Daytime Adaptive Optics for Deep Space Optical Communications

K. Wilson, M. Troy, V. Vilnrotter, M. Srinivasan,
B, Platt, M. Wright, V. Garkanian, H. Hemmati

JPL

September 12, 2003

Outline

- Daytime Optical Communications Challenge
- Analysis and modeling: Phase I
- Laboratory Demonstration: Phase II
  - Schematic Design
  - Key components
- Field Demonstration: Phase III
- Summary

Daytime Optical Communications Challenge

The Problem

- *Sun scattering from optical surfaces and sky background radiance are noise sources in the optical channel*
  - *Problem is worse as mission requires communications support at decreasing Sun-Earth-Probe angles*

The Challenge

- *How to maintain low-power-consumption, low-mass advantage of optical comm in daytime*
  - *Analysis shows daytime sky radiance can degrade link performance significantly*

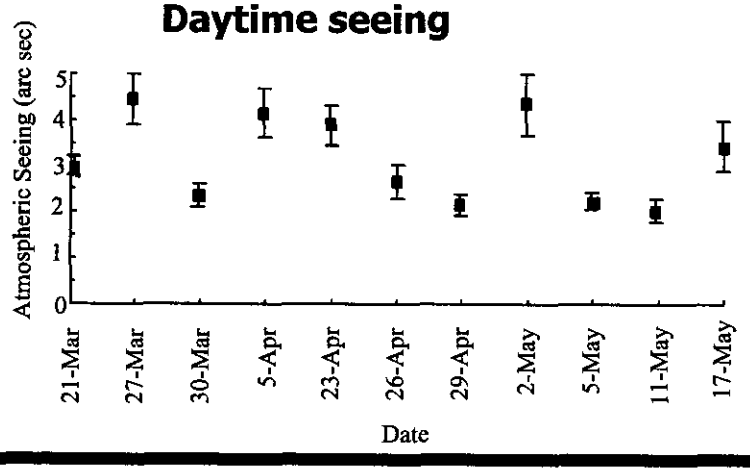
The Approach

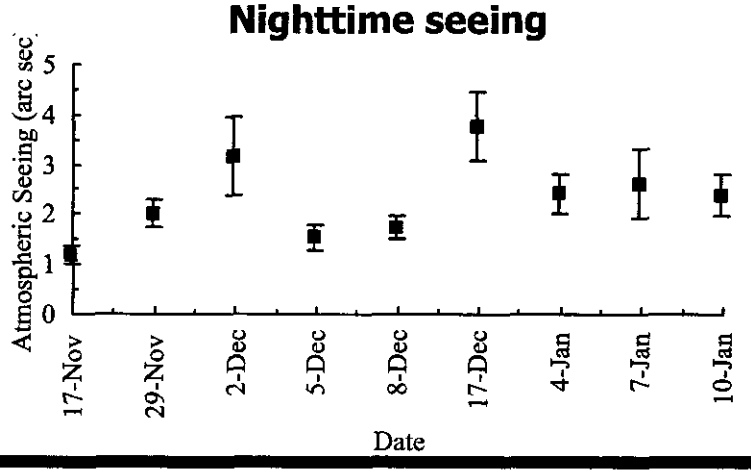
- *Use a combination of higher order PPM signaling formats and spectral and spatial filters to mitigate effects*
  - *Advanced signaling formats can increase the complexity of the spacecraft modulator and ground demodulator*
  - *Narrow line width spectral filters will need to be tuned to accommodate Doppler frequency shifts*
  - *Spatial filtering will require correcting atmospheric turbulence-induced wave front aberration*

Analysis and modeling: Phase I

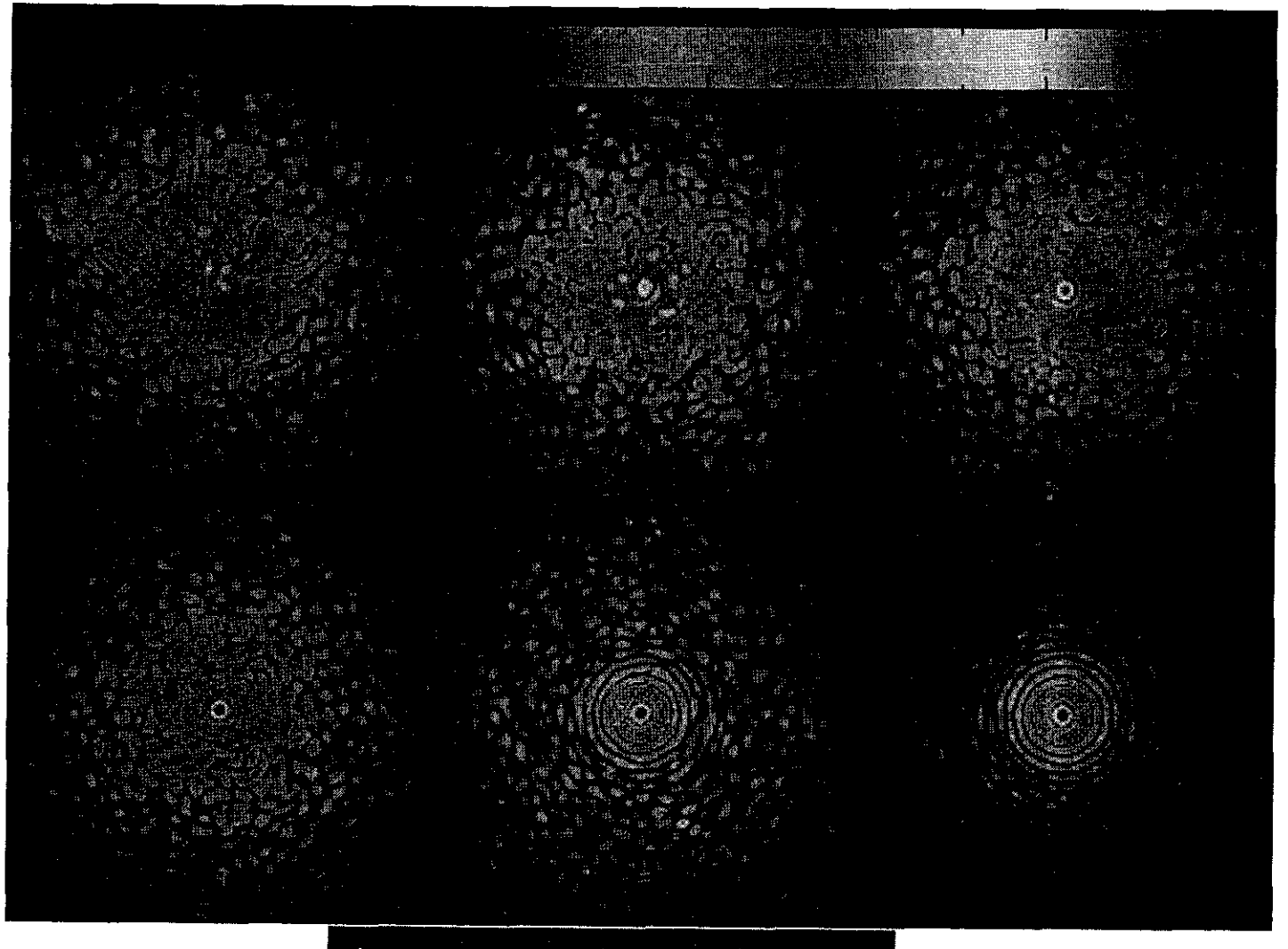
- Determine wave front aberration for nominal daytime atmosphere conditions at ground receiver site
  - Use measured atmospheric seeing values at proposed site
- Model wave front correction as a function of actuator density for expected atmospheric conditions
- Assess telecommunications system performance as a function of wave front correction for given background levels

Data taken at TMF during 1995-1996 GOLD Experiment at 0.8 μm





Actuator Density Model Results

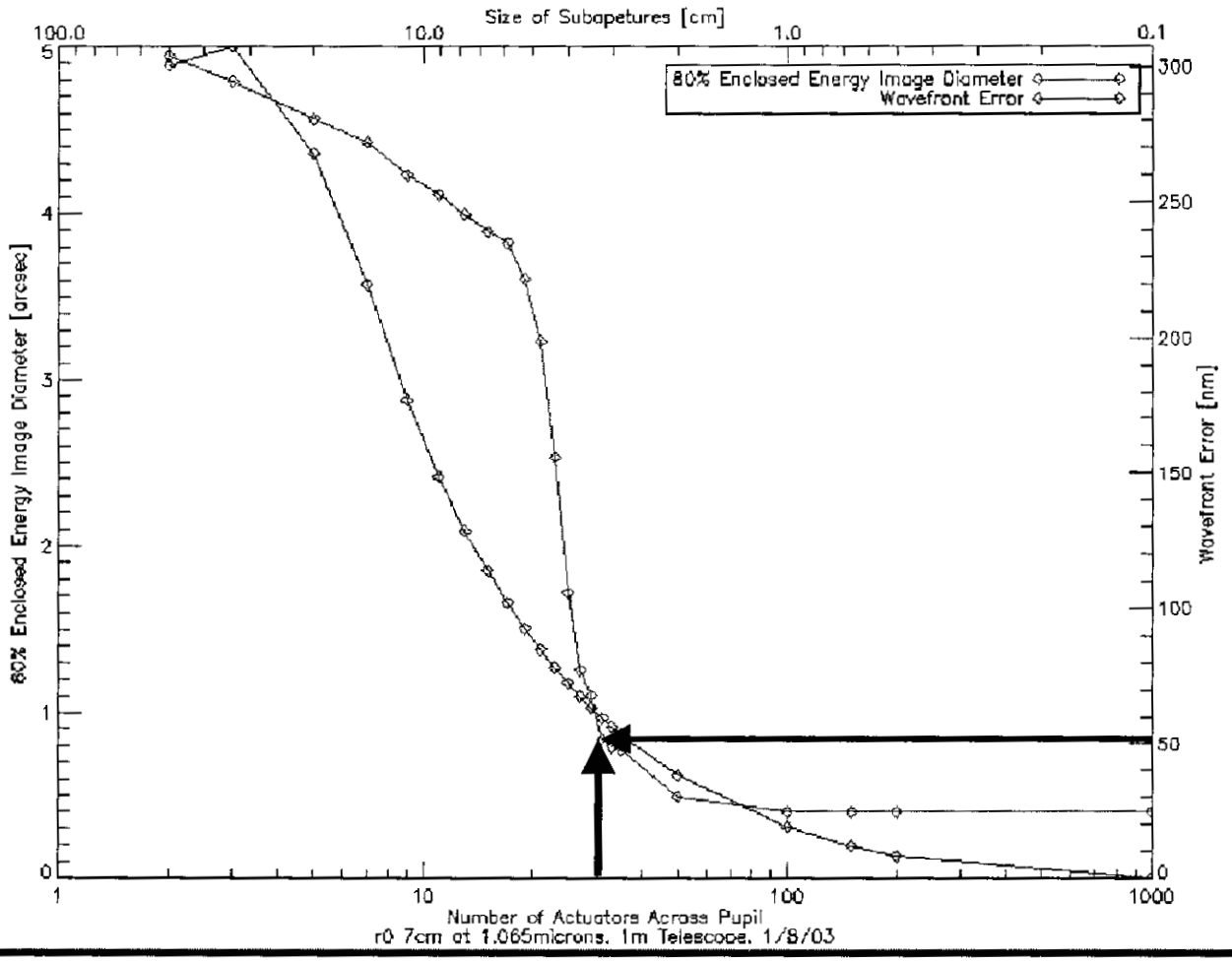


Actuator spacing =d, r_o =7cm

Modeling Turbulence & Wave Front Correction

- ***Model Parameters***
  - 1 meter telescope
  - Wavelength: 1.064 μm
  - r_0: 7cm at 1.064 μm (3.1 arcsec)
  - Number of actuators across pupil range from $(5)^2$ to $(200)^2$
- ***Method***
  - Create Kolmogorov phase screen
  - Extract a portion corresponding to 1-m
  - Create filter function based on DM actuator spacing
  - Filter the phase screen with DM filter function
  - Propagate phase screen to the image plane
  - Sample image at desired pixel scale

FOV of 80% encircled energy vs. # actuators



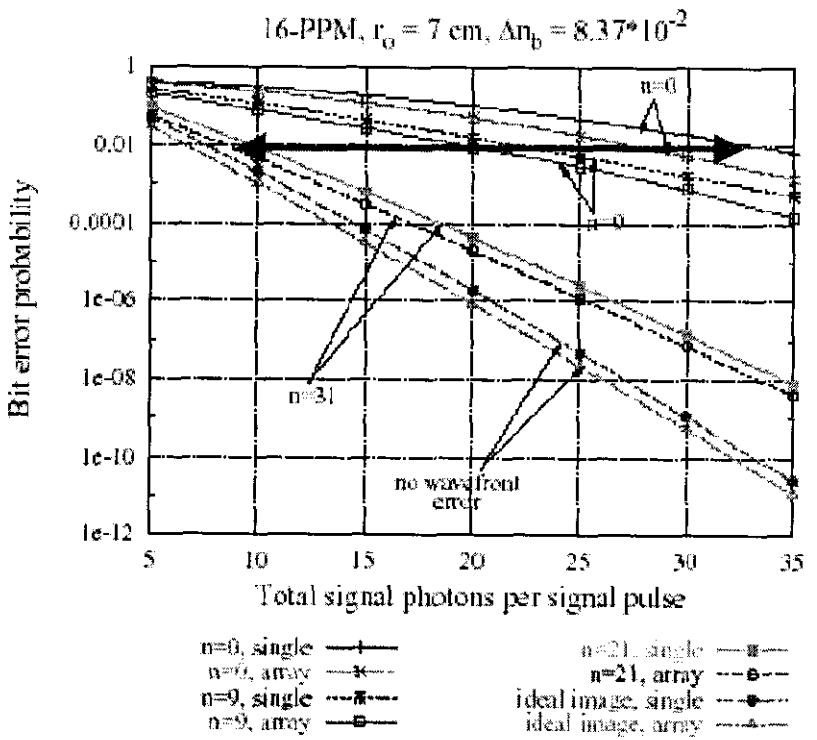
Conclusion: *Diminishing returns in performance for greater than $(30)^2$ actuators on 1-m aperture*

Modeling Performance of Comm Channel

- Use number of actuators as parameter to determine noise in receiver fov with 80% encircled energy
- Background light levels $\mu W/(cm^2\text{-}nm\text{-}sr)$
  - 0.5 => Background from clear sky 3-km altitude receiver station
  - 10 => Nominal sea level sky radiance
  - 100 => Sunlight scattered from optics
- Other model parameters
  - Fried parameter => 7- cm
  - Telescope aperture =>1- m
  - Receiver filter bandwidth => 1Å
  - Wavelength =>1.064μm
  - Data rate => 10 Mbps
  - Uncoded BER => 0.01

AO Gain vs. Background Noise

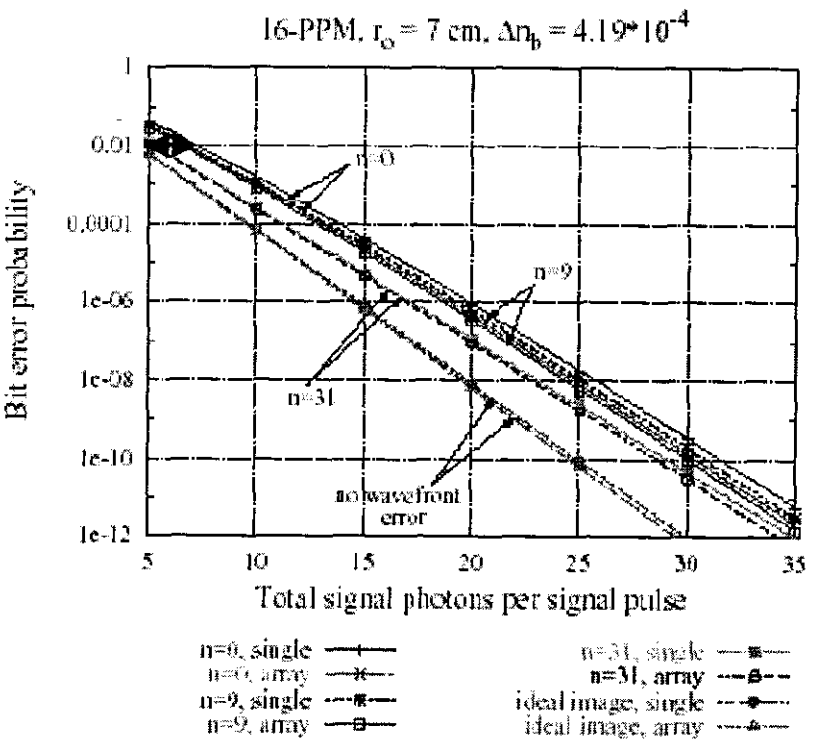
100 μW/(cm2-nm-sr)



5.7 dB Gain for 900 actuator DM

2.4 dB Gain for 97 actuator DM

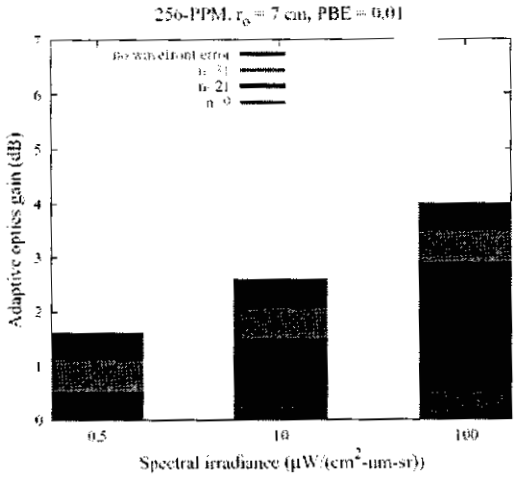
0.5 μW/(cm2-nm-sr)

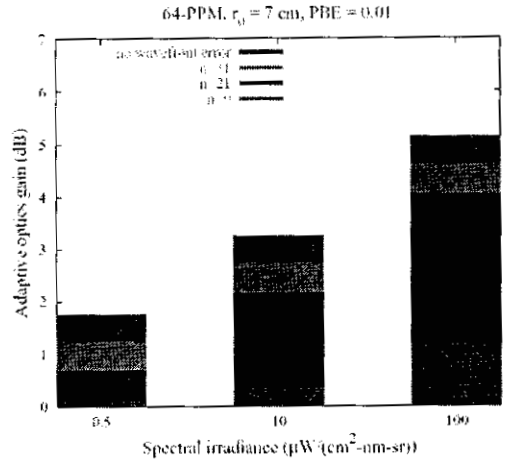


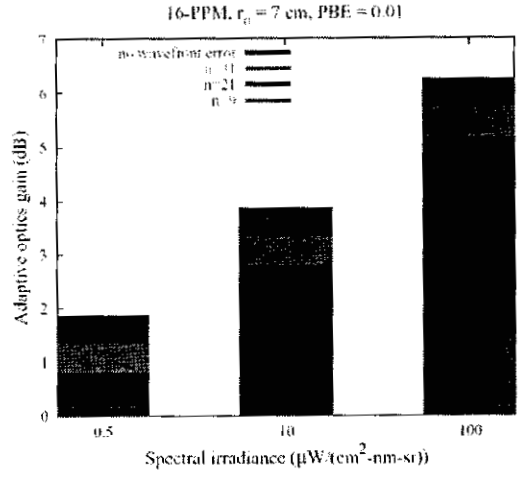
1.3 dB Gain for 97 actuator DM

0.2 dB Gain for 97 actuator DM

Results of Communications Analysis





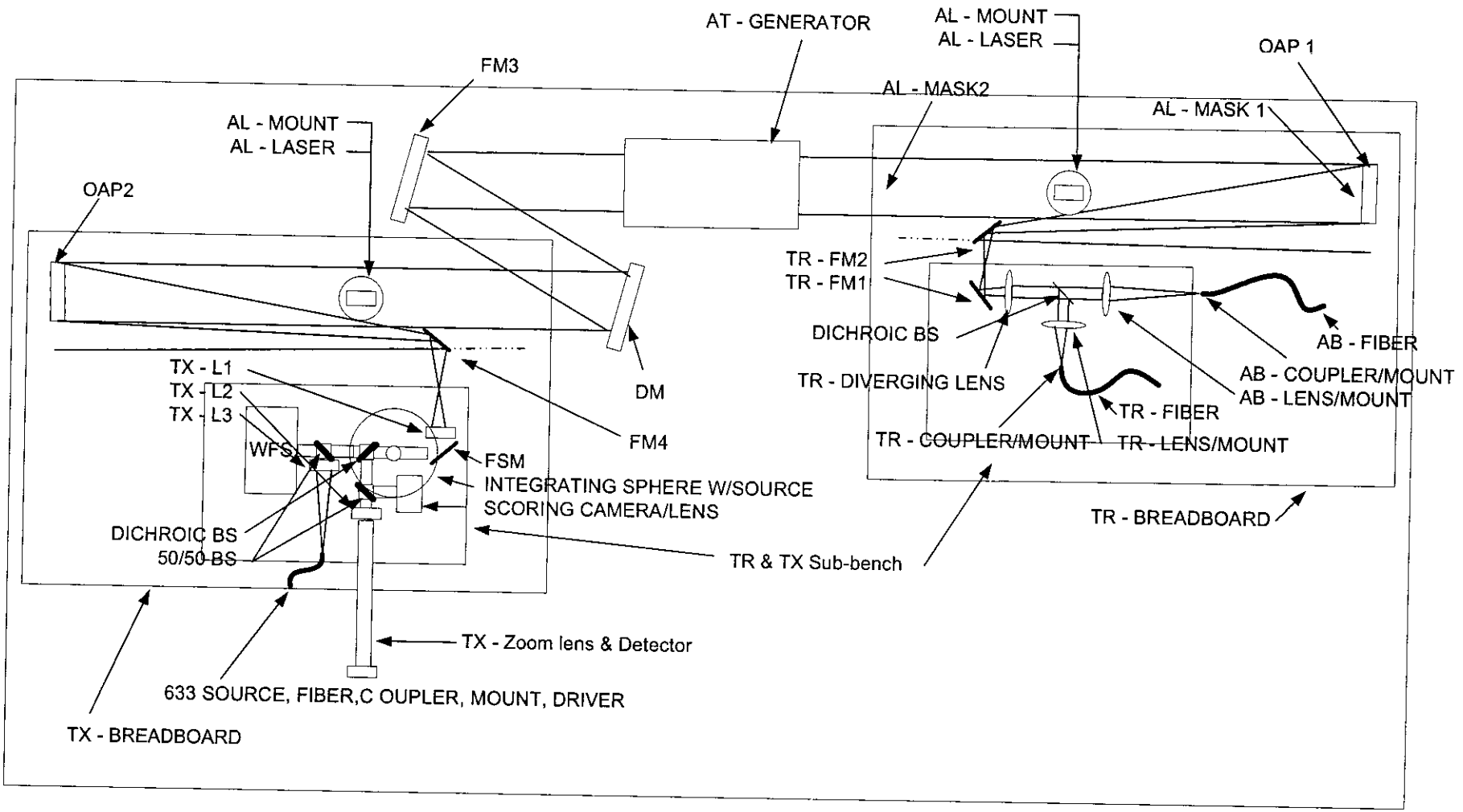


- **1-m aperture with $(30)^2$ actuator AO system can realize significant improvement in system performance at background levels and low signaling formats**
  - **1.1- 3.5 dB for 256 PPM**
  - **1.2- 4.6 dB for 64 PPM**
  - **1.3- 5.7 dB for 16 PPM**

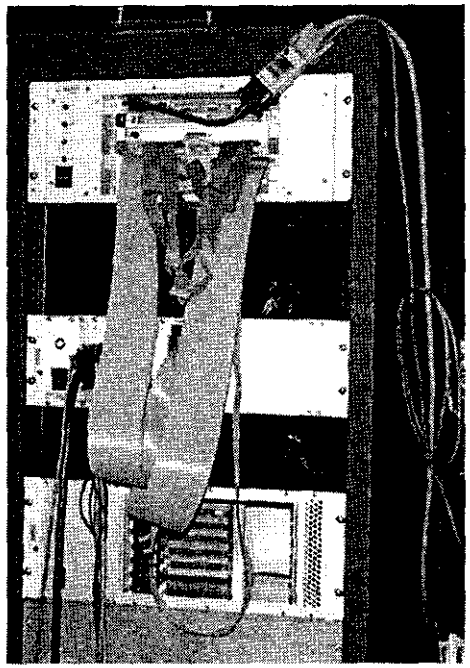
Laboratory Demonstration: Phase II

- **Objective**
  - To develop adaptive optics test bed to validate system performance models
- **Approach**
  - Simulate atmospheric turbulence and sky background level in optical train
  - Evaluate effect of signaling format, and adaptive optics wave front correction on BER of optical link
  - Demonstrate enhancement in link performance with adaptive optics
    - Assess performance as function of background level
  - Revise models as appropriate

Schematic of Laboratory Demo



Key Components



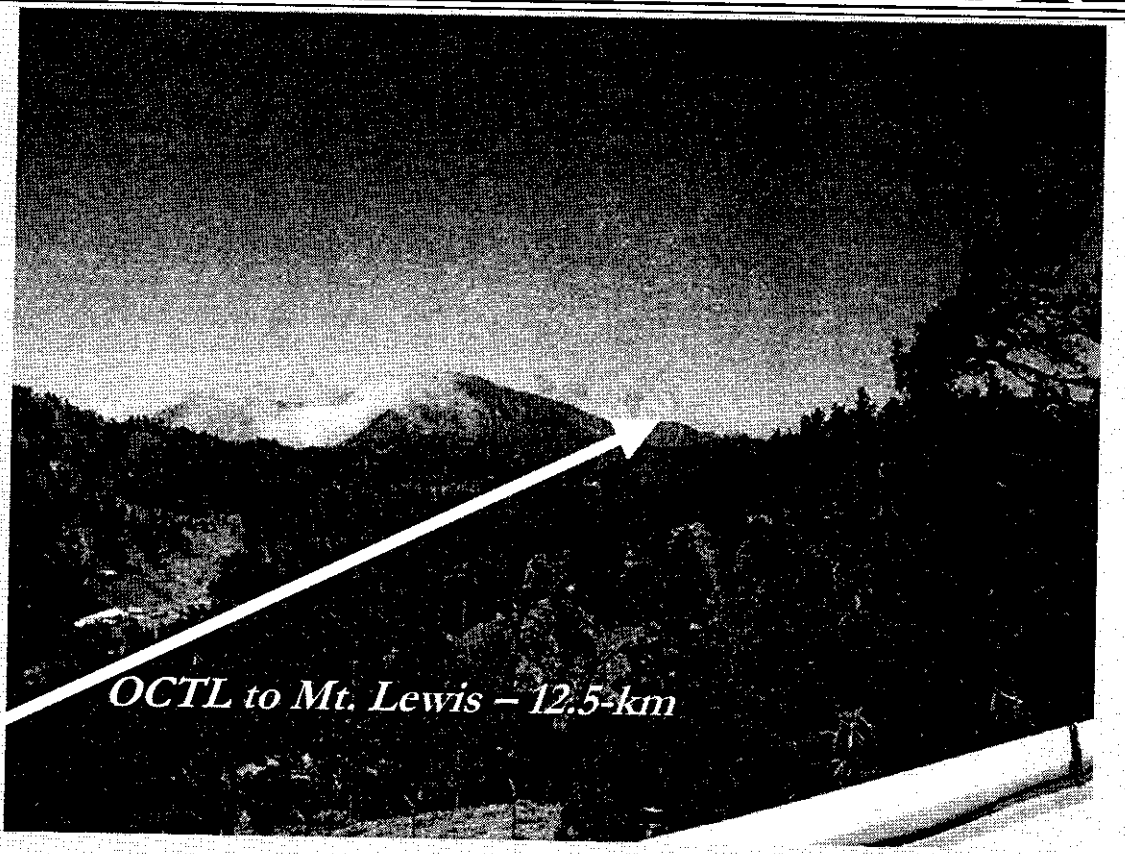
- Shack-Hartman WFS & Control Electronics
- 80x80 pixels (EEV39 CCD)
- Frame rate
  - 1100Hz full frame
  - >2KHz at 32x32 pixels
  - 3 to 7 electrons of read noise

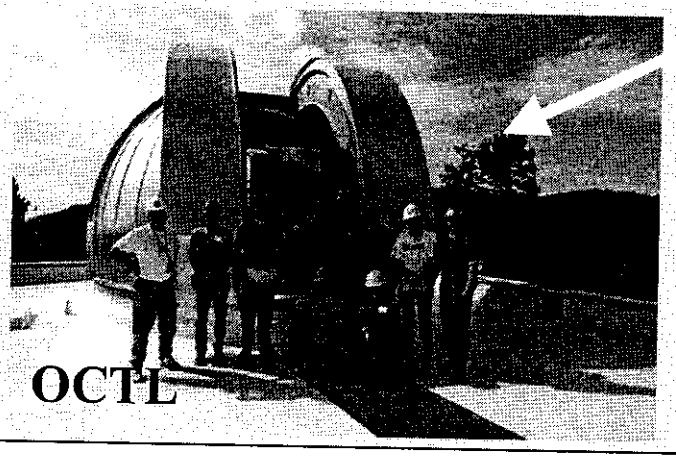
- 97 actuator Deformable Mirror
- 7mm actuator spacing
- 4 microns stroke
- >2KHz actuators bandwidth

Field Demonstration: Phase III

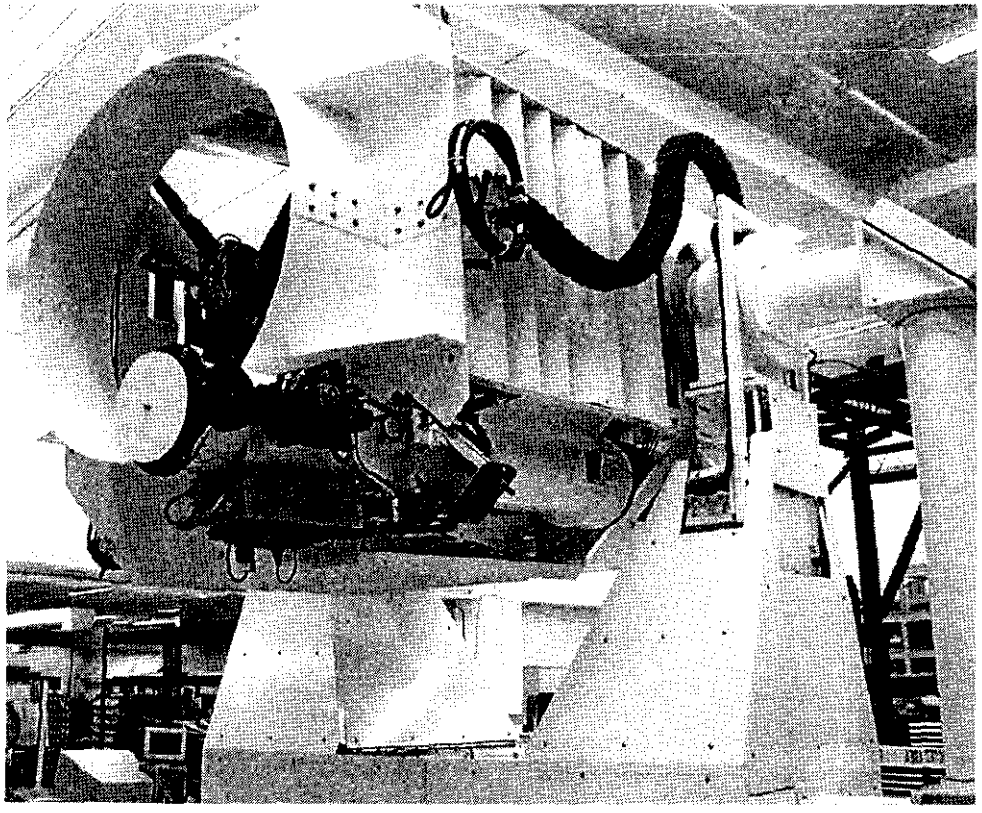
- **Horizontal path demo at TMF uses**
  - 1-m OCTL telescope
  - Transmitter at 12.5 km range
- **Telescope designed to**
  - Operate up to 30 degrees of sun without performance degradation
  - Operate down to 10 degrees of sun with 10% degradation
- **Results will enable**
  - Improvement in theoretical models
  - Techniques to be developed to enable optical comm at small Sun-Earth-Probe angles

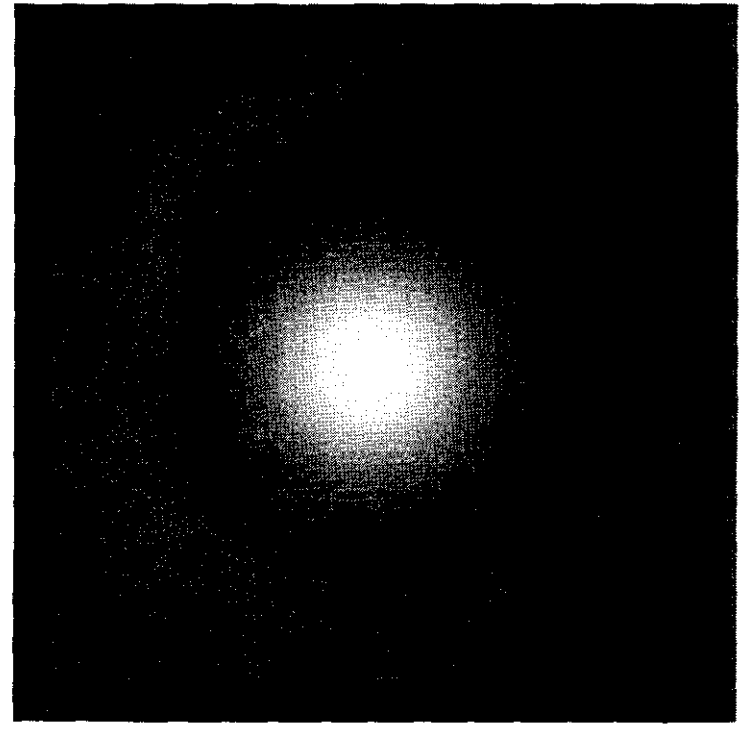
Horizontal Path Field Demo cont'd





Field Demonstration cont'd





Telescope PSF at 633 nm probe wavelength

- OCTL telescope to be installed at TMF is
  - Built to $\lambda/13$ RMS performance at 632 nm
  - Designed to operate at 30 degrees to Sun

Summary

- Analyzed improvement in optical comm link performance obtained by using AO in presence of background
- Analysis based on measured atmospheric seeing at TMF
  - Results show that improvement is dependent on communications modulation format and decreases with increasing M-ary PPM value
    - Gains as high as:
      - 6dB can be realized in high background environments at 16 PPM
      - 3.5 dB can be realized in similar background environment at 256 PPM
- Results show that 900 actuators/sq-m of aperture can achieve high background rejection
- Testbed to characterize AO system performance is currently being developed
  - Expect results in early 2004
- Described field demonstration using high optical quality OCTL telescope