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STUDY OF FINE SCALE SOLAR DYNAMICS

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This technical report has been reviewed and is approved for publication.


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19. ABSTRACT (Continue on reverse if necessary and identify by block number) A description of the new Lockheed 57-actuator segmented active mirror is given. Observational results from four observing runs at Sac Peak with the active mirror are presented, along with a Fourier analysis of these results. The active mirror is shown to be capable of producing near-diffraction limited results in average seeing conditions.					
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SUMMARY

Lockheed has had an operational 57-actuator segmented active mirror system for use in solar astronomy for several years. Recent upgrades, including strain gauge compensation on the actuators, beam interruption control circuitry, and microprocessor control of the higher order functions, have made the system extremely user friendly. The mirror can now be locked up on a target by merely pushing a button.

Four observing runs were made with the active mirror at Sac Peak under this contract. The most recent run was performed with the new active mirror system. In this last run, good corrected images were often obtained during brief periods of sunlight between clouds. These images have shown qualitatively that diffraction limited performance can be obtained in 2 arcsecond seeing, albeit at much lower contrast. A detailed Fourier analysis of the images has quantified this result.

Under this contract, we have obtained data which demonstrate the effectiveness of active optics in astronomy. We hope to obtain more data in 1989 under Lockheed IR funding. Particular emphasis will be placed on tracking of granulation dark lanes. The next major step should be the installation of an active mirror system at Sacramento Peak for use and evaluation by various scientific observers.

THE ACTIVE MIRROR SYSTEM

Figure 1 is a photo of the new Lockheed 57 actuator segmented active mirror. The reflective surface consists of 19 hexagonal mirrors. Each of these was cut from a ULE (ultra-low expansion) glass blank and polished to 1/10 wave or better. The mirrors are 1.1 inches across and are separated by .015 inch gaps.

Each mirror is glued directly to the top of three piezoelectric actuators which are housed in an Invar canister (Figure 2). The 19 canisters are bolted against an invar plate using hardened steel set screws and thrust washers as contact points. This mounting technique provides for mechanical stability and allows for easy alignment of the mirror segments.



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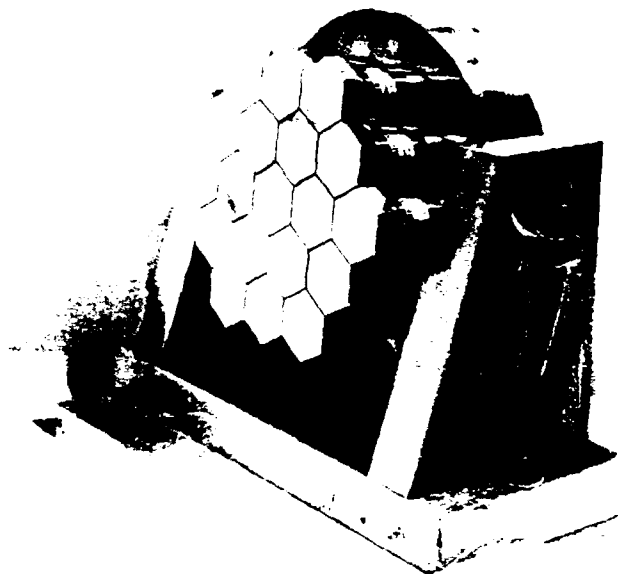


Figure 1. The Lockheed 57-actuator active mirror. The surface of the mirror is 5.5 inches across. Each segment is mounted on three actuators with strain-gauge compensation.

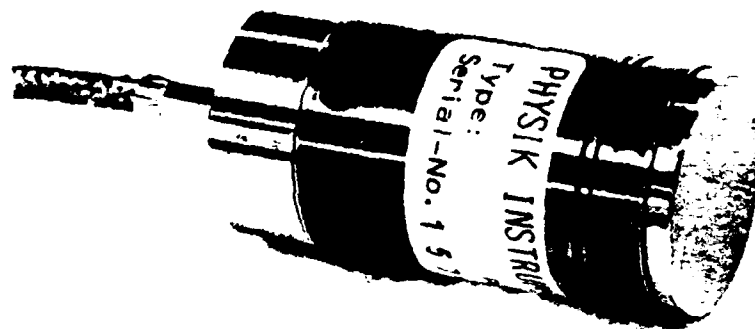


Figure 2. A piezoelectric canister. Each canister is made of Invar and contains 3 piezoelectric actuators with strain gauge compensation.

The actuators are biased at 40 volts and have an expansion range of ± 5 microns when operated at ± 40 volts. Each actuator has a strain gauge glued to its side, making it possible to monitor its length. With compensation control circuitry, the desired length of each actuator is maintained to less than 1%, virtually eliminating the creep and hysteresis normally associated with piezoelectrics.

Figure 3 shows the basic layout of the active mirror system. For simplicity, the drawing is not to scale and the imaging optics have been eliminated. The telescope forms a 20-inch solar image at the front of an optical table (a), where it is masked off to a 1-inch square. A field lens (b) is used to form an image of the entrance pupil of the telescope on the tilt mirror (c). This image is also formed on the active mirror (g). The tilt mirror is piezoelectric driven and removes the overall tilt in the beam due to the atmosphere, building vibration, etc. This mirror also serves as an auto alignment system which keeps the active mirror in the center of its operational range, thus eliminating the need for precise alignment between the wavefront sensor (j) and the active mirror.

A 6-inch collimated beam is formed with lenses (d) and (e) and sent through a Michelson interferometer. A white light interferogram of the active mirror is made using mirror (h) as a reference flat. The white light fringes are used for initial alignment of the active mirror. During normal operation, the reference flat is blocked off.

The wavefront correction occurs when the 6-inch beam reflects off of the active mirror and is sent back to the beam splitter (f). Part of the beam is transmitted through the beam splitter and back through the lens (e) slightly off axis to form the corrected image (optics not shown). The reflected portion of the beam is sent through 19 pairs of small lenses (h) which form 19 images of the sun on a Hartman wavefront sensor (j); each image corresponding to a particular segment of the active mirror. Thus, any tilts or aberrations in the wavefront are translated to motions of these images. The motions are measured with quad cell detectors on the wavefront sensor.

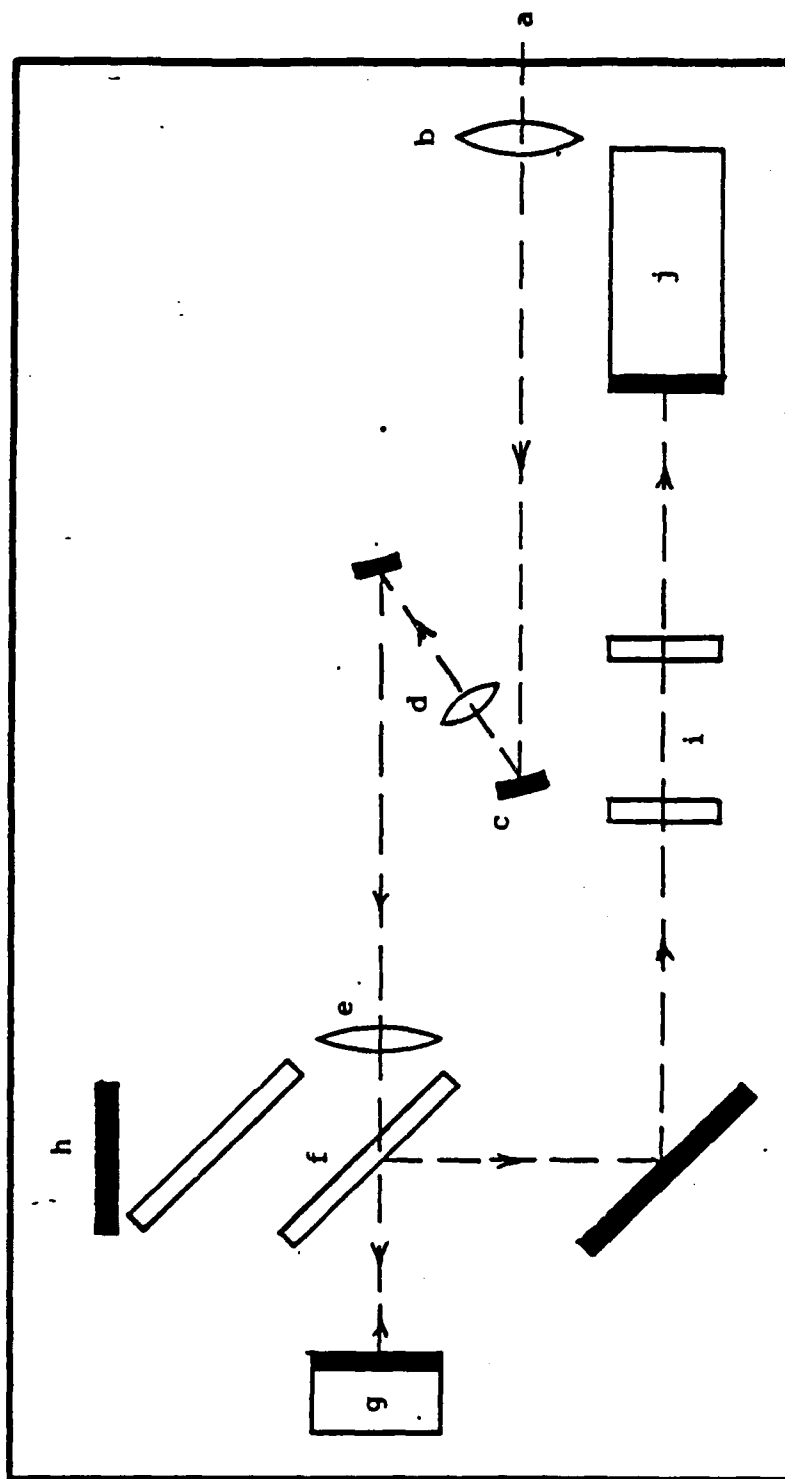


Figure 3. The optical layout. This drawing is not to scale. Normally, the system is set up on a 12 X 4 foot optical table. The imaging optics have been omitted for simplicity.

Nineteen individual control circuits constantly adjust the tilt of each mirror segment in order to keep the images centered on their appropriate quad cells. In doing so, the overall tilt is removed from the 19 subsections of the wave front corresponding to each active mirror segment. A separate set of electronics termed "the phase network" constantly monitors the tilts of the mirror segments and moves them in phase so that the active mirror surface is continuous. Once the local tilts and phase errors have been removed, the wavefront and, consequently, the corrected image should be relatively free from distortion.

For the purpose of making a comparison, an uncorrected image is made by inserting a 4% beam splitter into the optical path just after the tilt mirror (c). In this way, the uncorrected image has tilt removed, but no higher order aberrations. Using two more beam splitters and the appropriate imaging optics, video and digital image data of both the corrected and uncorrected images are recorded. If a wide field of view is desired, two film cameras can be inserted in place of or in addition to the other recording media.

The tilt correction of the active mirror provides an excellent opportunity to study the spatial and temporal characteristics of atmospheric turbulence, since the tilt of a mirror segment indicates what the overall tilt is on the corresponding section of the wavefront. The X and Y tilts of each mirror segment are sampled with 12-bit precision using a 128 channel Preston ADC, and stored in a microcomputer. The wavefront across the entire aperture can be sampled 292 times each second for 14 seconds, at which point the virtual memory in the computer is filled, and must be down-loaded to a floppy disk.

OBSERVATIONS

Lockheed has been operating its active mirror system for use in solar astronomy since about 1982. Its potential for correcting an image distorted by the atmosphere was demonstrated on two observing runs at Sac Peak, prior to the start of this contract. These results indicated that a significant improvement in image quality could be obtained through the use of active mirrors.

In September of 1985, the Lockheed active mirror was taken to Sac Peak for observations under this contract. The majority of this observing run was almost entirely unusable due to rain and heavy cloud cover. However, the weather cleared somewhat towards the end of the run and allowed us to align and fine-tune the active mirror optics. Unfortunately, there were no sunspots or pores on the sun to lock up the active mirror.

The electronics of the fast steering (tilt) mirror were modified to allow for tracking of low contrast objects such as granulation dark lanes. During a run lasting for approximately one hour, the tilt mirror was locked on granulation dark lanes. The lock was typically stable for a few minutes, then (as the granulation pattern changed) would "jump" to another lock-point a few arcseconds away, where it remained stable for another few minutes. Figure 4 shows results with and without this tilt-mirror correction. Sufficient ND filters were used to require an exposure time of .5 seconds, to simulate the light level through a narrow band filter.

Prior to the next observing run on August 17-30, 1986, a considerable amount of work was done under Lockheed IR funding to improve the active mirror system. Modifications in the analog control circuitry were made to reduce the time/temperature dependance of the various voltage levels, or biases in the control circuitry. The optics were also improved by obtaining a high quality achromatic lens to collimate the light onto the active mirror, and a new beam splitter and compensator plate for the white light interferometer.

In the first week of the observing run there were enough short periods of sunlight to align the apparatus, and to observe that these new optics did indeed result in a system with much smaller residual aberrations, and an extremely vivid set of white light fringes to aid in setting up the active mirror system. We also verified that the increased stability of the electronics resulted in a system that required very little electronic "re-tweaking" from one day to the next.

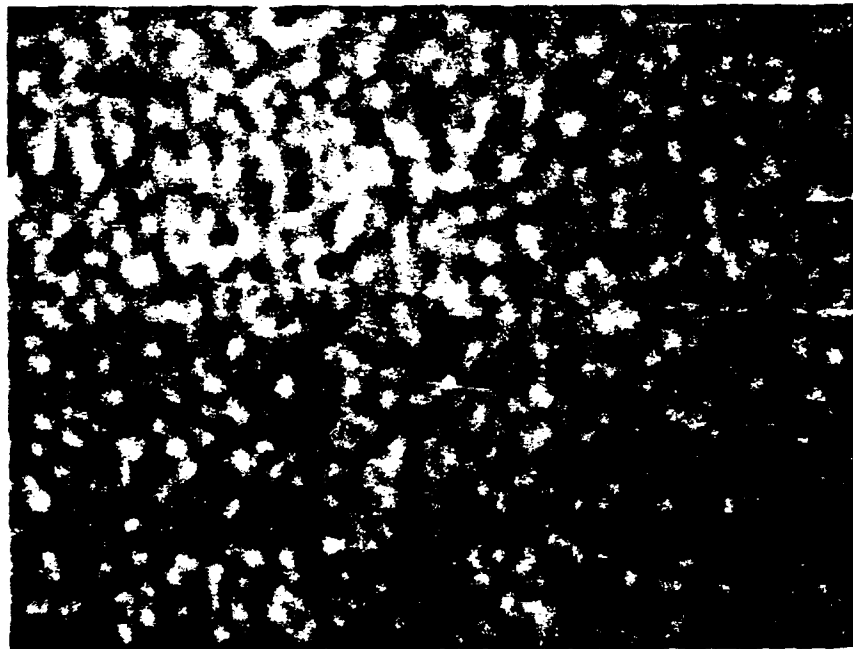
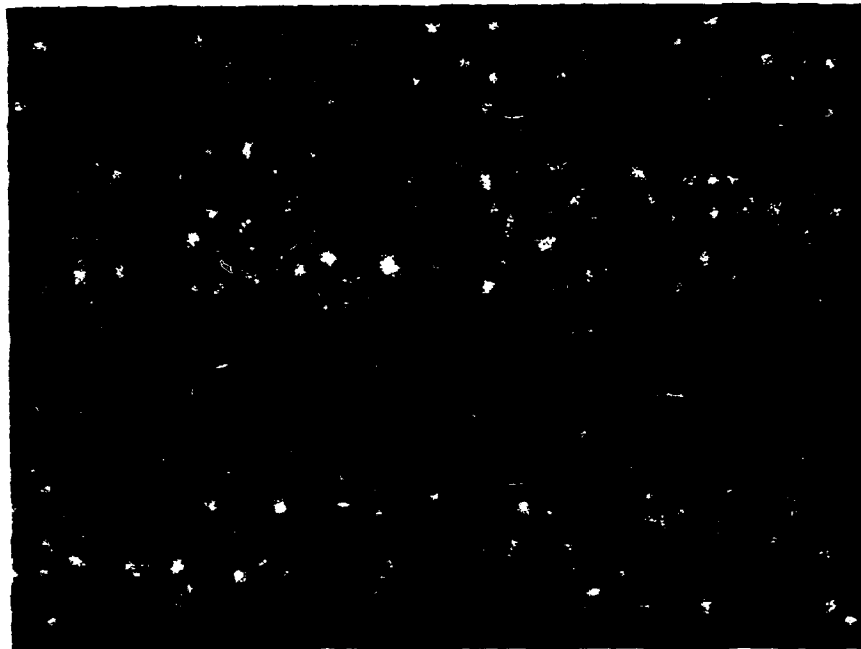


Figure 4. Solar granulation with (top) and without (bottom) correction by the tilt mirror locked on dark lanes.

The entire second week of the observing run was plagued by bad weather and heavy cloud cover, and no useful observations were made. The active mirror system was left at Sac Peak for use by Air Force personnel

In October 1986, the weather at Sac peak cleared up and we went to Sac Peak for an "impromptu" observing run. The active mirror was already set up from the last run. The active mirror was locked on a sunspot, but, unfortunately, a problem with the phase network arose (later determined to be a loose wire) which severely limited its use. We left Sac Peak after three days and later returned to retrieve the active mirror system.

The entire year of 1987 and half of 1988 was spent upgrading the active mirror system to the form described in the previous section. On July 3, 1988, the new active mirror system was taken to Sac Peak for the final observing run under this contract. This run proved to be extremely successful. As before, we were plagued by clouds and rain. However, the new system worked extremely well during the brief periods of sunlight that we encountered. On one occasion, we obtained a long sequence of video images by locking the active mirror up in 10-second intervals between clouds!

During July 6-10 we experienced two days of rain and 3 days of clouds with some intervals of sun in poor-fair seeing. During these intervals, we locked the active mirror on a variety of sunspots and pores and obtained about two hours of video taped images. From these observations, it became clear that a change in the magnification of the wavefront sensor lenslets would be necessary before we could get a good lock on small pores. Consequently, we decided to first take all of the sunspot data we needed, make the modifications, and then devote the remainder of the observing run to tracking small pores.

On July 11, we had a morning of good seeing. We obtained an impressive set of video data of a 10 arcsecond sunspot. On the 12th, we added digital cameras to the setup and obtained about 70 corrected and uncorrected image pairs of various sunspots in fair-good seeing.

On July 13, we made the necessary optical modifications to allow for pore tracking. On the 14th, we took about 100 digital images of small pores in poor-fair seeing conditions. The active mirror performed extremely well under these circumstances. The remainder of the run brought clouds, rain, and extremely poor seeing conditions.

DIGITAL IMAGE DATA

The observatory supplied two identical MDA (multi-diode array) cameras for recording digital image data; one camera for the corrected image, and one for the uncorrected image. Each camera had a 320 X 256 MDA array with a 1:1.25 aspect ratio (i.e., a square array). The two images were digitized simultaneously every 5 seconds and stored on computer magnetic tape. The exposures were 8 milliseconds long, essentially freezing the seeing.

To remove the effects of nonuniformities in the array detectors, dust on the imaging optics, and stray light, we applied a gain correction to the digital image data according to the formula

$$I' = \frac{(I-D)}{(F-D)} \langle F-D \rangle \quad (1)$$

where I is the original image, D is the dark current, and F is the average flat field. The dark current was obtained by averaging 50 exposures taken with the prime image blocked off. F was obtained by averaging 50 exposures taken near disk center while moving the field around. Finally, the arrays were expanded in the Y-axis by a factor of 1.25 to account for the aspect ratio of the camera pixels.

Figure 5 shows corrected/uncorrected image pairs of a small pore taken in various seeing conditions on July 14. The picture pairs are arranged in order of decreasing seeing quality. The field of view is 9 arcseconds square. In the first pair (a), the corrected image (top) shows a light bridge beginning to form across the pore. This feature is not visible in the corresponding uncorrected image (bottom). The uncorrected image, however, does have several small points of light which are not found in the corrected image. These points are speckle images of the light bridge and, hence, are not consistent from frame to frame. As the seeing conditions worsen, the pore in the uncorrected images reduces to nothing but a smear across the field. The corrected image, on the other hand, maintains a high resolution image of the granulation and pore, but at vastly reduced contrast.

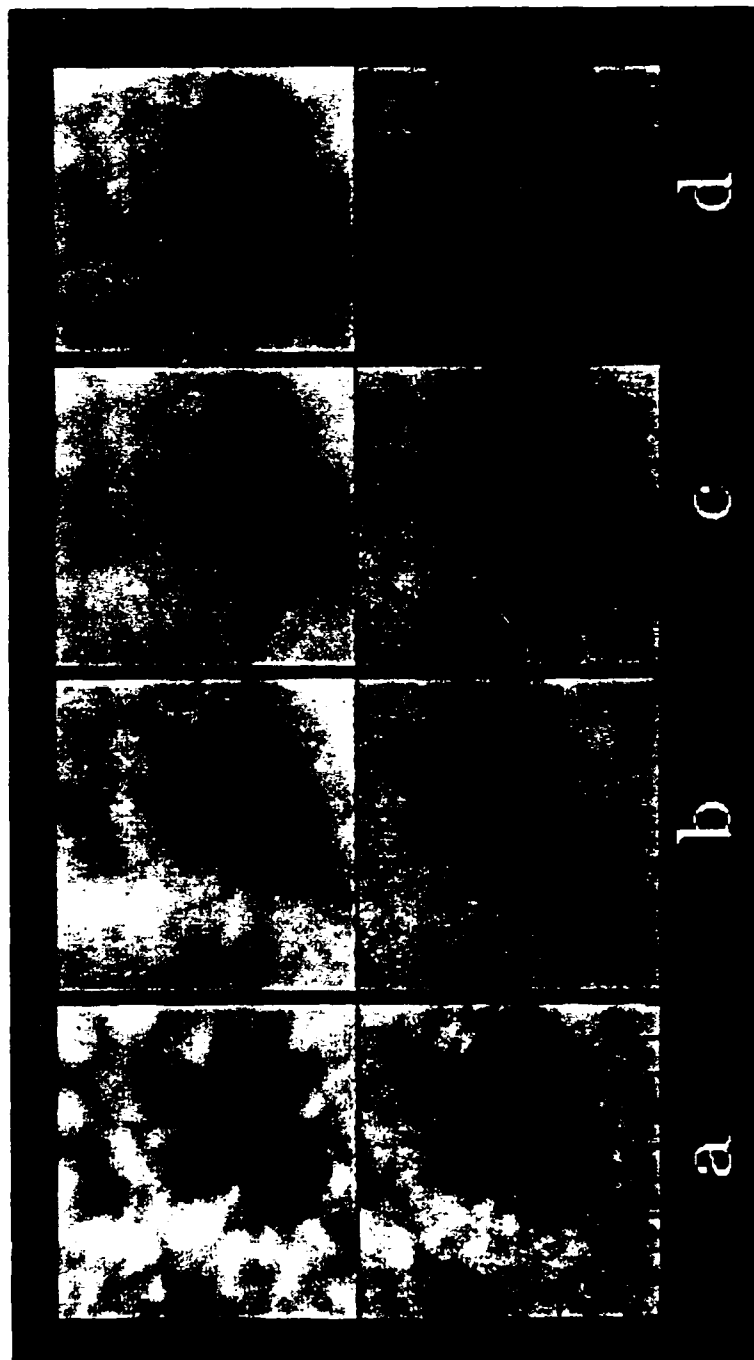


Figure 5. Pairs of corrected and uncorrected images of a small pore taken in various seeing conditions. Each corrected image (top) was taken simultaneously with the corresponding uncorrected image (bottom). The picture pairs are arranged in order of decreasing seeing quality. In the poorest seeing (d), the uncorrected image shows only a smear across the field of view, while the corrected image maintains the basic "T" shape of the pore. The field of view is 9 arcseconds square.

It is interesting to note how well the degradation of the images in figure 5 agree qualitatively with the predictions of computer simulations done by Smithson and Peri.¹ These simulations predict that as the seeing worsens, the contrast of the corrected image will decrease, but the high frequency information will remain. Figure 6 shows the evolution of a small sub-granule taken from the upper right corner of 6 corrected images, with the active mirror locked on a pore 5 arcseconds away. The contrast was enhanced by a factor of 5 to bring out the low-contrast information predicted by the simulations. In the last image (f), the sub-granule is only 1/4 arcsecond across, very near the diffraction limit of the telescope. These images were taken in roughly 2-3 arcsecond seeing.

Human beings do not normally perceive images with high frequency content to be of high image quality; rather they tend to look for high contrast and a large field of view.² Active mirror images taken in poor seeing intrinsically have low contrast. They also tend to have small fields of view since the isoplanatic patch may be small. Therefore, when comparing active mirror images to other images it is important that they be printed at the same size with the same field of view and with the same contrast. Figure 7 shows a comparison of a 4.3 arcsecond section of granulation taken from an uncorrected image (a), the same section of the corresponding corrected image (b), a section from the SOUP data (c)³, and a section of granulation images taken in the Canary Islands (d).⁴ All four images were printed at the same contrast level and with the same scale. The SOUP data and the Canary Island data represent the best images of solar granulation ever taken from space and from the ground, respectively. It is clear that the corrected image is comparable to the SOUP and Canary Island data.

¹R.C. Smithson, M.L. Peri, and R.S. Benson. "Quantitative Simulations of Image Correction for Astronomy with a Segmented Active Mirror." Applied Optics, vol. 19, no. 4 (1988), p. 1615.

²T.S. Huang. "PCM Picture Transmission." IEEE Spectrum, vol. 2, no. 12 (1965), 57-63.

³A.M. Title, et. al. "White-Light Movies of the Solar Photosphere from the SOUP Instrument on Spacelab 2." Advances in Space Research, vol. 6 (1986), p. 253.

⁴G. Scharmer, et. al. "Vortex Flow in Granulation." Bulletin of the American Astronomical Society, vol. 19, no. 4 (1987), p. 1118.

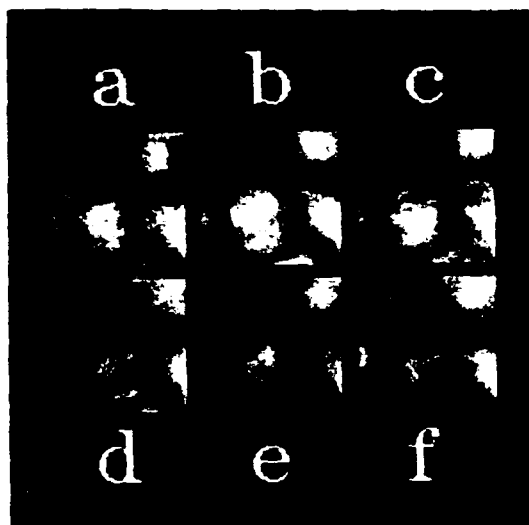


Figure 6. Evolution of a sub-granule. These 6 images were taken sequentially 5 seconds apart. The contrast has been artificially increased to show the high frequency information. The field of view is 3.65 arcseconds square. In the last image (f), the subgranule is only $1/4$ arcsecond wide, 80% of the diffraction limit of the telescope. The images were taken in 2-3 arcsecond seeing.

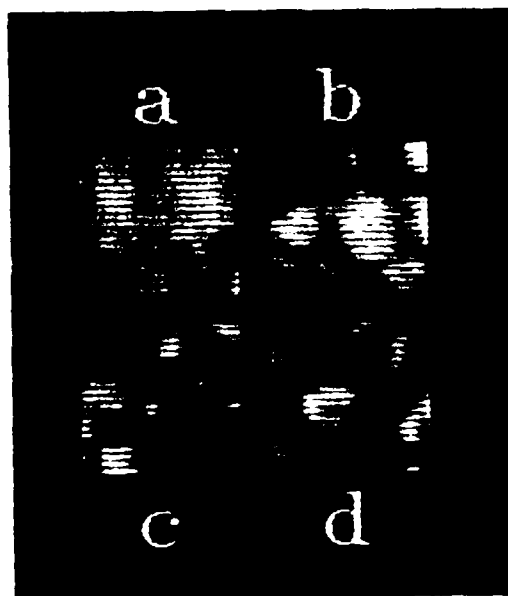


Figure 7. Four sections of granulation printed with the same field of view and contrast for comparison. (a) an uncorrected image, (b) the corresponding corrected image, (c) a section of SOUP data, and (d) La Palma data. The field of view is 4.3 arcseconds square. Based on high frequency content alone, the corrected image is comparable to the SOUP and La Palma images. The uncorrected image shows almost no information.

FOURIER ANALYSIS

Since we do not know exactly what the pore and the field surrounding it (figure 5) looked like before it was distorted by the atmosphere, we cannot exactly quantify the performance of the active mirror. We can, however, look at the relative improvement in the corrected images as compared to the uncorrected images. To this end, we calculate the power spectra of both images.

The digital images were taken with 8 millisecond exposures and, hence, contain speckle. As an approximation to a long-exposure, then, we will consider an average of 10 short-exposures. We have chosen 10 images taken in rather poor, but consistent seeing. The power spectra were calculated from the formula

$$P=Ck \int [F\{I(x,y)W(x,y)\}]^2 d\theta \quad (3)$$

and are shown as the dotted lines in figure 8 and figure 9. The integral is over the azimuthal angle in spatial frequency. (If the image is fairly isotropic, then the integration is justified.) $W(X)$ is a Blackman-Harris window⁵ which minimizes aliasing due to the edge effects. K is the radial portion of spatial frequency, and C is a scaling constant chosen so that the integral of the resulting 1-D power spectrum is equal to the square of the rms contrast of the original image. C , of course, depends on the frequency units chosen.

In order to make a fair comparison between the corrected and uncorrected power spectra, the noise power spectrum associated with each should be calculated and subtracted. The noise spectrum of the uncorrected data was obtained from 4 flat fields taken in extremely poor seeing while moving the telescope. These flat fields were corrected for gain variations according to equation 1 and then treated in the same manner as the image data with equation 2. The resulting four noise power spectra were averaged and then scaled to fit the image power spectrum in the noise region as shown in figure 9.

⁵F.J. Harris. "On the Use of Windows for Harmonic Analysis with the Discrete Fourier Transform." Proceedings of the IEEE, vol. 66, no. 1, (January, 1978).

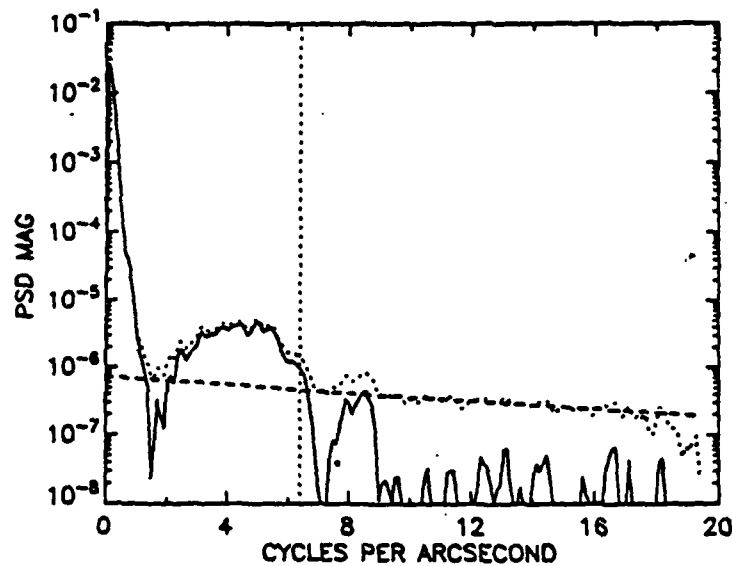


Figure 8. Power spectrum of an average of 10 sequential corrected images. The dotted line is the raw spectrum, the dashed line is the noise estimation, and the solid line is the raw spectrum minus the noise. The vertical dotted line shows the cutoff frequency of the telescope.

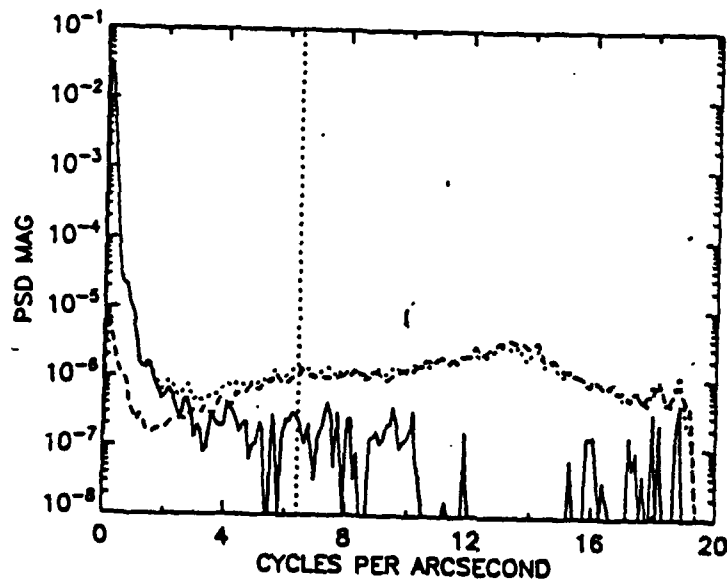


Figure 9. Power spectrum of an average of 10 sequential uncorrected images. The dotted line is the raw spectrum, the dashed line is the noise spectrum obtained from flat fields, and the solid line is the raw spectrum minus the noise spectrum. The vertical dotted line shows the cutoff frequency of the telescope.

Unfortunately, the same approach could not be used for the corrected camera noise power spectrum, as the corresponding flat fields had saturated pixels. As an approximation to the noise spectrum we performed a linear fit to the points in the power spectrum beyond the cutoff frequency of the telescope. The approximated noise spectrum is shown as the dashed line in figure 8.

The noise spectra were subtracted from the data spectra. The resultant noise-corrected power spectra are shown as the solid lines in figure 8 and figure 9. To quantify the relative improvement produced by the active mirror, we take the ratio between the corrected power spectrum and the uncorrected power spectrum. This ratio is shown in figure 10. We see that the corrected images have 2 or 3 times as much information the size of solar granulation (2-3 arcseconds) as do the corrected images. Beyond 1.5 cycles per arcsecond, the effect of the active mirror is really noticeable, since there is essentially no meaningful information in the uncorrected images on this scale. Beyond 7.5 cycles per arcsecond, the cutoff frequency of the telescope, the information in the corrected images drops to zero and all that remains is noise.

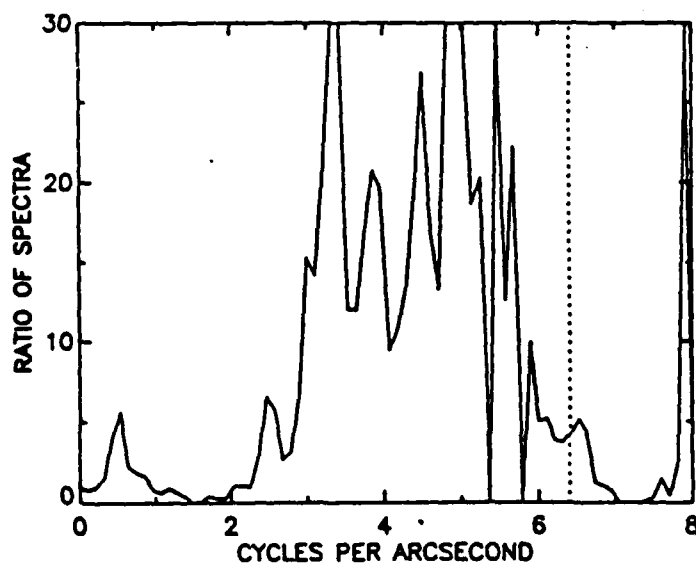


Figure 10. The corrected power spectrum divided by the uncorrected power spectrum. The vertical dotted line shows the cutoff frequency of the telescope. The effects of active mirror are most noticeable between 2 cycles/arcsecond and the telescope cutoff.

At about 1.5 cycles per arcsecond, the ratio mysteriously drops to zero, indicating an absence of information on this scale in the corrected images. Possibly there is a real absence of features on this scale in the image area. The data are still being analyzed at this time.

CONCLUSIONS

The observations described in this report represent a major advance in the application of active optics to solar observations. They have demonstrated that an active mirror used with a solar telescope in quite "average" uncorrected seeing on the order of 2 arc seconds can produce images comparable to the best ever taken, allowing the study of evolution of solar structures near the diffraction limit of the host telescope over an area on the order of 10 arc seconds in diameter.

Modifications to the active mirror itself (made under Lockheed independent research funding), while not a part of this contract effort, nevertheless produced a mirror system that has demonstrated a degree of user-friendliness not found in the earlier prototype mirror. We hope that additional observations to be made as a part of the Lockheed funded effort next year will provide further evidence that active optics can be a routine observing tool for solar observations.

It must be stressed that most of the data discussed in this report was taken in moments of sunlight between clouds, and that the mirror showed itself to be immune to the need for frequent re-alignment after loss of lock. The only remaining operational issue is the need for daily realignment of the mirror at Sacramento Peak - a need not present in sea-level testing at Lockheed, and which is caused by local heating of the strain-gauge bridge electronics. This problem is currently being fixed. No other problems were found that preclude the mirror from being used as a routine observing instrument.

A comment is in order regarding the use of the active mirror to provide image correction in areas away from sunspots and pores. As the granulation tracking data presented here shows, there is no difficulty in tracking granulation patterns with the present quad-cell based wavefront sensor. We have several hours of completely reliable granulation tracking using quad cells, both using single active mirror segment subapertures and the entire aperture of the host telescope. Because of the

approximate 10,000:1 signal-to-noise ratio of the quadrant detectors used, tracking could be maintained in uncorrected seeing as poor as 6 arc seconds. Under these extremely bad seeing conditions, of course, the mirror locks on low contrast intensity minima corresponding to "missing granules" because the granulation itself cannot be resolved.

The chief difficulty in making the active mirror lock on granulation is guaranteeing that the individual segments are locked on the same granulation minimum. The present mirror is equipped to do this by means of a computer-controlled outer loop that forces each segment to point in the same average direction as all the other segments. The necessary computer programs to do this will be written in 1989 under Lockheed IR funding.

The data taken under this contract have conclusively shown the potential of active optics for astronomy. Although we cannot submit a video tape as a part of this final report, we have presented pictures that we feel are representative of the capabilities of the active mirror. The next major step should be the installation of an active mirror at Sacramento Peak for evaluation by various scientific observers.

PAPERS

5 papers were written and/or presented under this contract:

D.S. Acton, T.D. Tarbell, and A.M. Title, "Power Spectrum of Solar Granulation from Space-based Observations," Abstracts of the Joint Spring Meeting of the Texas Section of the American Physical Society, March 6, 1987.

Photographs of solar granulation were taken with the Lockheed Solar Optical Universal Polarimeter (SOUP) aboard Spacelab 2 in July of 1985. Eight of these photographs were digitized with a microdensitometer. HD conversions, Hanning windows, 2-D Fourier transforms, radial averaging, and an MTF correction were applied to yield the power spectrum in average photospheric units.

D.S. Acton, P. Brandt, G. Scharmer, D. Dunn, T.D. Tarbell, A. M. Title, and R.C. Smithson, "Power Spectra of Solar Granulation, Bulletin of the American Astronomical Society, Vol. 19, No. 4, 1988, p. 1118.

Many high resolution images of solar granulation have been obtained from several different observing sessions at La Palma, Sac Peak, and Spacelab 2. Fourier analysis and MTF corrections have been utilized to yield the average power spectrum of each set of images. The spectra agree fairly well, even though the images were taken as long as 12 years apart, indicating that the spatial characteristics of solar granulation are fairly static. The power spectra are also in good agreement with a spectrum obtained by speckle-interferometric techniques.

R.C. Smithson, D.S. Acton, M.L. Peri, R.J. Sharbaugh, R.B. Dunn, O. van der Luhe, S.L. Keil, "Observational Results in Solar Astronomy with the Improved Lockheed Active Mirror System," Bulletin of the American Astronomical Society, Vol. 20, No. 4, 1988, p. 710.

Although earlier observations have demonstrated the feasibility of active correction of atmospheric seeing, active correction systems have been primarily laboratory devices. Lockheed has constructed a new generation active mirror system designed to eliminate many of the problems of earlier systems and thus to produce a "user friendly" mirror system that can be a routine tool for astronomical observations. This paper describes the first operational results from that mirror.

The active mirror system itself is described, and examples of solar observations made with the Lockheed systems are given. Operating characteristics of the new mirror are compared with older systems, particularly with regard to stability and ease of use. Although some additional improvements are yet to be made, there appears to be no reason why active mirror systems cannot now become routine observing instruments for astronomical observations.

D.S. Acton, "Results from the Lockheed Solar Adaptive Optics System," The Tenth Sacramento Peak Summer Workshop: High Spatial Resolution Solar Observations, Aug 16, 1988.

R.C. Smithson, "Adaptive Optics for Solar Observations," The Tenth Sacramento Peak Summer Workshop: High Spatial Resolution Solar Observations, Aug 16, 1988.