Kodak AMSD Industry Team

- **Eastman Kodak Company**
  - Mirror system design and manufacture
  - Integration and test

- **Moog, Schaeffer Magnetics Division**
  - Force actuator development and manufacture

- **Composite Optics Incorporated**
  - LTF and LTS furnace facilities
  - Reaction structure fabrication
Next Generation Optical Systems

- Next generation optical systems will need ultra-lightweight adaptive optics
  - Next Generation Space Telescope (NGST)
  - Space Based Laser (SBL)
  - Terrestrial Planet Finder (TPF)
- Advanced Mirror Systems Demonstrator (AMSD) addresses these needs
  - Provides ultra-lightweight adaptive mirror technology and manufacturing assessment
Semi-Rigid Mirror Approach

- Kodak’s concept for active mirror technology
  - Ultra-lightweight semi-rigid cored mirror with sparse force actuators
  - Very different than high density, displacement actuator approach
- Kodak built and demonstrated semi-rigid approach in 1989 on a 2.5 meter testbed
- The AMSD joint venture allows concept to be updated using latest technology

System phase and figure control to visible tolerances over long periods of time completed
Semi-Rigid Concept

- Fabricate a high performance classical stiff mirror with good wavefront quality
  - Reduce the weight to enable larger systems
  - Reduce stiffness versus passive wavefront control systems to allow figure control
- Separation of Phase and Figure control are key features of Kodak architecture
  - Force actuators control figure
    - Soft spring provides forgiving interface to mirror
    - Insensitive to small motions of reaction structure
    - Force feedback can be used between optical updates for figure maintenance
  - Three displacement actuators control phase

Displacement based system. Mirror follows reaction structure

Force Feedback based system. Mirror isolated from reaction structure
Figure Control

- Actuator array provide figure control for on-orbit aberrations
  - Power – Driven by global temperature changes
  - Astigmatism – First mode aberration always shows up
  - Trefoil – Mount induced errors with respect to reaction structure instabilities
- Sparse actuator array combined with rigid mirror provides correction for on-orbit errors
- Concept also provides other key advantages
  - Fewer degrees of freedom required in the wavefront sensing scheme
  - Lower system overhead due to fewer actuators
  - 1-g verification is easier due to stiffer mirror system
Figure Control Concept

- Each force actuator causes a global influence function over the surface of the mirror

  ![Center actuator influence contour]
  ![Corner actuator influence contour]
  ![Middle actuator influence contour]
  ![Outer edge actuator influence contour]

  Denotes location being actuated. Analysis/test repeated as required for all actuator locations.

- Unit influence functions derived analytically in MSC/NASTRAN to be used by figure control algorithm
Figure Control Concept

- **Influence function matrix used with respect to the observed wavefront error to minimize mirror figure error**
  - Typically use RMS wavefront but any definable algorithm could be used
  - Radius of curvature handled independently of figure error

- **Use of forces versus displacement feedback provides deterministic and repeatable results**
  - Instabilities in reaction structure are negated with force feedback
    - A force is a force is a force
  - No optical data required until next figure control update
AMSD Design Approach

- **AMSD program goals**
  - provide a mirror system design traceable to large deployable systems
  - provide a single mirror system design that meets AMSD requirements at both ambient & cryogenic operational temperatures

- **Telescope system architecture**
  - Optical control
    - provides excellent correction for radius and low order aberrations while minimizing the number of actuators
  - Dynamic control
    - provides sufficient stiffness to stay within capture range of dynamic controls while minimizing system weight

- **Manufacturing and test capabilities**
  - Optical test
    - provides means for gravity off-loading during telescope level optical test
  - Optical fabrication
    - provides a mirror which is manufacturable within a reasonable schedule and cost
Actuator Locations Traded

- **Mount positions** maximize first mode of mirror
- **Actuator trades**
  - 10 configurations as shown and rotated 30 deg
  - wavefront correction factors and surface slope recovered for each case
Actuator Location Trade Results

- **7 actuators**
  - excellent ROC & figure control
    - 99.6% ROC correction
    - >96% low order figure correction
  - vertical axis test slope & B.O. are too large for traceable 1-g test
  - horizontal axis test OK

- **16 actuators**
  - excellent ROC & figure correction
  - good vertical axis test parameters
    - slope 4 micro-rad
    - B.O. uncertainty 2.4nm rms
    - gravity error 0.016 \( \lambda \text{rms} \) (\( \lambda = 3 \mu\text{m} \))

16 actuators selected for AMSD baseline
(driven by need for traceable 1-g test support)
**Sensitivity to Actuator Failure**

- AMSD design is very tolerant of actuator failure
  - due to use of low stiffness force actuators

![Correctability vs. Actuator Failure Chart]

**Correctability vs. Actuator Failure**

- Trefoil
- Astigmatism
- Power

Failed Actuator No.: 1, 2, 3, 4, 5

Correctability $[1-(\text{output}_{rms}/\text{input}_{rms})] \times 100$

0% 10% 20% 30% 40% 50% 60% 70% 80% 90% 100%
AMSD Mirror System Overview

- Ultra-lightweight stiff ULE™ mirror (sandwich construction)
- Stable composite reaction structure (Composite Optics Incorporated)
- Force Actuators (Moog Schaeffer Magnetics Division)
- Single design for AMSD ambient & cryo
Mirror Description

- 1.4m x 3.65cm
- 11.18 kg (7.65 kg/m²)
- fn = 151 Hz free

**Construction**
- All ULE™ glass
- Segmented core
- Abrasive waterjet cut core elements
- Low temp fusion
- Low temp slumping

**21 parts total**
- 2 face plates
- 13 full-hex core segments
- 6 half-hex core segments

Advanced Mirror System Demonstrator Program
Mirror Design Features

- Process mirror blank as a flat using inexpensive plano processing techniques
- Fabricate mirror blank using small repetitive parts
  - Reduces processing risk prior to mirror fusion when the parts are fragile
  - Parts can easily be replaced prior to fusion
- Once fused, the mirror blank is very robust

Segment Requirements
9 – A’s
4 – B’s
6 – C’s
Waterjet Cut Mirror Cores

Mirror core segment shown to the left.
Close-up view of the vent holes in the core cells shown below. Note that the cover glass is still in place.
Mirror Facesheet Status

- Face sheets completed using standard methods
- Processed as roundels through Blanchard, grind and polish
Mirror Facesheet Status

- After polishing, facesheets cut into hex shape and break edge added
Mirror Assembly Operations
AMSD Blank
Plate Thinning

- After fusion, plates require thinning to reduce weight
- AMSD plates are thinned in Kodak’s Large Machining Center
Back Plate Polishing

- Back plate is shined prior to slumping into an asphere
- No further processing required on back plate
Mirror Blank Prior to Slumping
Aspheric Generation

Off-Axis Generation Machine (OAG) used to impart final asphere onto AMSD mirror

10 micron P-V surface generated
Small Tool Grind and Polish
Optical Testing
Full Aperture - Figure Convergence

Post Blocking
Surface Figure
19 waves P-V
3.5 waves RMS
RoC 10,000 mm

Post-Ion #1
Surface Figure
4.9 waves P-V
0.63 waves RMS
RoC 10,000 mm

OAGM

HeNe

Post-Ion #2
Surface Figure
2.4 waves P-V
0.34 waves RMS
RoC 9999.988mm

Post-Ion #3
Surface Figure
1.05 waves P-V
0.06 waves RMS
RoC 10,000.003mm
Actuators

- All actuators have been delivered from Moog
- Cryo testing has demonstrated acceptable performance
Reaction Structure

- Reaction structure has been delivered from COI
- Assembly weights about 8 pounds
- Structure cryo cycled at XRCF
Final Integration and Test

Advanced Mirror System Demonstrator Program
Evolution of Lightweight Optics

- Kodak has continued to develop technology to reduce the areal density of mirrors and optical systems

- Cryo test results will be available in mid-May