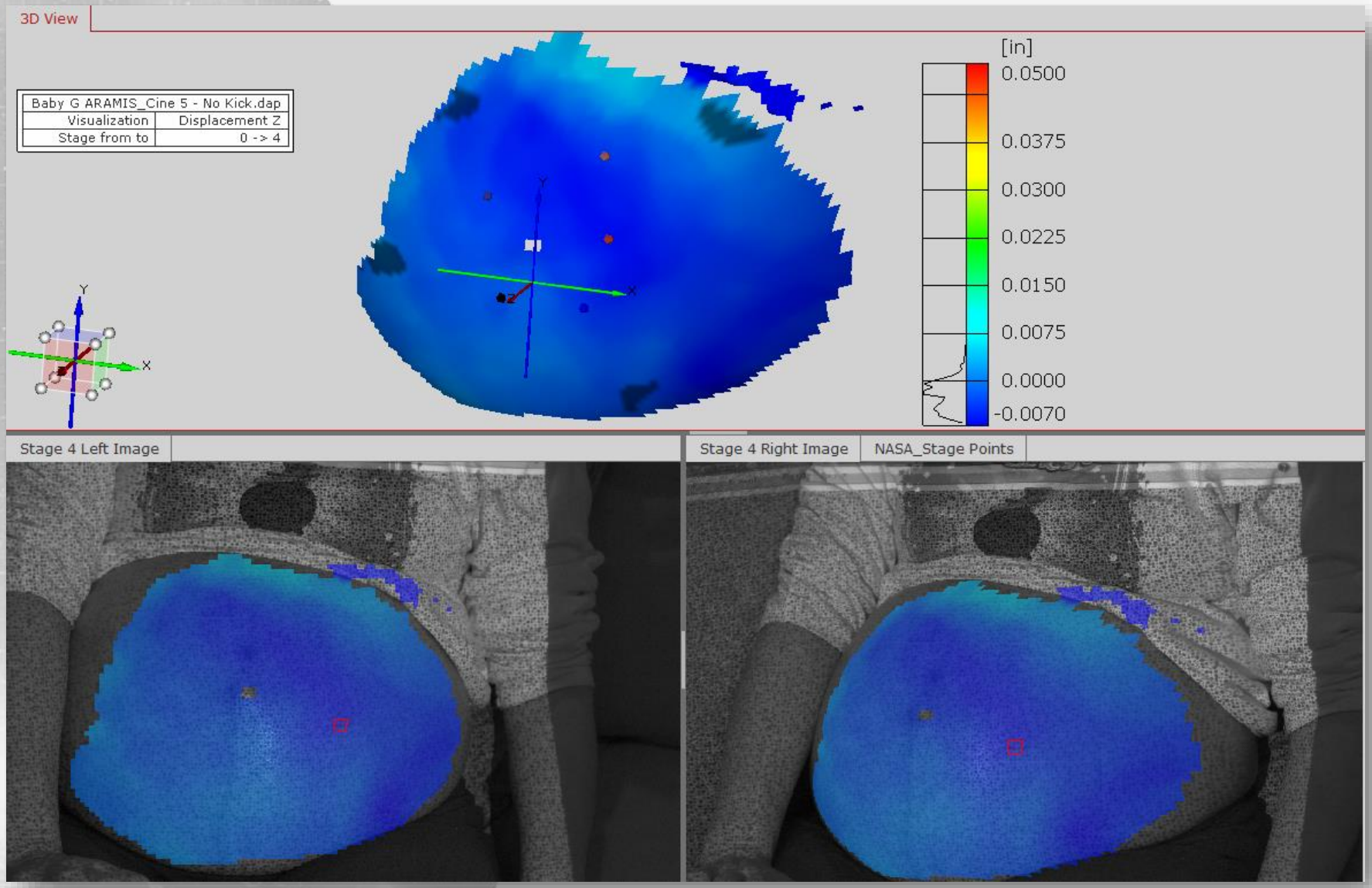
The possibilities of dynamic data collection are endless…

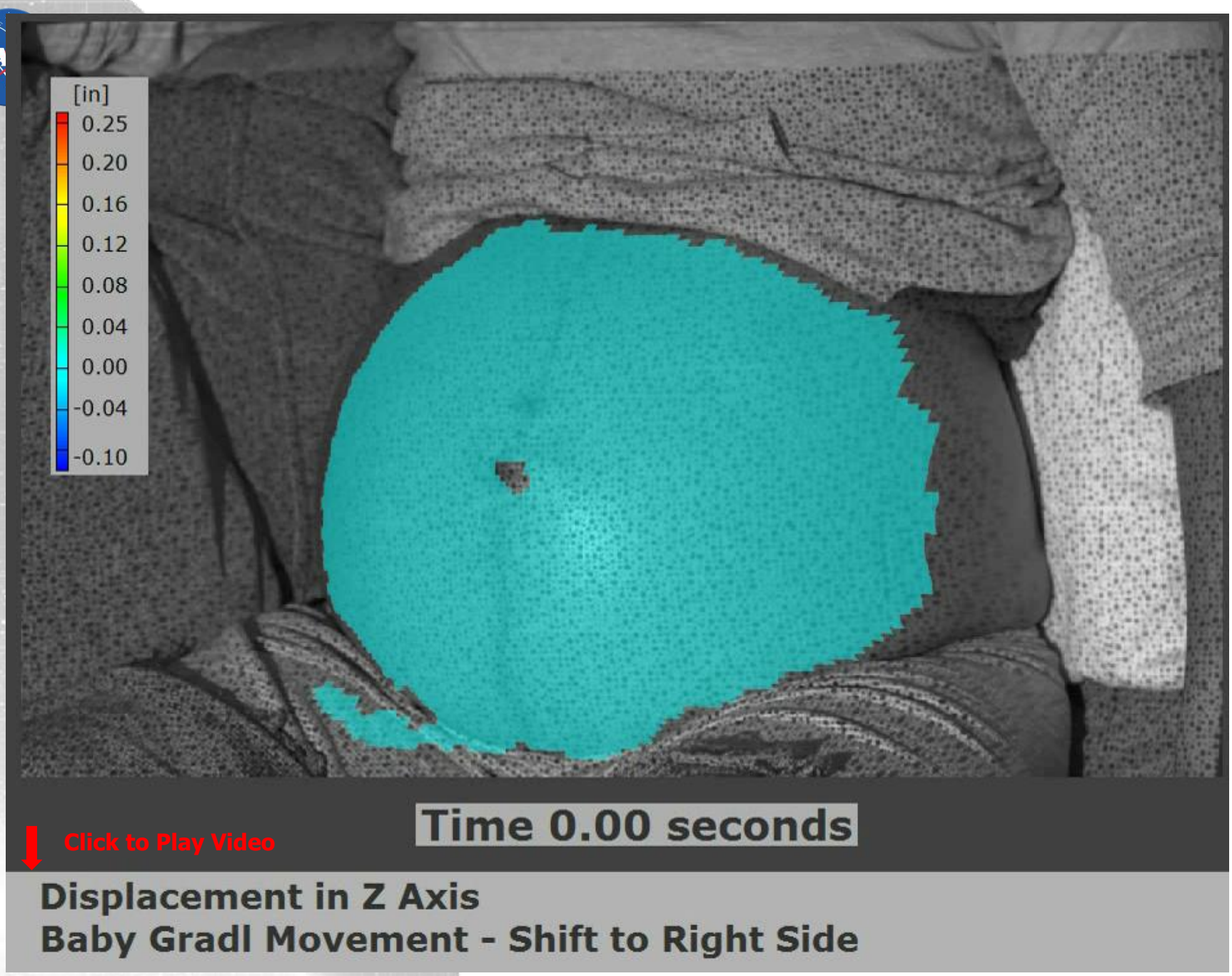
Dynamic responses require an input to excite the system…

Images were collected using a projected pattern instead of painting a speckle pattern on her belly…
High Speed cameras were post triggered after movements felt.

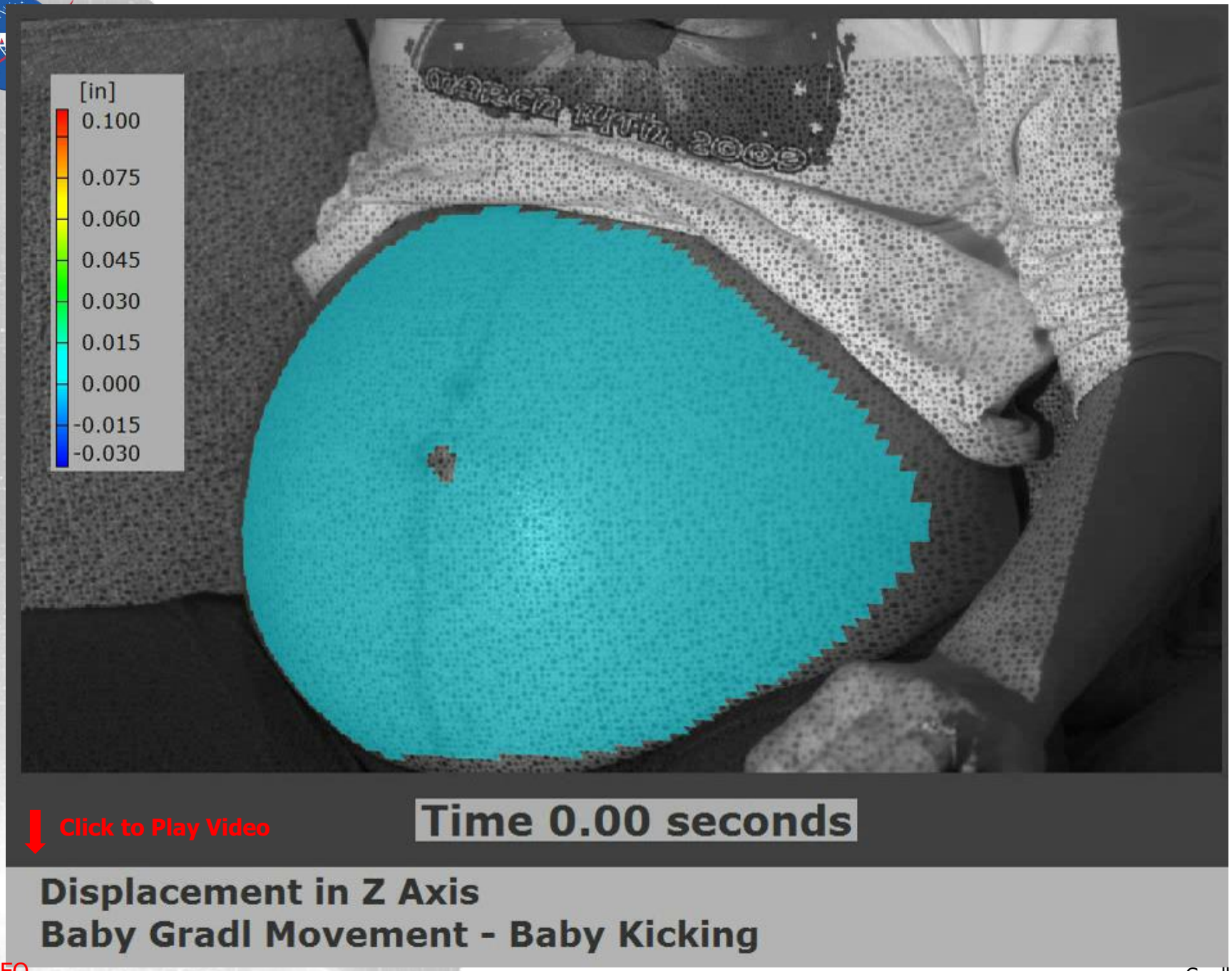


To ensure that kicks and movement data was real a background test was conducted with no baby movement (to correct for breathing and body motion)

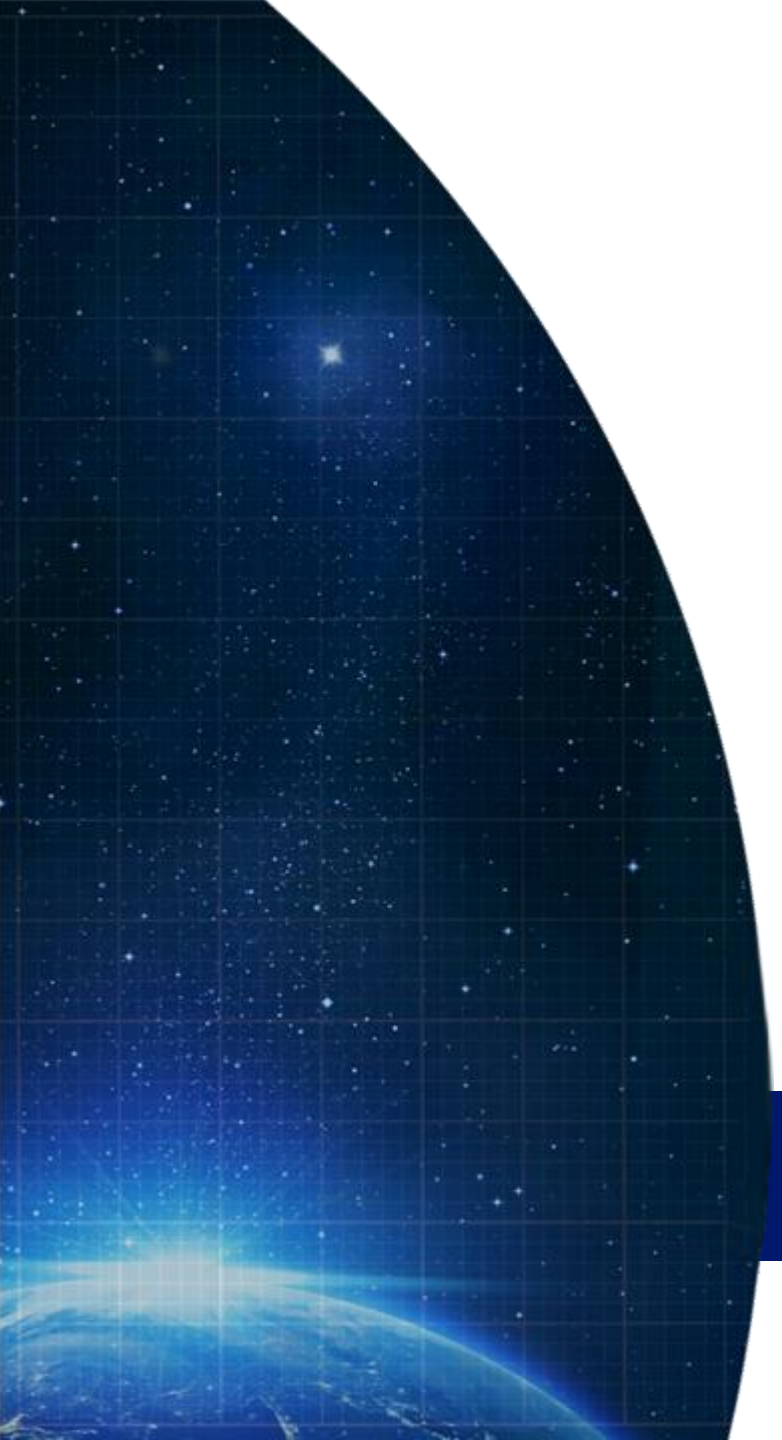



[in]
0.25
0.20
0.16
0.12
0.08
0.04
0.00
-0.04
-0.10
Time 0.00 seconds
Click to Play Video
Displacement in Z Axis
Baby Gradl Movement - Shift to Right Side

VIDEO


[in]
0.100
0.075
0.060
0.045
0.030
0.015
0.000
-0.015
-0.030
Click to Play Video
Time 0.00 seconds
Displacement in Z Axis
Baby Gradl Movement - Baby Kicking

VIDEO



Contact: Paul Gradl
NASA MSFC
256.544.2455
Paul.R.Gradl@nasa.gov

BACKUP

References

Gradl, P.R. “Dynamic Measurements for Rocket Engine Hotfire Testing.” Trilion Quality Systems Optical Metrology Workshop, Huntsville, AL on June 20, 2013

Gradl, P.R. “Application of Optical Measurement Techniques during Fabrication and Testing of Liquid Rocket Nozzles.” Paper presented at 62nd JANNAF Propulsion Meeting/8th Liquid Propulsion Subcommittee, June 1, 2015. Nashville, TN

Gradl, P.R. “Digital Image Correlation Techniques Applied to Large Scale Rocket Engine Testing.” To be presented at AIAA Joint Propulsion Conference, Salt Lake City, UT. July 2016.

Black, R., Gradl, P.R. “Resurrecting the F-1 – 3D Scanning to Digitally Capture the Saturn V Main Engine”. Capture 3D Measurement Innovation 2012, August 23, 2012. Costa Mesa, CA.

Gradl, P.R. “Application of Optical Measurement Techniques during Stages of Pregnancy”. To be published in Summer 2016, TBD.

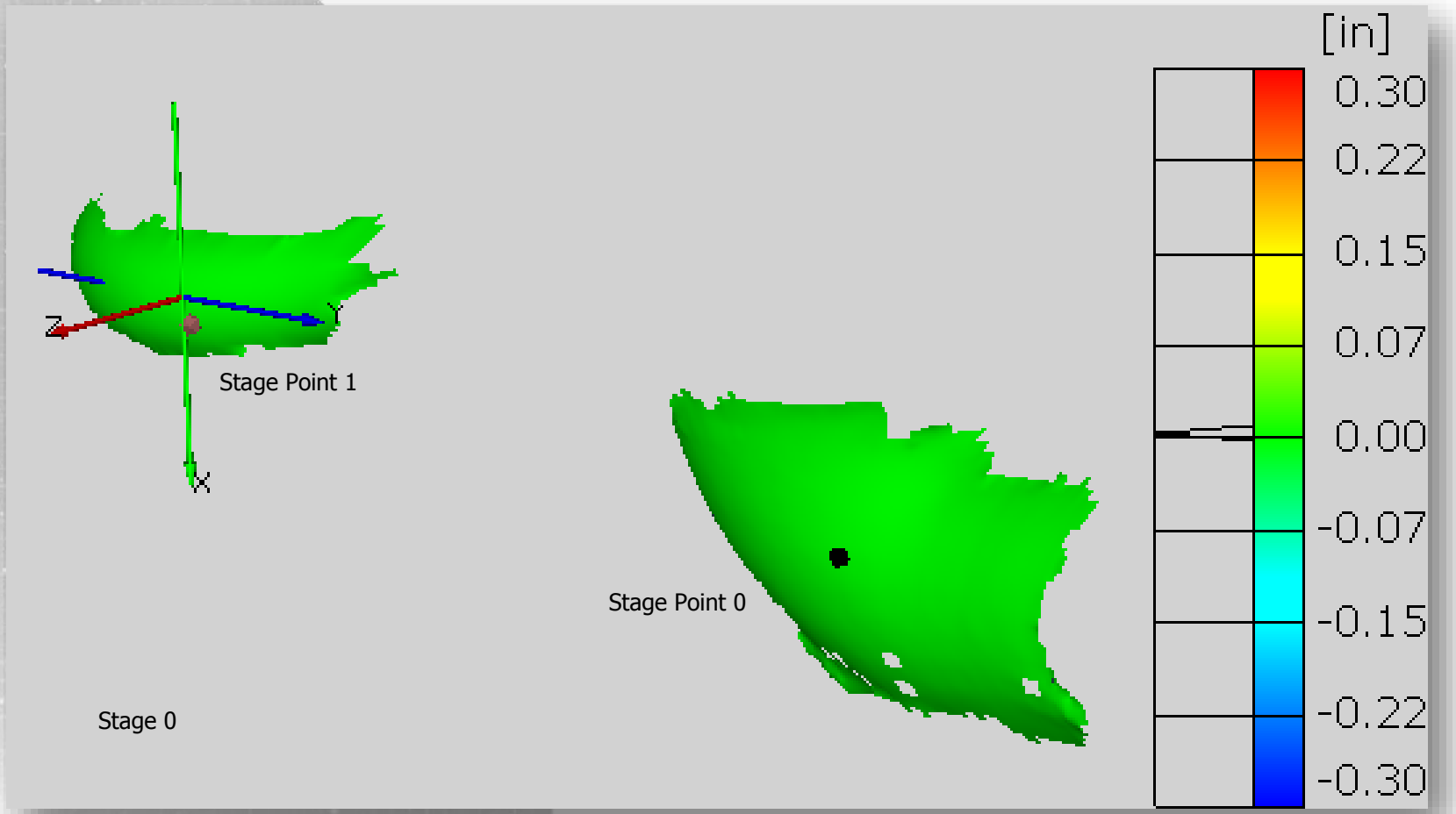
Kynard, M., Gradl, P.R. Town Hall Panel. “Where’s My Apollo Vision for the Future?”. Structured Light and D.I.C. presented to forum at AIAA Propulsion and Energy 2014, Cleveland, OH.

Cannon, J., Gradl, P.R. Status of Liquid Engines Optical Measurement Techniques presented to Integrated High Payoff Rocket Propulsion Technology (IHPRT). Presented September 2012, April 2013, March 2014.

Gradl, Paul. “Digital Image Correlation Techniques Applied to Large Scale Rocket Engine Testing”. To Be Presented at AIAA Joint Propulsion Conference. July 25-28, 2016.

Gradl, Paul. “Rapid Fabrication Techniques for Liquid Rocket Channel Wall Nozzles”. To Be Presented at AIAA Joint Propulsion Conference. July 25-28, 2016.

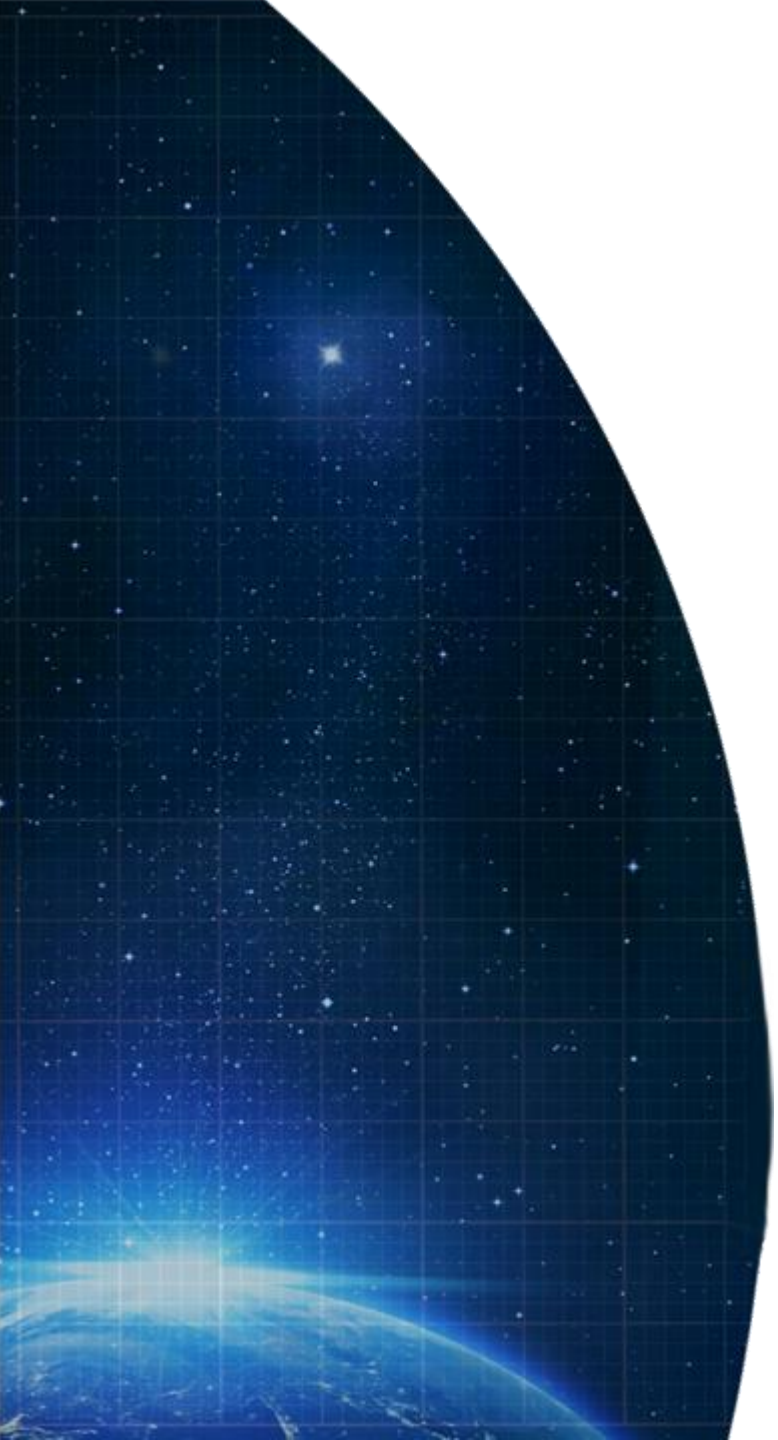
ARAMIS Full Surface Models from Data Collection



Full 3D surface data collected for each "stage" or period of time

Presenter Biography

Paul Gradl is a senior propulsion engineer in the Propulsion Division, Combustion Devices Design and Development Branch, at NASA Marshall Space Flight Center (MSFC). He leads manufacturing, design, development and testing of liquid rocket engine nozzles and nozzle extensions and has supporting a variety of nozzle development and flight programs over the last 12 years. These programs include large scale tube wall and channel wall nozzles, additive manufacturing (3D printing of metal) of nozzle components, novel approaches for channel wall closeouts and hotfire testing of nozzles and combustion chambers. Paul has been involved and led technology development supporting a variety of combustion chamber and nozzle manufacturing techniques for nozzles and recently advanced optical measurement techniques (Digital Image Correlation and Dynamic Photogrammetry) for use during component manufacturing and test. He has authored and co-authored over 14 journal articles and conference papers and holds a patent in his field. Paul has a bachelor's degree in Mechanical Engineering and MBA from Gannon University as well as a Masters in engineering from University of Alabama Huntsville. Mr. Gradl has received numerous NASA and industry awards including two NASA Exceptional Achievement Medals, MSFC Research and Technology, NASA Technology Transfer, Engineering Partnership Award, ARES Program Made It Happen, MSFC Certificate of Appreciation, and was a NASA Space Flight Honoree.




NASA