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Stars, Companions, and their Interacions: A Memorial to Robert H. Koch

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Robert H. Koch's Work on Lightweight Medium-Aperture Mirrors

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After a visit by Peter Waddell from the University of Strathclyde, Glasgow, UK in 1991, Robert H. Koch launched a program at the University of Pennsylvania to build lightweight pneumatic membrane mirrors, initially for balloon flight observations where weight is at a premium. Mirror cells were fabricated from sizes 0.18 m to 1.77 m, and experiments conducted to characterize the mirror figure and stability. Most of the work stopped after Prof. Koch's retirement in 1996 until 2006 when the authors expressed an interest in building an array of medium-aperture portable telescopes. The program restarted in earnest at Gravic, Inc. in Malvern, PA in 2008 with Koch using his extensive observational astronomy experience to guide the fabrication of a fully operational 1.07 m membrane mirror telescope with an optical tube assembly weighing under 45 Kg. Residual wavefront aberrations remediation resulted in Koch and the authors investigating membrane tensioning techniques with different cell designs, active secondary wavefront correction, photometric algorithms for aberrated images, and the use of additional lightweight mirror substrates from the Alt-Az Initiative Group, such as foamed glass. The best result for the lightweight mirrors was a point spread function spot size of several arc seconds. A lightweight 1.6 m cast aluminum cell alt-az telescope was subsequently designed by Koch and the authors for prime focus use.

Keywords: membrane mirrors, optical aberrations, telescope arrays

1. INTRODUCTION

The Flower and Cook Observatory (FCO) of the University of Pennsylvania (Penn) housed a 0.72 m (28 inch) Fecker Cassegrain reflector in a traditional observatory dome (Koch 2010, Fig. 1). The late Robert H. Koch (1929-2010) was a Professor in Penn's Department of Astronomy and Astrophysics, and an avid user of the reflector. The authors of this paper worked with Koch at FCO for many years in the roles of an electro-optician and observatory caretaker (RJM) and graduate student and later colleague (BDH). Many times Koch expressed to the authors his interest in obtaining a much larger research instrument to reduce photon shot noise in program object measures and noted that the FCO observatory dome was oversized and could accommodate a 1.0 m or larger aperture reflector. As a result, Koch was interested in medium-aperture mirrors for a larger terrestrial telescope and for research programs, such as balloon flight experiments, where the optical tube assembly and mirror weight must be minimized. Koch (2010) and Holenstein et al. (2010a,b) describe some of Koch's work on medium-aperture mirrors.

Fig. 1. The reflector dome at the Flower and Cook Observatory was capable of housing a 1.0 m or larger telescope. This picture was taken in the late 1990's looking towards the southwest. The trees to the south needed trimming and were a constant observing hazard.

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This report summarizes those previously described efforts and adds details on Koch's other projects related to lightweight medium-aperture mirrors.

2. EARLY EFFORTS 1991-2000

2.1 Pneumatic Mirrors

Professor Peter Waddell from the University of Strathclyde, Glasgow, UK visited the Laboratory for Research on the Structure of Matter at Penn in 1991 to give a lecture on the history of television. Waddell carried with him a small 0.20 m (8 inch) aperture mirror with a polyester Mylar reflecting surface that he demonstrated to Koch, and other Department of Astronomy and Astrophysics members, could be varied in focal length by sucking on a small tube. Manly (1991) provides an overview of Waddell's mirrors. Koch approached the department chairman, Professor Kenneth Lande, and funds were allocated to build some prototypes, initially for balloon flight observations where weight is at a premium.

Between 1991 and 1996, mirror cells were fabricated from sizes 0.18 m (7 inches) to 1.77 m (70 inches), and experiments were conducted to characterize the mirror figure and stability. Several people participated in the fabrication and testing of the mirrors: Robert Hee served as the professional machinist, the late Samuel Seeleman and Koch as amateur ones and opticians, Richard Mitchell as the hardware and electronics specialist, and several graduate students as technicians. Three pneumatic imaging systems were designed, built, and tested, and a few department demos and talks were presented. Koch visited Waddell's lab in the UK in 1994 and studied his 0.61 m (24 inch) pneumatic mirror that had been kept under a substantial pressure difference for more than a year. Koch's departmental efforts on the mirrors continued past his retirement in 1996 until about 2000.

Modern pictures of early Penn pneumatic mirror prototypes appear in Figs. 2 and 3. A thin (0.2 to 7.2 mil) aluminized reflective Mylar membrane was clamped between machined surfaces. The entire assembly was then rotated or pressed down onto a machined Plexiglas ring to pre-tension the membrane and eliminate wrinkles. A variable amount of air was removed to produce the desired focal ratio (*f*/0.5 to *f*/10). The aluminum and Plexiglas cells would hold a vacuum for months and never leaked any appreciable air even with thin films.

Fig. 2. Recent image of Koch holding a 0.30 m (12 inch) aperture pneumatic mirror built at University of Pennsylvania in the early 1990's.

Fig. 3. Recent image of Koch holding a small carbon fiber optical tube assembly containing a 0.18 m (7.25 inch) pneumatic membrane mirror. Carbon fiber was chosen for its light weight, strength, and low coefficient of thermal expansion.

2.2 Balloon Flight Experiments

An interesting application of medium-aperture mirrors Koch and Lande explored in the mid-1990's was to make a lightweight telescope assembly suitable for visible and near infrared observing of point photometric sources from a high-altitude balloon. Funding for an initial project was secured by Lande from a National Aeronautics and Space Administration student grant. Koch designed the optics, Lande and Mitchell designed the electronic payload, and six undergraduate students from Penn participated with department staff in the construction, testing, and launch. The electro-optics used differential global positioning system to calculate the payload rotation direction and rate (spin). Two oppositely oriented charge-coupled device (CCD) cameras were used at prime focus in kinetics mode to clock pixels at a rate to counteract the spin. The pneumatic mirrors and related control system were as yet not producing an image of sufficient optical quality so a 0.5 m (20 inch) Zerodur mirror was purchased for the initial flight. Figs. 4 and 5 show details of the telescope payload.

In 1995, the team and parts were relocated to the Balloon Flight Facility of the Goddard Space Flight Center on Wallops Island in Virginia for final assembly and testing. The launch day was clear with little wind for the morning flight. The balloon and payload were laid out on the tarmac with the prevailing wind direction taken into account. However, as the balloon was being filled with gas, the wind changed direction and the payload was shaken. The rest of the flight was a great success, but the computer hard drive had apparently failed at an altitude of only about 20 m and little data was recorded. Additional balloon flights were conducted before funding ran out.

A videotape of Koch describing the balloon flight equipment and observing goals exists and was played, in part, by Lande at the Stars, Companions, and their Interactions: A Memorial to Robert H. Koch Conference held at Villanova University in August, 2011.

Fig. 4. Preparing for a launch at Wallops Island in 1995. Robert Koch is in the center foreground working on the dual charge-coupled device cameras at prime focus, and Kenneth Lande is on the left working on the balloon payload.

3. RECENT EFFORTS 2006-2010

3.1 Pneumatic Mirror Telescope

In 2006, Bruce Holenstein discussed with Koch his interest in building a pair of large-aperture light buckets for a revival of stellar intensity interferometry (Genet & Holenstein 2010). Some plans and designs were pursued, and work on the pneumatic mirror project was re-engaged in 2008 when Holenstein, Mitchell, and Koch started a new collaboration, and brought Kevin Iott onboard as designer and machinist and Dylan Holenstein on as a lab technician.

The program was hosted at Holenstein's employer, Gravic, Inc. in Malvern, PA, and in 2009 the fabrication of a fully operational 1.07 m (42 inch) membrane mirror telescope was completed. The mirror assembly and truss weighed under 45 Kg (100 lbs.). Figs. 6-8 detail the construction and deployment of the telescope.

3.2 Pneumatic Mirror Performance

A limit of 1 to 2 arc minute point spread function (PSF) Full width at half maximum (FWHM) was reached with the 1.07 m telescope. Analytical work described in Holenstein et al. (2010b) details the expected photometric performance of the aberrated image from the telescope. The signal-to-noise-ratio (SNR) was deemed to be insufficient

Fig. 5. Completed telescope payload about to be launched at Wallops Island in 1995. Koch is walking towards the carbon fiber telescope truss tubes that Lande is holding. The electronics were located in the silver-colored, sealed and pressurized cylinder in the lower part of the image.

Fig. 6. Koch is observing the wooden mirror cell constructed by a carpentry student from a local trade school. Variable length truss tubes are temporarily setting inside the mirror cell. An epoxy surface later added to the cell to reduce leaks added weight, but the structure still remained under 35 Kg (77 lbs.).

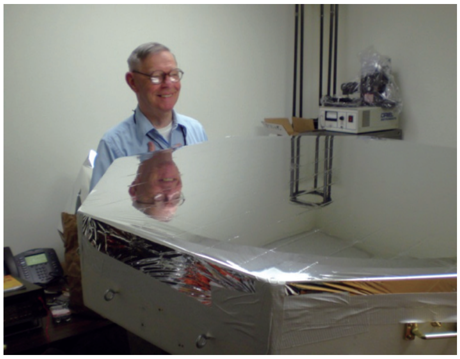

Fig. 7. Koch is peering at the pre-tensioned Mylar polyester film that has been attached to the mirror cell before the top retention ring has been attached. A vacuum of about 30 millibars for 2 mil film would produce an *f*/2 focal ratio.

Fig. 8. Koch taking a break on the hot July, 2009 day just before first light of the 1.07 m pneumatic mirror telescope. Rich Mitchell is seen in the mirror reflection. The pneumatic control system and battery are on the ground below the Kevin Iott-designed and built IPI 393 GEM mount. A custom-built high-speed electrometer photometer is at prime focus.

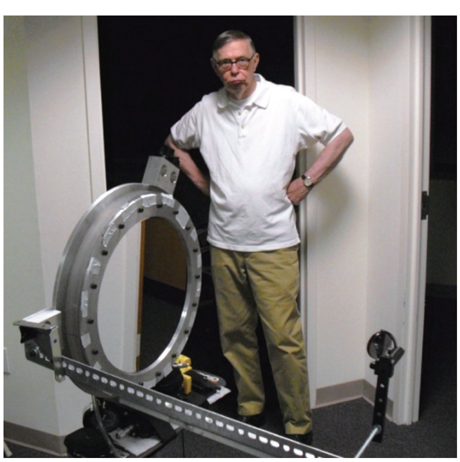

Fig. 9. Robert Koch is pondering a solution to remedy aberrations arising from the biaxial Young's modulus of Mylar which was preventing the 0.3 m pneumatic mirror located on a test stand from operating at the expected performance level.

except for very bright stars and so remedial work was conducted on the pneumatic mirror cell design (Fig. 9).

Further residual wavefront aberrations remediation resulted in the team investigating membrane tensioning techniques with different cell designs that counteract the approximately 4% difference in the Young's modulus between the transverse and longitudinal manufacturing directions of Mylar. Koch and the authors also designed and started building an active secondary mirror using piezoelectric actuators for conjugating the primary mirror wavefront aberrations. Koch outlined some photometric algorithms and strategies for processing highly astigmatic images. Additionally, lightweight mirror substrates from the Alt-Az Initiative Group were tested. One such alternate substrate mirror is made from fused plate glass over foamed glass by OTF Designs LLC (Oak Hill, FL, USA). An image of one experimental mirror cell is shown in Fig. 10.

Traditional metrics for assessing mirror optical quality failed for the highly aberrated lightweight mirrors built and tested by the team. For example, two pneumatic mirrors with the same peak-to-valley and root mean square (RMS) surface height measures would give vastly different optical performance as characterized in Fig. 11.

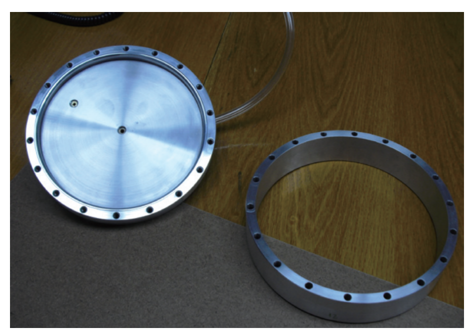

Fig. 10. Disassembled CNC machined cell for a small pneumatically-formed mirror. The edges contacting the membrane were precision machined and polished to minimize the cell design as a source of aberrations.

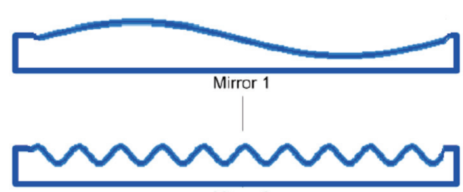

Fig. 11. Cartoon of exaggerated edge-on views of two mirrors with the same peak-to-valley, root mean square (RMS) surface height, and Strehl ratios measures of their aberrations. The bottom mirror scatters photons into a larger diameter point spread function because the RMS gradient norm (RMS slope) is much larger.

A Bath interferometer was built and used to make interferograms of sub-regions of the mirrors under test. These interferograms were stitched and analyzed to produce Zernike wavefront coefficients characterizing the aberrations. An analytical technique was devised to estimate from the Zernike coefficients the rms gradient norm of the wavefront and the rms surface slope, and from that the FWHM of the PSF. The interferograms of the pneumatic mirrors indicated that astigmatism dominates. The 1.07 m pneumatic mirror had astigmatism as the dominant aberration at a magnitude of between 50 and 100 waves P-V of visible light. This corresponds to a 100 to 200 microradian rms gradient norm at the surface. The best foamed glass mirrors tested had an rms gradient norm at the surface ten or more times better, at between 5 to 10 microradians. These latter mirrors produce a PSF spot size several arc seconds in diameter, a value which is near the lowland atmospheric seeing level.

3.3 Cold Silvering Experiments

A major risk to a large mirror exists whenever it needs to be recoated. Most large professional observatories install vacuum deposition equipment in their domes so that the primary mirror does not have to travel a significant distance to get a new coat of reflective metal. Koch and Holenstein met in 2010 with Sagar Venkateswaran, the president of Peacock Labs in Philadelphia, PA to discuss an alternate solution for medium-aperture mirrors. Peacock manufactures a product for cold silvering of hard surfaces. They also manufacture a clear overcoating agent called Permalac for preventing tarnish on silvered surfaces. Fig. 12 shows some small test mirrors undergoing tests. It was found that the Strehl ratios of the mirrors were preserved for the silvered mirrors, but the silvered and Permalac overcoated mirrors only remained useful for astronomy purposes when the protective overcoat was applied "extra thin" (under 5 μm). For the overcoated mirrors, the rms wavefront error measured with a Bath interferometer increased by 0.12(± 0.02) waves at 550 nm.

The optical quality of some medium-aperture mirrors developed is sufficient for high cadence aperture photometry, spectroscopy, high time resolution astronomy, and other observing projects that only require very modest spot sizes or on-axis light gathering. The best mirrors that Koch and the authors tested encircled 94% of the energy (i.e., two times the FWHM) with PSF spots that are viable for photometry of 13th magnitude and brighter objects so that scintillation, and not program object shot nor the background (sky), is the limiting noise source for fast cadence and high time resolution photometry.

3.4 Some Future Plans

The team designed a 1.6 m cast aluminum cell alt-az telescope for prime focus use (Fig. 13). The estimated construction cost of USD $65k is relatively low vs. a traditional substrate mirror telescope because the mass of the optical tube assembly is only 230 Kg (500 lbs). The design is flexible enough to accommodate alternate mirror substrates such as those being researched by the Alt-Az Initiative Group including spun epoxy, foamed glass, and slumped meniscus plate glass. An array of these lightweight telescopes will offer a substantial reduction in scintillation noise and improvement in the overall SNR of program object measures compared with a monolithic mirror of the same effective aperture. In fact, Genet & Ho-

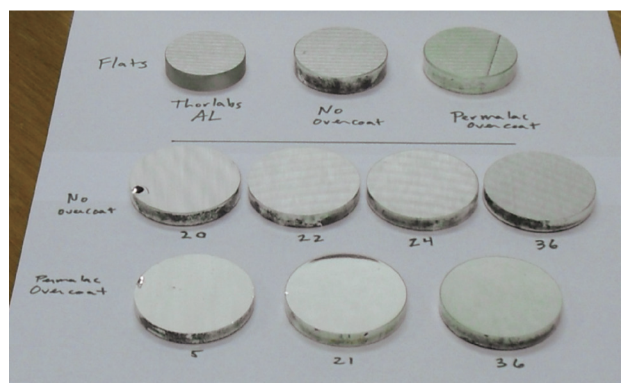

Fig. 12. Calibrated flats and mirrors which have been cold silvered with Peacock Labs solutions. The upper right flat and the front row of mirrors have been overcoated with an extra thin layer of Peacock's Permalac solution causing a slight yellowing in the visible appearance and a reduction of about 7% in the reflectivity.

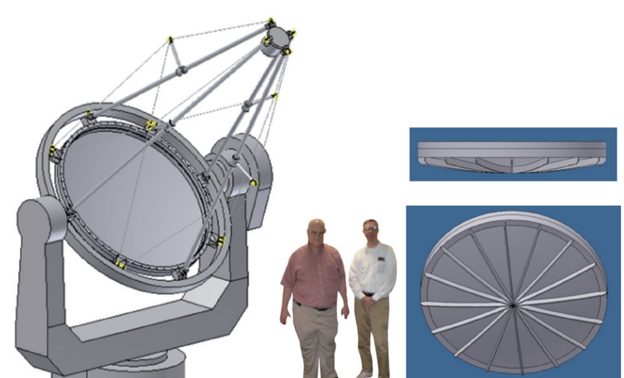

Fig. 13. One point six meter alt-az telescope design for a pneumatic mirror with a cast aluminum cell. Cutout images of Koch and Mitchell are included for scale.

lenstein (2010) show that a seven-element array of 1.5 m aperture telescopes all observing the same 10th magnitude program object at a dark, 3,000 m elevation observing site, and combining output can produce 60% of the photometric performance of a traditional single-mirror 8 m aperture telescope. This feat can be done for under 1% of the cost of the 8 m telescope.

4. RESULTS OF KOCH'S MIRROR WORK

Robert H. Koch was a polymath who was able to operate on many levels. He had a keen interest in all aspects of astronomy including building novel telescopes to solve specific observing goals. During the last two decades of his life he was able to lead and participate in numerous lightweight medium-aperture telescope building projects. Work started by Koch on mirrors continues today at Gravic, Inc. with plans to eventually build an East coast USA array of seven or more 0.75 to 1.5 m telescopes with high speed Photometrics Cascade 512B emCCD cameras at prime focus. Koch mentored numerous undergraduate and graduate students along the way and passed on his love of astronomy to many. Fig. 14. is characteristic of how many of us remember him.

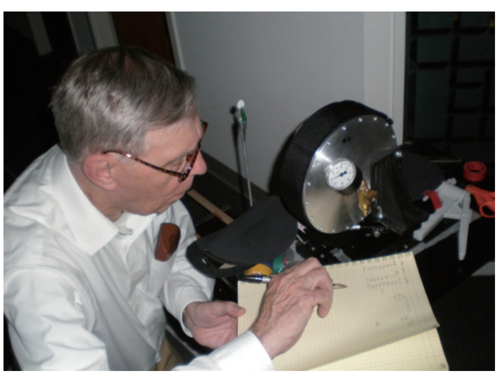

Fig. 14. This picture of Robert Koch hard at work is typical of how many of his students and colleagues recall him. Koch liked to graph experimental measures in real-time and this provided immediate insight into the phenomena under study.

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