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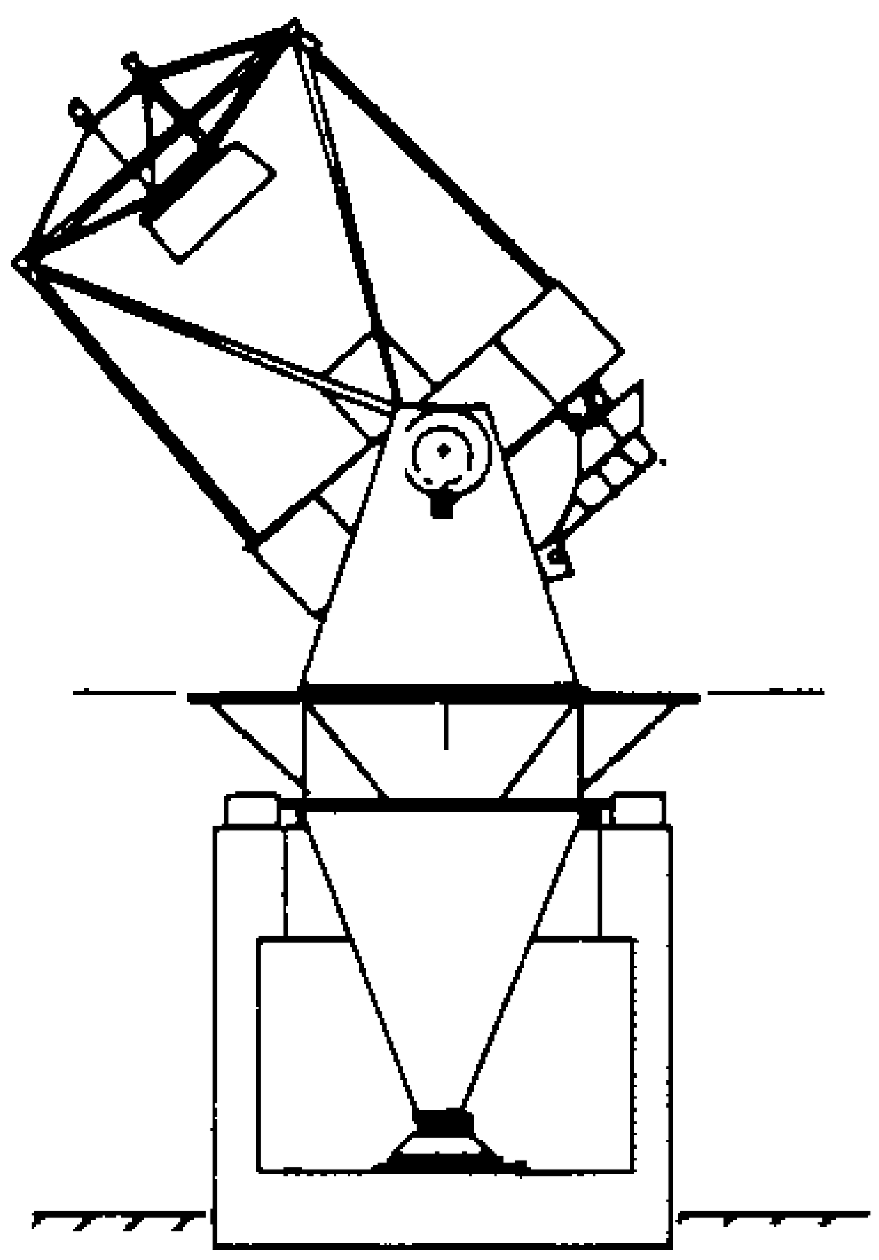

3.5 Meter Telescope

NOAO Testing Procedures for Large Optics

L. Stepp, G. Poczulp, E. Pearson, N. Roddier

WODC 02-17-01

Presented at SPIE

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Larry Stepp, Gary Poczulp, Earl Pearson, and Nicolas Roddier

National Optical Astronomy Observatories*

P. O. Box 26732

Tucson, Arizona 85726

ABSTRACT

In this paper we describe optical testing procedures used at the National Optical Astronomy Observatories (NOAO) for testing large optics. The paper begins with a discussion of the philosophy behind our testing approach, and then describes a number of different testing methods used at NOAO, including the wire test, full-aperture and sub-aperture Hartmann testing, and scatterplate interferometry. Specific innovations that enhance the testing capabilities are mentioned. NOAO data reduction software is described. Examples are given of specific output formats that are useful to the optician, using illustrations taken from recent testing of a 3.5-meter, f/1.75 borosilicate honeycomb mirror. Finally, we discuss some of the optical testing challenges posed by the large optics for the Gemini 8-meter Telescopes Project.

1. PHILOSOPHY

The next generation of ground-based optical telescopes, currently being designed and constructed by a number of astronomical organizations around the world, will require mirrors of unprecedented size and accuracy. Testing these mirrors will be difficult, involving several characteristic problems:

1. Relative vibration between the mirror and the test equipment is hard to control because of the large distance separating them.
2. If the light path is not in a vacuum, temperature-induced variations in the index of refraction of the air can cause dynamic fluctuations in the measured wavefront under turbulent conditions, or systematic errors caused by layering of air under static conditions.
3. The fast primary f/ratios of modern telescopes require optical tests that will cover a wide angle.
4. The large size and fast f/ratios also produce very large departures from a best-fit sphere, sometimes more than a thousand microns. If a light source is placed at the paraxial center of curvature, the circle of least confusion formed by the reflected rays can be several centimeters in diameter.
5. A large number of polishing iterations is normally required to finish a large aspheric mirror to close tolerances. Therefore, frequent testing is needed, but it can take quite a bit of time to set up each test of a large mirror.
6. Test facilities for large mirrors can be very costly.

Over the last 30 years a philosophy for coping with the problems of large optics testing has been developed at NOAO. The key points about this philosophy are summarized on the next page.

* Operated by the Association of Universities for Research in Astronomy, Inc. under cooperative agreement with the National Science Foundation.

- For every critical testing stage, more than one test method will be required. These test methods should be based on different physical principles. If the testing represents a new challenge (for example, a longer path length or a greater aspheric departure than previously encountered) it is important to develop more than two test methods, to avoid long project delays in case one of the methods proves to be unsatisfactory.

- At least one test method must provide continuous surface information to allow the smoothness and continuity of the polished surface to be measured.

- When possible, auxiliary optics should be avoided, particularly if a functional test of the auxiliary optics is difficult to perform. For any critical testing stage, at least one test method should be available that does not require auxiliary optics. If this is not feasible, two methods that use completely different auxiliary optics should be available.

- All tests must be relatively insensitive to vibration.

- A mirror must be tested on a support that is identical in function to its final telescope support, in the same orientations in which it will be used. In order to separate the effects of the polished surface, axial support, and lateral support it is necessary to test the mirror in three orientations. However, for a telescope with active control of the mirror figure, testing in only two orientations may be acceptable.

- When testing steeply curved surfaces, it is not acceptable to map measured mirror deformations onto the surface as though it were flat. For example, interferometry normally measures departures from a reference spherical shape. The measured surface information must be converted to a true Cartesian coordinate system before further processing (for example a polynomial fit) is attempted.

- Whenever possible, the test equipment should be remotely operable, so heat and vibration from testing personnel can be isolated from the test setup. Also, the more convenient the equipment is to use, the lower the chance of operator error.

- It is necessary to continually work on the development of new test methods, to have a chance of meeting new challenges as they arise.

2. TESTS OF THE WIYN TELESCOPE 3.5-METER PRIMARY MIRROR

An application of this philosophy can be seen in the testing program for the 3.5-meter WIYN Telescope primary mirror, the largest mirror currently in fabrication at NOAO. This mirror has been polished to a spherical figure, to facilitate testing at the center of curvature. It is currently being used in an extended program to test the mirror support, thermal control, and active optics systems for the WIYN Telescope[1]. Part of the current program is the development of test methods that will be needed for finishing the mirror. These methods are summarized in Table 1.

The NOAO large optics facility was designed for fabrication of mirrors up to 4 meters in diameter. A test tower extends from the ceiling of the facility, 20 meters above the level of the polishing machine, which is set below ground level. A large basement room opens in front of the polishing machine and the machine table can be tilted to allow horizon-pointing testing of mirrors. Figure 1 shows a moveable light-weight shroud that can be placed between the polishing machine and the lower part of the test tower to reduce air currents that cause seeing effects. Figure 2 shows some of the test equipment in the tower at the center of curvature of the 3.5-meter mirror. The optical axis of the mirror comes through the center of the hole in the optical table. Part of the test equipment has been removed for clarity. Several different pieces of test equipment can be set up, so that each can be quickly and easily slid into position on horizontal slides. Figure 3 shows the aluminized mirror in its cell. Figure 4 shows some of the optical test equipment at the horizon-pointing test station in the basement, with the mirror in the background. The test equipment can also be seen re-imaged in the mirror.

Several test methods are planned for each stage of the work. This is necessary because each test has limitations. Some tests require auxiliary optical elements, whose performance must be verified by other independent tests. Some tests provide only partial information about the surface. And, when extending the range of test capabilities, it is always possible that a planned test may prove impractical.

Table 1
Summary of Planned Optical Tests for the WIYN Telescope Primary Mirror

Testing Stage	Planned Tests	Null Corrector Required?	Continuity
1. Aspherizing	Spherometers	No	No
	10.6 um PS Interferometry	Yes	Yes
	Wire test	No	No
	Hartmann test	No	No
2. Final Figuring	Foucault test	Yes*	Yes
	Hartmann test	No	No
	Scatterplate interferometry	Yes	Yes
	Phase-shifting interferometry	Yes	Yes
3. Figure measurement in telescope	Hartmann-Shack	No	No
	Curvature sensing	No	Yes
	Lateral shearing interferometry	No	Yes

* Foucault testing can be performed without a null corrector, but more useful information can be gained when a corrector is used.

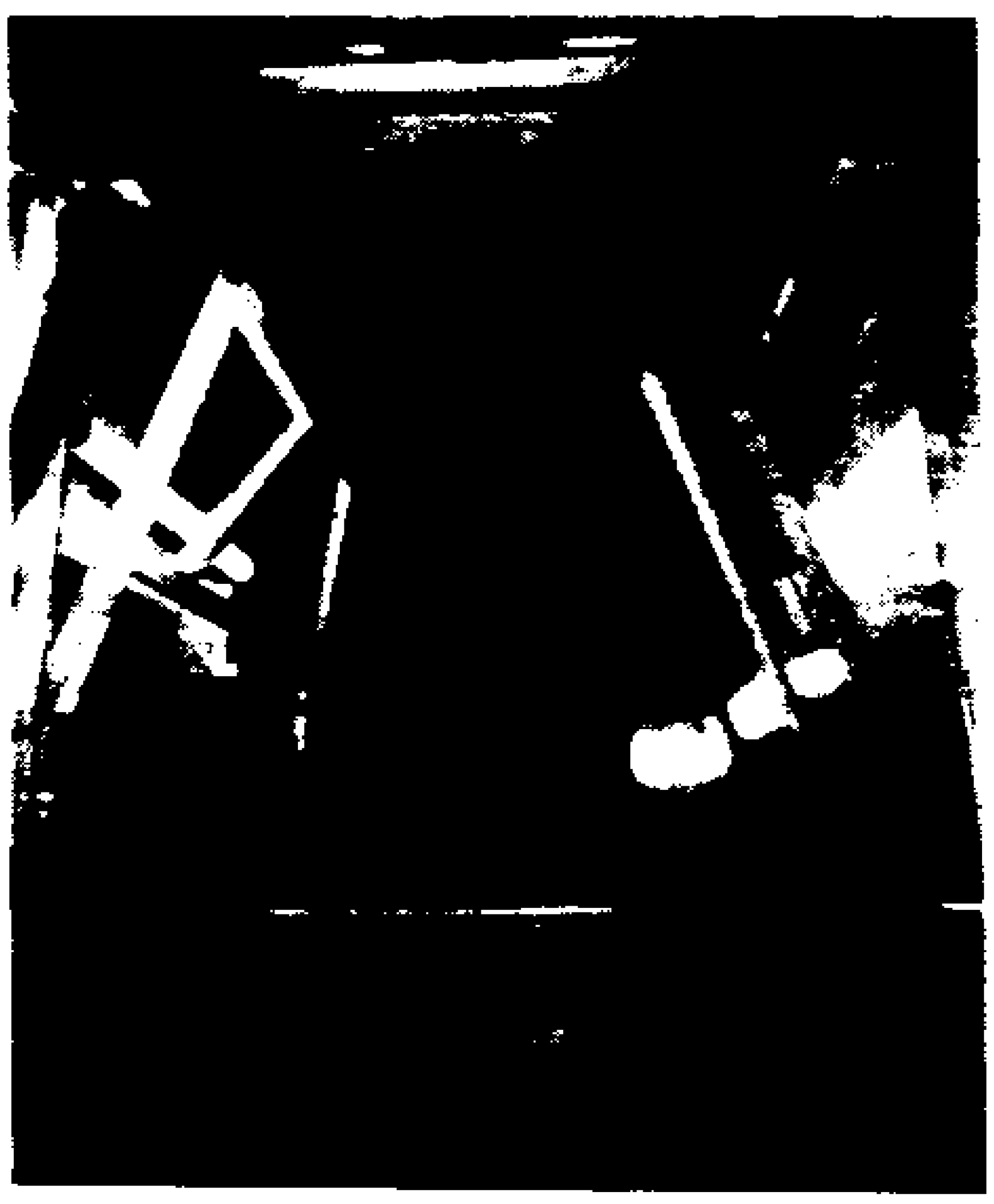

Figure 1. A portable shroud has been placed between the polishing machine and the base of the test tower.

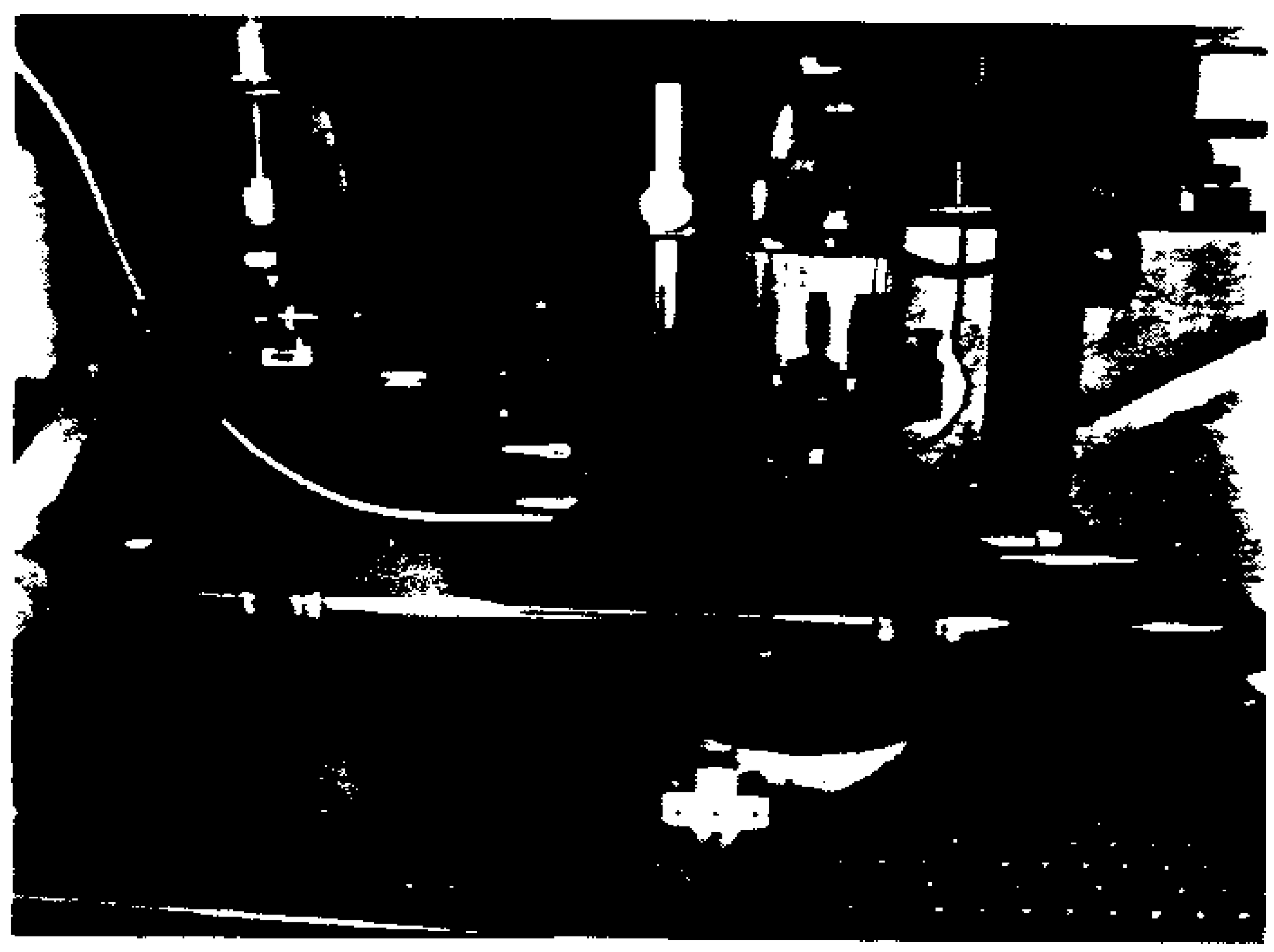

Figure 2. Optical test equipment in the tower above the 3.5-meter mirror, which is 12 meters below the hole in the optical table. The scatterplate interferometer is on the left, the Hartmann light source and camera are on the right.

Two major difficulties occur during aspherizing. First, it is difficult to measure the surface before it has been polished to a specular finish. Second, many test methods require a surface that is within a few microns of either: (1) a sphere, or (2) the intended asphere, for which a null corrector has been built. The departure of the WIYN primary from the best-fit sphere is 170 microns, so there is an extensive "no-man's-land" between the spherical and finished aspherical conditions.

Figure 3. The 3.5-meter mirror, aluminized and in its cell, mounted on the table of the 4-meter polishing machine.

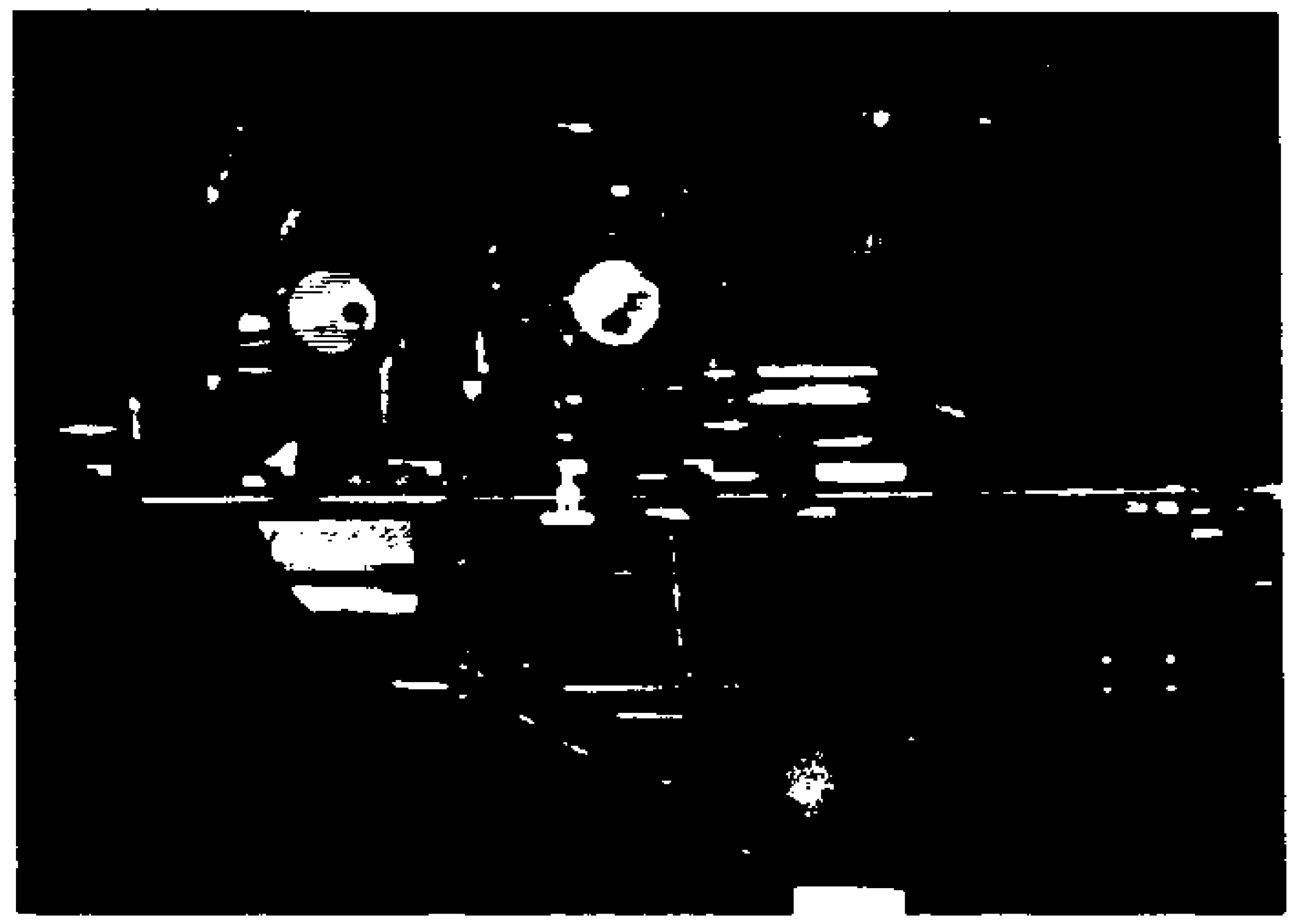

Figure 4. Horizon-pointing test equipment. The mirror can be seen in the background, with the inverted image of the test equipment reflected in its surface. Note the reference mirror mounted in the central hole of the 3.5-meter mirror.

Some information can be obtained with a bar spherometer, which can measure the surface curvature in radial and tangential directions by measuring the sagittal depth of the curve over the length of the bar. Much more complete information can be obtained from a phase shifting interferometer operating at 10.6 microns wavelength. At 10.6 microns, a finely ground surface is reflective enough to produce interferograms. If the mirror is within several tens of microns of a sphere, or within several tens of microns of the intended asphere, the full mirror surface can be mapped. An infrared-transmitting null corrector is required to measure the asphere, and it is difficult to devise a functional test for such a corrector. Confirmation of its performance must be obtained from other independent tests once the mirror has been polished to a specular surface.

Two tests we will use to measure the aspheric 3.5-meter mirror without using a null corrector are the wire test and the Hartmann test. These can be performed once the surface has been polished to a specular finish (we have no current plans to develop wire or Hartmann tests that work in the infrared). Both of these tests yield slope information at points on the mirror surface by tracing reflected beams of light. The wire test measures the position where the normals to a given zone on the mirror intersect the optical axis. The general shape of the mirror surface can then be determined. This can serve as a useful starting point for the Hartmann test.

The Hartmann test can take many different forms, but in general narrow beams of light are reflected from different spots on the mirror to a focus, and the pattern of spots is recorded by a camera at or close to the best focus. For tests of the 3.5-meter mirror we are using a perforated metal screen placed directly in front of the mirror surface to block most of the light shining on the mirror from a point source at the center of curvature (see Figure 5). The holes in the screen allow narrow beams of light to reflect from the mirror, forming spots on a CCD chip, also at or near the center of curvature. The positions of these focus spots are compared to their expected positions and the differences are a measure of the slope errors at the sample points. It can be difficult in practice to identify each spot unless the general character of the mirror figure is known in advance.

One significant advantage of the Hartmann test is its insensitivity to vibration and seeing effects. A time exposure of 10 seconds or longer will produce a slightly blurred image of each spot, but provided the vibration and seeing conditions are randomly varying, their effects can be averaged out. The centroid position of each spot will provide a true measure of the slope of the corresponding point on the mirror.

Use of a CCD camera allows the information to be fed directly to the computer program for data processing and the results can be obtained rapidly. For the 3.5-meter mirror testing we are using a camera made by Photometrics, Inc. with a Thompson 1024 x 1024 detector. The pixel size is 19 microns, giving a full detector size of approximately 2 cm x 2 cm. The size of each spot is determined by a combination of the geometric effects caused by displacement from best focus, and the diffraction effects caused by the size of the holes in the screen. In our current setup the spot sizes are about 20 pixels diameter.

The Hartmann test equipment is being developed to allow testing the f/1.75 hyperboloidal surface (certain features would not be needed for testing spheres). The screen is made of four separate quadrants as shown in Figure 6. Each quadrant is tilted and bent to follow the curved surface of the mirror, to reduce vignetting of the beams when testing the aspheric surface. The screen takes the form of a shallow 8-sided pyramid. The full screen has 532 circular holes. While the mirror is spherical, all the spots can be recorded on the CCD simultaneously while still allowing enough separation to make spot identification simple (Figure 7). For the aspheric figure the circle of least confusion of the return beams will be larger than 2 cm across. Therefore we will test the mirror one quadrant at a time, with the other holes in the screen temporarily masked off. Previous experiments have been made with a Hartmann screen that covered only one quadrant of the mirror[2]. This screen was physically moved from one set of kinematic mounts to another as the screen was shifted from one quadrant to the next. This method proved difficult because the movements of test personnel shifting the screen caused small alignment changes between exposures. Our current screen can be thought of as four quadrant screens on a common mount. The Hartmann data reduction will be done quadrant by quadrant.

Figure 5. The Hartmann screen is being installed in front of the 3.5-meter mirror.

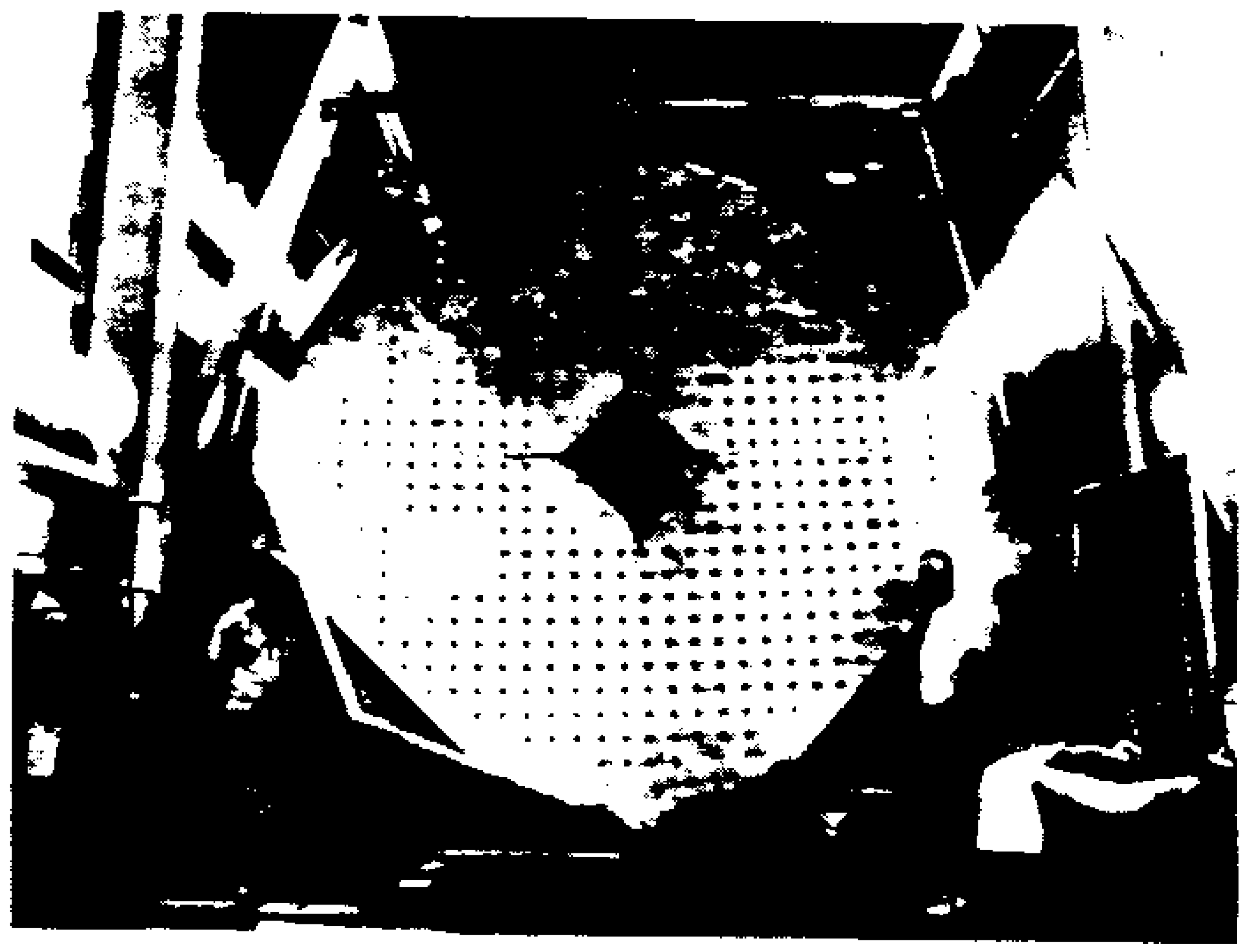

Figure 6. The 3.5-meter Hartmann screen is made of four quadrants mounted on a common framework.

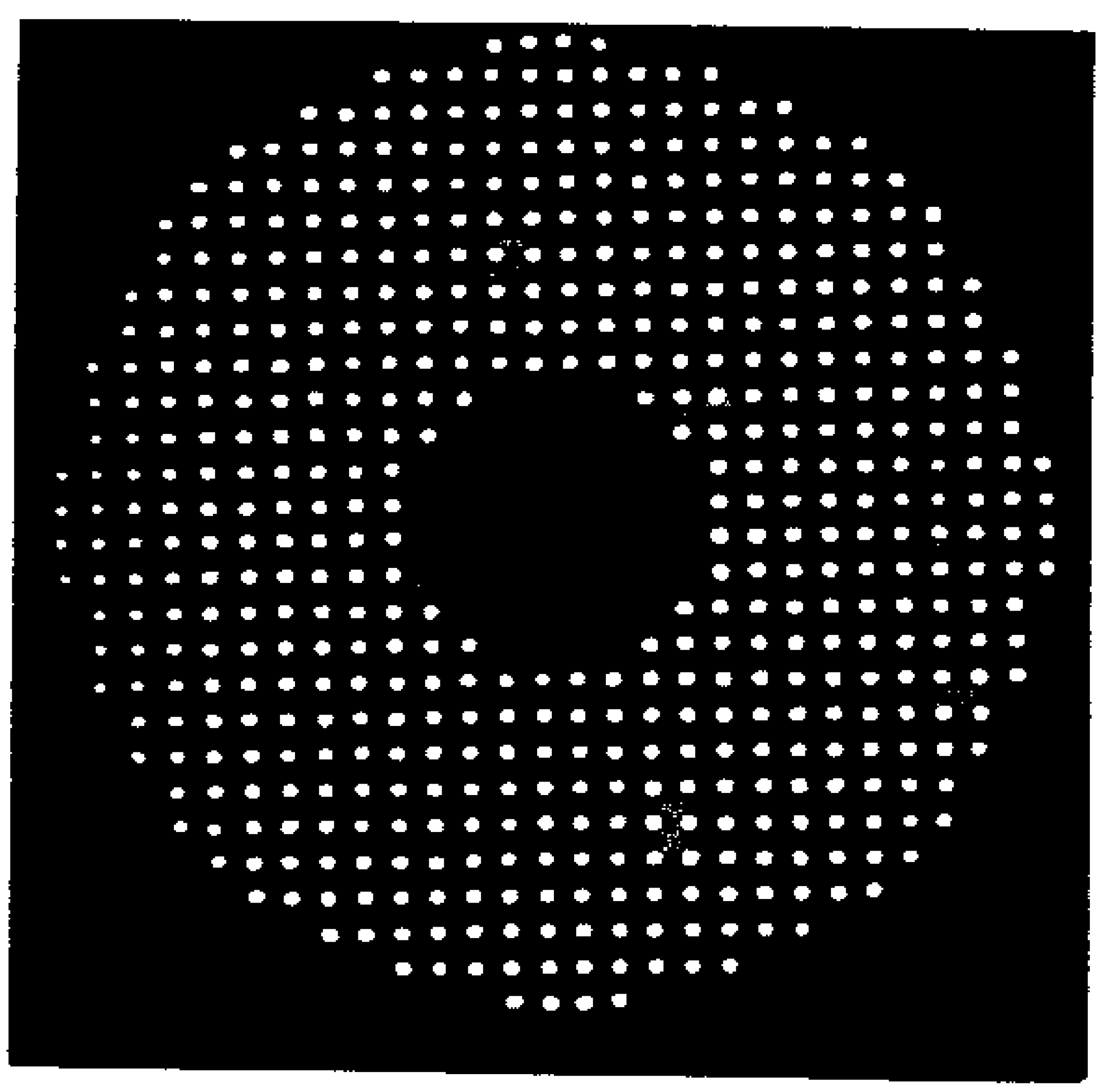

Figure 7. Hartmann spot pattern recorded from the spherical 3.5-meter mirror. The full size of the pattern on the CCD chip is about 2 cm square.

A pellicle beamsplitter is used to avoid physical interference between the source and detector. It has been difficult to obtain flat enough pellicles. If necessary, the beam splitter can be eliminated by shifting the light source and camera laterally a small amount. This can be accommodated fairly easily in the data reduction software if a full screen is used, but becomes more of a complication if the testing is done quadrant by quadrant.

One disadvantage of the Hartmann test is the lack of information about the mirror surface between sample points. Other optical tests are required to prove that the surface is smooth and continuous.

A simple Foucault knife-edge test can help determine the smoothness of the polished surface. On an aspheric mirror the test can be performed without a null corrector, but at f/1.75 much finer detail can be seen if a corrector is used. Features a few nanometers in height can be seen on the mirror surface, providing confirmation for measurements obtained by interferometry.

Phase shifting interferometry offers a number of advantages for testing large mirrors, including continuous coverage of the mirror surface with good spatial resolution, and potential accuracy of a few nanometers for measurements of surface feature heights. However, in the past commercial phase shifting interferometers have been sensitive to vibration. For example, previous attempts to test large mirrors in our polishing facility with two different brands of commercial phase shifting interferometers were unsuccessful because of the level of vibration present, even when testing late at night. Recent improvements to hardware and software now offer the possibility that at least some commercial units may be able to cope with the vibration. We hope to test one of these improved models in the near future.

Scatterplate interferometers are well suited to testing large optics. The scatterplate is a quasi common path interferometer, that uses a narrow reference beam that traverses approximately the same path to the mirror as the main beam. Vibration is not a significant problem if fast shutter speeds are used. Seeing effects can be reduced by averaging a number of independent measurements. The NOAO scatterplate interferometer and data reduction software have been described in a previous paper[3].

Several potential weaknesses of the scatterplate interferometer have been overcome by our development effort here at NOAO. First, we needed semi-automatic analysis of the interferograms, and we needed the ability to resolve surface errors with spatial scales of about 1/200 of the mirror diameter. Theseneeds have been met very well by the interferogram analysis software developed by Claude and François Roddier[4], and implemented by John Fox. Their software maps the phase of the interferogram, then unwraps the phase information to produce a phase map of the mirror surface. By displacing the interferometer to introduce 40 to 50 fringes of tilt in the interferogram, accurate high-spatial-frequency phase information is obtained. The accuracy of the analysis has been confirmed by comparisons with other methods. Phase maps have been matched to interferograms with zero tilt, as shown in Figure 8. Slope maps computed from the phase maps have been matched to knife-edge photographs. And calculated point spread functions have been compared to stigmatic images recorded through an autocollimating microscope placed at the center of curvature.

Second, we needed fast exposure times to freeze vibration effects. In our system a Photometrics 512 x 512 pixel camera records the interferograms. The shortest exposure available from the shutter on the camera is about 1/100 second. Under some circumstances this is not fast enough. Chris Koliopoulos suggested that an acousto-optic modulator could be used as a fast shutter on the input helium-neon laser beam. The beam is aligned so that it normally misses the entrance aperture to the interferometer. When the acousto-optic modulator is energized, the beam is diverted to align with the optical axis of the interferometer, and the beam momentarily illuminates the mirror. At present we are using exposure times of 1/4000 second with this equipment. A diagram of the NOAO scatterplate interferometer is shown in Figure 9.

Third, one characteristic of the scatterplate interferometer is a "hot spot" caused by the unscattered portion of the returning reference beam. Two simple innovations have made it possible to obtain high-contrast interferograms with no hot spot. Normally, the reference beam is focused onto the surface under test, as close as possible to the center of the aperture. As an alternative, we fabricated a separate reference mirror having the same radius of curvature as the larger mirror, and placed it on an adjustable mount in the middle of the central hole[5]. The reference mirror is adjusted to have a common center of curvature with the larger mirror. This technique allowed us to get good interferograms with the hot spot removed from the aperture under test. However, the hot spot still remained in the center of the interferogram, and the difference in intensity still caused some problems in the CCD image. Therefore, we placed a small occulting disk inside the camera on the window in front of the CCD chip. This blocks out light from the region of the central hole of the mirror, preventing the unscattered light from the reference beam from reaching the CCD.

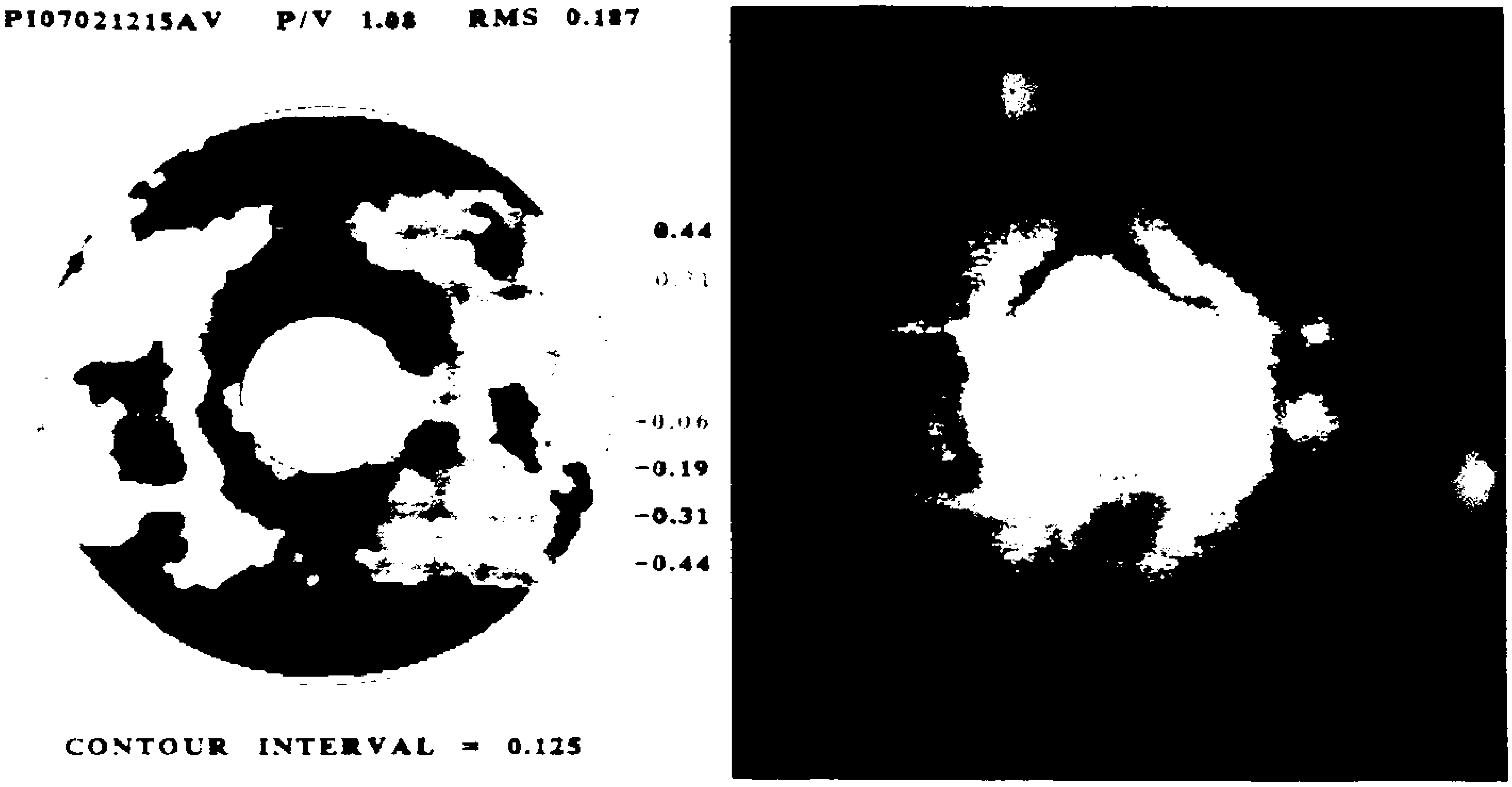

Figure 8. The surface error map on the left was computed by the Roddier analysis software. It is an average of maps made from 15 different interferograms. On the right is a single interferogram recorded on 35 mm film. In this interferogram tilt has been minimized in order to "fluff out" the fringes.

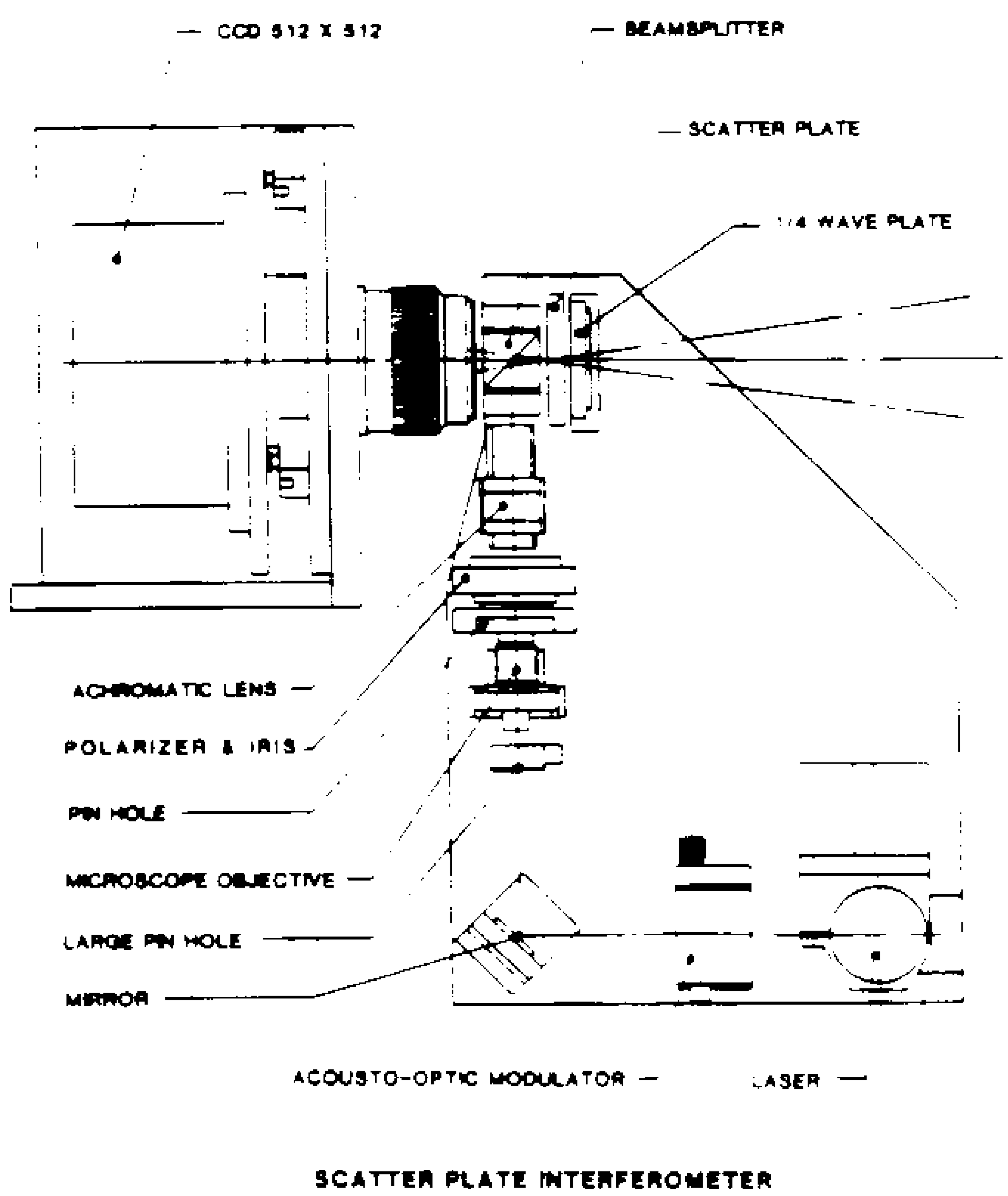

Figure 9. A layout diagram of the NOAO scatterplate interferometer.

3. OUTPUT OPTIONS

Once a surface error map has been created, either by analysis of interferograms, or by interpolation and integration of the Hartmann slope information, the information can be displayed in several different forms that are useful to the optician. Many of these display forms are fairly conventional: contour maps, slope maps, three-dimensional surface plots, point-spread functions displayed as two-dimensional image intensity plots, three-dimensional plots, or a radially-averaged cross section. These output forms are illustrated in reference 3. Four other display types that are particularly useful to the optician are illustrated below.

Figure 10 is a contour map with a superimposed grid that shows the locations of internal ribs in the 3.5-meter mirror. This is used as a "hit map" by the opticians, to plan areas for local polishing.

Figure 11 is a contour map with low spatial frequency errors removed. Our software allows subtraction of individual Zernike polynomial terms from the phase information, up to 80 terms. However, Figure 11 was not prepared by subtraction of the low-order Zernikes. Instead, it was prepared by varying the size of the apodization circle in the Fourier plane during interferogram analysis. First, a standard interferogram reduction is performed to produce a phase map containing all of the surface information. Then a second reduction of the same interferogram is performed, but with the apodization circle decreased in size, to produce a phase map with the high spatial frequency information filtered out. Finally, the second phase map is subtracted from the first to leave only the high frequency information. This method removes low spatial frequency errors more thoroughly than an 80-term Zernike subtraction. The resulting high-frequency map is useful for planning localized polishing to remove print-through. Note that the surface information shown in Figure 11 would be missing from a mirror surface map displayed as a Zernike polynomial fit.

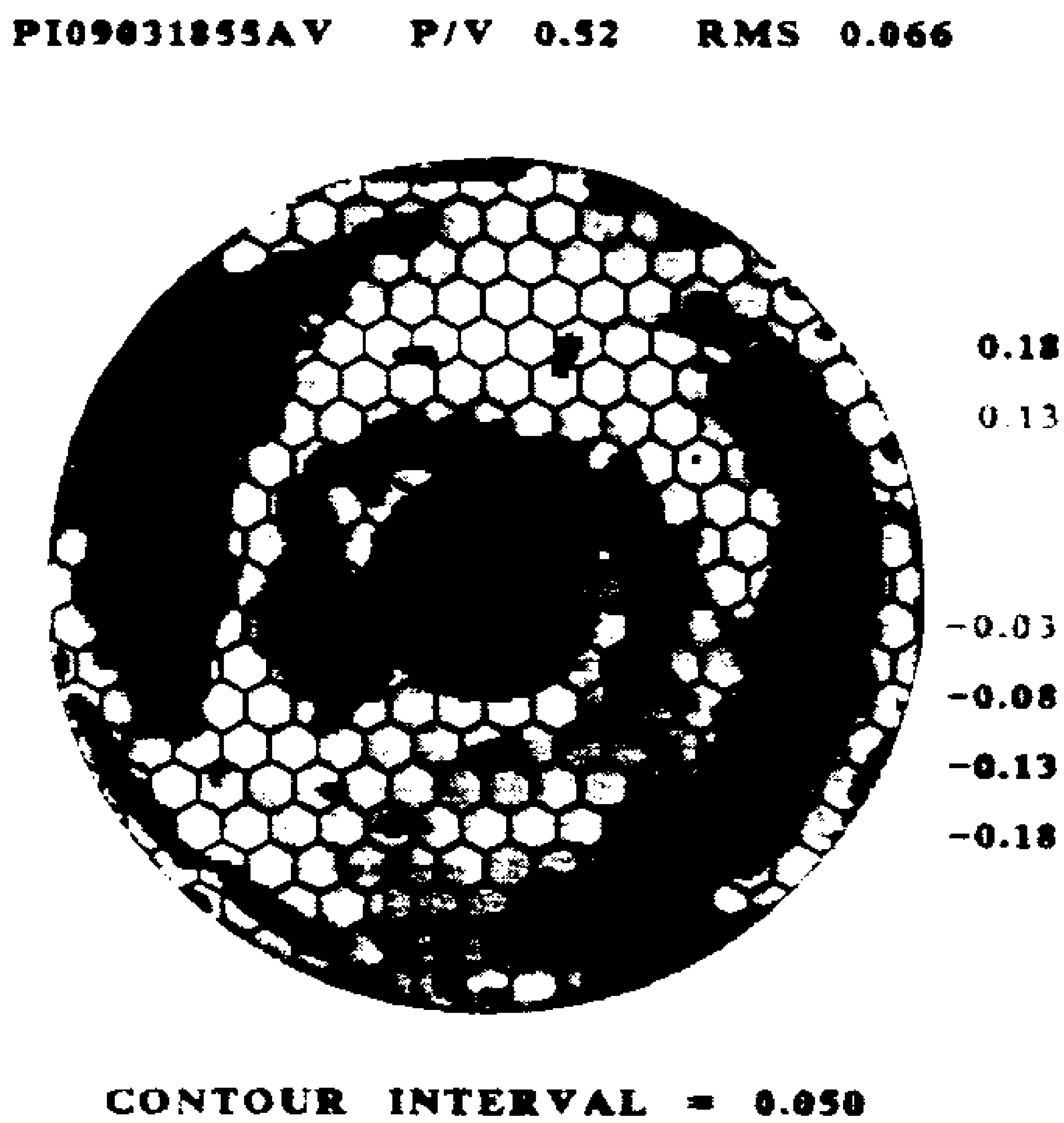

Figure 10. A "hit map" of the surface of the 3.5-meter mirror. The hexagonal grid lines have been added in the computer. This allows the optician to easily visualize locations where localized polishing is needed.

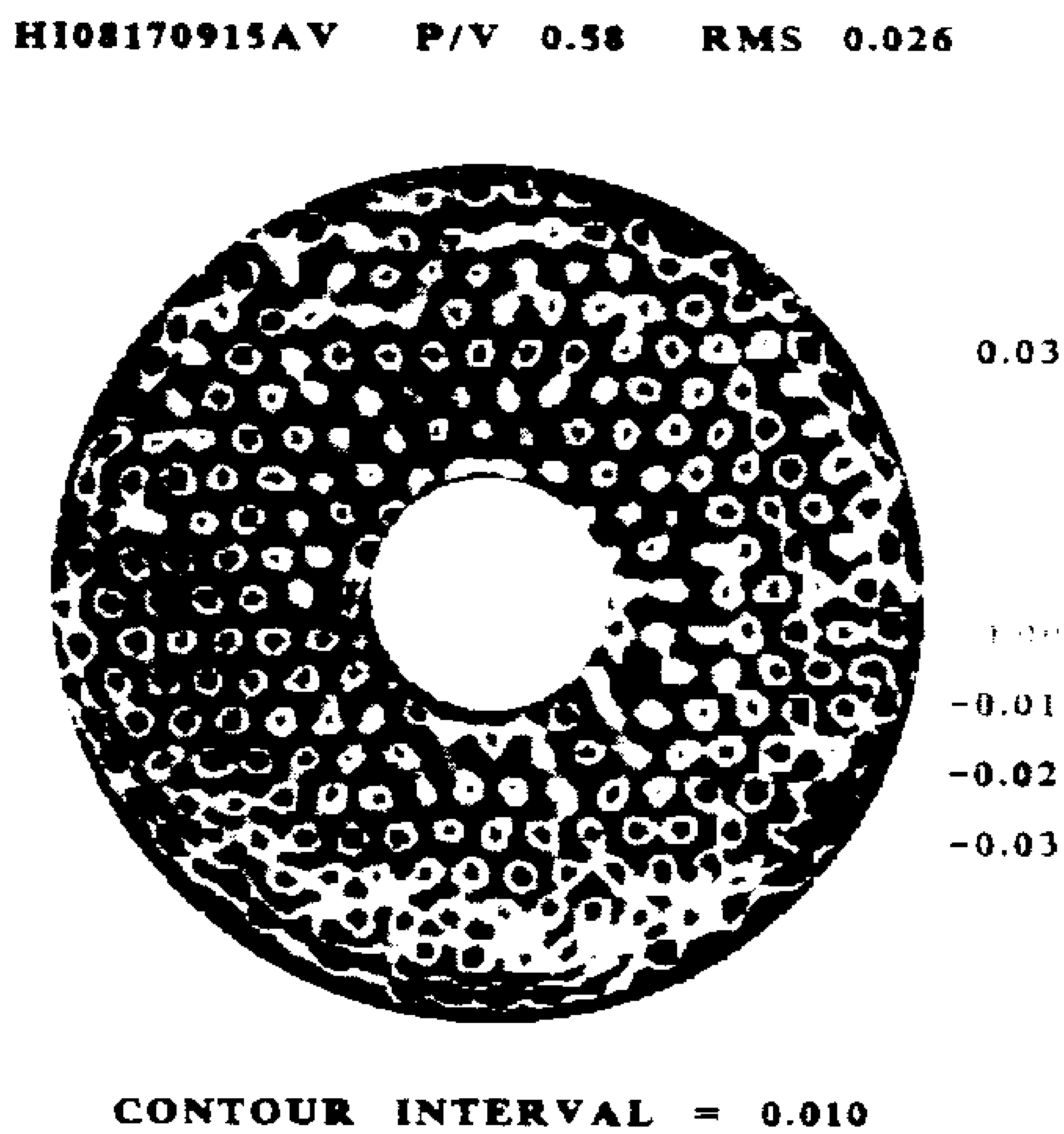

Figure 11. A contour map showing only surface errors of high spatial frequency. This map is from an early stage in figuring the 3.5-meter mirror, when high polishing pressures had created significant print-through.

The surface cross section display option is illustrated in Figure 12. The plane cut through the surface error map can be either vertical or horizontal, and it can be scrolled to the desired cut-through position. Cursor lines on the cross section display can be positioned by the operator to serve as calipers to measure the height of surface features. Examples of the uses of these three types of output by the opticians are described in a companion paper in this same proceedings[6].

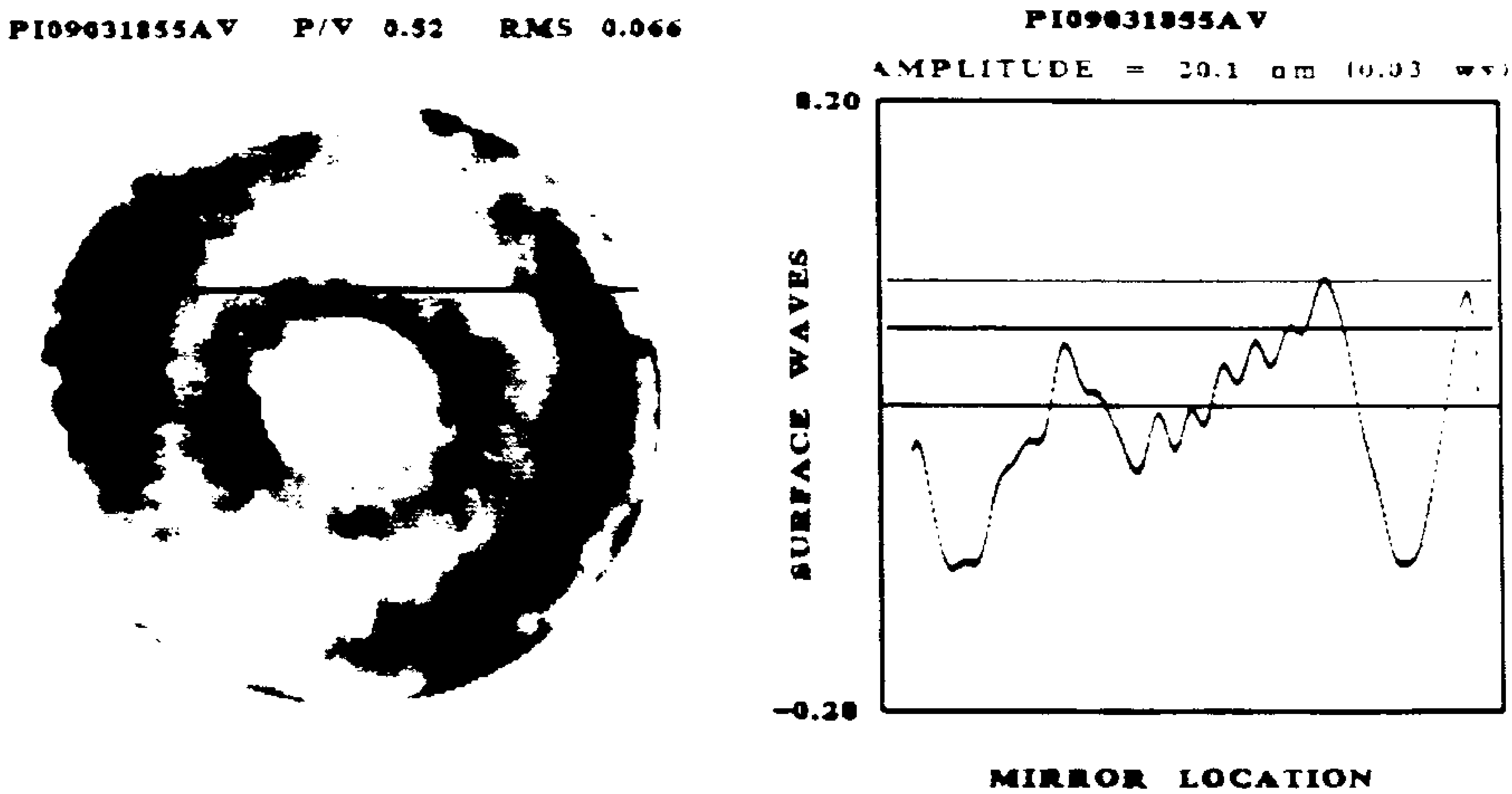

Figure 12. The cross section plot on the right is a cut through at the location of the line in the surface error map on the left. Adjustable cursor lines (the two horizontal lines above the centerline) allow quantification of the heights of surface features. The distance between the cursor lines is indicated at the top, in nanometers.

In recent years, some telescope projects have specified mirror surface quality with a structure function[7,8,9]. Figure 13 shows a structure function calculated from the (spherical) surface of the 3.5-meter mirror. To determine a point on the curve corresponding to a particular separation distance, our software calculates the RMS of the height differences between all pairs of points in the phase map at that separation, in twelve different directions (every 30 degrees).

4. FUTURE OPTICAL TEST DEVELOPMENT

At NOAO we try to continually look ahead, to anticipate upcoming testing requirements. As mentioned above, we are currently developing test methods that will be needed for the aspheric polishing of the 3.5-meter mirror. We are also taking advantage of the opportunity to develop figure sensing systems for the WIYN Telescope while the 3.5-meter mirror is spherical. Among the possible candidate tests are Hartmann-Shack, curvature sensing, and lateral shearing interferometry. In the telescope, each of these methods would use light from a star to test the aspheric optics of the telescope. An analogous situation exists in the optics shop when testing a spherical mirror with a light source at its center of curvature.

The Gemini 8-meter Telescopes Project presents other testing challenges. The primary mirrors will have a paraxial radius of curvature of 28.8 meters. This will make the control of vibration and seeing difficult. The aspheric departure of the f/1.8 primary mirrors will be more than 1200 microns. In a Hartmann test, the circle of least confusion of the reflected rays will be larger than available CCD chips. And, it will be difficult to test such large mirrors at three different orientations, for example zenith pointing, horizon pointing, and at a position in between.

Each Gemini Telescope will have three secondary mirrors. Their diameters range from 1.04 to 2.5 meters. A full sized Hindle sphere for testing these mirrors would be approximately 7 meters in diameter. The distance from the test equipment, at the position of the long conjugate of the hyperboloid, to the secondary mirror will be as much as 18 meters.

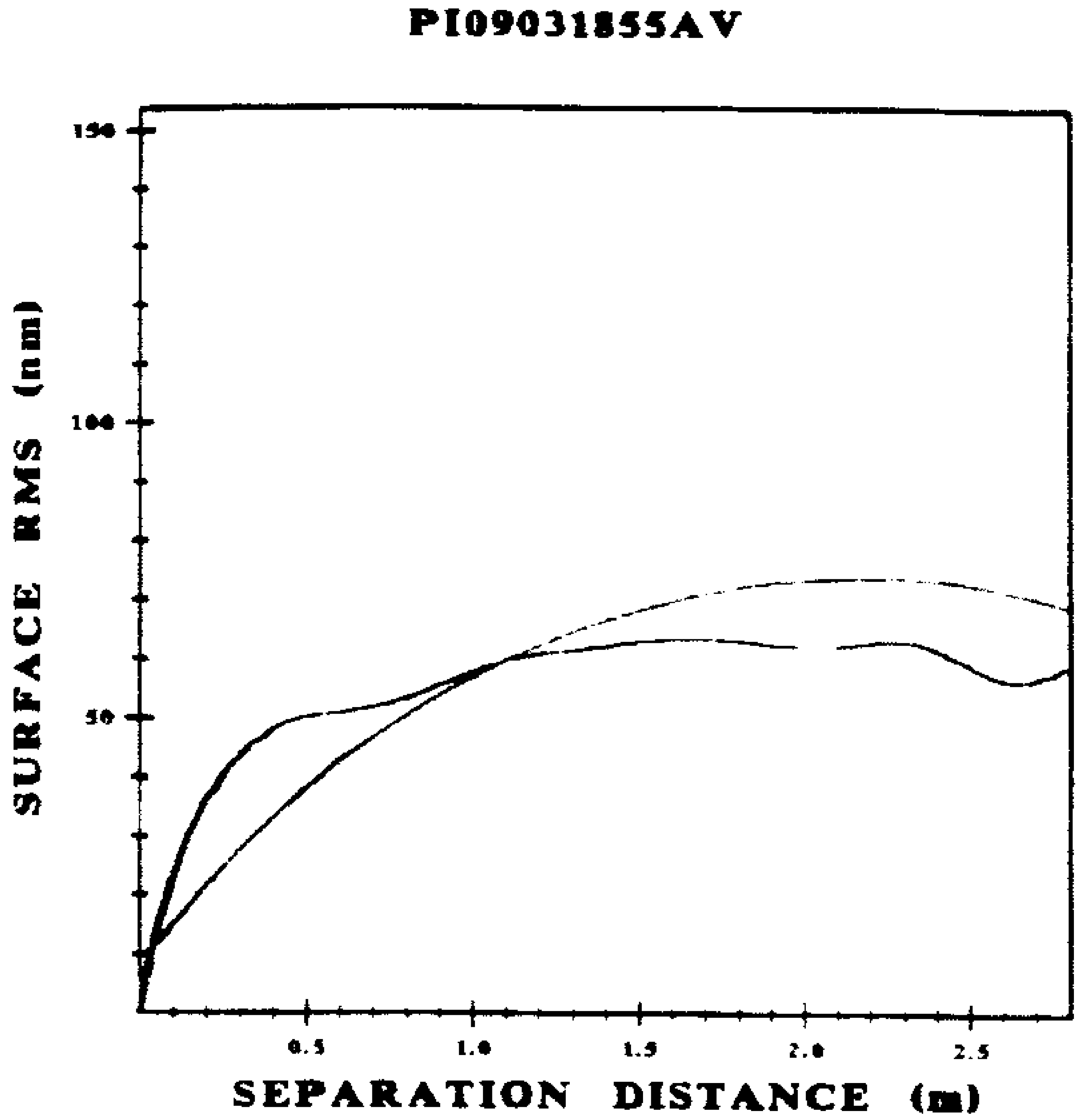

Figure 13. A measured structure function for the spherical 3.5-meter mirror surface. The smooth curve is the WIYN Telescope specification for the finished asphere.

Precise matching of radius of curvature and conic constant of the primary and secondary mirrors will be required. Surface figure measurements must be accurate to a few nanometers, with a spatial resolution of one to two centimeters. And a test must be developed to evaluate the surface finish by measuring scattered light. To meet these testing challenges we will work with commercial test equipment manufacturers, try to stay informed about large optics testing at other scientific facilities, and continue our own program of testing development.

5. ACKNOWLEDGEMENTS

We would like to thank the members of the Advanced Optical Telescope Technology program who have helped develop the testing methods described in this paper: Dave Dryden, John Fox, Charles Harmer, Bob Harris, Ron Harris, Larry Junco, Ming Liang, Lee Macomber, and John Richardson. We would also like to thank Chris Koliopoulos for helpful suggestions, and Claude Roddier for continued improvements in the interferogram-reduction software.

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