

Correcting Thermal Deformations in a Meter-Scale Reflector System using Piezocomposite Actuators

S Case Bradford

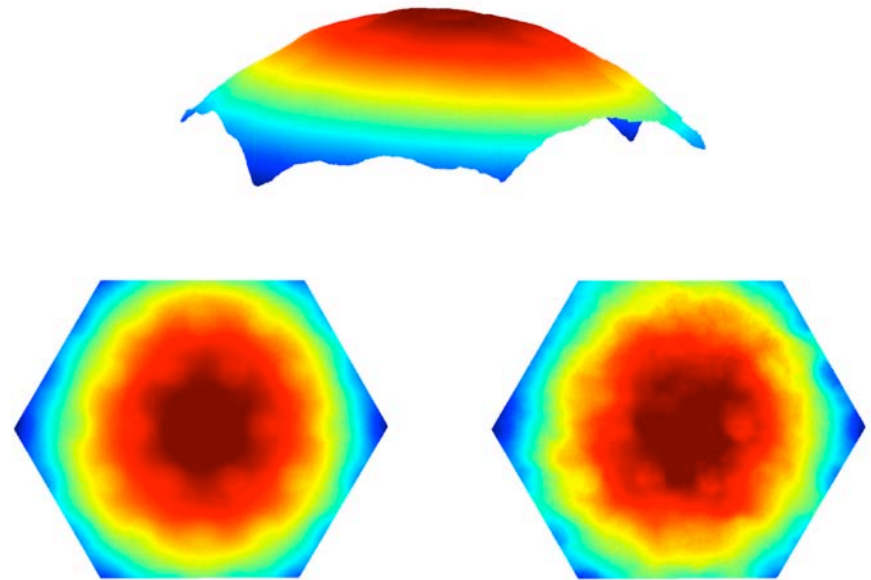
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Jet Propulsion Laboratory,
California Institute of Technology

W Keats Wilkie

NASA Langley Research Center



$\bar{w}$

$$\bar{u} = \left(\frac{d\bar{w}}{d\bar{u}} \right)^{-1} \bar{w}$$

22-23 SEPTEMBER 2011

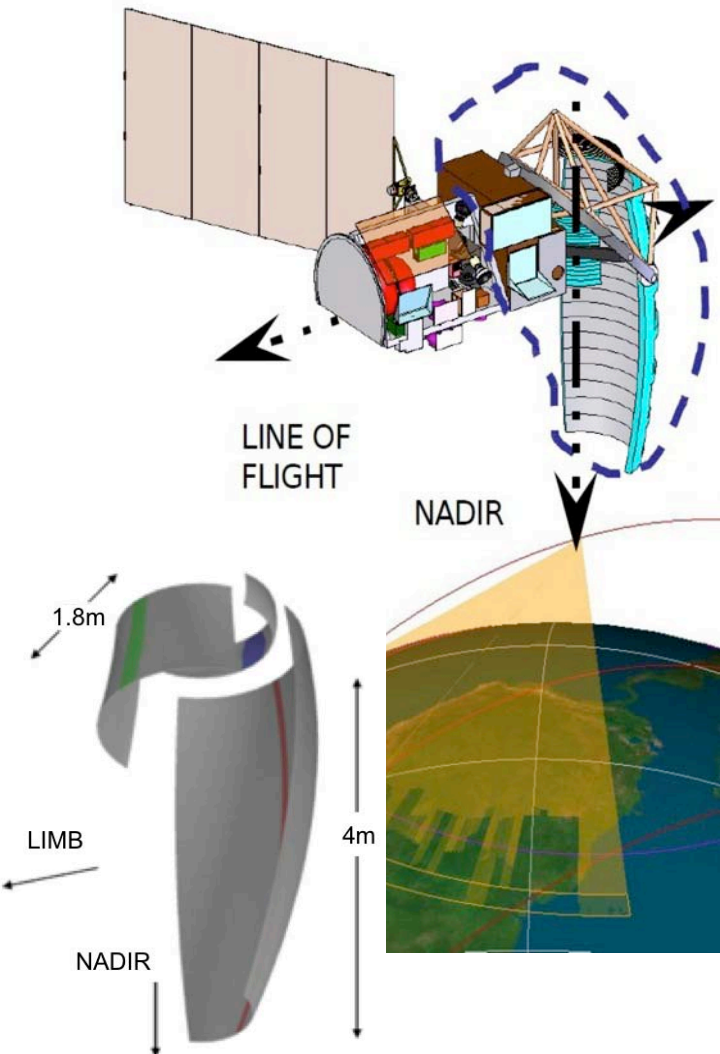
International Symposium on Piezocomposite Applications
Dresden, Germany

OUTLINE

- Active Composite Reflector Concept and Development
 - Scanning Microwave Limb Sounder
 - MFC Actuators
- Test Facility: Advanced Large Precision Structures Laboratory
 - Precision Environment Test Enclosure
 - Speckle Laser Holography Interferometer
- Active Composite Reflector Testing
 - Wavefront and Surface Control
 - Thermally-induced Deformations
- Bench-scale Active Reflectors
 - Absolute Surface Measurement and Control

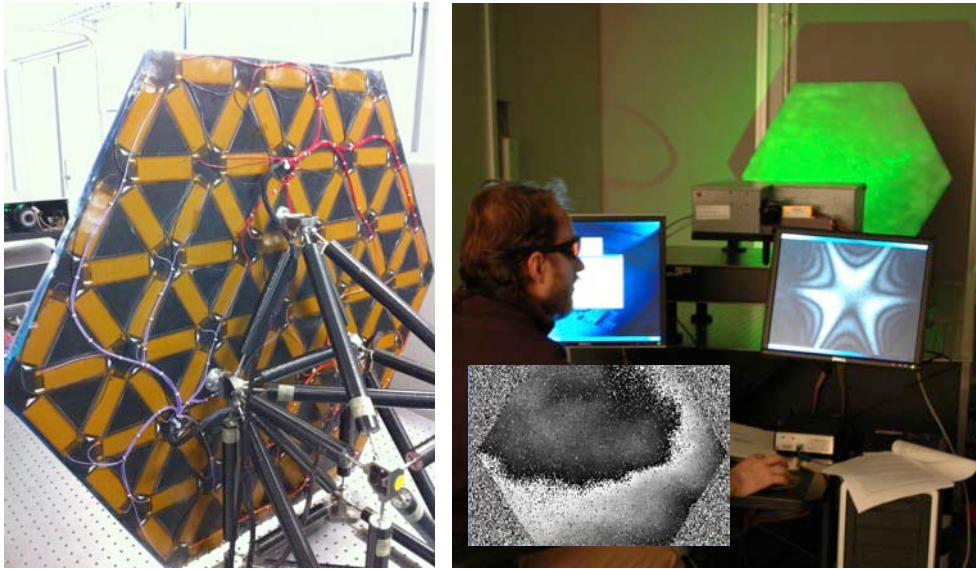


Large, high-precision composite reflectors for future space missions are likely to be costly to manufacture and heavy, e.g., SMLS



- Scanning Microwave Limb Sounder instrument (SMLS)
 - SMLS features a very large (4 m) composite primary reflector
 - Surface shape error tolerance: 12 micron RMS
 - SMLS mission orbit presents a challenging thermal environment for large, exposed reflectors
- Constructing a large composite reflector that can maintain its required shape in this thermal environment will be difficult
 - Expensive to manufacture to required tolerances
 - Purely passive structure can be very heavy
- An active composite reflector capable of adjusting its shape in situ to maintain required tolerances can be:
 - Cheaper to manufacture (less manufacturing precision needed as shape is correctable)
 - Lighter (reduced structural mass needed to maintain required shape; again, correctable)
- *We are investigating the feasibility of active composite reflectors as alternatives to purely passive reflector designs*

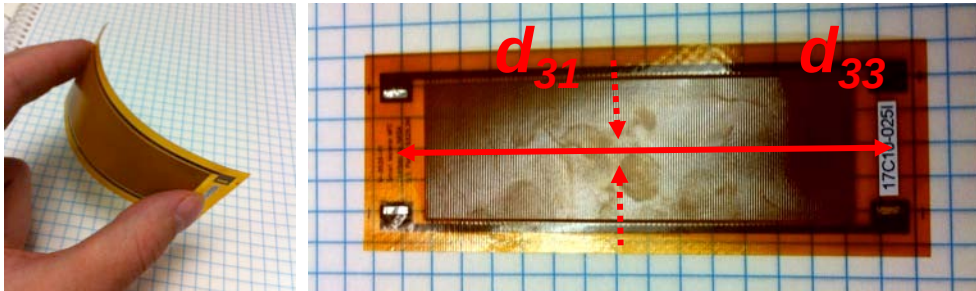
Active Composite Reflector Testbed



Our testbed article is an array of flat piezo-electronic composite actuators embedded in the back face sheet of a 0.8 m lightweight reflector panel.

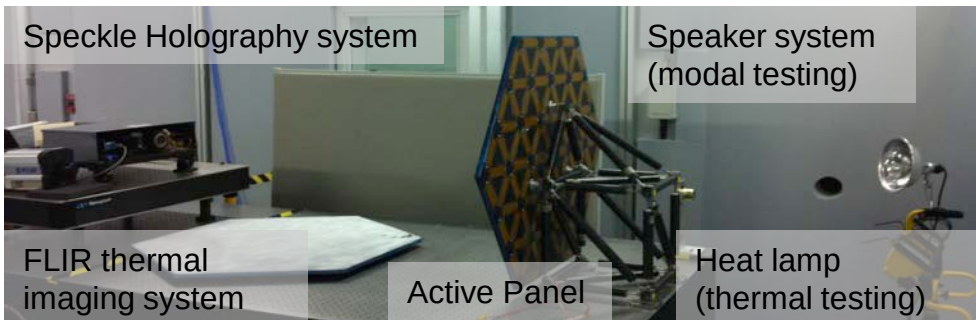
- 90 individually addressable actuators

Speckle Laser Holography Interferometer measures surface deformations (relative) to better than 25 nm over a 2 m field of view for both static and dynamic testing.



The actuators use interdigitated electrodes to transfer applied voltage to a flat sheet of piezoelectric fibers. The resulting actuator is thin and flexible, suitable for embedding in existing manufacturing processes or for retrofitting an existing panel.

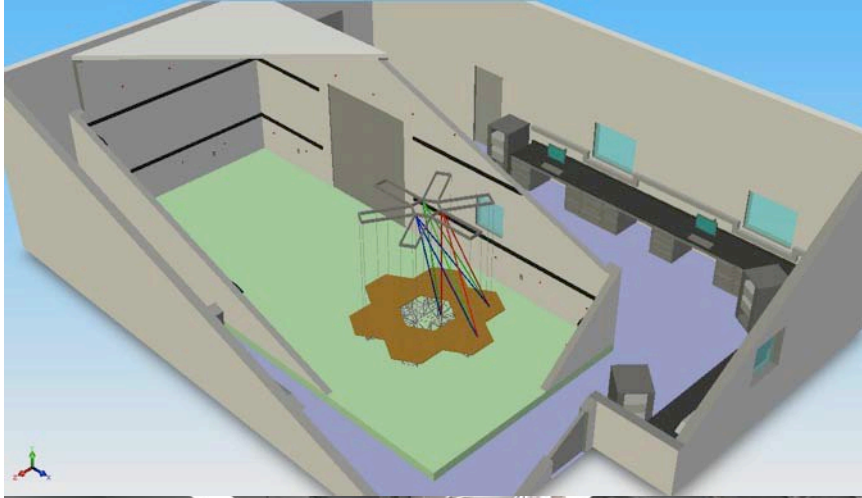
- Recognized as “NASA invention of the year” (March 2007)
- Flew aboard STS-128 (March 2008)



National Aeronautics and Space Administration
Jet Propulsion Laboratory
California Institute of Technology



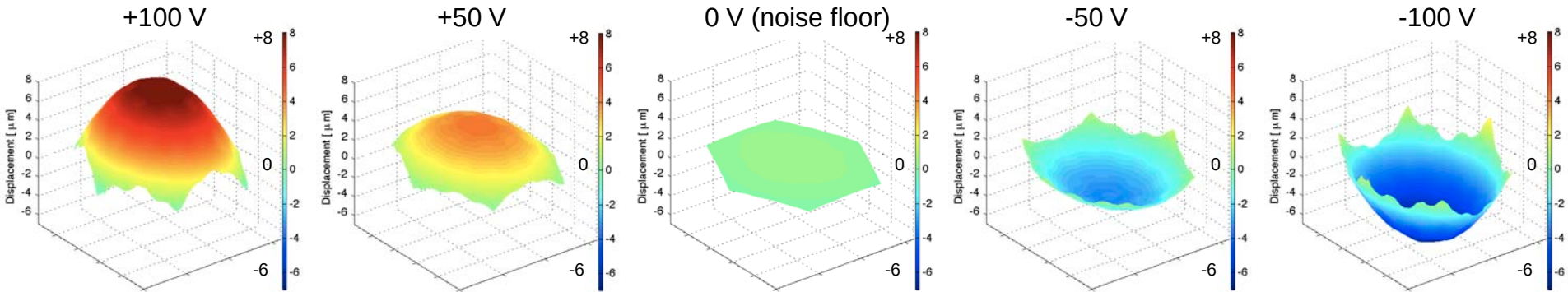
Precision Environment Test Enclosure



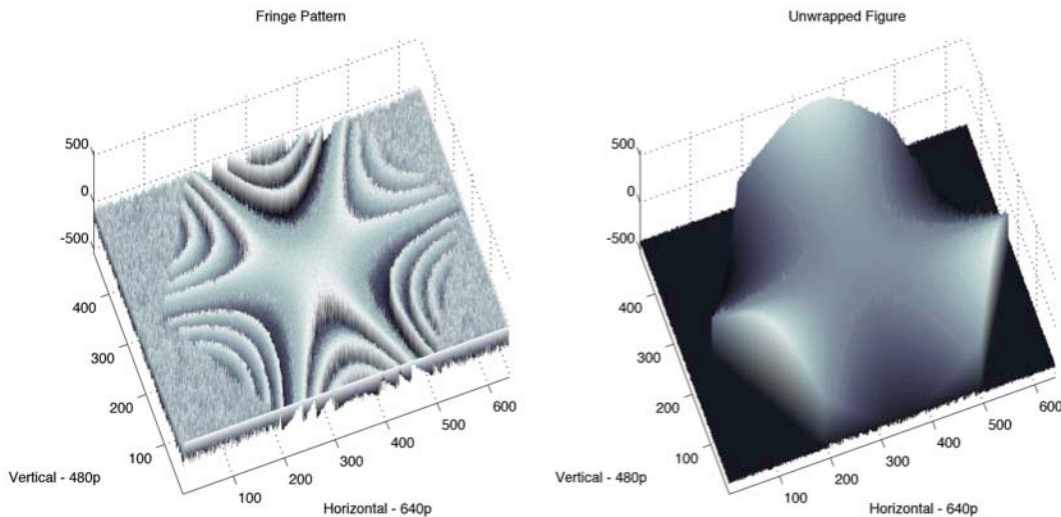
JPL Precision Environment Test Enclosure (PETE):
CAD view of the PETE inside Building 299 cleanroom,
photograph of PETE with 8m deployable structure
(SABUR - JPL/ATK/AFRL/CSA).

- **Precision Environment Test Enclosure (PETE)** in Advanced Large Precision Structures Laboratory clean room
 - 10m x 5m x 3m test enclosure, mounted on isolator bearings. The PETE has structural mount points on walls and ceiling suitable for gravity offload systems, with a reinforced floor grid.
 - Provides thermal (< 0.01 deg C per hr) and seismic (< 0.0001 G rms) and acoustic (< 35 dBA) stability for precision testing.
 - Dedicated metrology systems for the characterization of test hardware.
- The **Active Composite Reflector** testbed requires the thermal and vibration stability of the PETE. Displacement measurements and surface control at ~ 25 nm resolution would otherwise require a vacuum chamber to remove the effects of air-path disturbances.

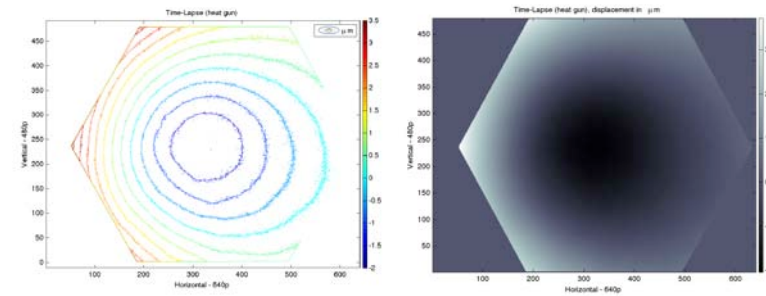
Active Composite Reflector



Investigations into actuator authority across a ± 100 V range (actuators have a useful operating range of -500 to +1500 V)

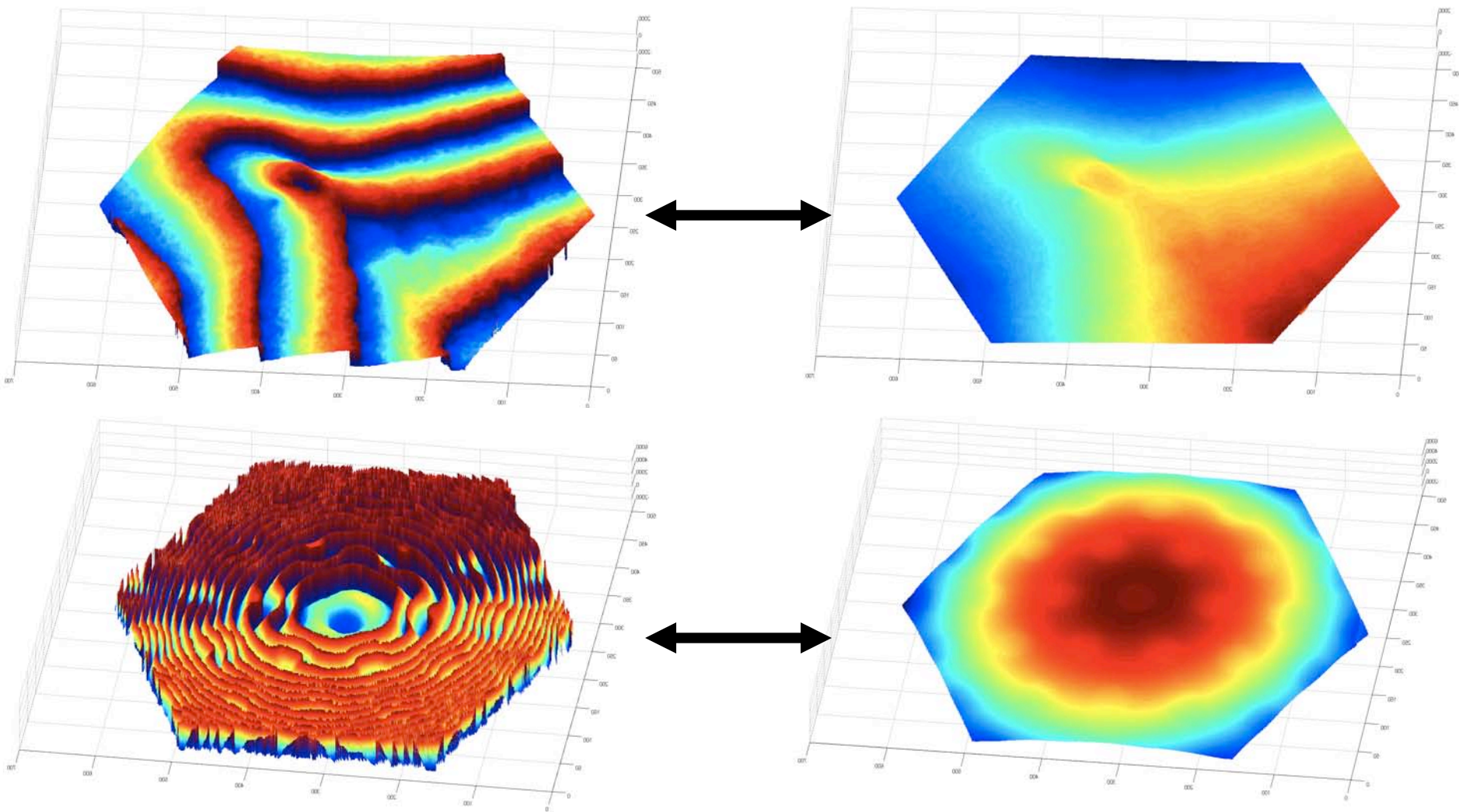


*Fringe pattern (L) and phase-unwrapped dynamic mode shape (R);
380 Hz trefoil mode, acoustic excitation source*

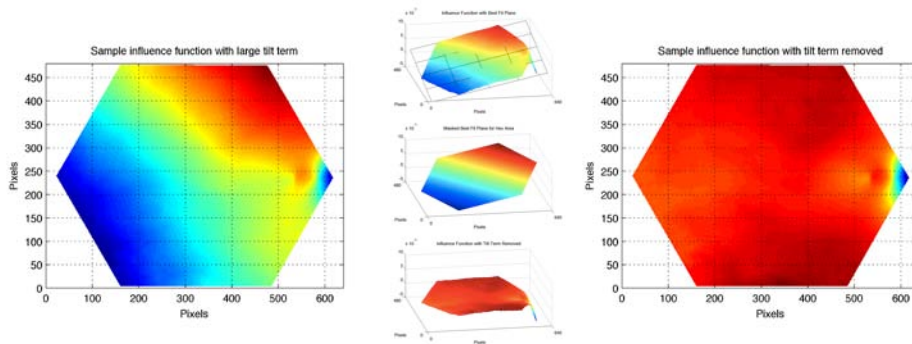


*Thermal deformation measurement; heat gun
directed at back face sheet*

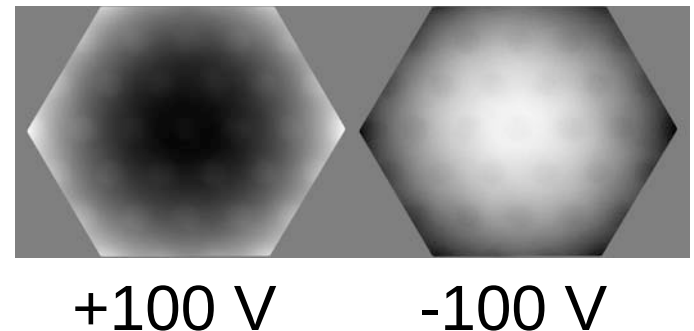
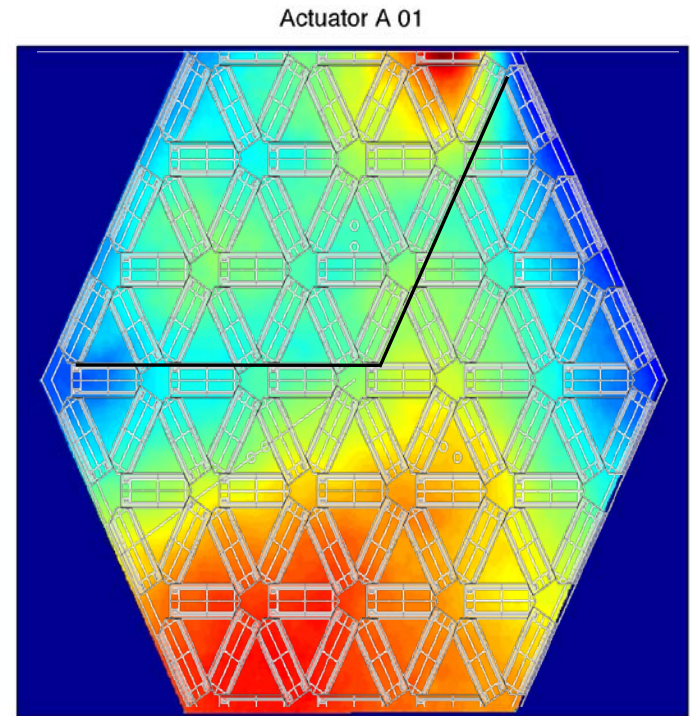
Unwrapping Fringes



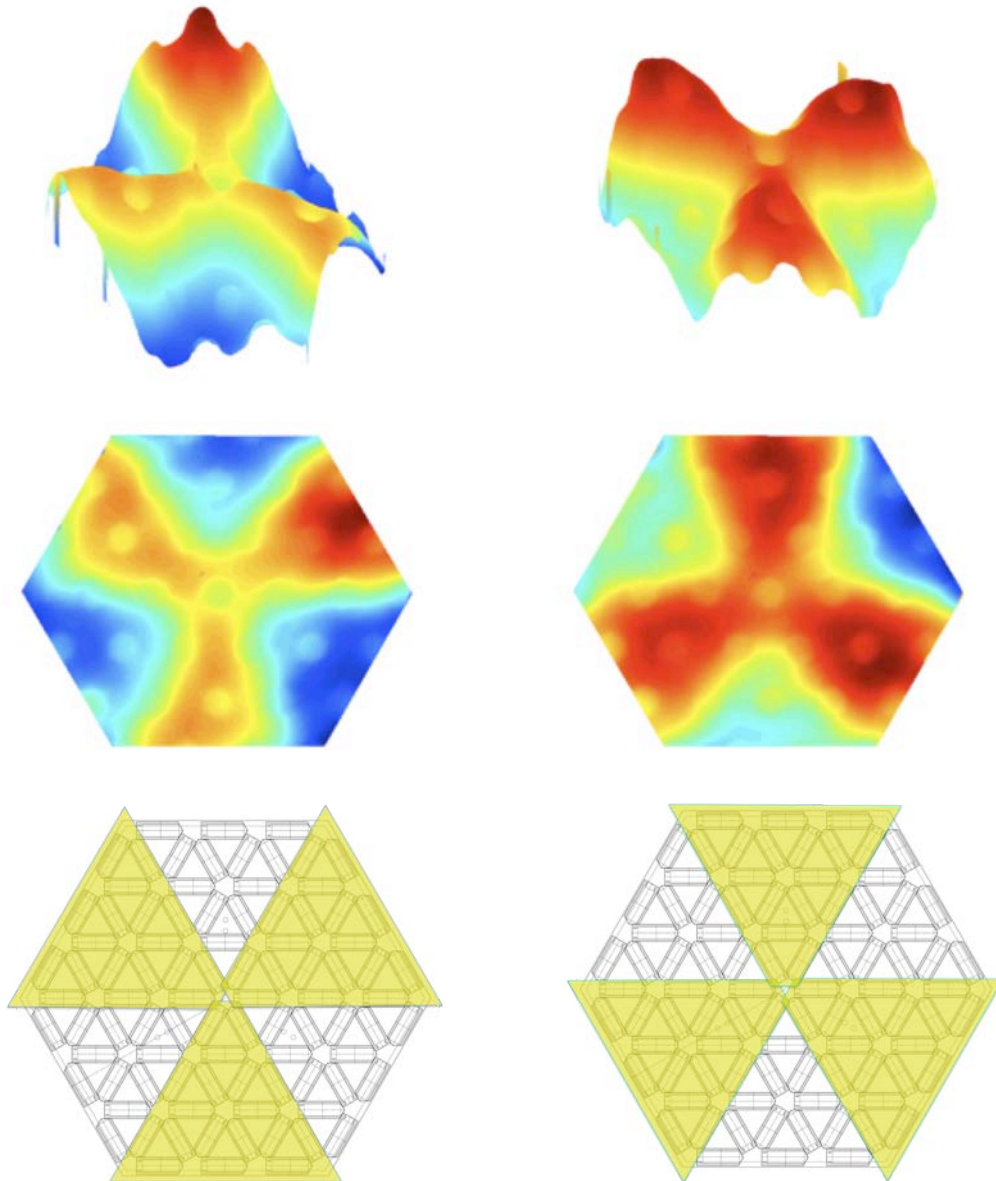
Active Composite Reflector



- Investigations into individual actuator authority: measuring each actuator to determine the influence on surface flatness.
- Driving all actuators with the same voltage generated displacements in the power/focus mode (note printthrough effects).

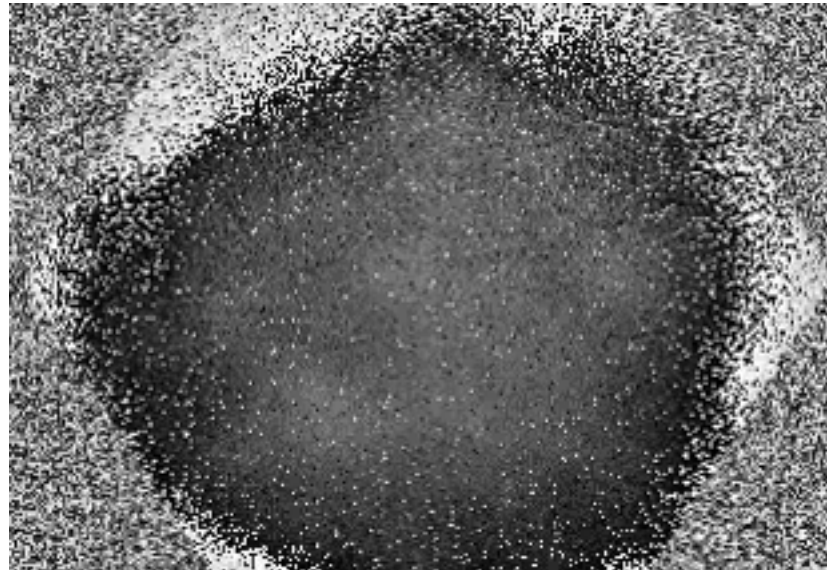


Active Composite Reflector

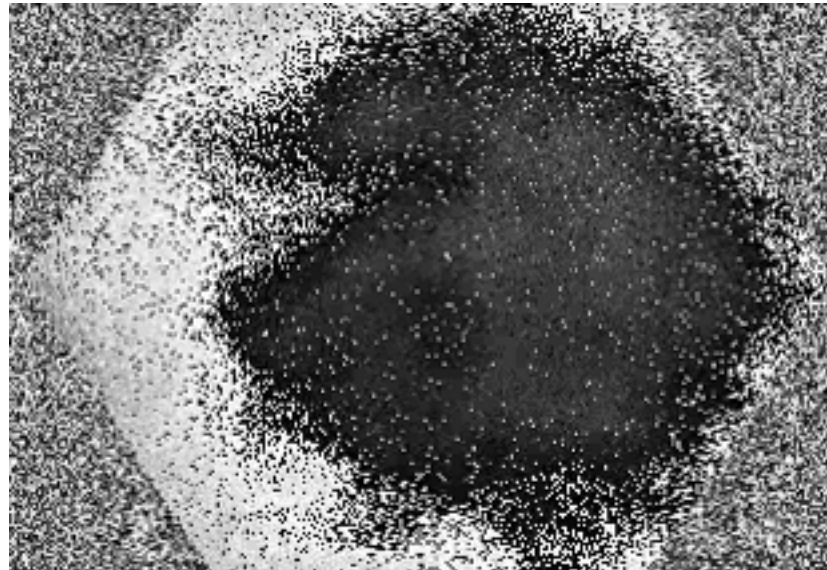


- Different shapes can be driven by wiring batches of actuators to receive a common signal. Here a 100 V pattern is applied to the shaded yellow actuators only.
- More complicated profiles address each actuator individually.

Reflector Surface Measurement



Reflector Surface Measurement



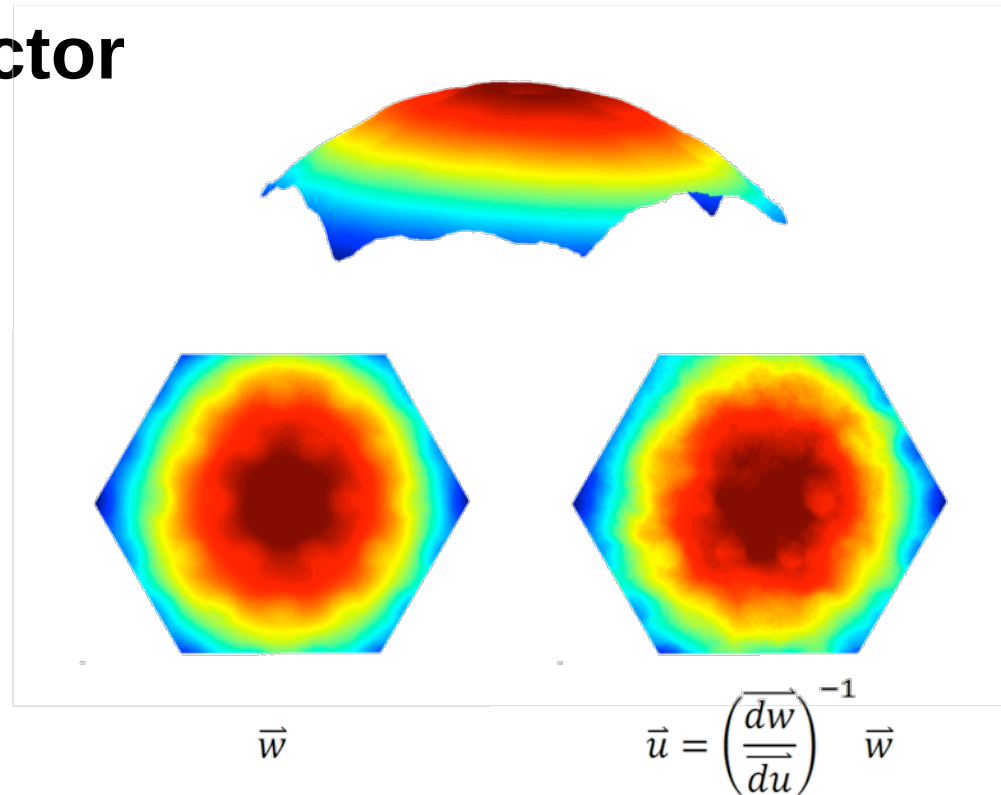
Active Composite Reflector

- A modeled wavefront can be expressed as a product of a sensitivity matrix with a set pattern of input voltages:

$$\vec{w} = \left(\frac{\overrightarrow{dw}}{\overrightarrow{du}} \right) \vec{u}$$

- Inverting this equation:

$$\vec{u} = \left(\frac{\overrightarrow{dw}}{\overrightarrow{du}} \right)^{-1} \vec{w}$$



$\vec{u}$

Voltage profile [number of actuators x 1]

$\vec{w}$

Wavefront [number of pixels x 1]

$\left(\frac{\overrightarrow{dw}}{\overrightarrow{du}} \right)$

Influence function matrix
[number of actuators x number of pixels]

Active Composite Reflector

$$\begin{pmatrix} \overrightarrow{dw} \\ \overrightarrow{du} \end{pmatrix} = \begin{bmatrix} \text{Hexagon 1} & \dots & \text{Hexagon N} & \dots \end{bmatrix}$$

$$\begin{pmatrix} \overrightarrow{dw} \\ \overrightarrow{du} \end{pmatrix} \begin{Bmatrix} 1 \\ \vdots \\ \vdots \end{Bmatrix} = \text{Hexagon 1}$$

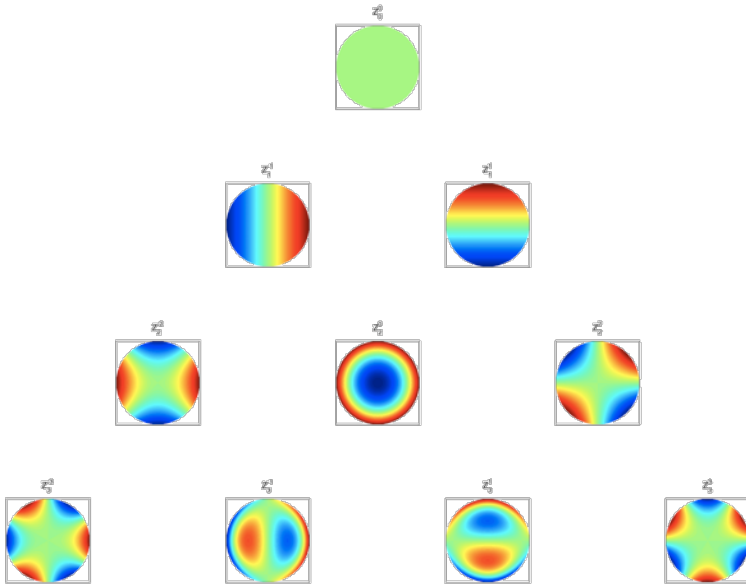
$$\begin{pmatrix} \overrightarrow{dw} \\ \overrightarrow{du} \end{pmatrix} \begin{Bmatrix} \vdots \\ \vdots \\ 1 \\ \vdots \end{Bmatrix} = \text{Hexagon 2}$$

$$\begin{pmatrix} \overrightarrow{dw} \\ \overrightarrow{du} \end{pmatrix} \begin{Bmatrix} \vdots \\ \vdots \\ -1 \\ \vdots \end{Bmatrix} = \text{Hexagon 3}$$

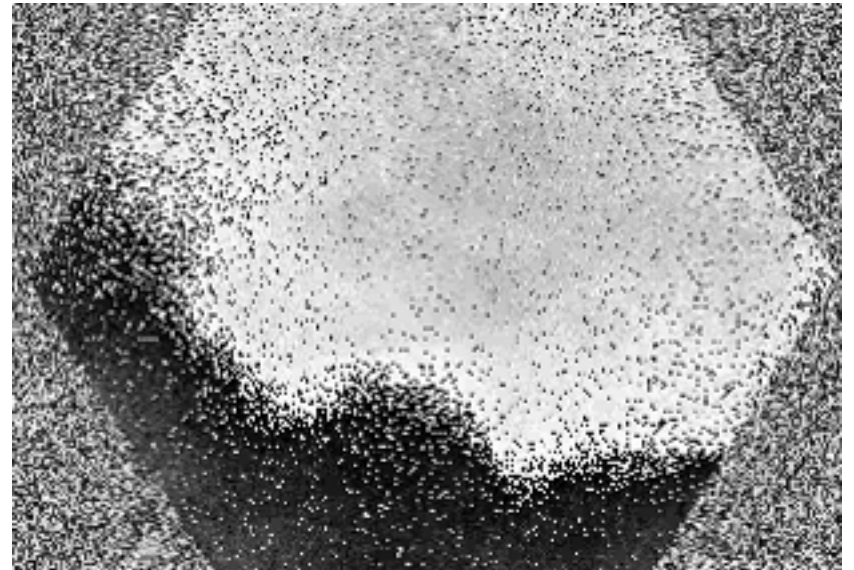
$$\begin{pmatrix} \overrightarrow{dw} \\ \overrightarrow{du} \end{pmatrix} \begin{Bmatrix} 1 \\ \vdots \\ -1 \\ \vdots \end{Bmatrix} = \text{Hexagon 4}$$

$$\begin{pmatrix} \overrightarrow{dw} \\ \overrightarrow{du} \end{pmatrix}^{-1} \text{Hexagon 4} = \begin{Bmatrix} 1 \\ \vdots \\ -1 \\ \vdots \end{Bmatrix}$$

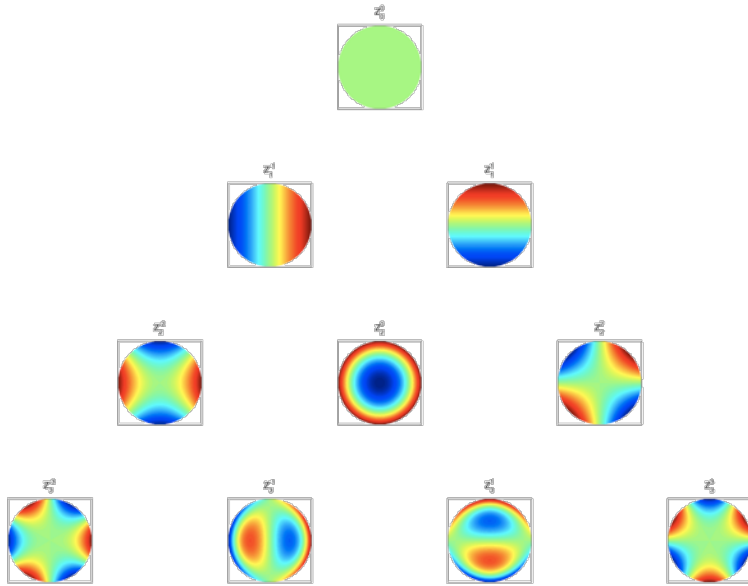
Commanding Arbitrary Shapes



Zernike Functions

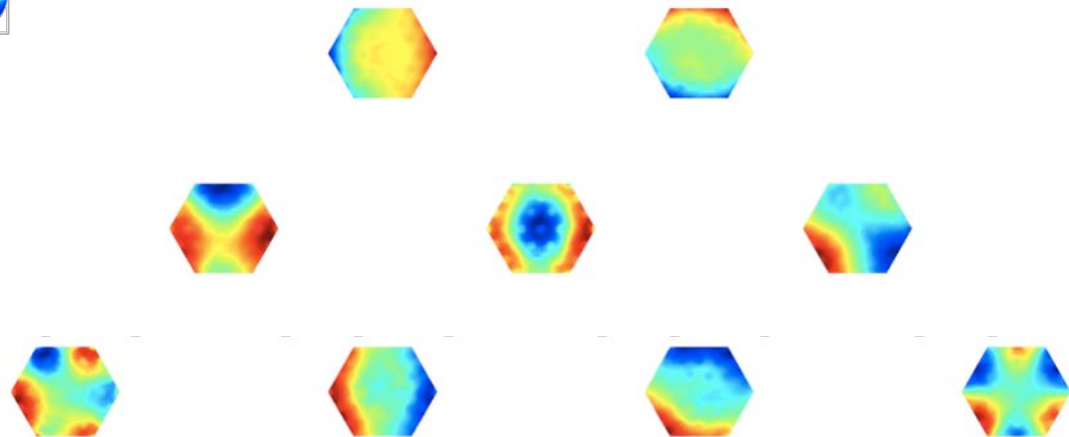


Commanding Arbitrary Shapes

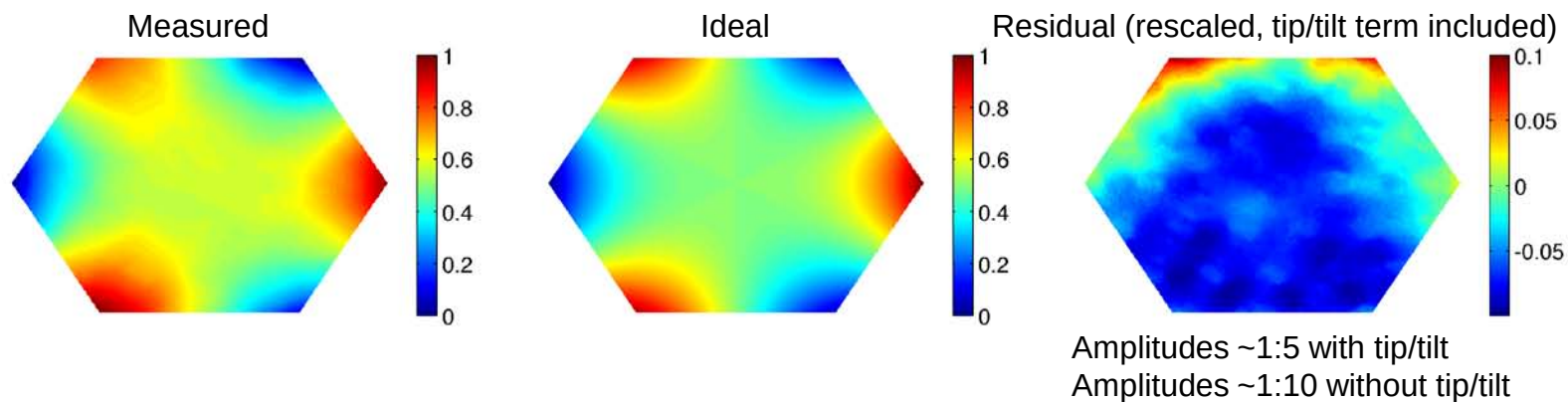
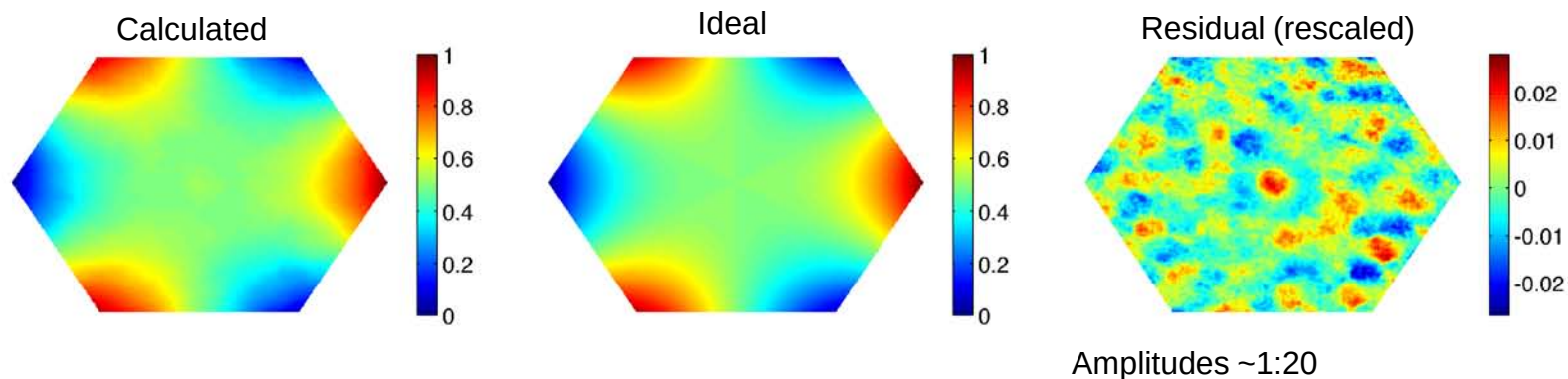


Zernike Functions

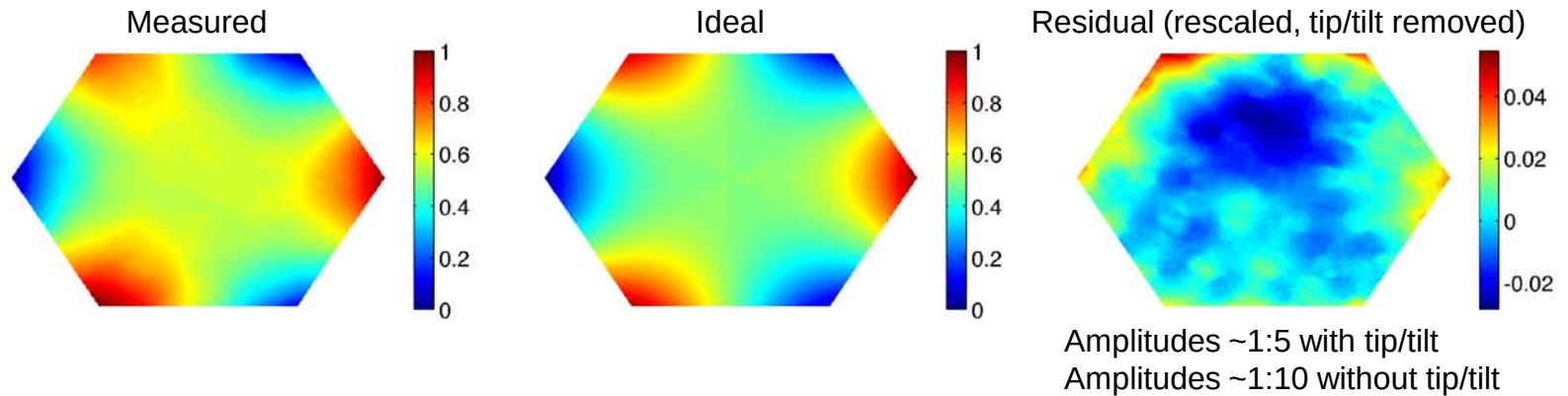
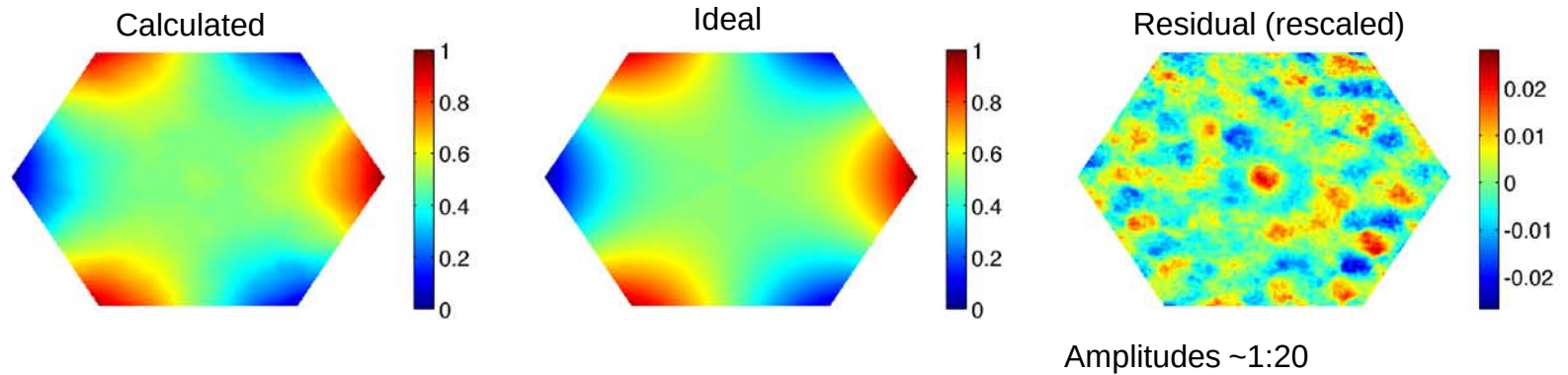
Measured Zernike Functions



Zernike Shapes and Residuals

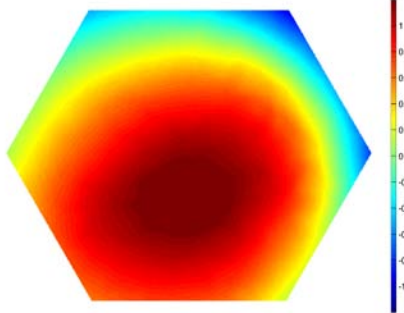


Zernike Shapes and Residuals



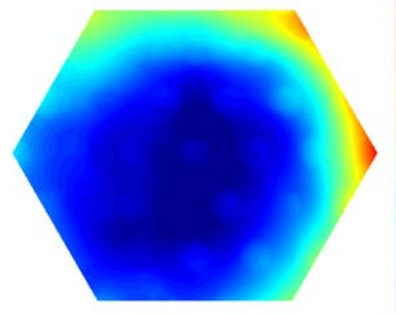
Thermal Deformations

Measured Thermal Deformations



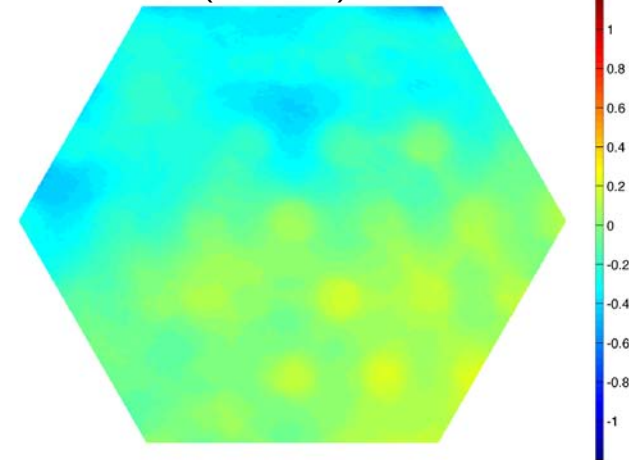
+

Commanded Correction Profile

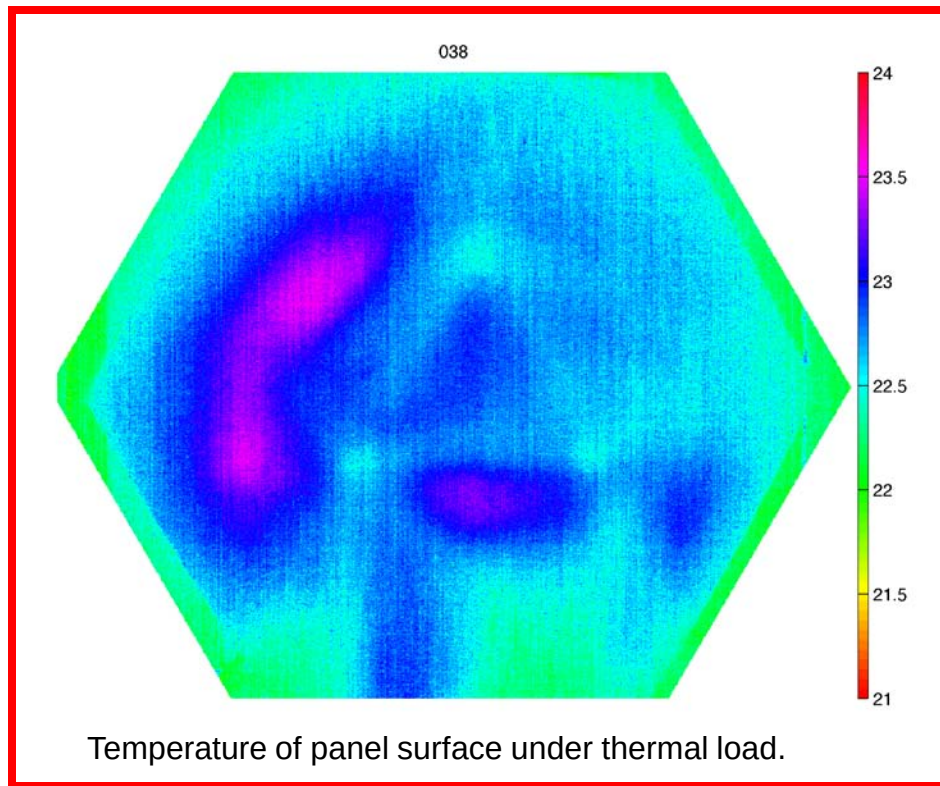
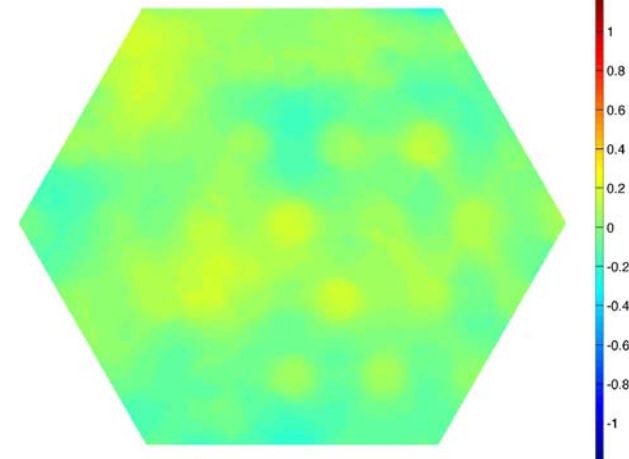


=

(Residual)



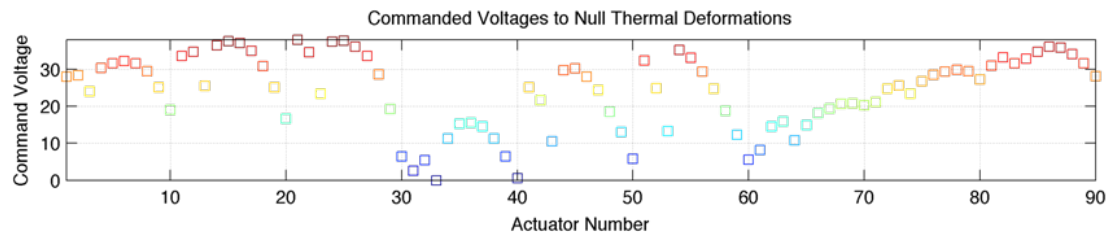
(Residual with tip/tilt removed)



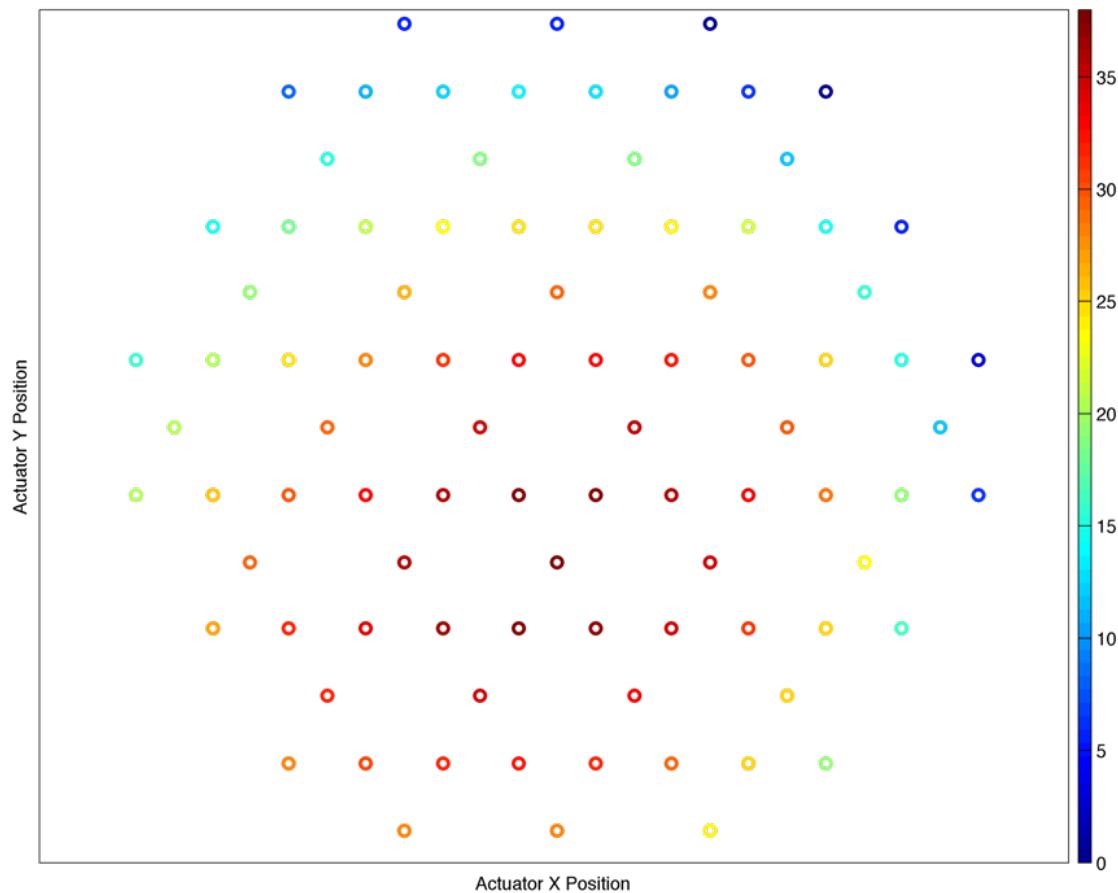
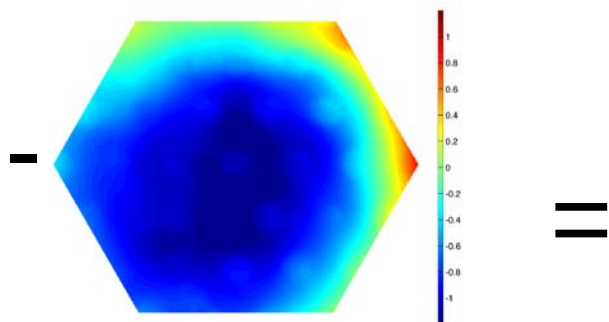
Temperature of panel surface under thermal load.

Thermal Deformations

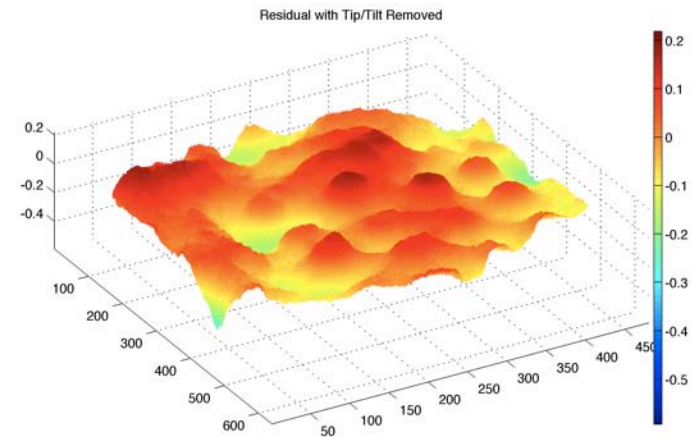
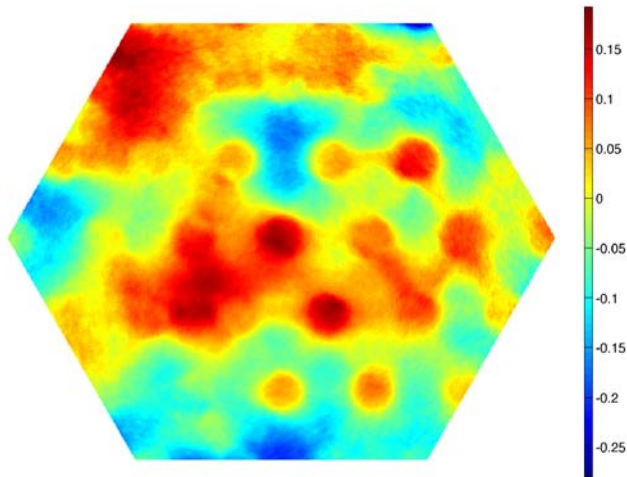
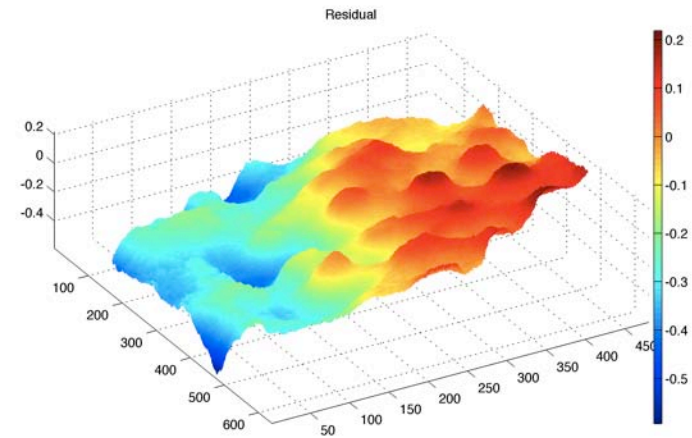
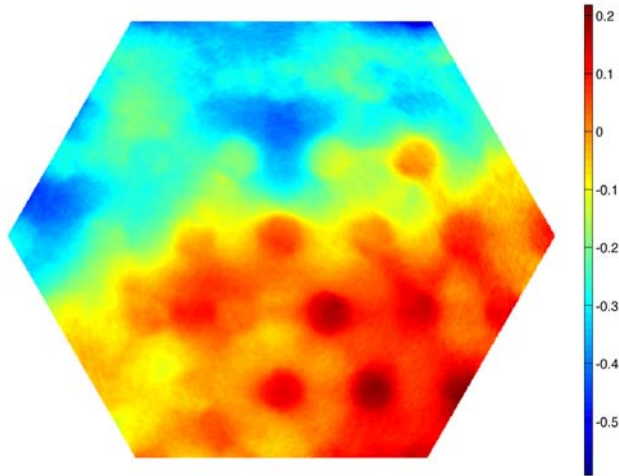
$$\vec{u} = \left(\frac{\vec{dw}}{\vec{du}} \right)^{-1} \vec{w} =$$



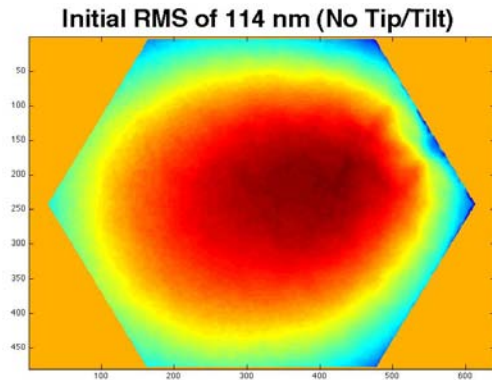
Commanded Correction Profile



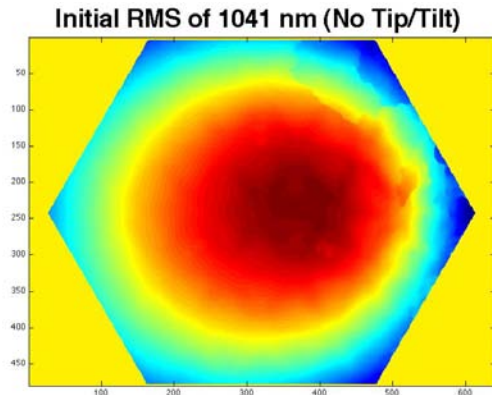
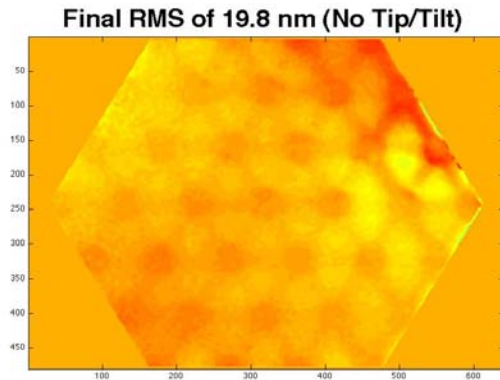
Thermal Deformations



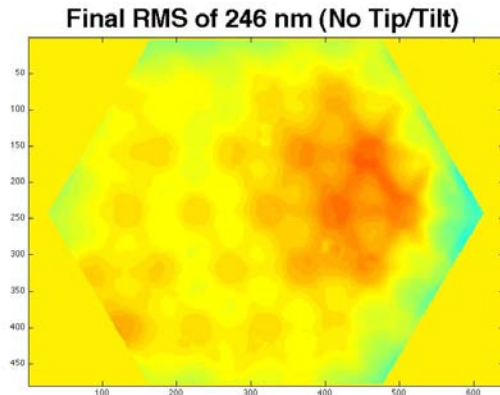
Thermal Deformations: Closed-loop Control



83% Correction



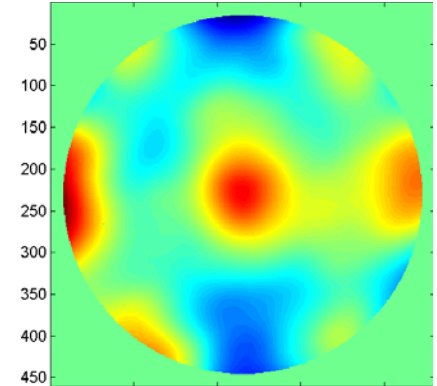
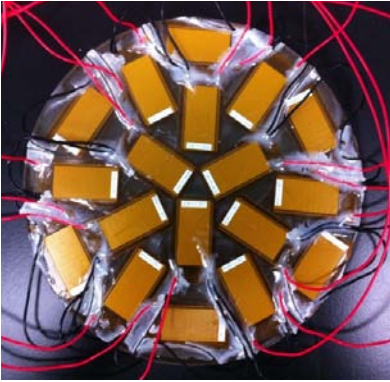
76% Correction



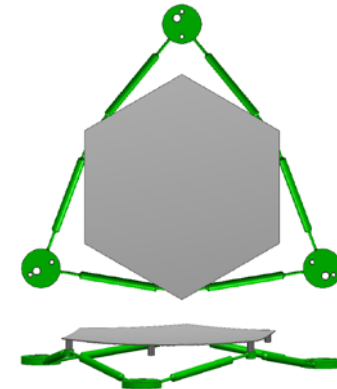
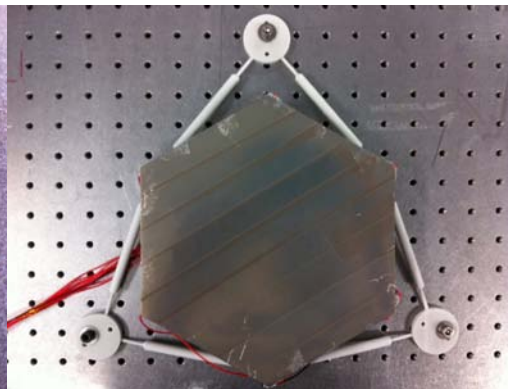
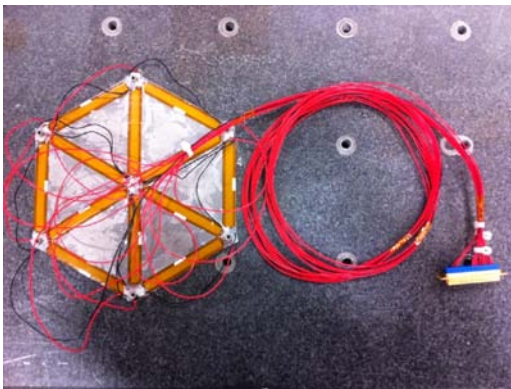
25% actuator saturation at 100 V limits corrections of larger induced deformations... but recall that we are using 0-100 V controller and actuators have an operating range of -500 to 1500 V

Bench-scale Reflector Concepts

“Flat” 15 cm borosilicate glass window with 18 actuators bonded to the back surface.
14 waves of surface error in focus are correctable to better than 1 wave using actuators.

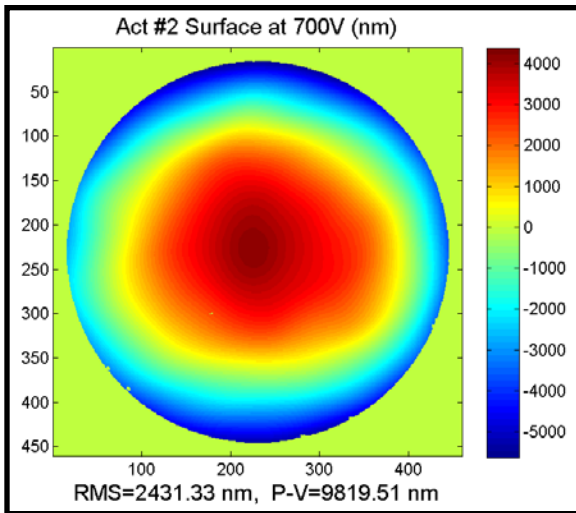


Spherically curved (F/D of 2.5) direct metal laser sintered reflector with 23 cm diameter and 12 actuators bonded to the back surface.

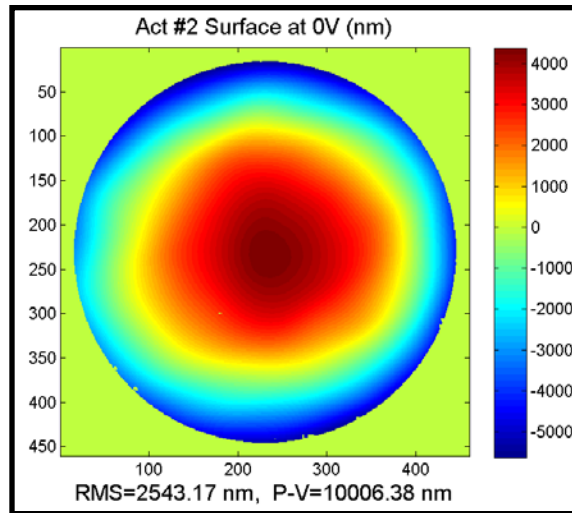


Active Optical Flat

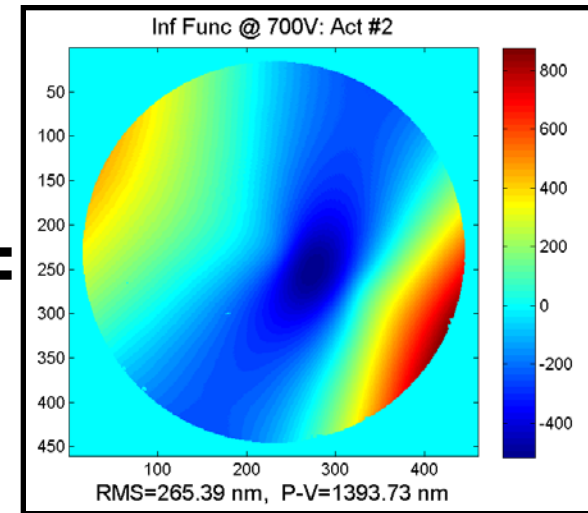
Act #2 Surface at 700V



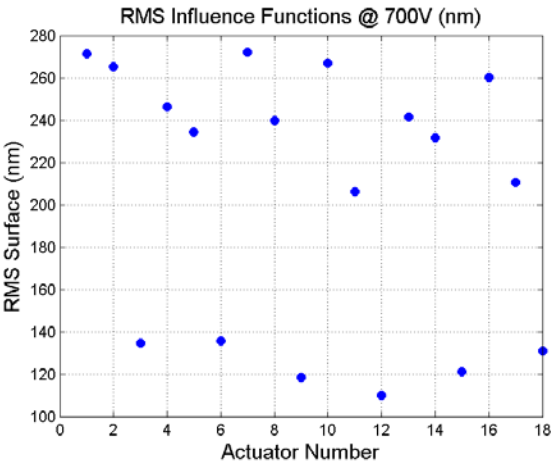
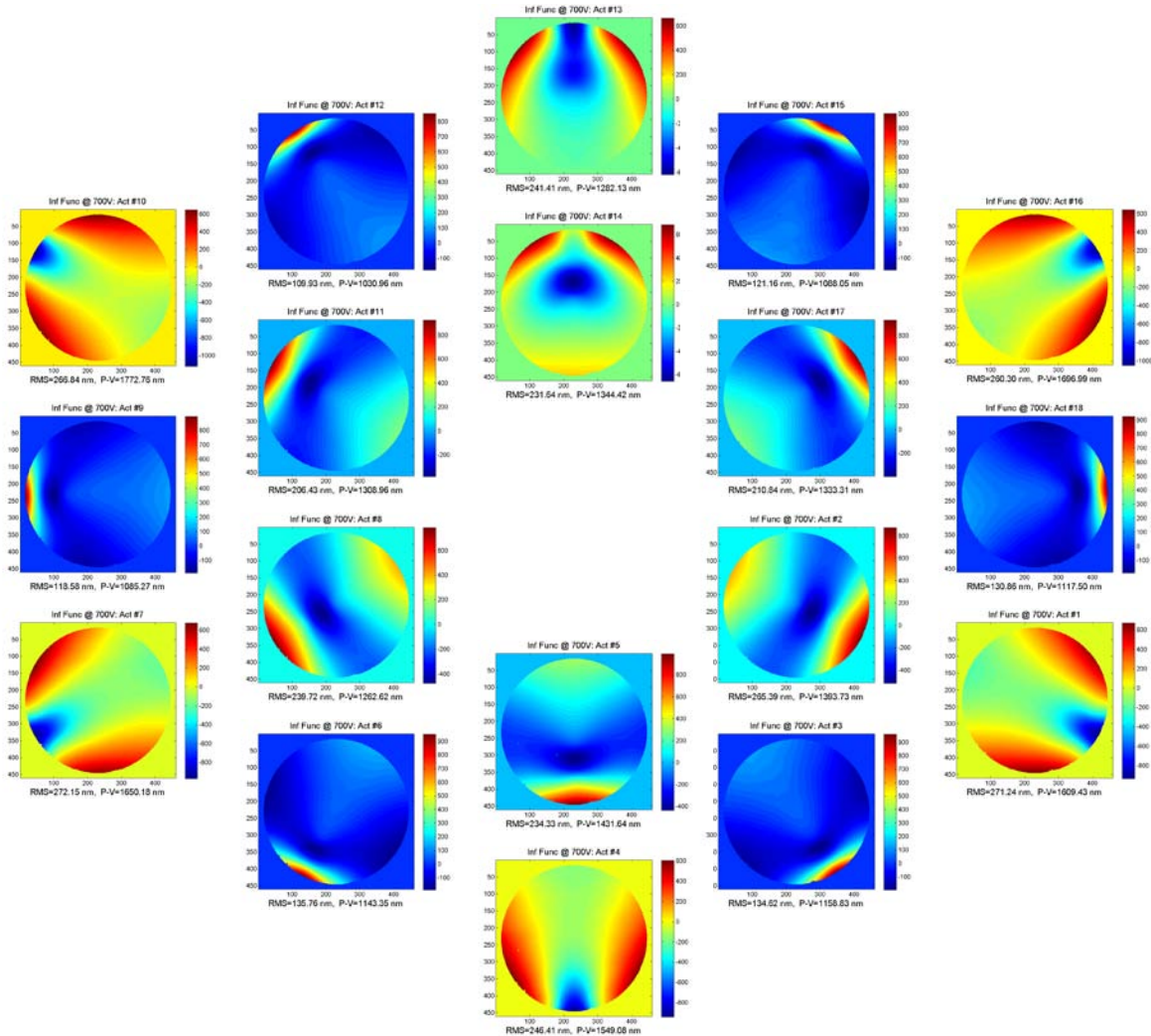
Act #2 Surface at 0V



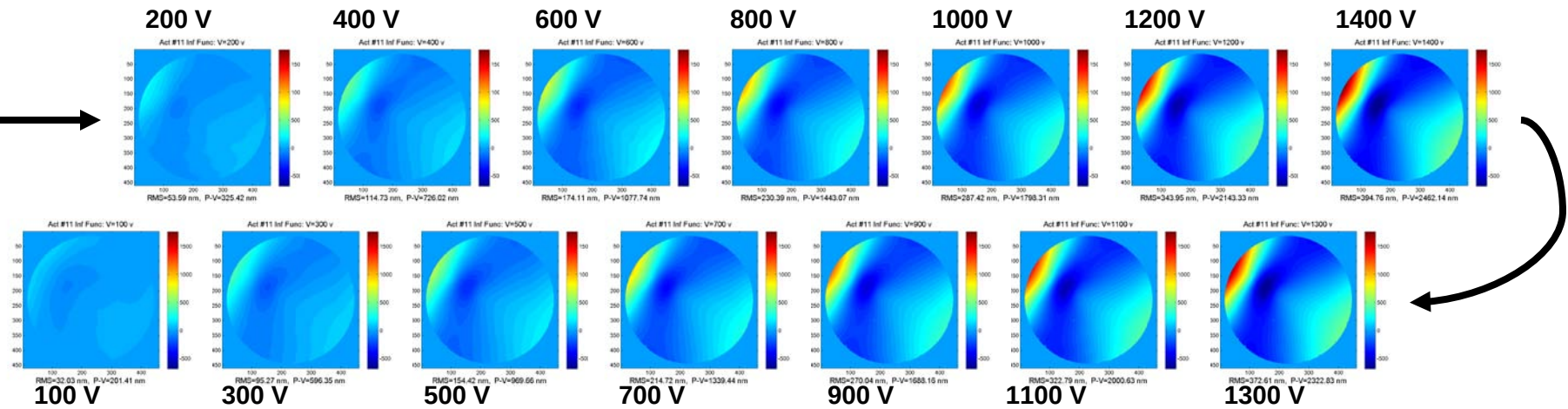
Act #2 Influence Function at 700V



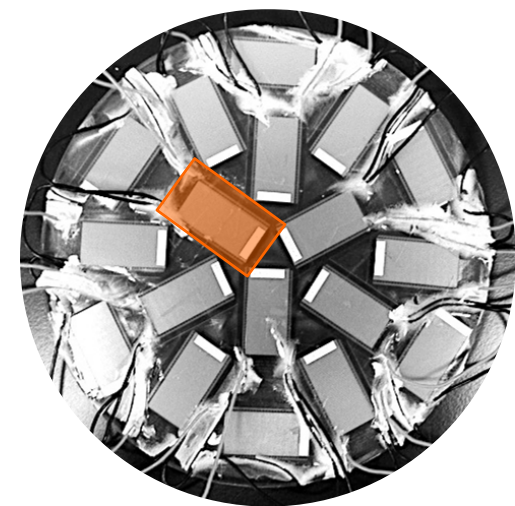
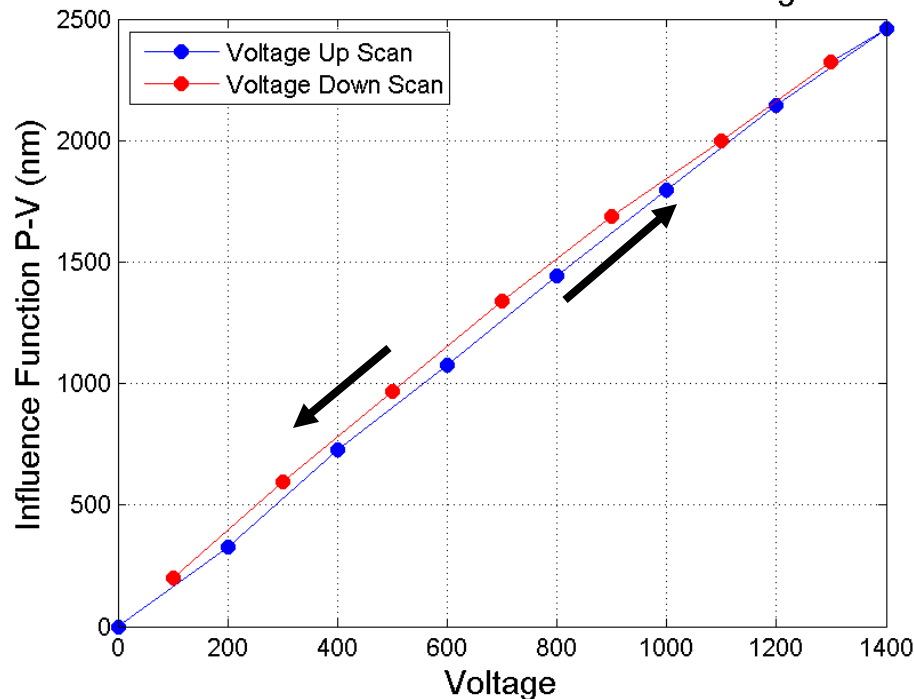
Actuator Influence Functions @ 700V



Individual Actuator Linearity



Act #11 Influence Function P-V vs. Voltage



Summary

- An Active Composite Reflector system can correct surface flatness of a 0.8 m test panel to sub-100 nm RMS.
- Arbitrary surface shapes such as Zernike functions can be imposed to very high fidelity. Thermal deformations are typically of low spatial frequency and can be approximated as sums of the first several Zernike shapes.
- Printthrough effects dominate the residual misfit between the commanded and modeled profile. With some care in actuator placement, the printthrough effects can be minimized or eliminated.
- Absolute surface correction (e.g., correcting as-built errors) can be accomplished using the same techniques as relative surface correction (e.g., correcting thermal deformations).



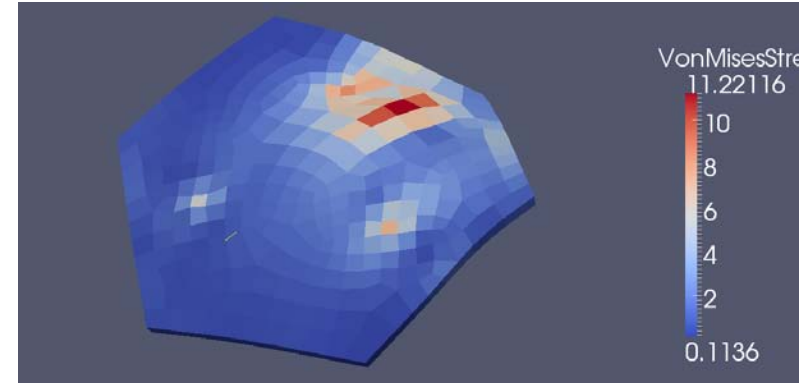
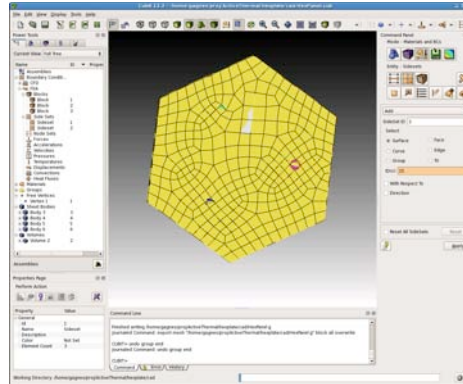
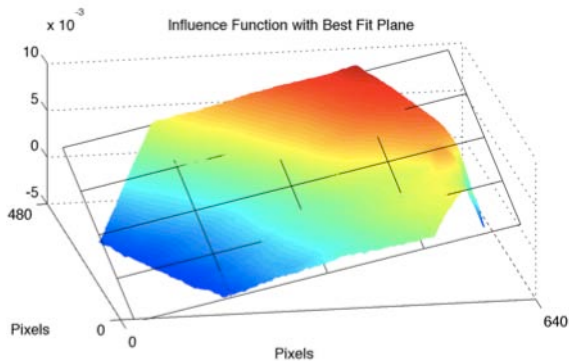
Backup Material



Reflector Surface Measurement

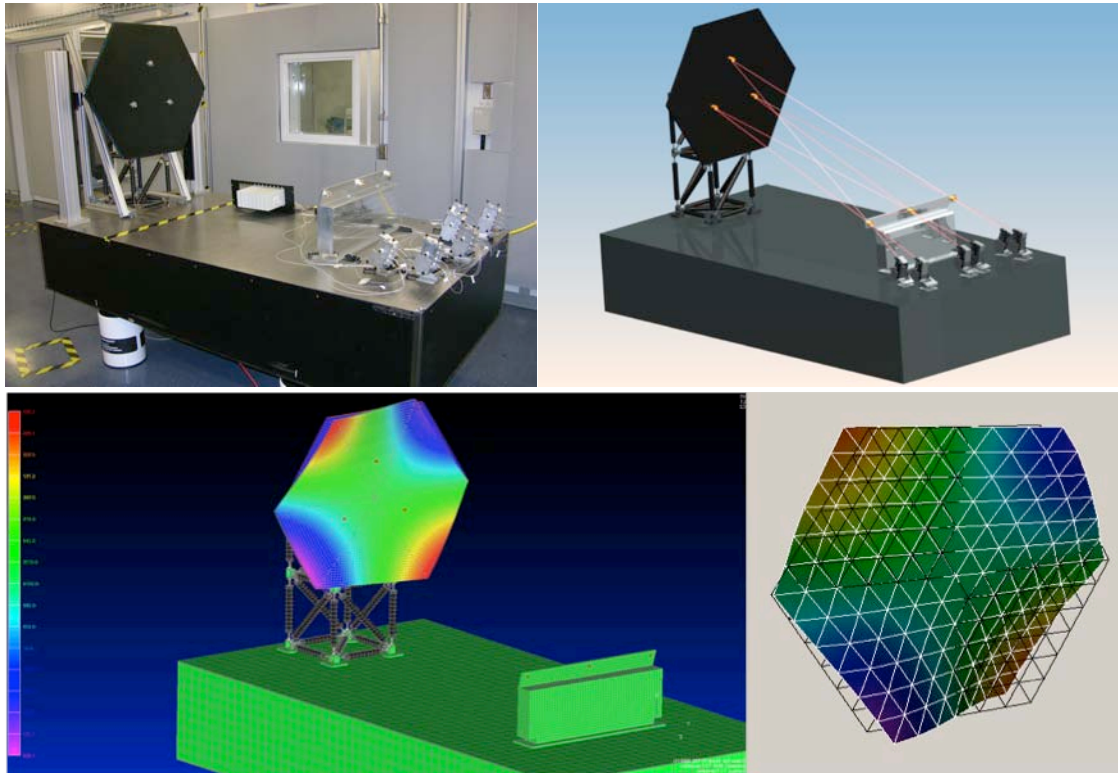


Active Composite Reflector: Scaling-Law Development



- An integrated multiphysics modeling effort reproduces the existing influence functions for the testbed panel.

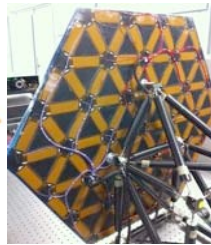
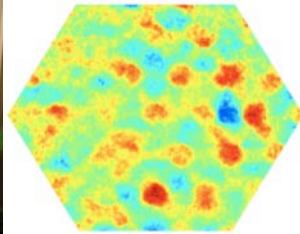
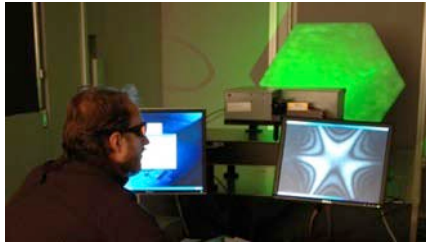
Precision Environment Test Enclosure



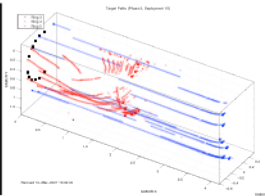
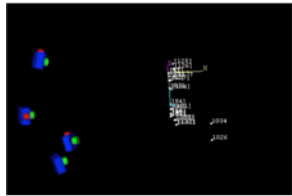
Precision Deployable testbed article and interferometric metrology system. Top row: photograph and CAD view of the system in the PETE. Bottom row: modeled and measured dynamic modes of the panel.

- A parametric truss and panel are measured using an interferometric range-gated laser metrology system. Retroreflective target positions are measured to within 5 nm (relative) and 500 nm (absolute) at a distance of several meters. The thermal stability of the PETE prevents the air path from interfering with the laser system. This test would otherwise require installation in a vacuum chamber.
- Model validation activity. A system model is compared with the results from a forced vibration test. A scanning laser doppler vibrometer is used to characterize 100 nm motions.

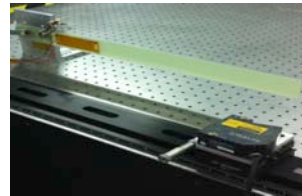
Precision Environment Test Enclosure



Speckle Interferometer, measuring the surface of a 0.8 m active panel. An array of flat piezoelectric actuators corrects thermally-induced deformations to better than 100 nm RMS.



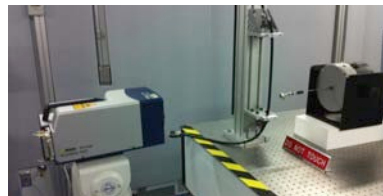
Videogrammetry cameras track the deployment path of an 8-m mast. A gravity offload system was installed in the PETE to allow for characterization of deployment repeatability and deployed system dynamics.



Active beam control testbed using flat piezo actuators and laser displacement sensor



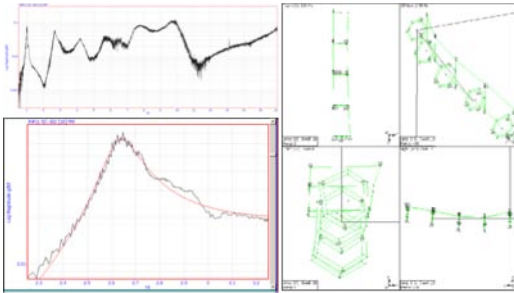
Fatigue test of an MSL flexure using the Scanning Laser Vibrometer



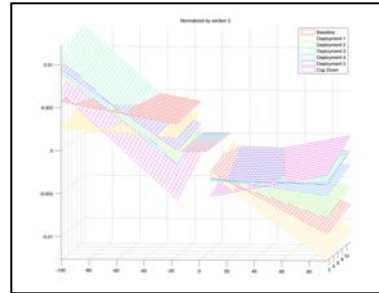
Scanning Laser Vibrometer and shaker during MGSE characterization tests

- A variety of non-contact metrology systems for characterizing test hardware.
- **Speckle laser holographic interferometer** measures surface deformations (relative) to 25 nm over a 2 m field of view for both static and dynamic testing.
- **Scanning laser doppler vibrometer** for measurements of velocity (10 nm/s to 10 m/s, from DC to MHz), typically used in scanning mode to capture operating deflection shapes over several square meters of a test article.
- **Laser displacement meter** measures absolute position of a single point to sub-micron over a displacement range of 1 cm.
- **Videogrammetry** camera system measures the absolute position of a coded target to sub-mm anywhere in the test chamber. Also works in static **photogrammetry** mode.
- **Range-gated metrology system** measures displacements of a retroreflective target to 5 nm relative and can measure absolute position to sub-micron levels, with a range of several meters.

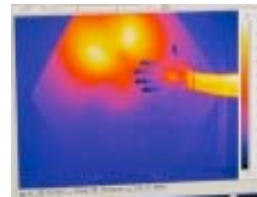
Precision Environment Test Enclosure



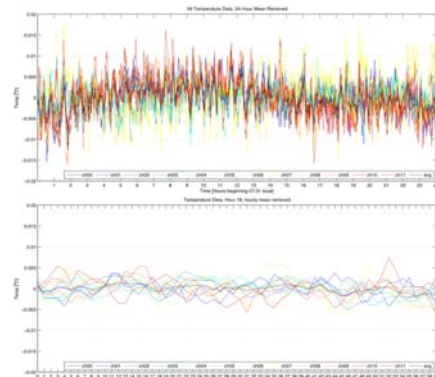
Dynamic test data: 54 accelerometer channels, transfer function to load cell under forced vibrations applied at the midpoint of an 8-m deployed mast



Deployment repeatability of 5-m panel



Thermal camera demonstration



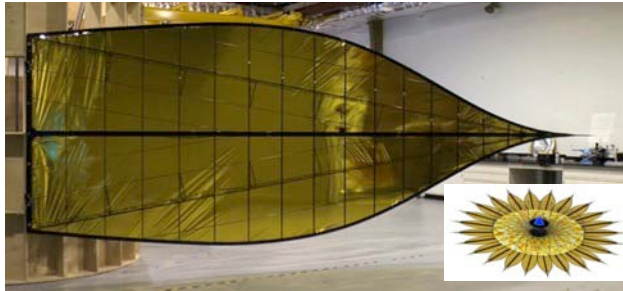
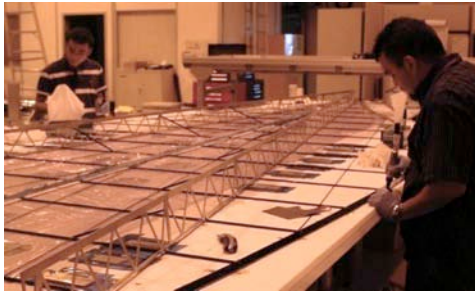
Temperature in PETE over 24 and 1 hour intervals under a kW of thermal load. Stable to within 0.01 deg C RMS, per hour and per day



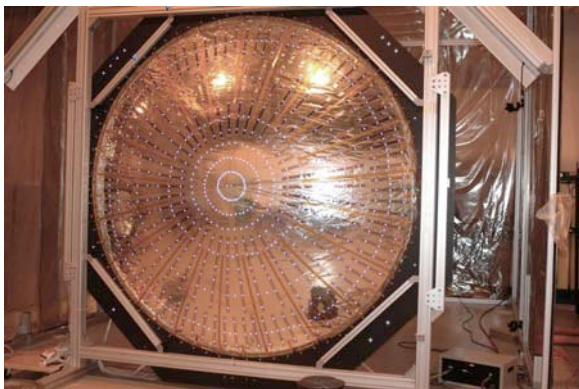
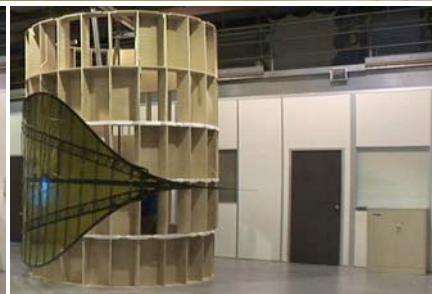
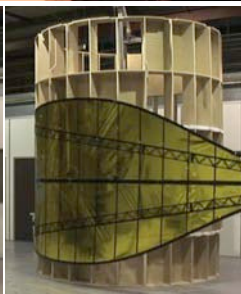
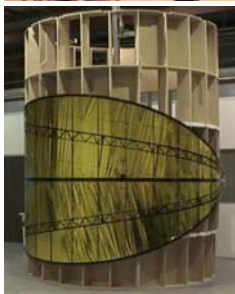
More than 200 AD channels in an expandable, customizable, rack system.

- Digital data acquisition system with 132 24-bit channels at up to 100 kHz (e.g., accelerometer or load cell), multiple I/O controller cards, 64 thermocouple channels, 64 heater control channels, and a separate DA control feedback system.
- Dynamic test hardware includes a large selection of accelerometers, load cells, shakers/amplifiers, signal conditioners, strain gages.
- Thermal test hardware includes a FLIR thermal camera, thermocouples, and PRTs. The PETE has an array of thermal sensors for temperature control.
- Additional manufacturing and deployment measurement capability using V-STARs Geodetics and Leica laser tracker systems.
- Most systems can be used in the PETE or in the ALPS high bay facility.

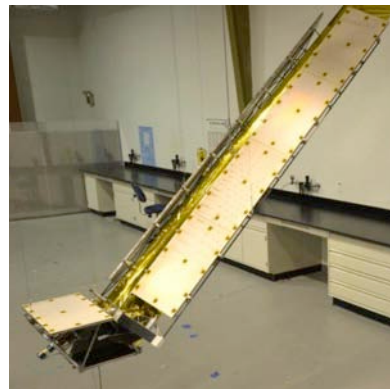
High Bay



Manufacturing and deployment testing for a 7.5 m starshade petal. At left, construction in the ALPS high bay and fully deployed petal. Below, deployment sequence as petal unwraps from central hub. The full starshade would have 24 petals (inset left).



2.4 m inflatable membrane reflector with PVDF actuators for controlling the surface



5m x 0.2m Ka-band radar panel demonstration, stowed and deployed.

ALPS Laboratory Capabilities

- The **ALPS Laboratory** enables the development and testing of precision structures, with specific applications for:
 - Electromechanical and optical systems
 - Rigidizable and inflatable structures
 - Lightweight mechanical structures
 - Large aperture support structures
 - Large, lightweight, deployable structural systems such as RF antennas, sunshields, solar arrays, occulter, decelerator systems, and solar sails.
- **ALPS Project Support Team** has a dedicated suite of instrumentation and data acquisition systems for the characterization of prototype and flight hardware.
- The **PETE** provides a stable test environment for static and dynamic characterization of hardware systems at the nanometer scale.
 - Thermal control of the PETE allows for long-term thermal/structural testing.
 - The PETE thermal and vibrational stability is required for advanced laser metrology systems and nm-scale testing that would otherwise require a vacuum chamber.
- The **ALPS High Bay** facility is suitable for construction and concept development of large precision structures, including deployment testing and gravity offload fixture design.
 - 1-ton crane at 4.25 m from high bay floor, large (5.5 m wide) high bay door

