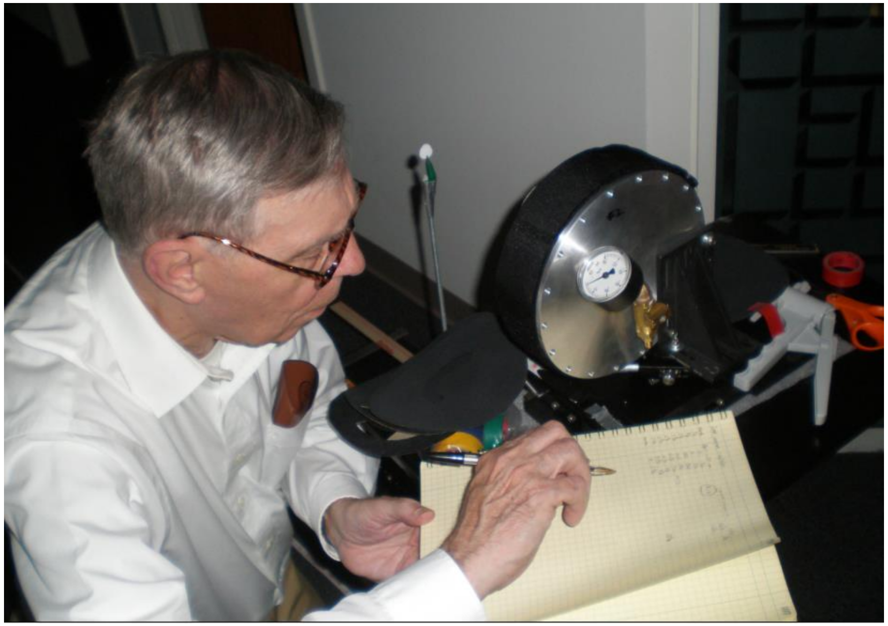
Lightweight Medium-Aperture Mirrors for Astronomy and Power Generation

Bruce D. Holenstein
Gravic, Inc.
November 7, 2011

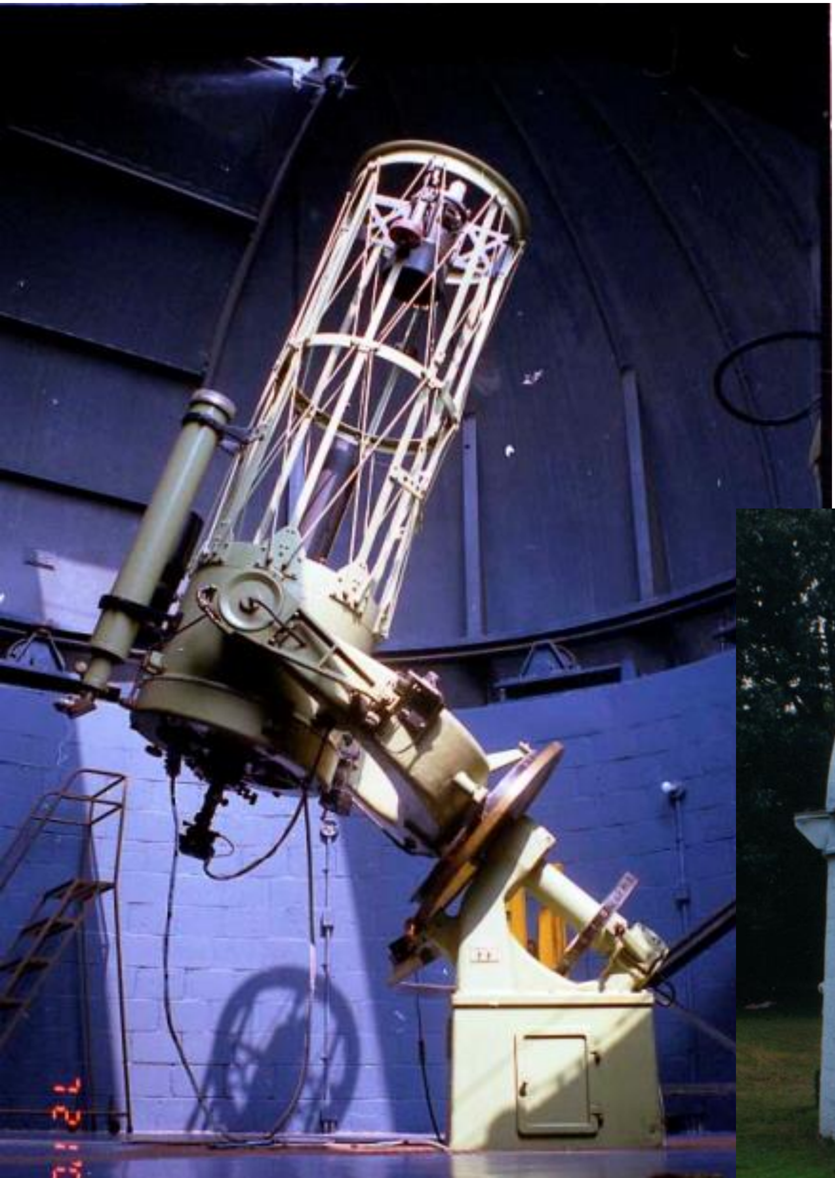
Agenda

- Background & Need
- Lightweight Mirrors & Mounts
- Optical Metrics & Remediation
- Some Future Astro Plans
- Solar Power Synergy



R. H. Koch
1929-2010

Background



- FCO housed a 28-in. Cassegrain & 15-in. Siderostat
- Had oversized dome
- RHK had a long-term interest in a bigger primary mirror

Early efforts 1991-1996

1991 Peter Waddell demoed small pneumatic cell at Penn

Peter Waddell
SPIE *OE Magazine* Oct. 2001

Modern photos of early Penn cells and CF scope

Robert Hee (machinist), RJM (electro-optics), RHK and Samuel Seeleman (optics) plus grad students

Signal-to-Noise-Ratio Dependencies

How do the factors affect the Signal-to-Noise-Ratio (SNR) of program measures?

$$SNR = \frac{N_{Star+Sky} - N_{Sky}}{\sqrt{N_{Star+Sky} + N_{Sky} + N_{Detector} + S^2}},$$

where *Ns* are counts and *S* models atmospheric scintillation

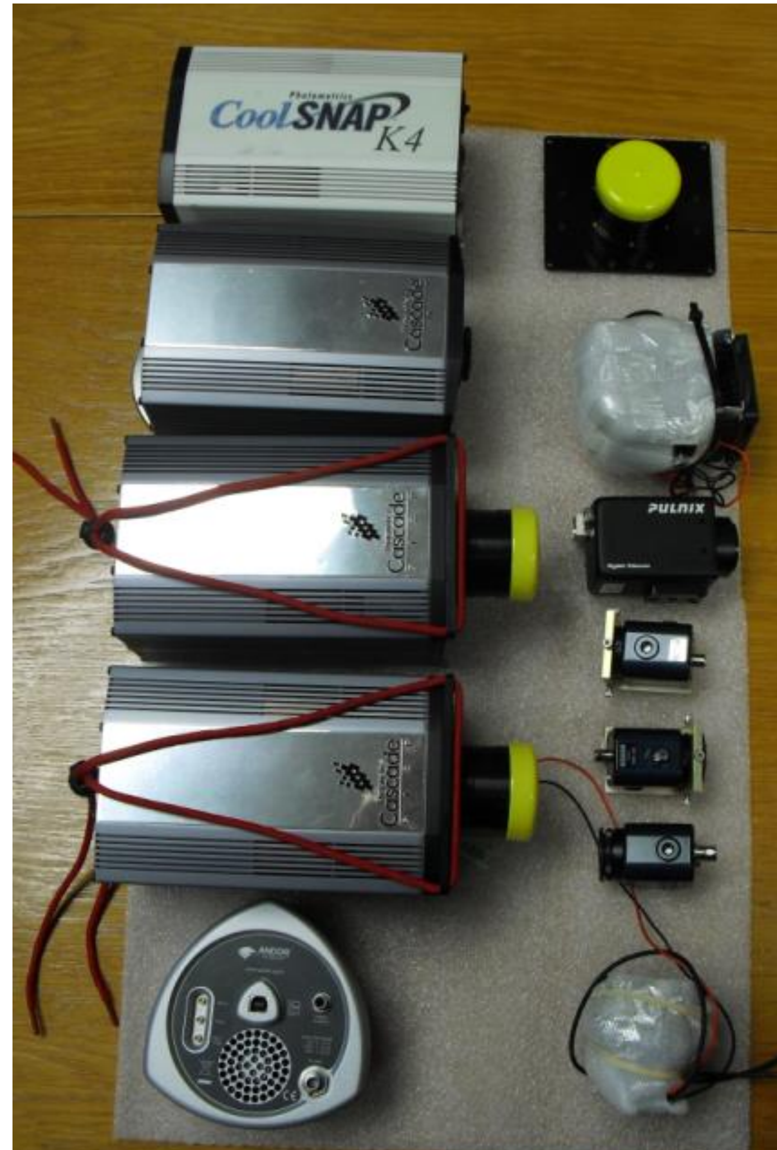
Dependency: Sky and Star

- Increase program object signal, decrease sky
  - Need large, affordable, and portable scopes
- New mirror making technologies
  - Balance needs, e.g. focal plane diaphragm size vs. aberrations

42-inch pneumatic mirror prototype at Gravic Labs

Dependency: Scintillation

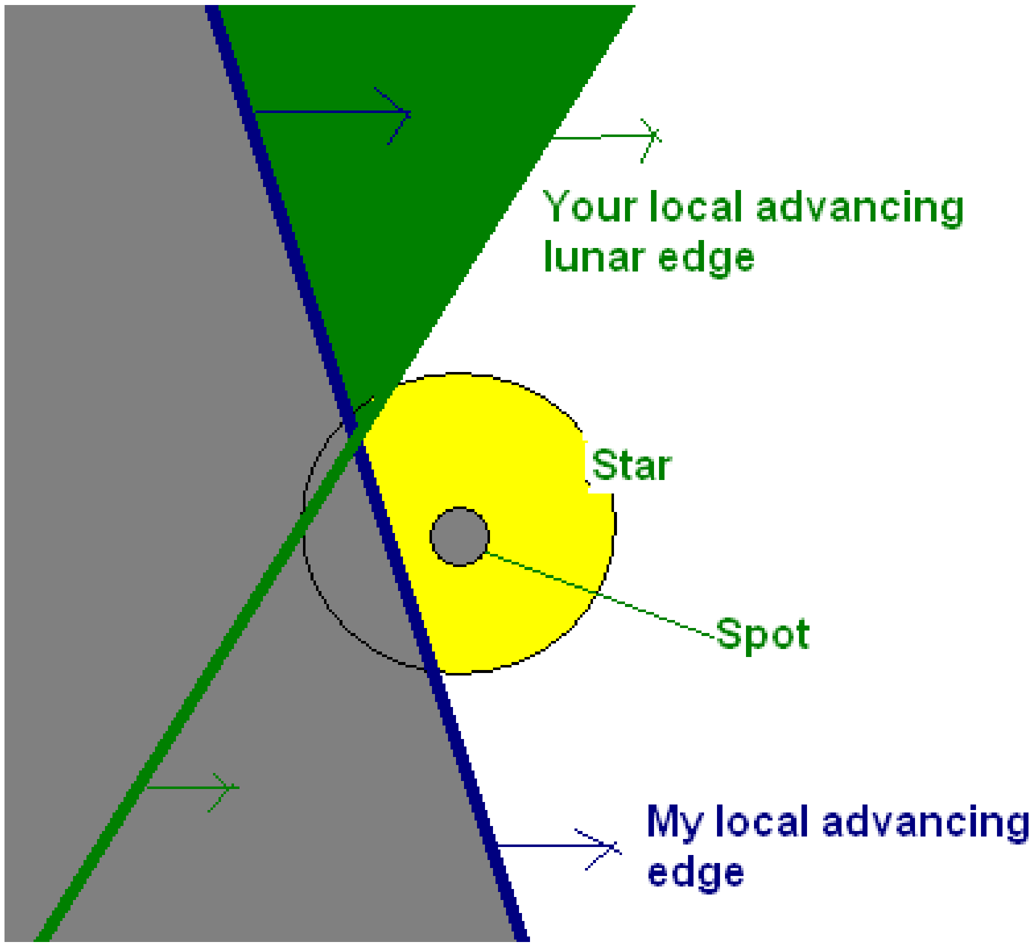
- Some cases we can't increase integration time
  - Need about 200+ fps in visible for lunar occultation diffraction patterns
- Mitigate it
  - Increase objective diameter
  - Move to a higher altitude
  - Reduce central obstruction size
  - Utilize arrays of scopes



Low noise, High-speed cameras

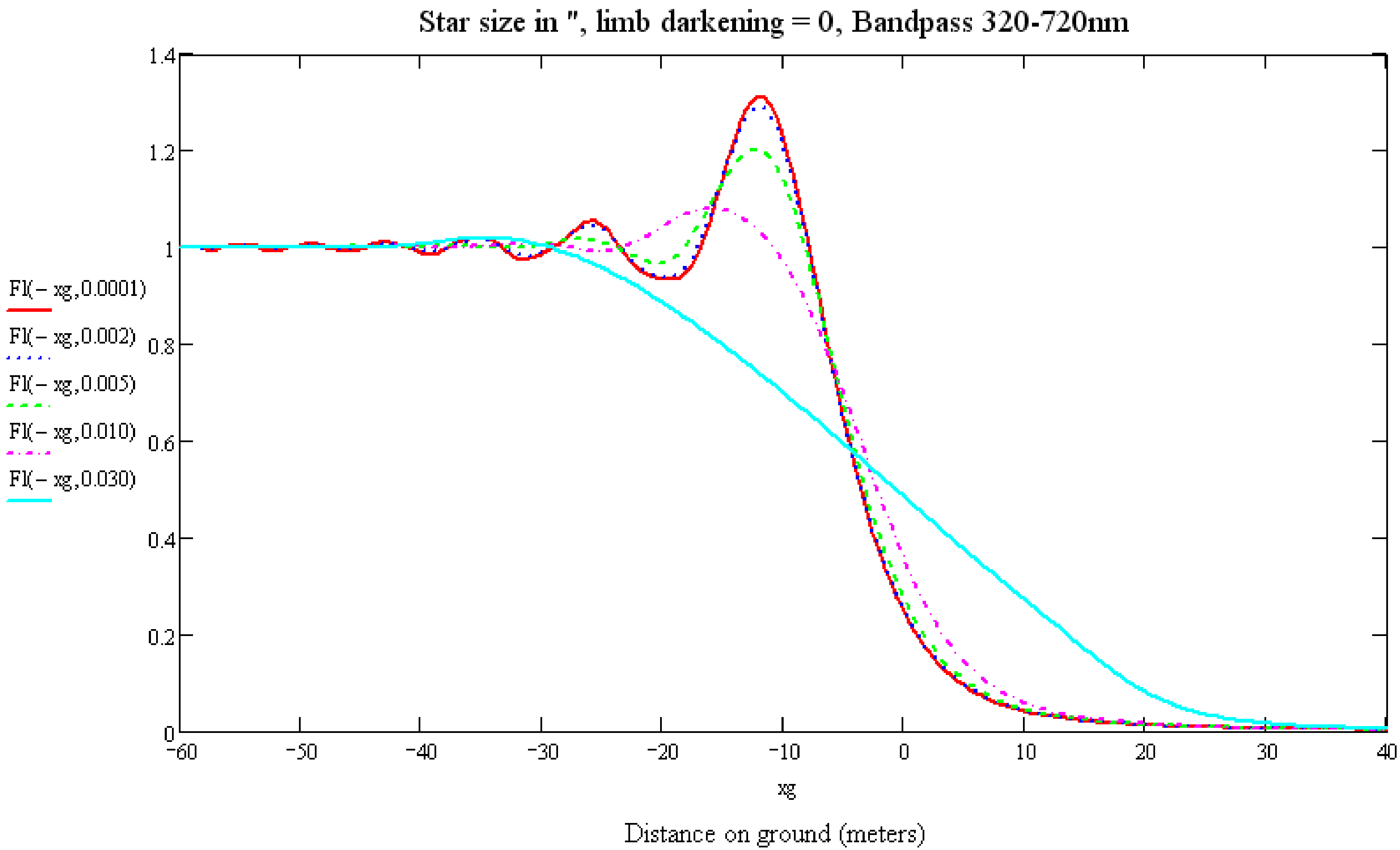
Occulted Object Science Potentials with a Sufficient SNR

- Presence/absence of stellar companions
  - Separations, PA, relative luminosity
- Stellar sizes
- Limb darkening laws
- Presence of plages and spots
- Circumstellar disks
- Detection of hot Jupiters



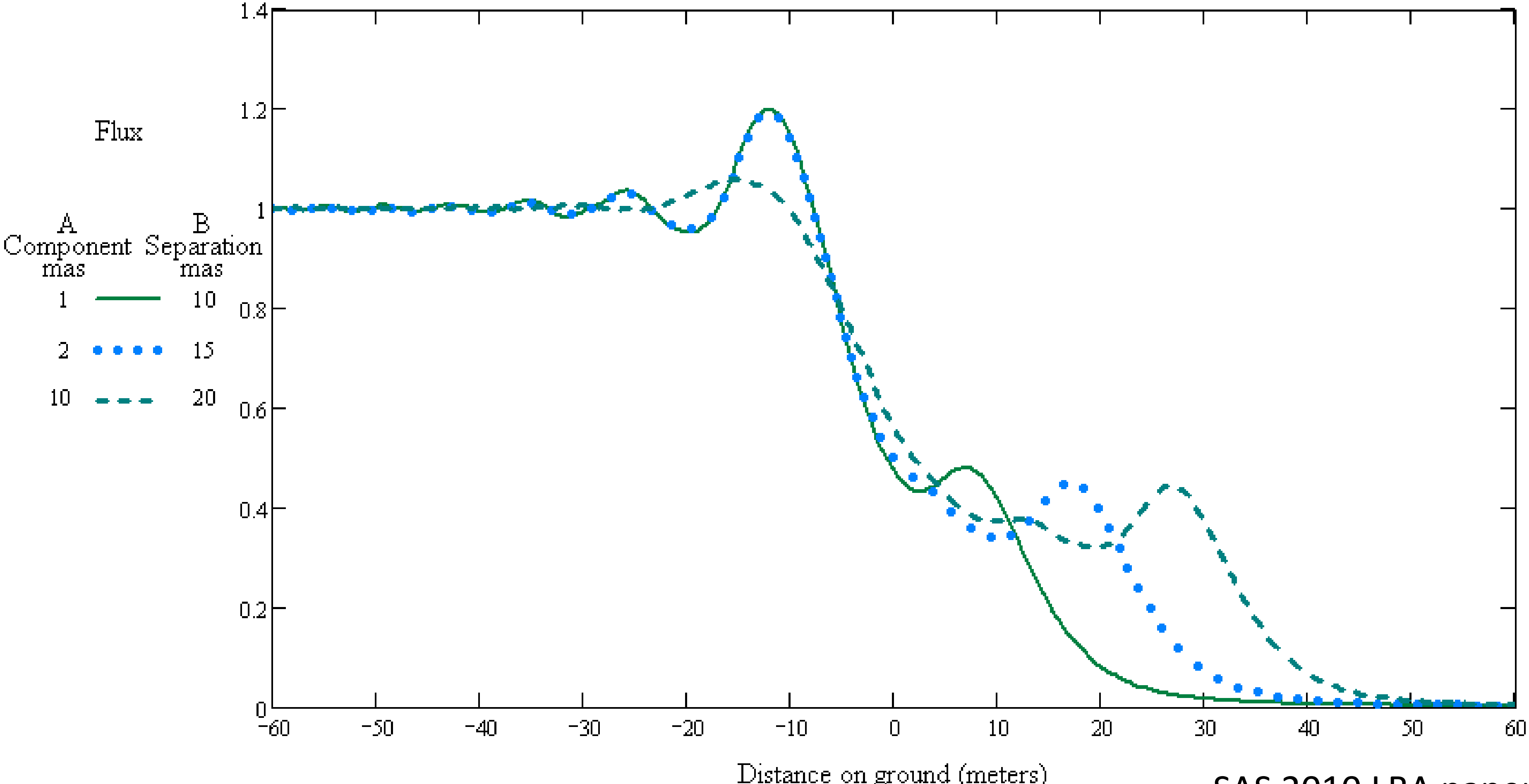
Lunar Occultations Examples

Theoretical diffraction light curves for different sized stars (0.1 to 30-mas)



Lunar Occultations - Binaries

Theoretical diffraction light curves for three different binary systems



SAS 2010 LBA paper

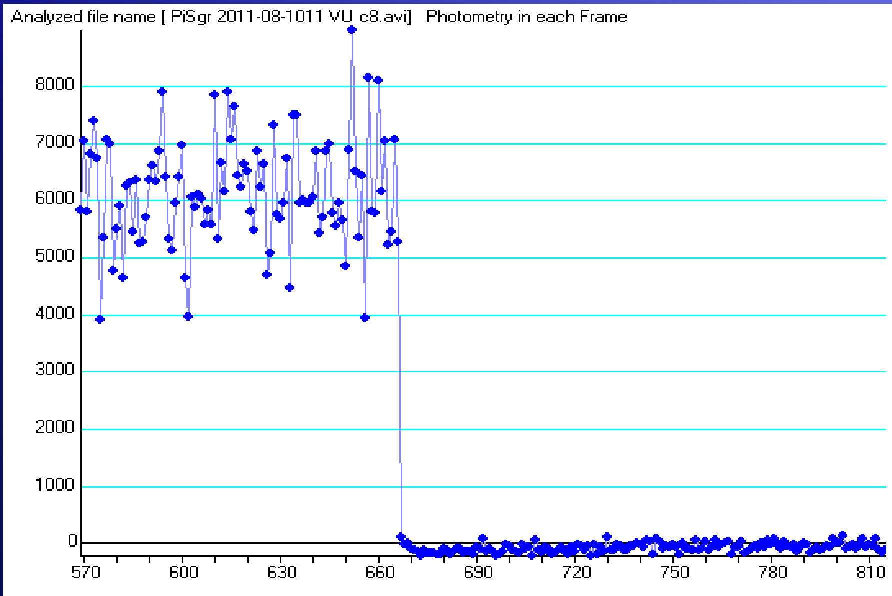
Pi Sgr Lunar Occultation

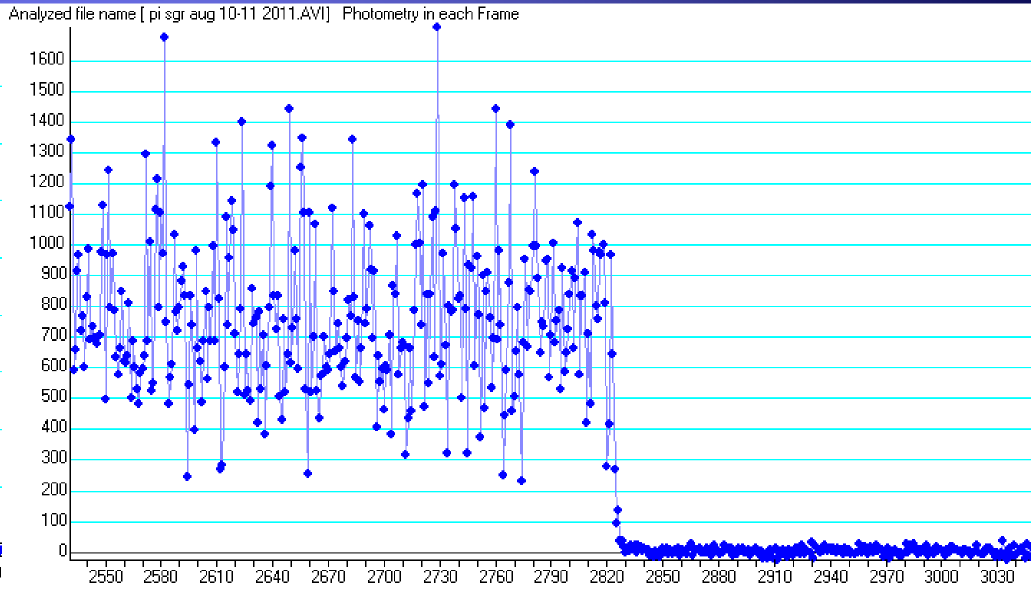
Villanova, August 10, 2011

Mendel Hall Lawn
Two C8's + cameras

GPS Video Time
Insertion on VU C8 feed

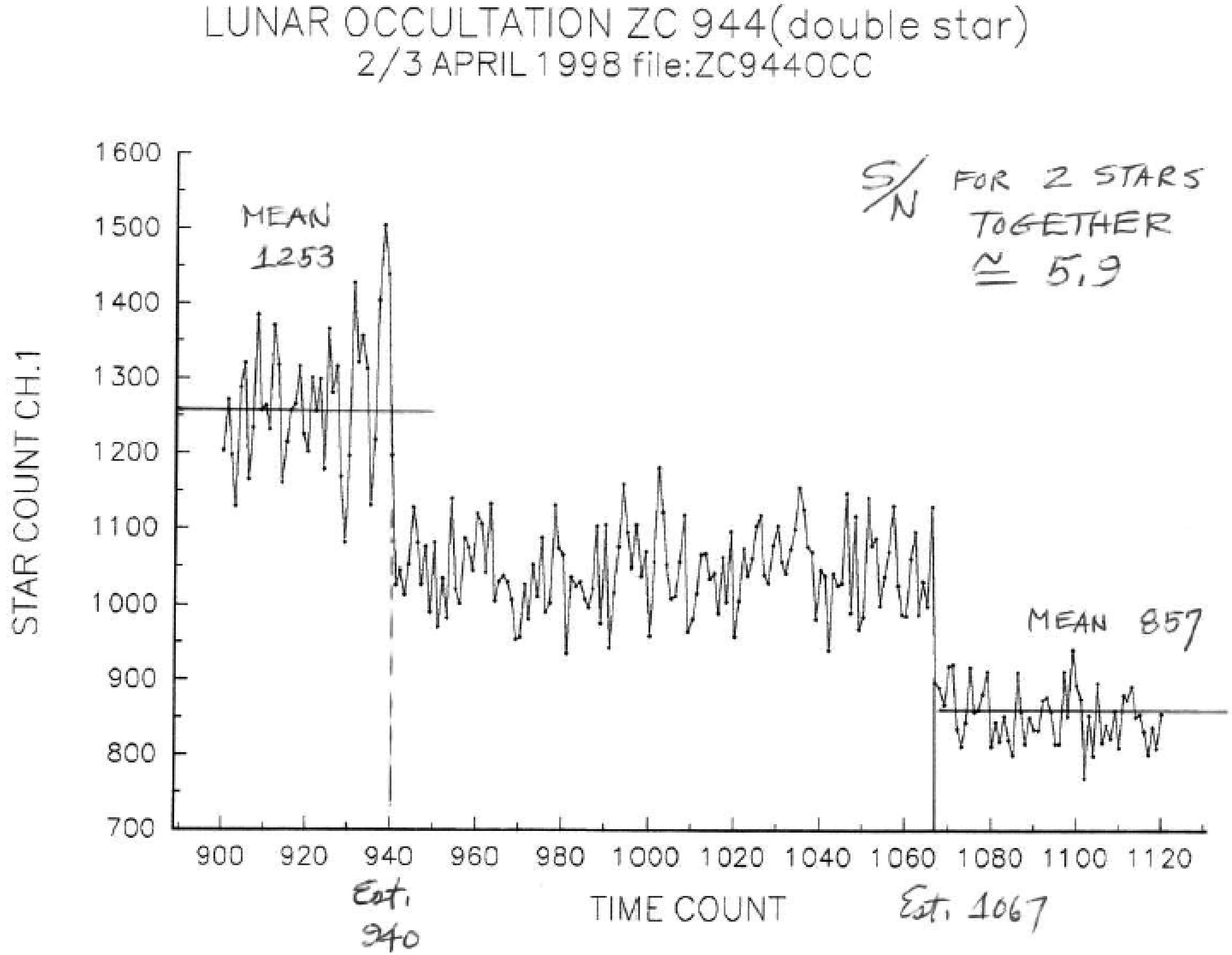
Pi Sgr Lunar Occultation II
Villanova, August 10, 2011





Villanova C8, 164CEX-2 CCD, no filter, 30fps 9.4mas per datum

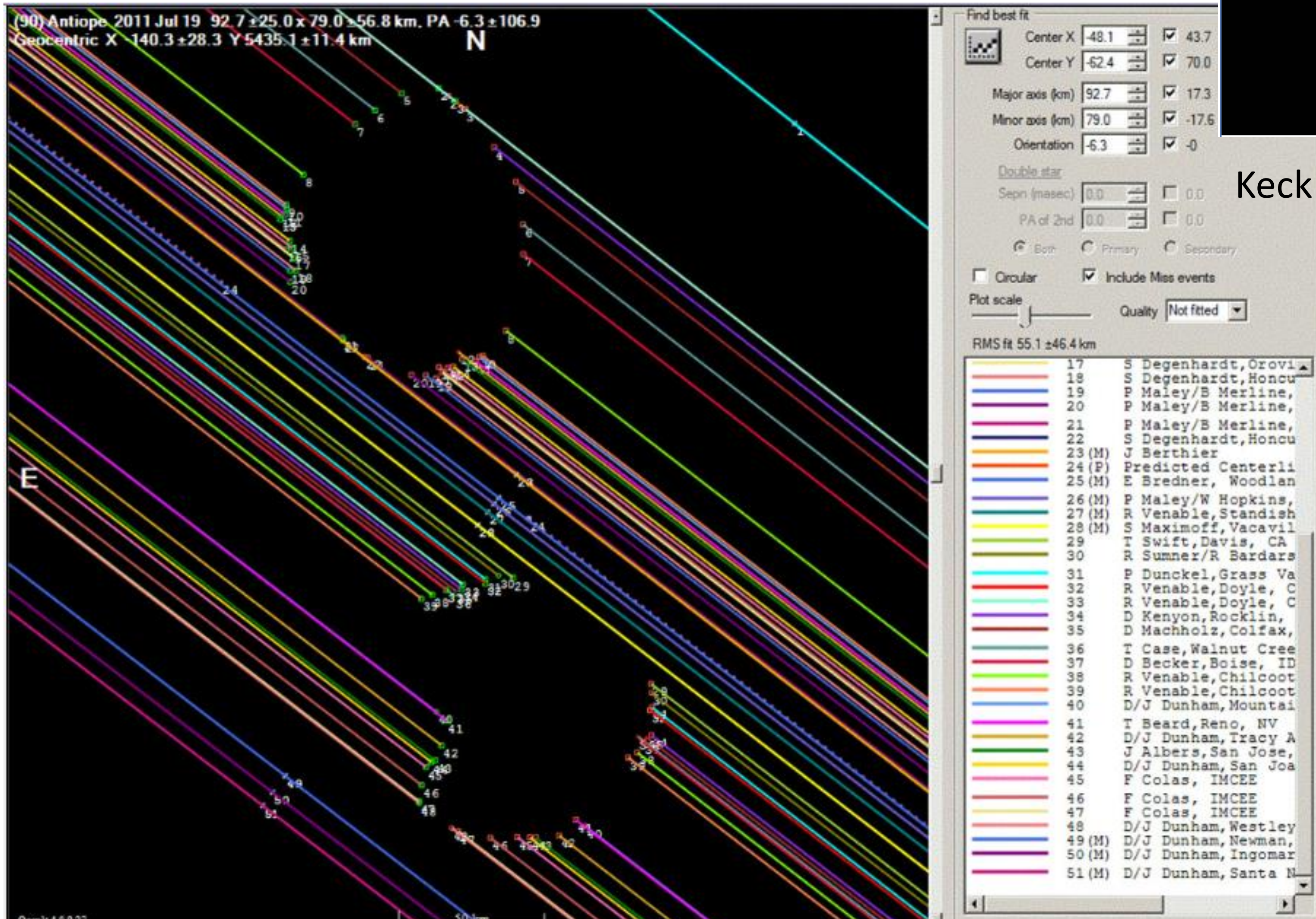
Gravic C8, Andor Luca-S emCCD, Sloan r filter, 120fps, 2.4 mas per datum

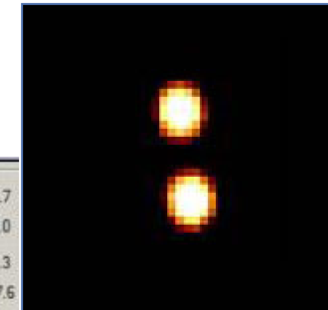


- 15” Siderostat at Flower and Cook Observatory, Malvern, PA by R. H. Koch, R. J. Mitchell and W. J. Blitzstein
- Occult4 lists close double 0.39”, Limb=0.190”/sec
- 127 15-ms samples = 0.362” separation

Asteroid Occultation Timings

IOTA Asteroid Timing





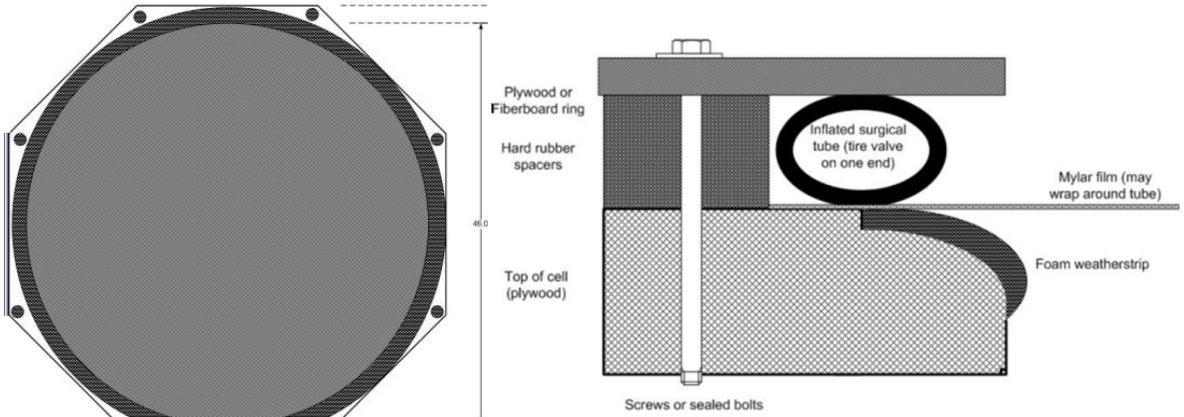
Keck (Sky & Tel)

- Antiope success – July 19, 2011

Lightweight Mirrors and Mounts

- Pneumatic Mylar
- Foam glass
- Spun epoxy
- Slumped meniscus
- OTA's and Mounts

42” Pneumatic Mylar Cell



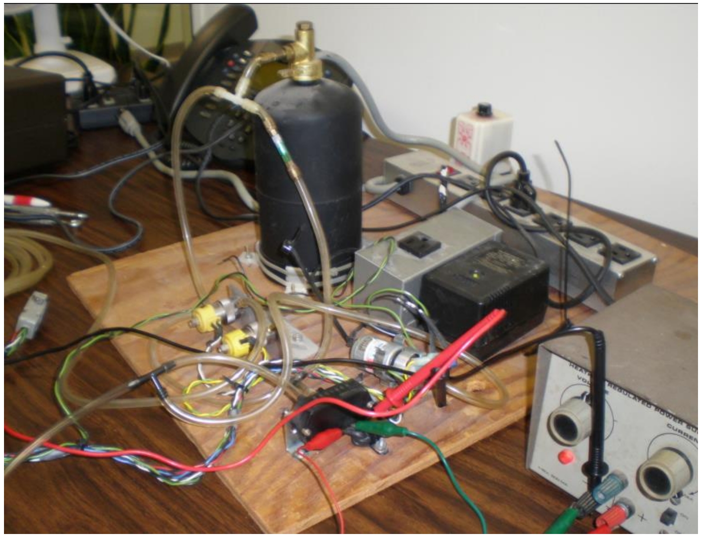
Pneumatic 42” Cell construction

Williamson student carpenter

Rolled Mylar about to be cut

Pneumatic Control

Properly tensioned membrane



Pneumatic control made with surplus parts

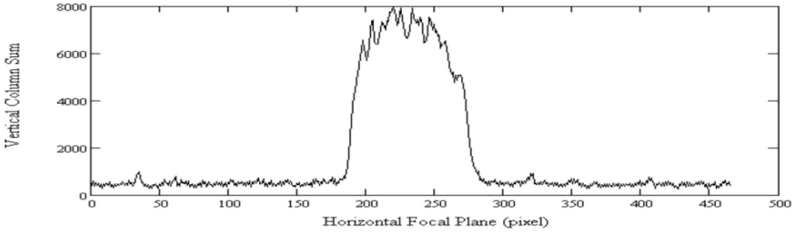
Looking for leaks

Pneumatic Mirror Results

42-in. scope with Gravic high-speed photometer in 2009

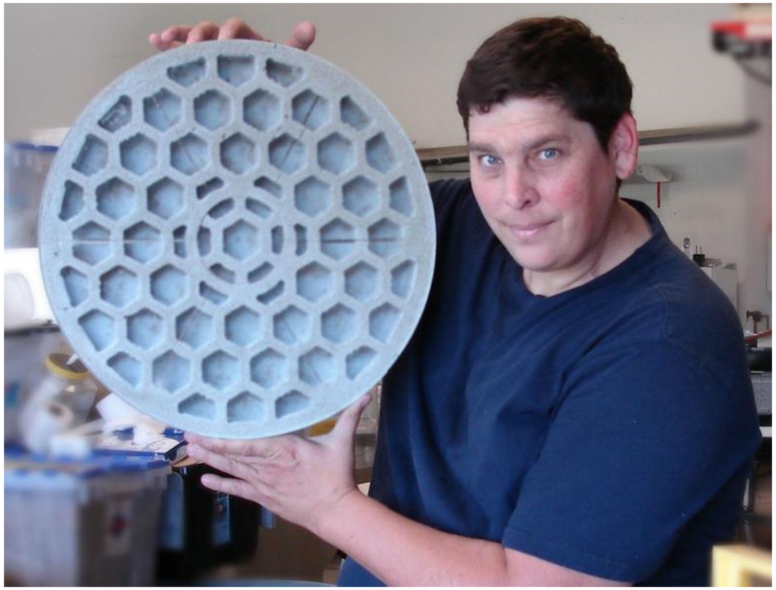
Image of tower shows astigmatism

Vega 12-in cell, f/4 w/0.5 FR, 5.0 μm/pixel



Holenstein, *et. al.* 2010

Alt-Az Initiative Mirrors

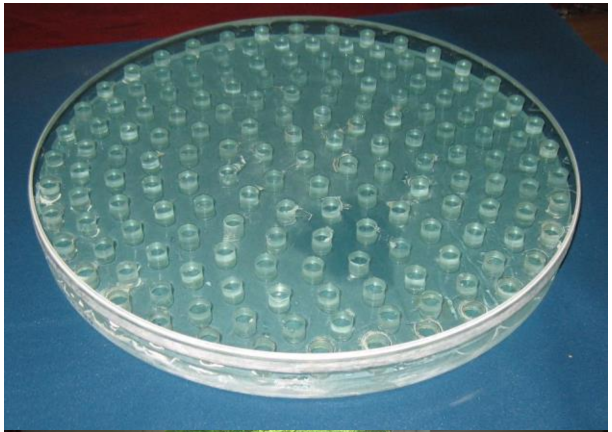


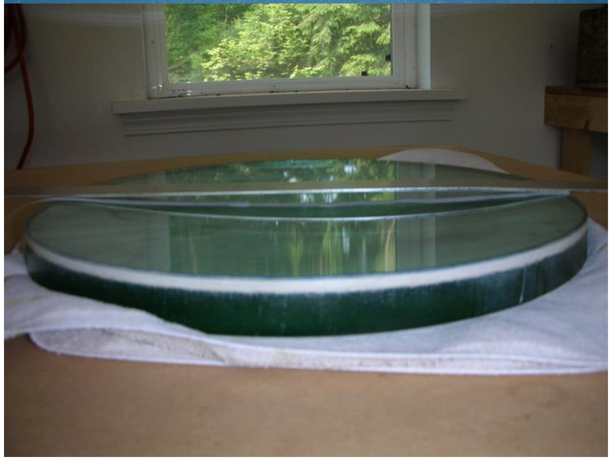
Andrew Aurigema's plate glass slumped over foamed glass substrate mirror

David Davis's 60-in. tessellated glass over foamed glass (D.D. with suspenders, Russ Genet with hat)

Alt-Az Init. Mirrors II

- Lisa Brodhacker/ Lander University – spun epoxy
- Tong Liu/Hubble Optics – plate glass sandwich
- Mel Bartles & others - slumped meniscus





Portable Medium Aperture Mounts and OTA's

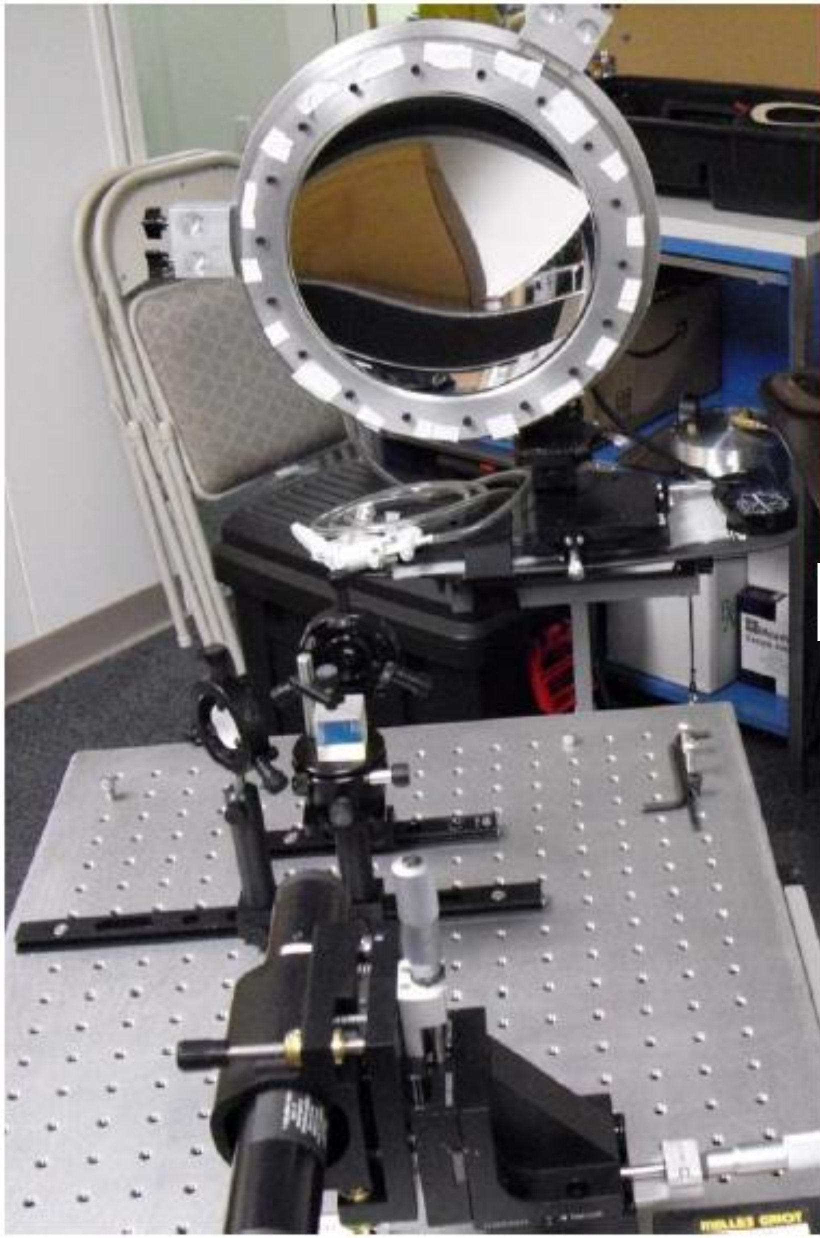
Hubble Optics UL20
0.5-m at Gravic

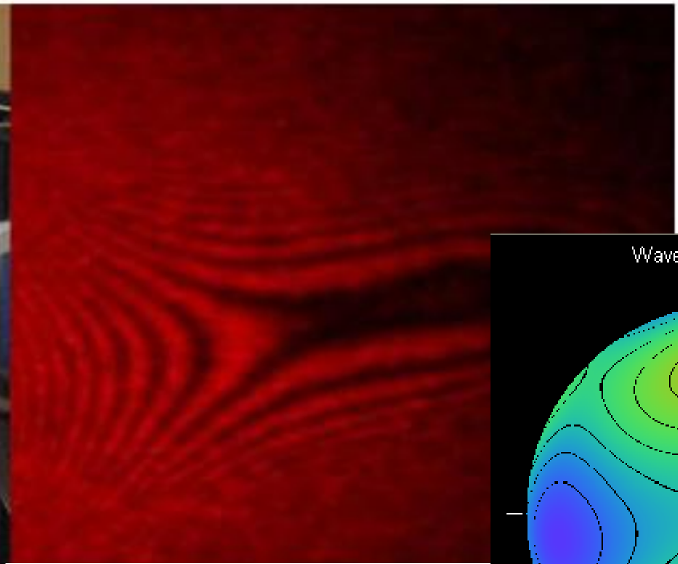
Alt-Az Initiative/Russ Genet's 1-m

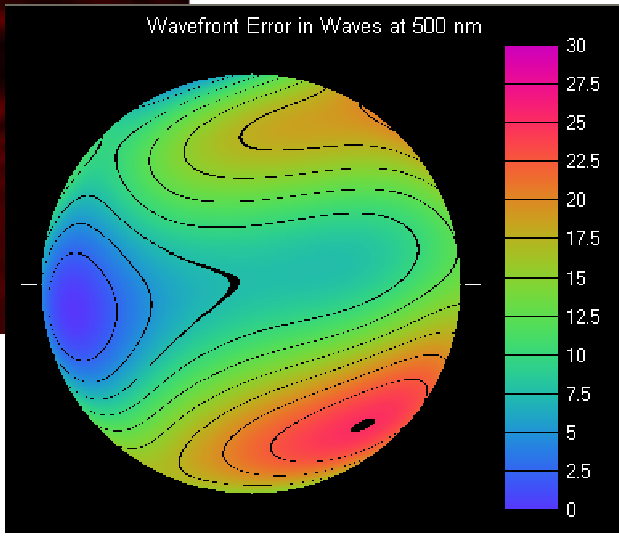
Portable Medium Aperture Mounts and OTA's II

Cal Poly and Russ Genet's 1.5-m

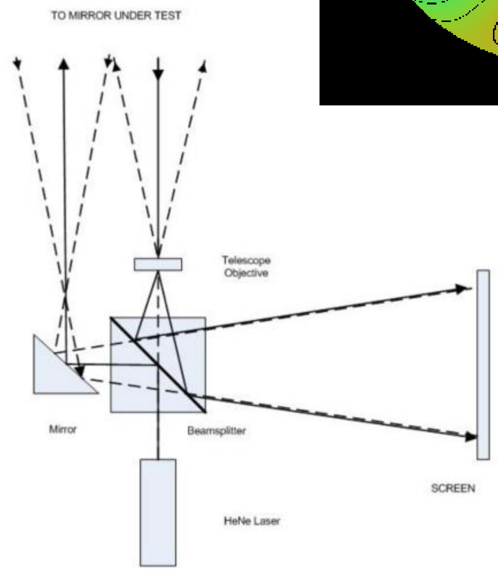
Optical Metrics - Gauging Progress



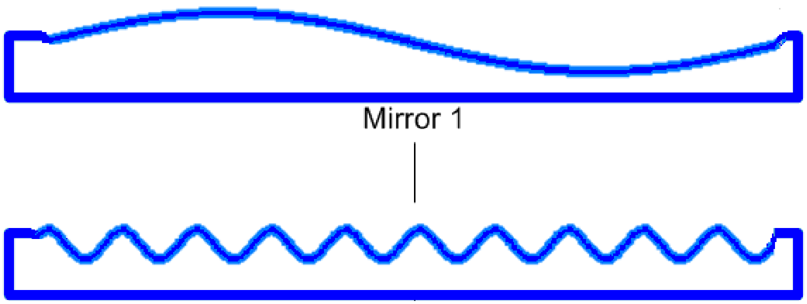




Bath Interferometer



Figures of Merit



Zernike wavefront representation, *W(ρ,θ)*, is used for the estimation of **σ** and $|\boldsymbol{\Delta\varphi}|_{\mathbf{rms}}$ (rms slope)

1 $$W(\rho,\theta) = \sum_j a_j Z_j(\rho,\theta)$$

2 $$\sigma_W^2 = \langle W^2(\rho,\theta)\rangle - \langle W(\rho,\theta)\rangle^2 = \sum_{i=2} a_j^2$$

3 $$\nabla W(\rho,\theta) = \frac{\delta W}{\delta \rho}\,\boldsymbol{e_\rho} + \frac{1}{\rho}\frac{\delta W}{\delta \theta}\,\boldsymbol{e_\theta}$$

4 $$|\Delta\phi|_{rms} = \frac{\|\nabla W\|_{rms}}{D/2}$$

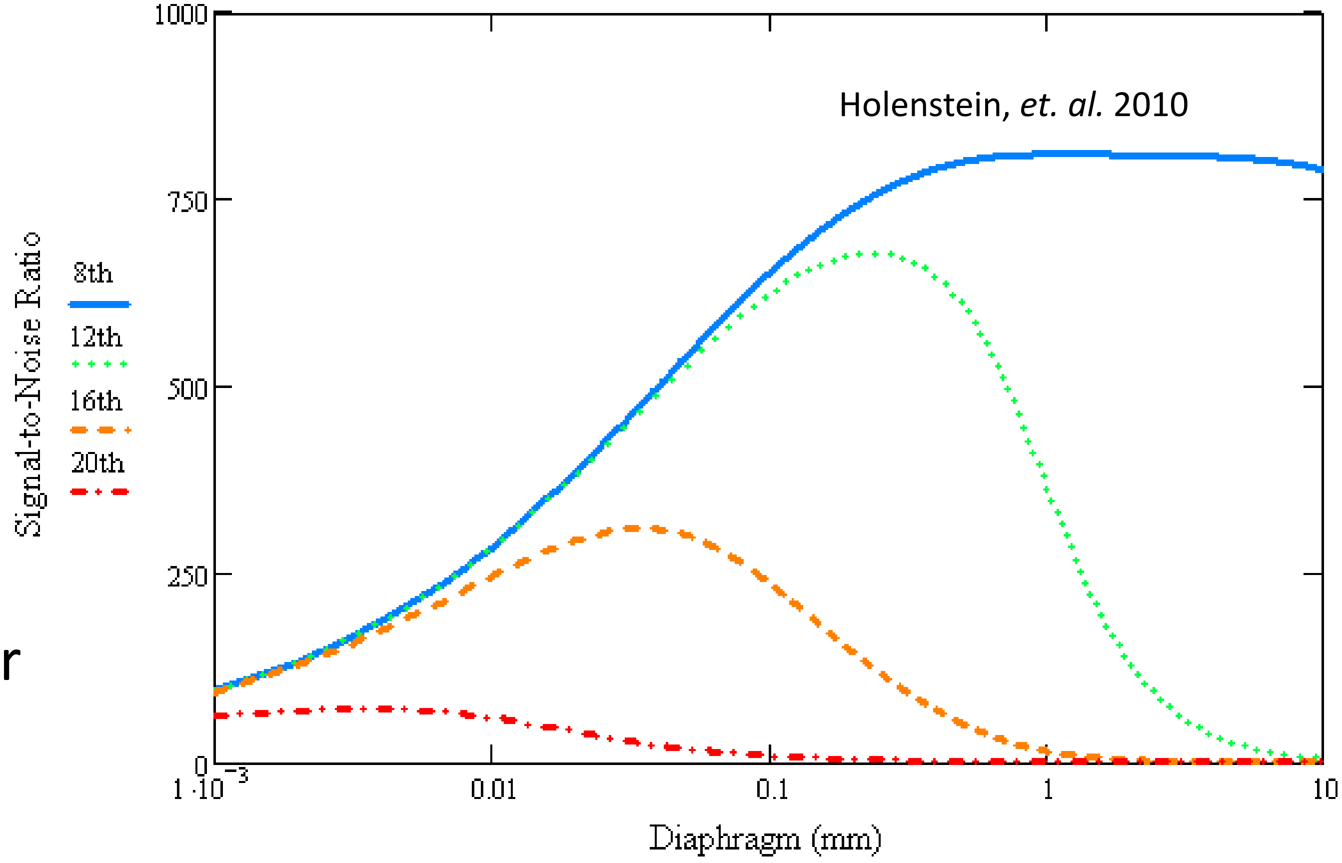
Diameter of CoC from local slope flaws

5 $$d_{CoC,local\ slope}(n') \approx 4n'F\,|\Delta\phi|_{rms}$$

F focal length, and *n'* multiplier determines the encircled flux fraction

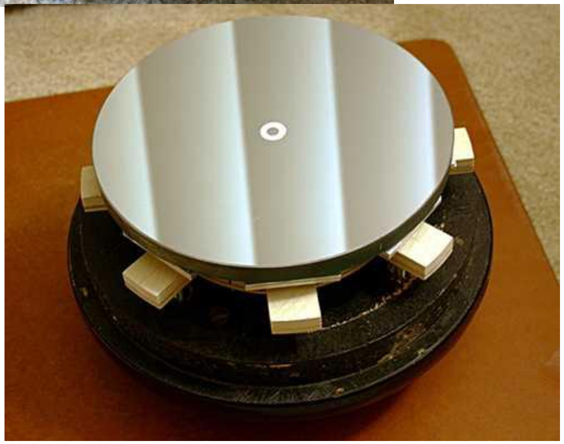
Figures of Merit II

- Local slope aberrations : 10 waves rms gradient norm
- 4 program star cases; *V* = +21 / arcsec squared background
- *f*/1.9, 1.6-m mirror
- Scintillation 1000-m, air- mass 1.5



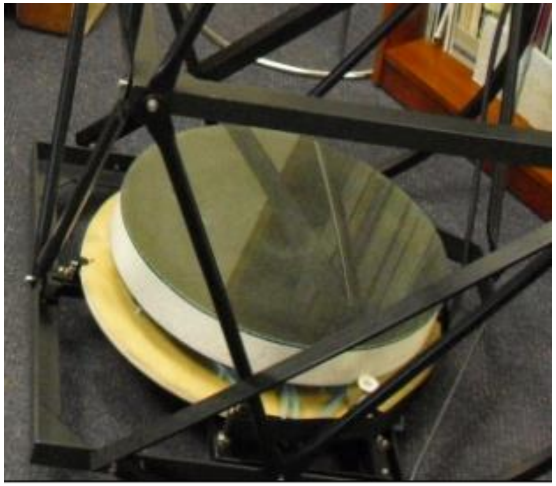
Wavefront Remediation - Active Primary Mirrors

Fixtures designed to counteract primary aberrations



Mike Connelly’s deformable 8” cell

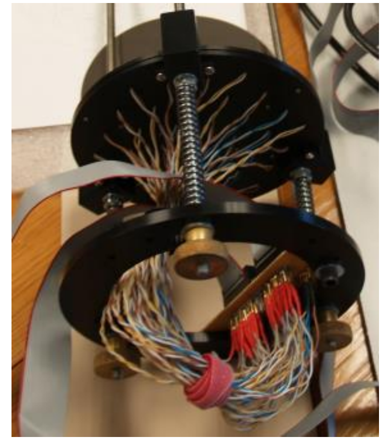
Russ Genet’s 1-m warping harness



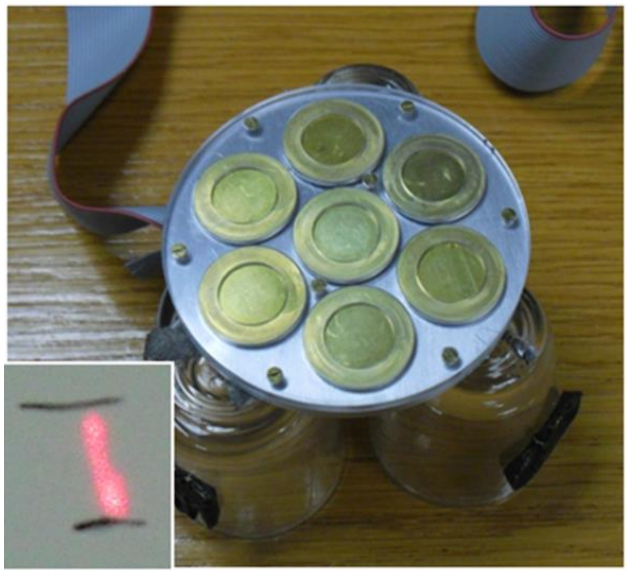
Gravic pneumatic warping cell for 18” foam glass mirror

Wavefront Remediation - Active Secondaries

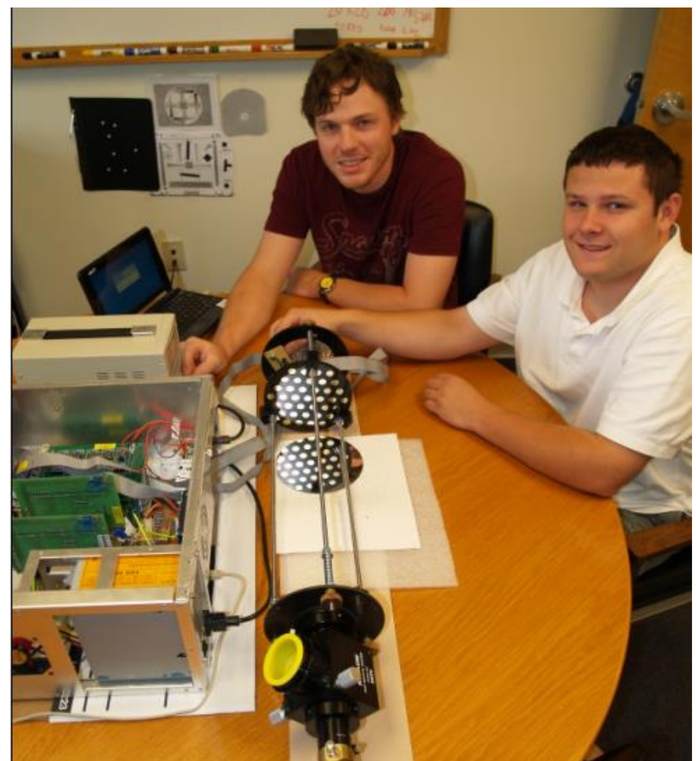
Active secondary mirrors built to conjugate primary aberrations



37-actuator 6-in. diameter design ready for final assembly



- Unblocked piezo deflection of +/-35 microns over 120VAC
- About 0.2microns/Volt
- 10-g swing +/- 150V



Controller, actuators, high-speed photometer

2011

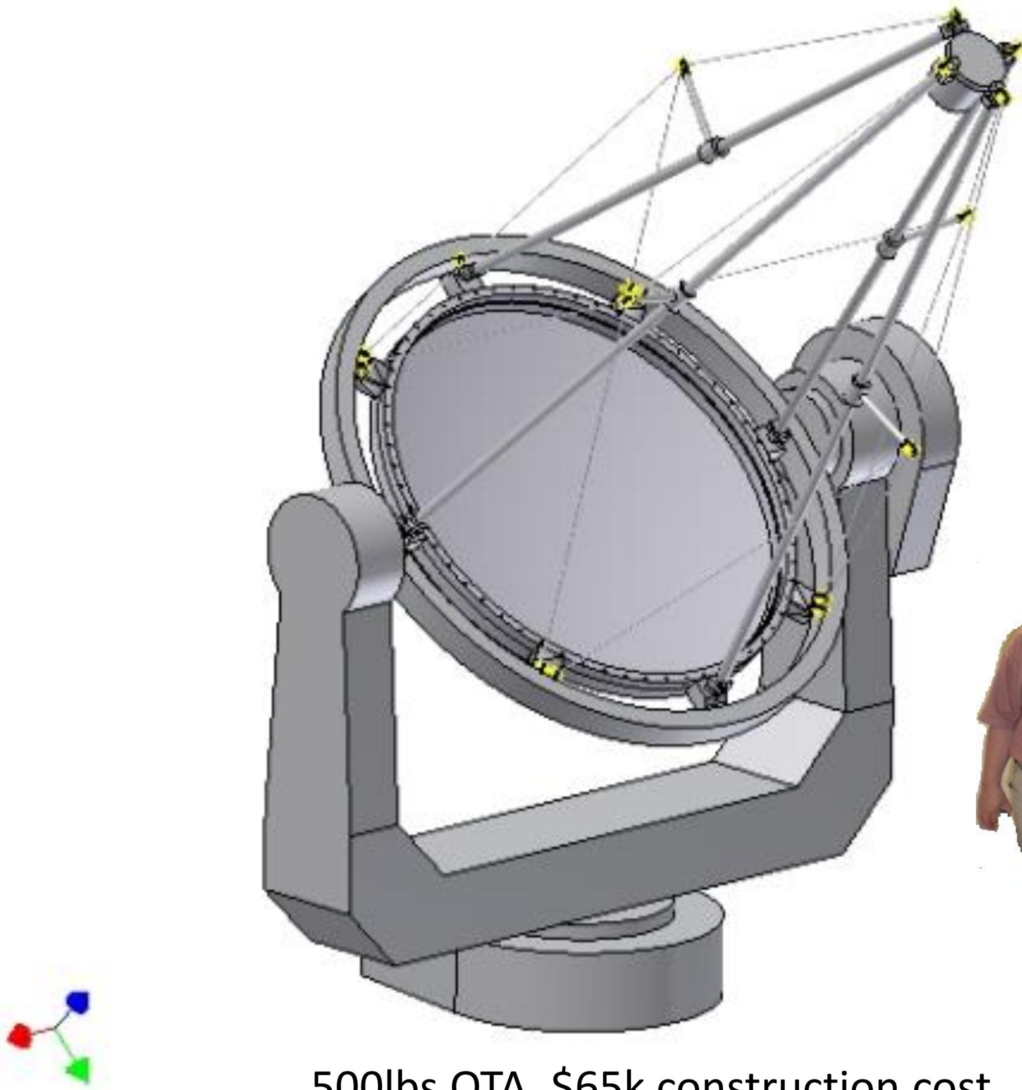
Gravic's Future Astro Plans

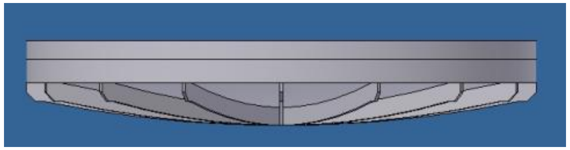
- 7 to 10 elements 0.75 to 1.5-m
- Configurable
  - Minimize scintillation
  - Maximize coverage
- East Coast location
  - <2500 ft. elevation typical
  - 1-2 arc second seeing
- Automated, Queue Scheduling
- Min. 3 astronomers, 1 tech.

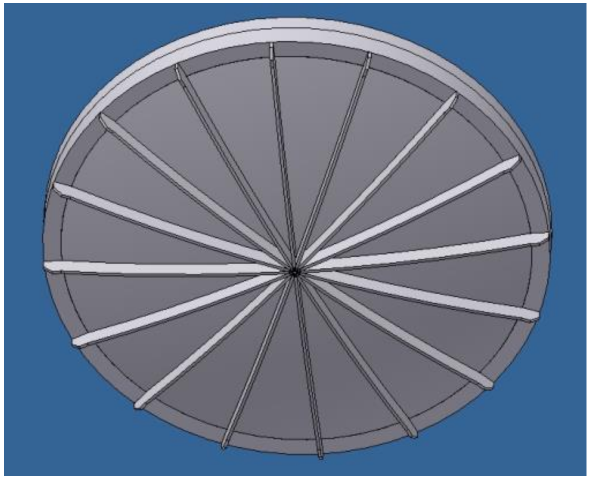
Coudersport, PA (5 hrs.)

International Dark Sky Park

1.6-m Alt-Az Design







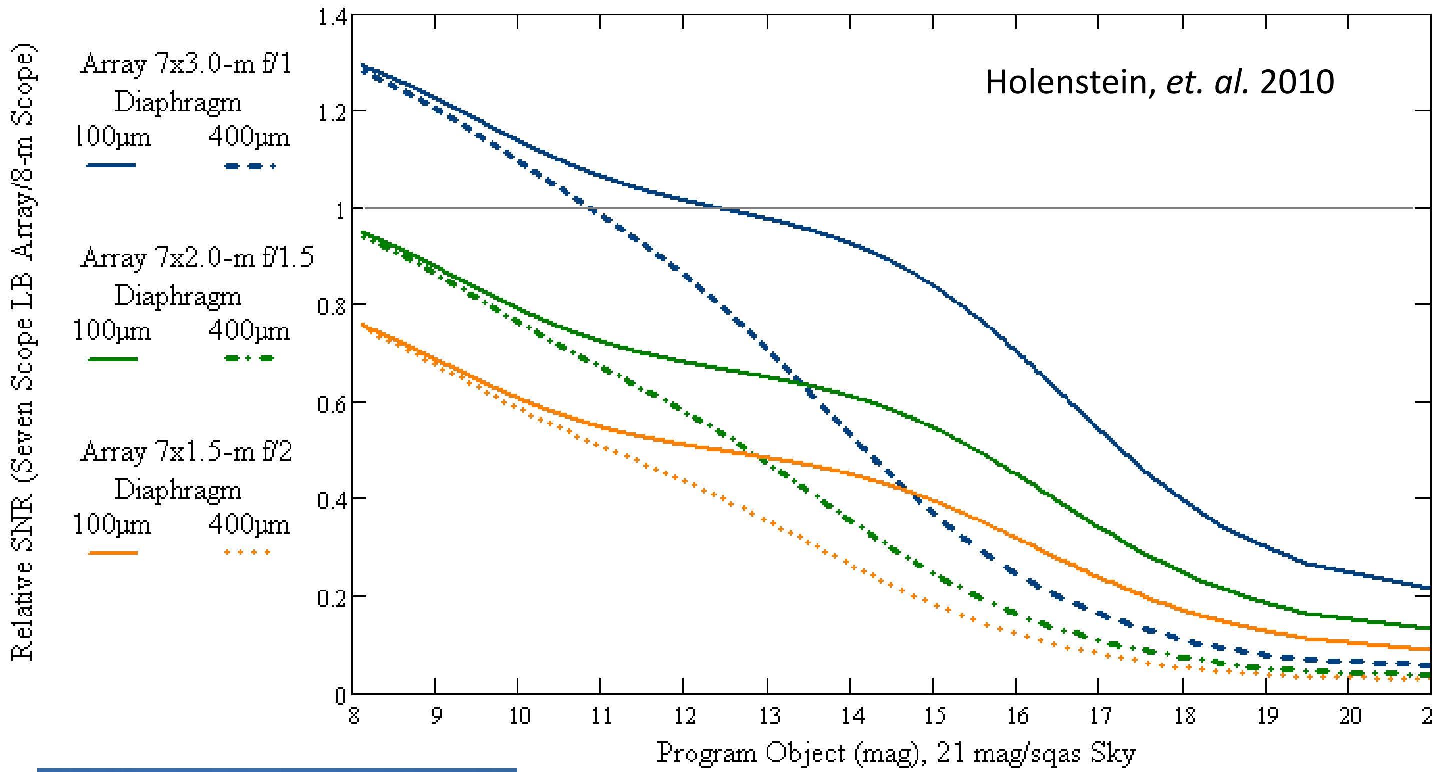
500lbs OTA, $65k construction cost

7-Element Arrays vs. Traditional

7-element LBT array *vs* . One 8-m f/1 scope

2 relative diaphragm diameters (400, 100 vs 40 micron on 8-m)

Scintillation at 3000-m, 1.5 air-mass



Other Array Benefits

- *Reliability. Immediate and independent confirmation of rare, transient events*
- *Availability. Graceful failure rather than all at once*
- *Independence. Geographic area avoids clouding out the array*
- *Transportability. Moveable elements to avoid bad weather or seek advantageous observing locations*
- *Expandability. Add more array elements later as funds allow.*

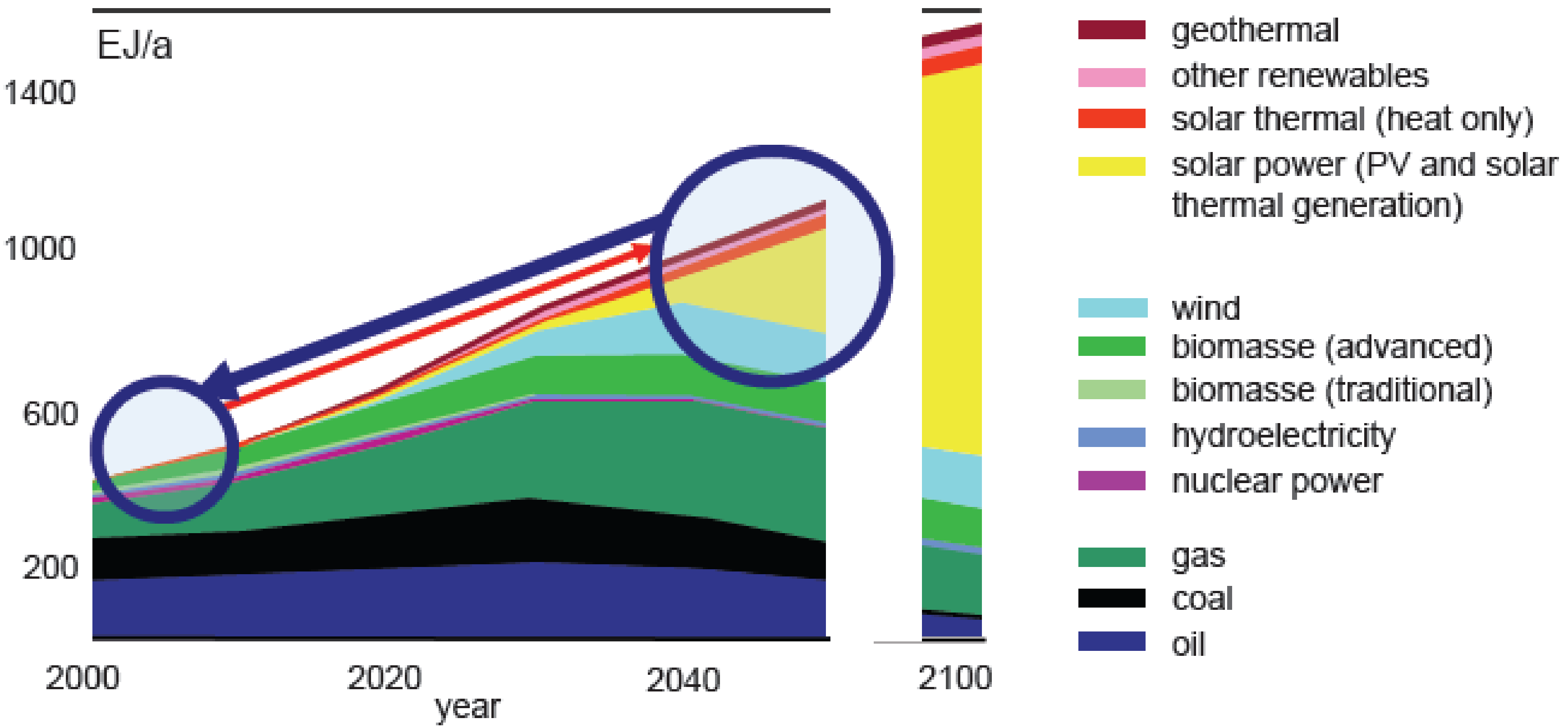
Astro-Solar Power Synergy

Solar resource available : much more than we need

The Earth receives from solar radiation in 10 days as much energy as the known fossil reserves

- 2007 World energy primary consumption: 138×10^{12} kWh
- But about 100×10^{12} kWh of equivalent electricity
- Growing at a rate of 2.3%/y
- Equivalent to the energy produced annually by 10^9 CPV dishes of 36 kWp each
- Requires 360,000 km^2 or an area of 600 x 600 km

Solar roadmap – Increasing role in the coming years



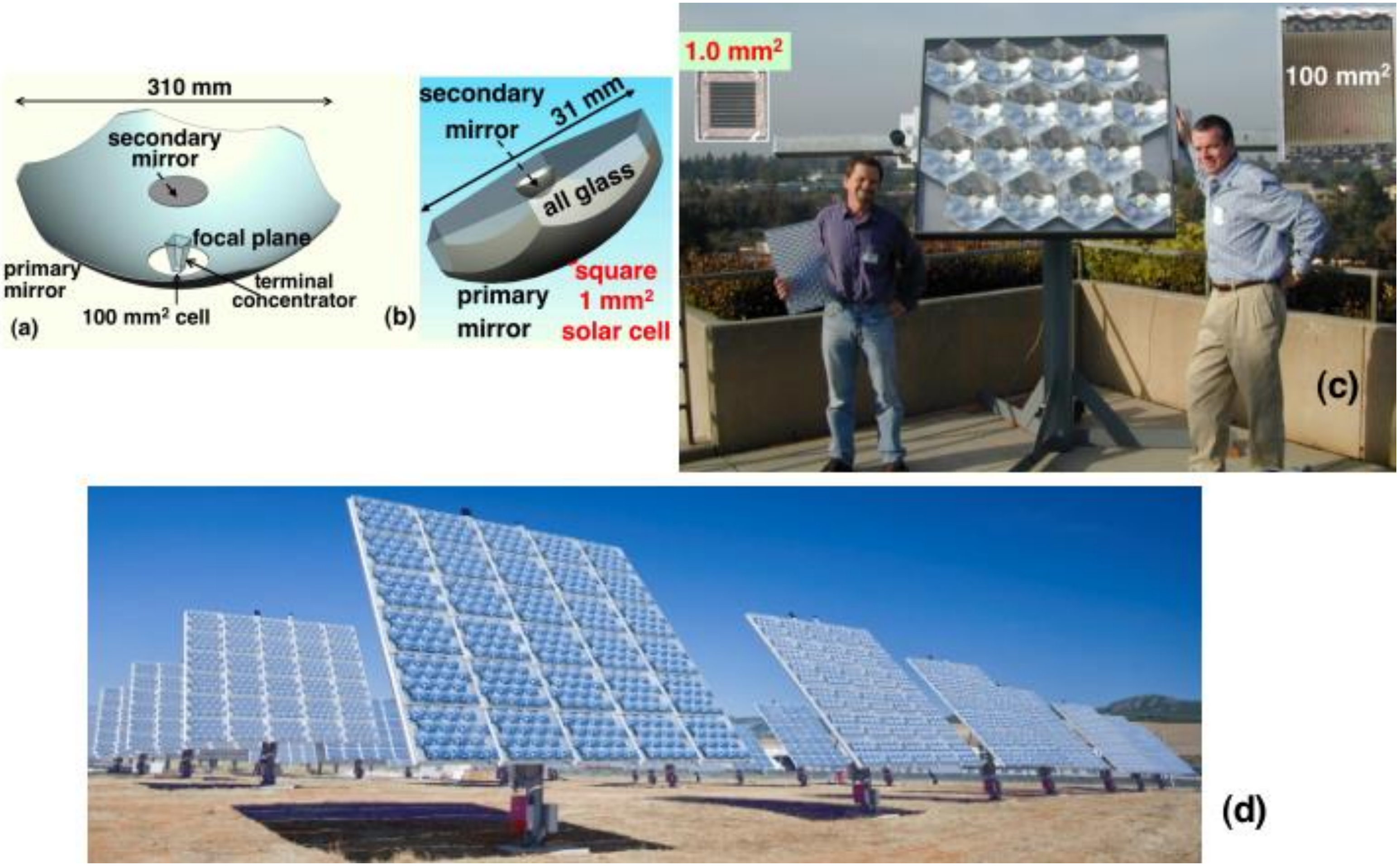
Source: German Advisory Council on Global Change, 2003, www.wbgu.de

Large Commercial Efforts

(DOE 2011-10 report)

Typical Solar Fields for Various Technology Types (clockwise from upper left):
Solar Parabolic Trough (Source: NREL/SR-550-32282),
Solar Power Tower (Credit: Sandia National Laboratories. Source: NREL),
Photovoltaic (Credit: Arizona Public Service. Source: NREL), and
Dish Engine (Credit: R. Montoya. Source: Sandia National Laboratories).

Example CPV
Jeffrey M. Gordon (2010)



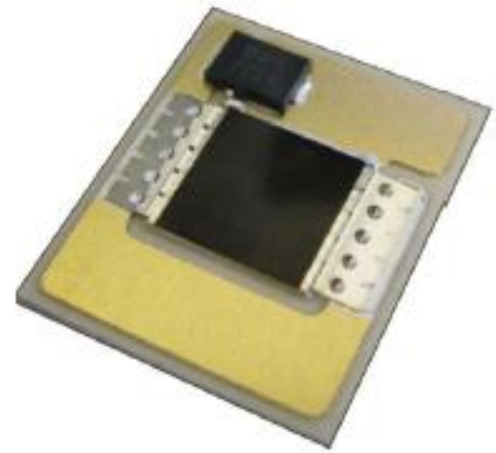
Preliminary

S P E C T R O L A B

A **BOEING** COMPANY

*Prototype Product

CCA 100 C1MJ Concentrator Cell Assembly



A concentrator cell assembly (CCA) consists of a Spectrolab state of the art triple junction solar cell and a bypass diode attached to a ceramic substrate. This assembly provides a robust package for easy integration into a solar concentration system.

The ceramic substrate offers excellent thermal conductivity and a compatible coefficient of thermal expansion with the solar cell. High current carrying interconnects are attached to the solar cell using Spectrolab's proprietary welding process.

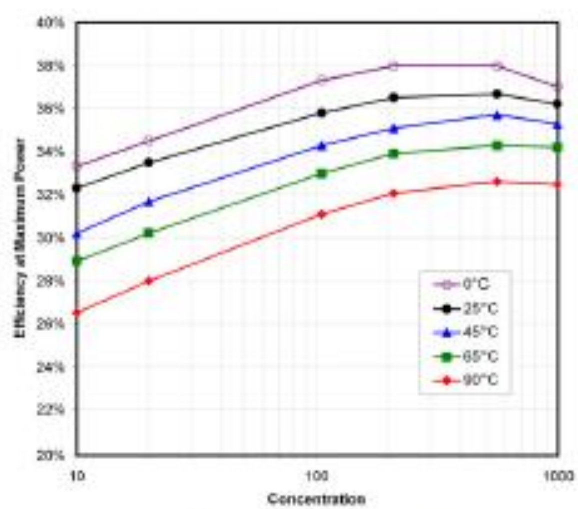
Large solderable and weldable surfaces are provided for attachment of wire leads or connectors.

The cell is attached to the ceramic substrate virtually void free using a proprietary process that is designed for efficient heat transfer away from the solar cell surface.

Specifications

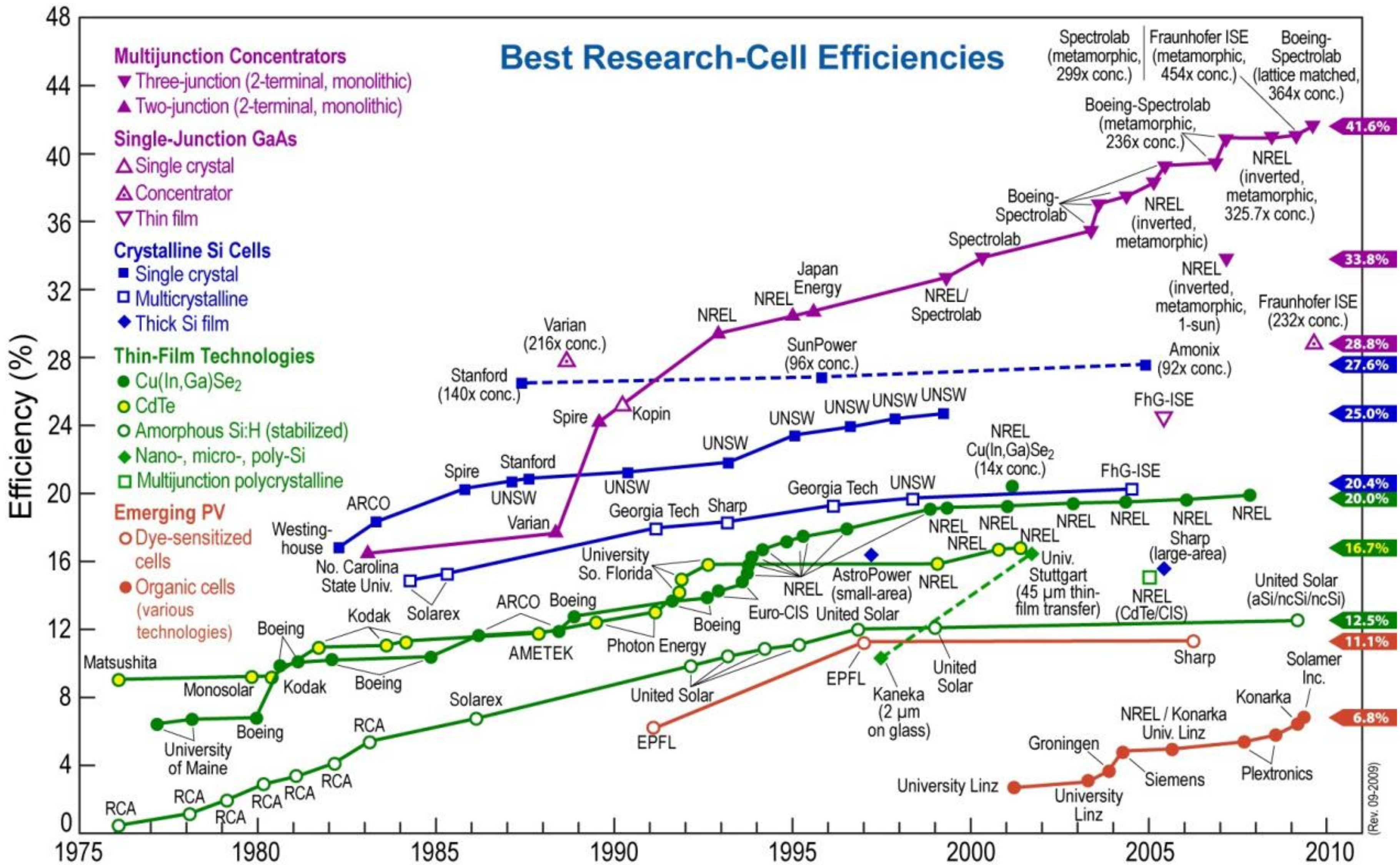
Cell	*CDO 100, C1MJ Typical performance efficiency: 37%*
Cell aperture	*98.9mm²*
Ceramic Carrier	*Direct bonded copper with Au/Ni surface plating (front and back surfaces) on a Al_2O_3 substrate*
Diode	*12A Schottky*
Operating temp	*-40°C to 100°C*
Maximum temp	*180°C*
Thermal resistance	*≤ 0.22°C/W (modeled)*

**These CCAs are considered prototypes because they have not yet completed Spectrolab's internal qualification process.*



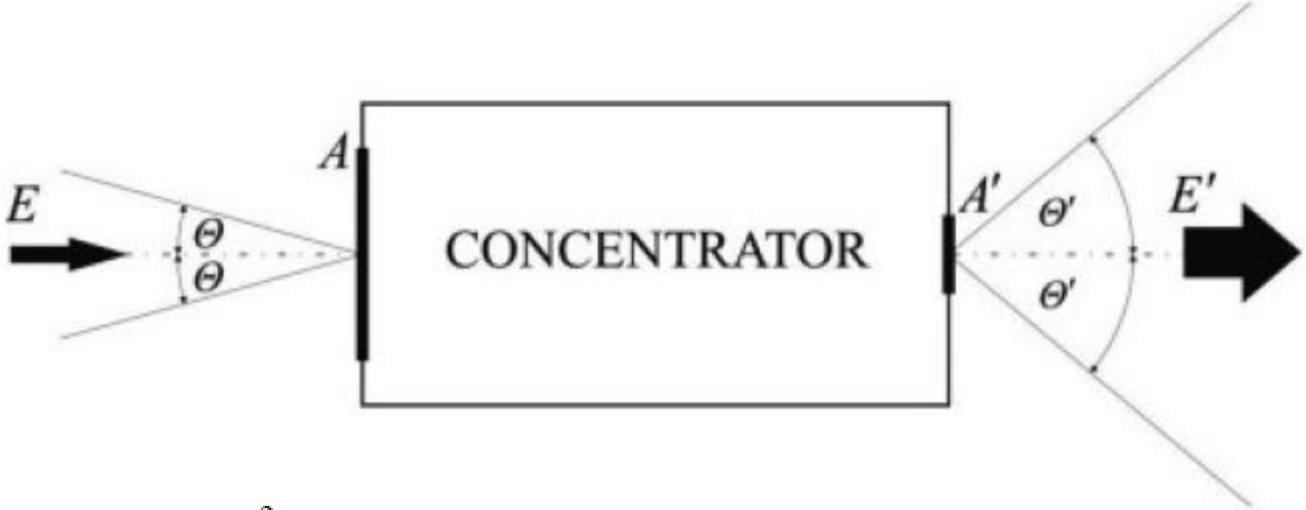
Efficiency Characteristics

NREL (Nov. 2009) ***Technical Report***
NREL/TP-520-43208



Thermodynamic Limit

- Entendu conservation



$$C = \frac{A}{A'} = \frac{\sin^2 \Theta'}{\sin^2 \Theta}$$

- *C* for Sun ~ 46,200

Combined technologies

Mobile Solar, C = 1.0

+

Epiphany Solar Water Systems 2.4-meter satellite

= Electricity + hot and clean water for those off-grid

Some Future Solar R&D Plans

- Combined Portable Solar Power Units
  - Electricity and hot water
- Improve active secondary technology to increase concentration

Flux collector - Pneumatic Mylar Mirror Telescope at Gravic

Summary

- SNR depends on multiple factors, scintillation can be beaten back with large primary mirrors & distributed arrays
- New mirror substrates and technologies are being perfected for lightweight, portable and affordable telescopes
- Solar power and astronomy communities can benefit from each other’s R&D

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