History and Principles of Shack-Hartmann Wavefront Sensing

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The Shack-Hartmann wavefront sensor was developed out of a need to solve a problem. The problem was posed, in the late 1960s, to the Optical Sciences Center (OSC) at the University of Arizona by the US Air Force. They wanted to improve the images of satellites taken from earth. The earth's atmosphere limits the image quality and exposure time of stars and satellites taken with telescopes over 5 inches in diameter at low altitudes and 10 to 12 inches in diameter at high altitudes.

Dr. Aden Mienel was director of the OSC at that time. He came up with the idea of enhancing images of satellites by measuring the Optical Transfer Function (OTF) of the atmosphere and dividing the OTF of the image by the OTF of the atmosphere. The trick was to measure the OTF of the atmosphere at the same time the image was taken and to control the exposure time so as to capture a snapshot of the atmospheric aberrations rather than to average over time. The measured wavefront error in the atmosphere should not change more than $\lambda/10$ over the exposure time. The exposure time for a low earth orbit satellite imaged from a mountaintop was determined to be about 1/60 second.

Mienel was an astronomer and had used the standard Hartmann test (Fig 1), where large wooden or cardboard panels were placed over the aperture of a large telescope. The panels had an array of holes that would allow pencils of rays from stars to be traced through the telescope system. A photographic plate was placed inside and outside of focus, with a sufficient separation, so the pencil of rays would be separated from each other. Each hole in the panel would produce its own blurry image of the star. By taking two images a known distance apart and measuring the centroid of the images, one can trace the rays through the focal plane. Hartmann used these ray traces to calculate figures of merit for large telescopes. The data can also be used to make ray intercept curves (H'- tan U').

When Mienel could not cover the aperture while taking an image of the satellite, he came up with the idea of inserting a beam splitter in collimated space behind the eyepiece and placing a plate with holes in it at the image of the pupil. Each hole would pass a pencil of rays to a vidicon tube (this was before CCD arrays and image intensifiers). The two major problems with this idea were the weak intensity of the projected ray spots and the accuracy of measuring the centroid of the blurry pencil of rays. A trade-study was performed using the diameter of the holes, distance between the hole plate and the vidicon, and angular measurement accuracy as variables.

Dr. Roland Shack was involved in the study and soon came to the conclusion that the only workable solution was to replace the holes in the plate with lenses. For the first time, the idea of measuring the wavefront error, at the same time an image is taken of the satellite or star, seemed to be feasible. The configuration for the first Shack-Hartmann sensor

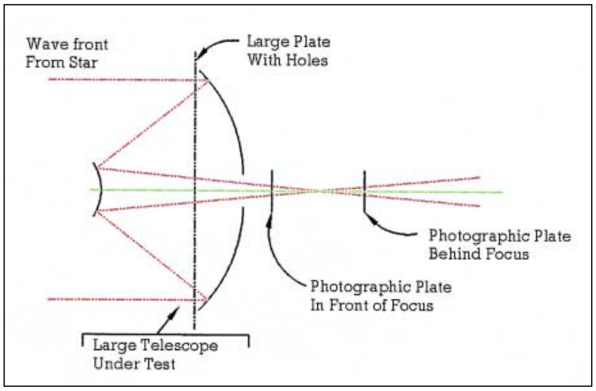

Figure 1. Optical schematic for an early Hartmann test.

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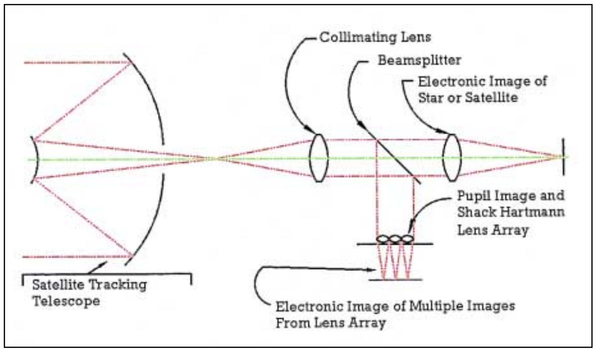

Figure 2. Optical schematic for first Shack-Hartmann sensor.

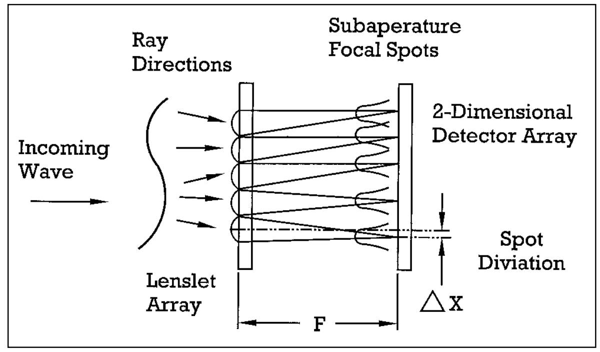

Figure 3. Illustration shows how displacements of focused spots from the lens array represent wavefront tilt.

is illustrated in Figure 2. The concept of measuring displacements of the spots formed by the lens array to calculate wavefront tilt is shown in Figure 3. Just as the derivative of the wavefront optical path difference (OPD) map produces wavefront slopes, the integration of wavefront slopes produces wavefront OPD maps.

At that time, Dr. Ben Platt was a Research Associate working in the Infrared Materials Lab at the Optical Sciences Center, University of Arizona, for Professor William Wolfe. Part of his time was spent helping Shack set up the Optical Testing Lab. He was given the task of purchasing an array of lenses to test the concept. The semiconductor industry was making arrays of lenses with short focal lengths, ~6 mm, and relatively large diameters, ~6 mm. Lenses with a diameter of 1 mm and focal length of 100 to 150 mm were required for the design. No one could be found to fabricate these lenses. Platt tried about six different methods before developing one that worked. Some of the methods tried included the following:

1. The end of a steel rod was polished with the correct radius and pressed into a metal surface in a square pattern. Epoxy and thermal plastic were used to mold a lens array from the indented surface.

2. Commercial arrays of short focal length lenses were used with index fluids where the difference in refractive index produced the desired focal length.

3. Lenticular lens screens from 3-D pictures were tried with index fluids.

4. Thin cylindrical lenses were fabricated and assembled into crossed arrays.

5. Thick cylindrical lenses were purchased, ground into thin slabs, and glued together.

Dr. Platt finally decided that the only way to produce the long focal lengths with 1 mm center-to-center distances was to use crossed cylindrical lenses and to polish the surfaces into a very flat low expansion optical flat. The optical shop at the university was asked to polish the lenses. They had no experience in this area and could not provide support. Platt designed and fabricated a polishing machine that used a cylindrical rod of nylon about 120 mm in diameter and about 150 mm long with a hole through the center so it could slide back and forth on a steel rod. The rod was supported from two arms that allowed the nylon roll to be lowered and raised over the optical blank. The optical blank was attached to a tilt table and translating stage for aligning the optical blank to the nylon polishing tool and for translating the blank to the next cylindrical lens location. A mechanical counter was attached to the steel arm supporting the rod to keep track of the number of polishing strokes at each lens location. After several weeks of trial and error, the system was ready to be transfered to an optician. The optician started with a 150-mm-diameter, 25-mm-thick disk of Cervet, polished to $\lambda/20$. Fifty grooves were polished across the center of the blank. Two square pieces were cut from the grooved area.

Platt made a mount for compression, molding a 1-mm-thick square plate of optical grade thermal plastic (Plexiglass) between the two Cervet squares. Many attempts were made to produce good quality lens arrays. Two sets of molds were also broken in the process. Each heating and cooling cycle in the molding process took several hours. So, Platt decided to work all day and most of the night in his wife's kitchen. His wife's electric knife sharpener was used to trim the Plexiglass plates. Her apron and oven mittens were also used to remove the molds from the oven. After a few weeks, the process was perfected and good quality lens arrays were being produced. For at least the next 5 years, all lens arrays used in Shack-Hartmann wavefront sensors were

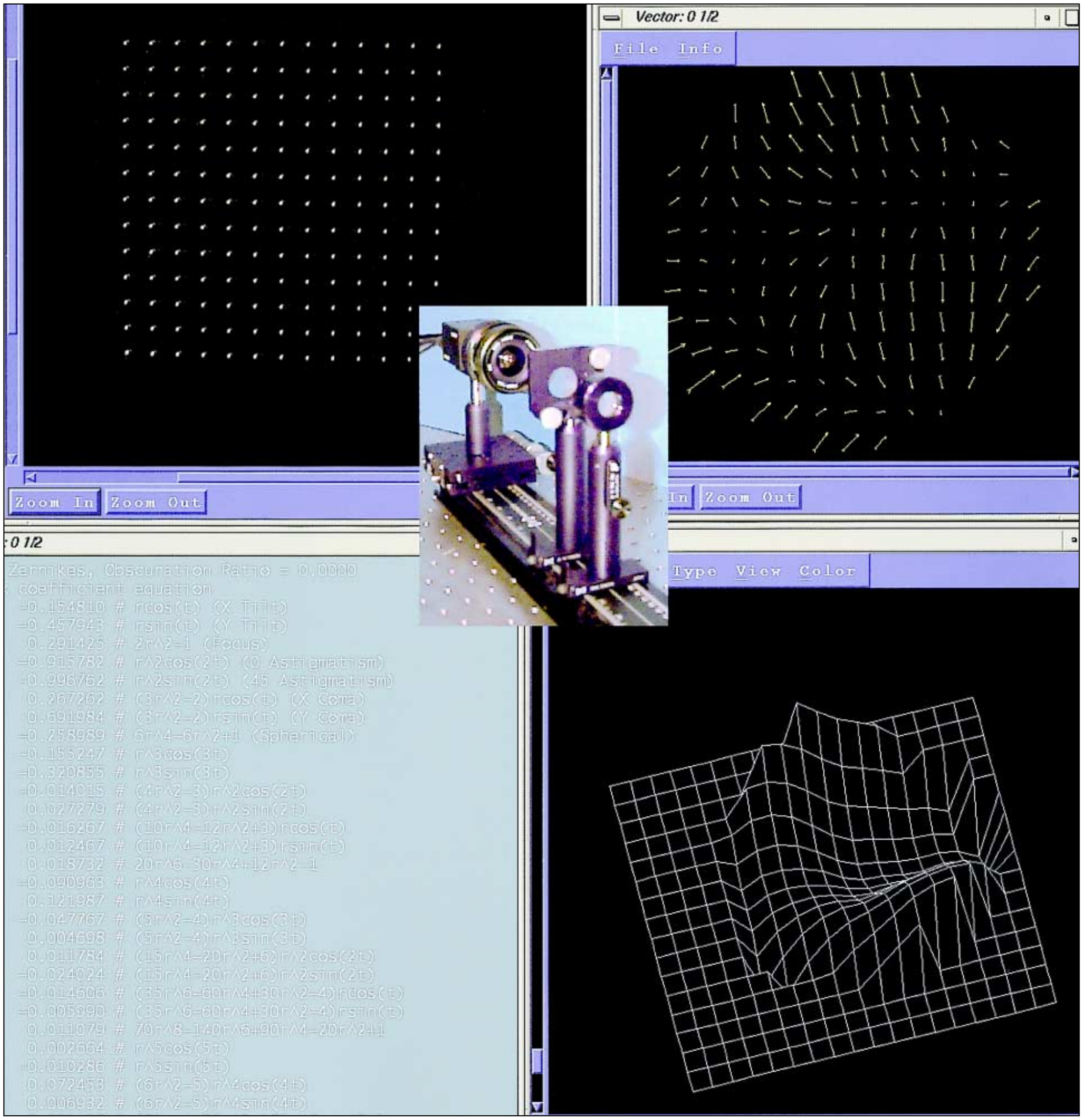

Figure 4. Recent image from Adaptive Optics Associates (AOA) shows the optical set-up used to test the first Shack-Hartmann sensor. **Upper left)** Array of images formed by the lens array from a single wavefront. **Upper right)** Graphical representation of the wavefront tilt vectors. **Lower left)** Zernike polynomial terms fit to the measured data. **Lower right)** 3-D plot of the measured wavefront.

made by Platt in his wife's kitchen. Because of the high risk of breaking the molds, Platt took the molds with him when he left the university and made lens arrays, on request, for Shack, without charge. Several students used the arrays in their research projects.

The Air Force project was simulated in the laboratory. The target was a scaled photograph of a satellite using the correct angle of illumination. A 35-mm reflex camera was used to record the focused spots from the lens array. The focused patterns were low-resolution images of the satellite and not just spots. All images were identical so this did not affect the ability to determine centroids of the images. Atmospheric aberrations were simulated with a static phase plate. A pinhole was later used for a test target. Figure 4, provided by Adaptive Optics Associates (AOA), shows a recent set-up that illustrates the set-up used in 1971. The upper left image shows what the spot pattern looked like. The upper right image shows a vector representation of the wavefront tilts. The length of the arrow illustrates the magnitude of the tilt and the direction of the arrow illustrates the angle of the tilt. The lower left image is the Zernike polynomial fit to the calculated wavefront. The lower right image is the plot of the measured wavefront.

A reference set of spots were taken with a calibrated wavefront in order to make accurate measurements. This was necessary because of residual aberrations in the optical set-up. To account for shrinkage in the film, both sets of dots were taken on the same slide of film. We tried two methods of generating the reference set of spots: one method offset the reference set of spots by introducing a tilt in the wavefront, and the other method used color film and no offset. This method requires optics with an acceptable amount of chromatic aberrations. The color separation method was easiest to work with. Two methods of separating the two sets of spots were used. One method used a measuring microscope and color filters over the eyepiece. The other method used color filters over a slide projector and a Vernier caliper. Both methods produced results that were repeatable to $\lambda/50$. Accuracy was determined by a tolerance analysis and by comparing the measured results of an aberration plate, using the Shack-Hartmann sensor, to the measured results of a commercial Zygo interferometer. Accuracy was determined to be at least $\lambda/20$.

An article was written on the Lenticular Hartmann Screen in March 1971 for the Optical Sciences Center newsletter at the University of Arizona. In that same year, Platt presented a paper on the Shack-Hartmann Sensor at an OSA meeting in San Diego, CA. An attempt was made to file for a patent through the University of Arizona. The application was never filed.

A complete system was designed, fabricated, and delivered to the Air Force in the early 1970s to be used on the satellite-tracking telescope at Cloudcroft, NM. The system was never installed and the facility was later decommissioned.

Shack also worked with astronomers in Europe. He gave lens arrays to any astronomer that wanted one. During that time, Ray Wilson was responsible for the alignment and testing of all large telescopes at the European Southern Observatories (ESO). Wilson fabricated a wavefront sensor with one of the lens arrays he received from Shack and tested all the large telescopes at the ESO. He discovered that they were all misaligned and that he could properly align them with the data from the new tester. Wilson published a paper on this work in April of 1984. He sent a copy of the paper to Shack, thanking him for introducing this new tester to him and coining the name "Shack-Hartmann sensor." In 1974, Platt received a telephone call from Europe and was asked to build Shack-Hartmann wavefront sensors. Platt was not able to build them at that time because the start-up company he was working for would not allow him to work on any other project or to work on the side.

The military and the astronomers had parallel wavefront sensor and adaptive optics programs. Both groups also developed the laser guide star concept at nearly the same time. The military was always one or two steps ahead of the astronomers because they had better funding and higher technology hardware.

Platt later left the start-up company and went to work for the University of Dayton Research Institute on a contract at the Air Force Weapons Center. While there, he proposed a Shack-Hartmann wavefront sensor to test the beam quality of the laser on the Airborne Laser Lab. He also proposed a scanning Hartmann tester. Both instruments were fabricated and used in the laboratory. Several copies of the scanning Hartmann sensor were fabricated and used in several field tests. They received very little attention because of the classification of the program. During the late 1970s, Platt also proposed to use the scanning and non-scanning Shack-Hartmann sensors to measure the flatness of semiconductor disks.

During the same time period, Adaptive Optics Associates (AOA) was developing (for the Air Force) adaptive optics that would compensate for the earth's atmosphere. They started out with a scanning Hartmann system and ended up with a standard Shack-Hartmann wavefront sensor using lens arrays. AOA developed their own lens arrays and eventually sold them commercially. Massachusetts Institute of Technology (MIT) developed methods for making lens arrays using binary optics. Soon afterward, other organizations started making lens arrays using binary optics. When the lens arrays became easily available, more and more people started experimenting with the Shack-Hartmann sensor. Now, several companies are selling Shack-Hartmann sensors commercially.

Software to convert the 2-D tilt data into 2-D wavefront data is another major part of the wavefront sensor. The first software program was written at the University of Arizona. They had developed a program for reducing interferograms. This program was later modified to reduce shearing interferograms. Since shearing interferograms represent wavefront tilt, it was easy to modify this program to reduce Shack-Hartmann data. This program was made available to the public for the cost of copying. AOA developed its own software package for commercial and military applications. Most of the astronomical groups also developed their own software. Soon, the software was easily available.

In the mid 1980s, Dr. Josef Bille, from the University of Erlangen-Nurnberg, started working with Shack to use the lens array for measuring the profile of the cornea. Bille was the first to use the sensor in ophthalmology. He used it first to measure the profile of the cornea and later to measure aberrations in the eye, by projecting a point source onto the retina. His first published paper was in 1989.

In 1985, Platt formed a company to provide optical instruments and consulting support to the government and commercial organizations. One of the instruments he wanted to produce commercially was the Shack-Hartmann sensor. He wrote several proposals for different applications, including an application to the National Eye Institute (NEI) of the National Institutes of Health (NIH) for corneal topography. By the time the proposal was resubmitted, photorefractive keratectomy (PRK) was replacing radial keratotomy, and NEI was looking only at corneal topography instruments that could measure the profile of a diffuse surface.

The next major milestone in the United States for using the Shack-Hartmann sensor in ophthalmology occurred with the work of David Williams at the University of Rochester. He was the first (in the United States) to use the Shack-Hartmann sensor for measuring aberrations in the eye. He also demonstrated improved imaging of the retina by coupling the Shack-Hartmann wavefront sensor to a deformable mirror, generating the first adaptive optics system used in ophthalmology.

The United States military started using the Shack-Hartmann sensor in 1974 to test lasers, and in the early 1980s, in adaptive optical systems. From 1974 to 1996, Platt wrote proposals to use the Shack-Hartmann sensor for applications ranging from aligning telescopes, testing lasers, testing semiconductor disks, to measuring the profile of the cornea. Current applications for the Shack-Hartmann sensor in ophthalmology, astronomy, adaptive optics, optical alignment, and commercial optical testing are too numerous to list. Hundreds of programs using the Shack-Hartmann sensor can be found on the Internet. It is currently the most popular wavefront sensor in the world for applications other than standard optical testing of optical components. Although the Shack-Hartmann sensor is being used to test optical components, it is not expected to replace the interferometer—only to complement it.