LASER INTERFEROMETER GRAVITATIONAL WAVE OBSERVATORY
- LIGO -
CALIFORNIA INSTITUTE OF TECHNOLOGY
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Comparative Results from Pathfinder Polishing

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1 PURPOSE

This document summarizes and compares the performance achieved by the various contractors during the polishing portion of the Pathfinder Technology development program. The Purpose of the Pathfinder program is to determine the current state of the art in substrate polishing and metrology. This information is then incorporated in the LIGO specifications for polishing of Core Optic Components (COC) which are used in the LIGO interferometers.

Of the four vendors contracted to do polishing for the Pathfinder demonstration, three produced substrates which indicate that the LIGO specifications can be met repeatably. There were instances for all polishers where one of the surfaces was "out of spec". This was in most cases well understood and due to a time constraint which would not allow for re-polishing.

2 ACRONYMS

COC	Core Optic Component
CSIRO	Commonwealth Scientific and Industrial Research Organisation
GO	General Optics
HDOS	Hughes Danbury Optical Systems
LIGO	Laser Interferometer Gravitational Wave Observatory
REO	Research Electro Optics

3 REFERENCES

Polishing Specification, Pathfinder	LIGO-E950104-00-D
Technical Specifications Pathfinder Substrate	LIGO-E950012-00-D
CSIRO/Pathfinder Surface Metrology (Kells)	LIGO-C961846-00-D
HDOS/Pathfinder Surface Metrology (Kells)	LIGO-C961845-00-D
Final Report by CSIRO to LIGO (CSIRO)	LIGO-C960511-00-D
LIGO Pathfinder Optics Data Review (HDOS)	LIGO-C960674-00-D

4 GOALS

Phase maps from the Calflat mirror, polished by HDOS, are the baseline surfaces used in FFT modeling of LIGO performance. The Calflat was known, at the time, to be an example of the state of the art in polishing and the specifications for Pathfinder were based loosely on the Calflat mirror. These specifica-

The specifications which went to vendors with full metrology contained surface requirements which were broken into three spatial frequency bands. Surface Figure, Surface Errors and High Spatial Frequency Band. The specifications which went to the Superpolishers did not contain the Surface Errors section. There was also a much tighter (1Angstrom vs. 4 Angstrom) microroughness requirement for the Superpolishers. In all other areas the specifications were identical.

Through the course of the Pathfinder program a few problems were found with the way the specifications had been written. There were no scratch or dig requirements. There was no method called out for evaluating the polish on the bevels and sides. The frequency bands which were covered by the Surface Figure, Error and Microroughness requirements were based on bands covered by 'typical' instruments and had no basis in the LIGO requirement. This created problems for vendors who had different versions of the measurement equipment.

5 PERFORMANCE

5.1. Commonwealth Scientific and Industrial Research Organization

5.1.1. Process

CSIRO completed polishing of four surfaces using a teflon lap technique. The substrate is first polished on pitch to bring it to within one wave of the final figure, then put on a teflon lap for a matter of a few hours. This polishing technique allows for only one substrate to be polished at a time. However, due to the inherent nature of the teflon lap, once the polishing parameters are understood, each substrate coming off that lap will have the same characteristics. The figure of the two curves polished by CSIRO on the large polisher were essentially the same to within 7 nanometers peak to valley.

During polishing of the second curved surface the lap developed a defective area; as a result the curved surface of SN 002 had a number of sleeks after polishing. Since there was not time left in the program to re-condition the large lap, the second curve was finished on a smaller diameter lap. The smaller lap is known to produce radial zones when polishing a substrate this large. These zones can be seen in the CSIRO metrology. CSIRO included phase map data from the large lap polish of SN002 to demonstrate the reproducibility of the teflon technique.

5.1.2. Performance

CSIRO completed the polishing of the Pathfinder substrates within the LIGO specification. Polishing performance as measured by CSIRO can be found in section 5.3 of the CSIRO final report. Performance as compared to other vendors can be found in section 6 of this document. The polishing at CSIRO was accomplished on schedule and within the production budget. The contract management budget was exceeded by 13 person-days due to an underestimate of commitment of personnel to the review meetings.

5.1.3. Metrology

The CSIRO metrology was found to be acceptable for the purposes of generating LIGO substrates. The metrology was performed using a 15cm aperture WYKO for the surface profile measurements. Although this aperture was smaller than that required by the specification (20cm) it was agreed that this would be acceptable for use during pathfinder. CSIRO demonstrated the quality of the substrates out to the required 20 cm diameter by providing phase maps which were offset from center. CSIRO also performed a 3 flat test using SN 006 as one of the flats. This test provides absolute data along one cross sectional line of the substrate

For surface roughness measurements CSIRO used a TOPO interference microscope with a 3D head and 40X magnification. In this configuration the measurements did not fully span the spatial frequency range required by the LIGO specification. The data gathered on the substrate surfaces for Pathfinder using this instrument are thought to be near the noise floor of the instrument. CSIRO would need to improve upon this measurement technique or demonstrate a capability to read at or below 2 Angstroms for the LIGO production work.

5.2. General Optics

5.2.1. Process

General Optics uses a proprietary super polishing technique into which LIGO has no visibility. The substrates are polished one at a time on pitch. This process makes repeatability a matter of timing. Since pitch and grit are always changing the rate of figure and smoothness change must be controlled such that they both reach the optimum values at the same time.

5.2.2. Performance

Six surfaces were polished at GO during Pathfinder, four or five of these would be acceptable for use within LIGO. GO polished one piece for submission to the Pathfinder program. LIGO later had two other blanks polished at GO which were to be used as test spares in the laboratory. Upon the discovery that the first polish done by GO had been measured at NIST to be the best surface of all pathfinder optics, the other two were sent immediately to NIST. In all, two of the six surfaces were less than perfect, but still quite close to the LIGO specification. A review of the phase maps generated at GO showed that evidence was present in their own metrology which indicated that these surfaces could have used more polishing. This information has been shared at GO and has created a new awareness within the company of the level of their metrology. Performance as compared to other vendors can be found in section 6 of this document.

5.3. Hughes Danbury Optical Systems

5.3.1. Process

HDOS uses a conventional large polisher with a pitch lap for LIGO substrates. This lap can accommodate two LIGO substrates at a time. The substrates were on the lap for roughly two weeks during figuring. Initial polishing on the large lap left the curved surfaces of the substrates outside the Surface Error specification for the central eight centimeters. Due to schedule constraints the curves were "hand hit" in an effort to bring them within specification in this central area. No attempt was made at supersmoothing.

5.3.2. Performance

HDOS completed the polishing of the Pathfinder substrates at the level of the LIGO specification for Surface Errors over the full 20 cm diameter aperture. HDOS asserted that, given more time, they could have produced substrates which were within the tighter central specification. Polishing performance as measured by HDOS can be found in the HDOS final review presentation. Performance as compared to other vendors can be found in section 6 of this document.

HDOS experienced significant schedule delays because the interferometer they had planned on using for the Pathfinder work had been dedicated to another program. LIGO was roughly three months behind the planned schedule for placing the polishing order. Once the order was placed HDOS went about procuring a new interferometer, this had to be set-up and calibrated. In all, the procurement of the new equipment extended the schedule by roughly four months over the originally planned four month duration. HDOS was notified by LIGO that the substrates were due at NIST and that HDOS would have a month to finish the polishing. HDOS delivered the substrates to NIST as requested.

The extended schedule did impact the overall cost, although not in direct proportion to the schedule over run. HDOS estimated a 20% over run and has invoiced 17% over the initial contract value.

5.3.3. Metrology

HDOS metrology was found to be acceptable for the purposes of generating LIGO substrates. HDOS used a Zygo Mark GPI Fizeau phase shifting interferometer with beam expansion to a 30 cm aperture. HDOS presented an extensive error analysis during the final review. Parts of this presentation are proprietary and are not included in this distribution. The proprietary section covers the theory of how data files are manipulated to obtain an absolute calibration of the system.

Microroughness was measured using a TOPO microscope phase shifting interferometer. Measurements were taken with both the 2.5X and the 20X objective, spanning the specified spatial frequency range. The microroughness was found to be at or slightly above the level of the specification.

5.4. Research Electro Optics

5.4.1. Process

REO also uses a proprietary superpolishing technique. It appears, from the results of NIST metrology, that the lap size it too small to accommodate an optic the size of a LIGO test mass.

5.4.2. Performance

Neither surface of the REO substrate would qualify as a LIGO Core optic. REO delivered their piece 11 months behind schedule.

6 COMPARATIVE METROLOGY

6.1. Surface Figure and Surface Errors

Figure 1 shows the Power Spectral Density (PSD) for the initial set of Pathfinder substrates measured at NIST. The curved surface polished by General Optics was the best of the group. All of these substrates nominally meet the specification except for the two HDOS surfaces which do not meet the Surface Error specification over the central 8 cm diameter region.

Several Zernike terms are removed in this analysis because it is believed that there is an instrumental artifact in the NIST data which adds spherical aberra-

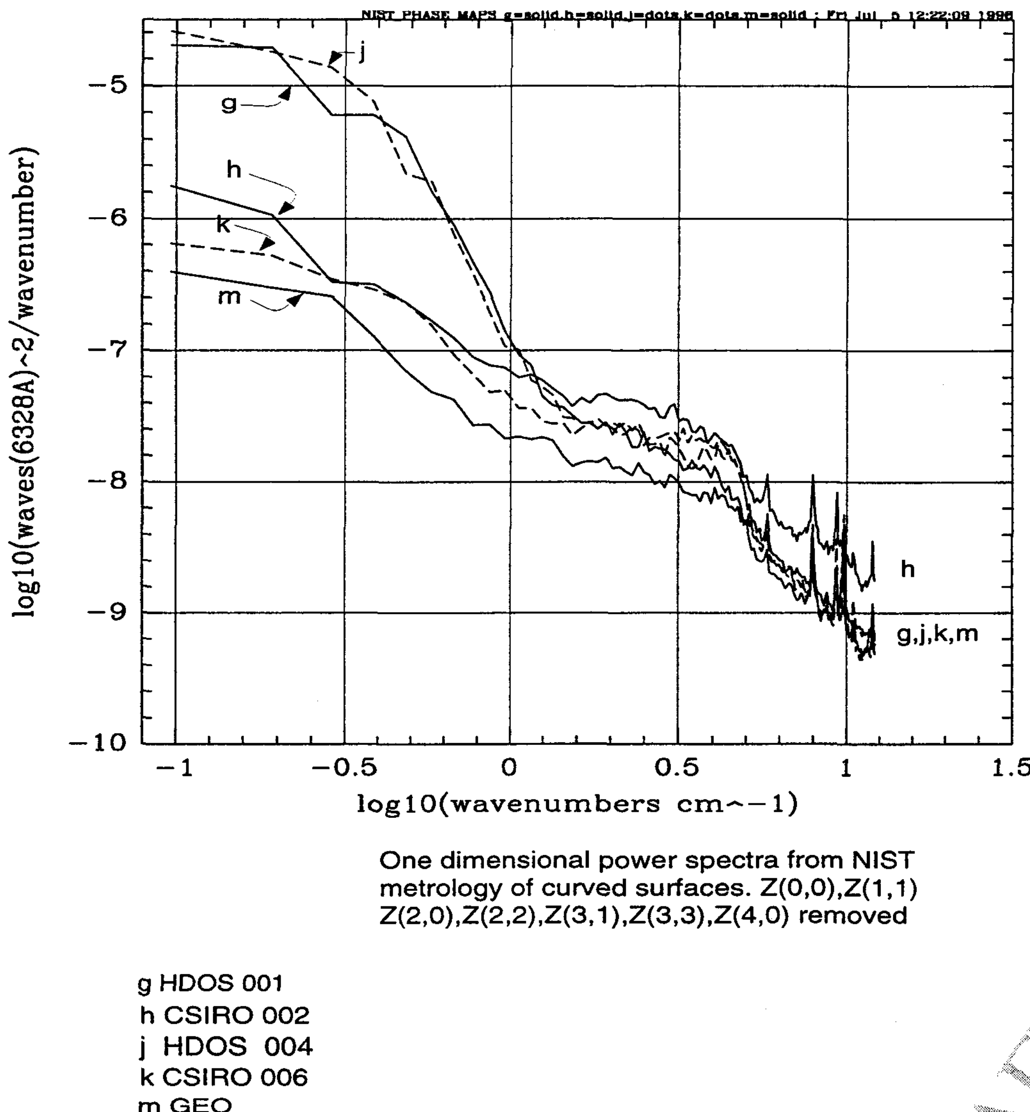


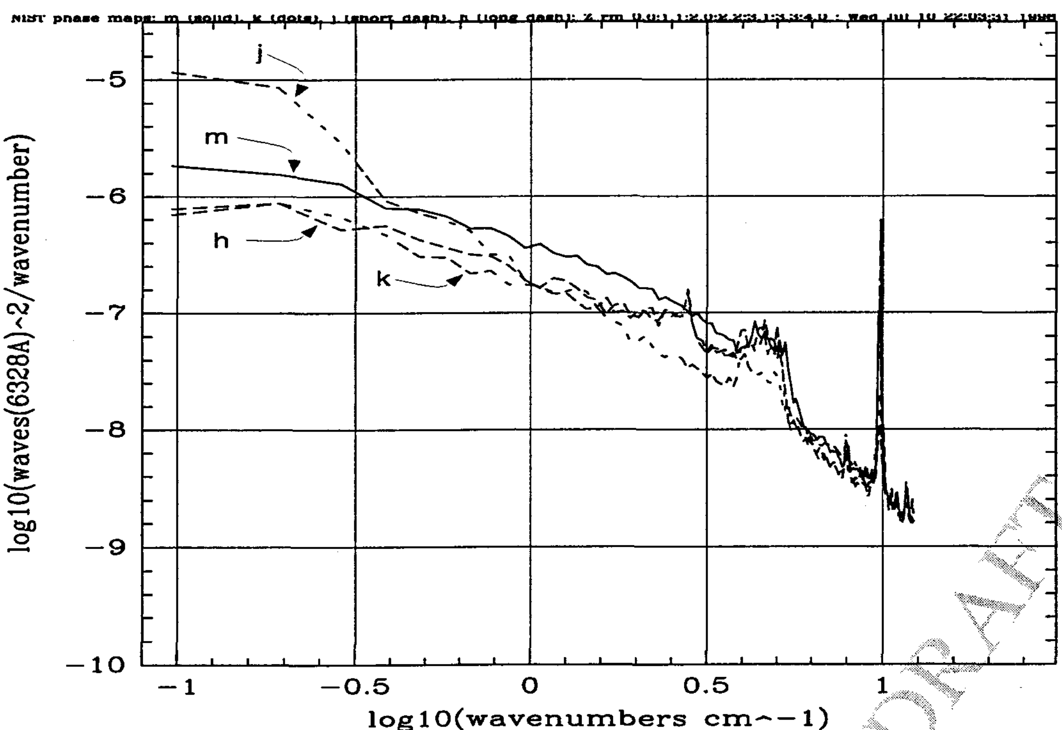
Figure 1: Comparison of Curved surfaces as measured at NIST.

tion to the curved surfaces. The data at higher frequency (above ~ 6 cm^{-1}) may be suspect since all but one start to look very similar. Being at high frequency this does not contribute significantly to the rms for any substrate. There is good agreement on measurement of the curves between NIST and HDOS and between NIST and CSIRO except that the CSIRO data drops below the NIST data at high frequency. For more information about the vendor and NIST comparisons please see "CSIRO/Pathfinder Surface Metrology (Kells), LIGO-

C961846-00-D" and "HDOS/Pathfinder Surface Metrology (Kells), LIGO-C961845-00-D"

The measurement of the flat surfaces at NIST (Figure 2) is slightly suspect. There are features at 0.7 and 1 on the x axis which are measurement artifacts. If these are, as suspected, due to vibration of the interferometer then there could be an overall increase in the amplitude of these data. Both CSIRO and HDOS reported doing better on the flat surfaces than on the curves. A comparison of Figures 1 and 2 does not show this, another reason to be skeptical of the NIST data on the flat surfaces. It was also noted in the graphic of the phase map from the GO piece that there appear to be fringes present, making this measurement, in particular, suspect.

Although the absolute scale may be suspect there are some interesting things to be seen from the shape of the flat surface PSDs. The PSD for the HDOS flat surface is seen to have less slope at the lower frequencies than the PSDs for the curves. This indicates that the "hand hitting" done on the curves does indeed



All spectra derived from phase maps with Z(0,0),Z(1,1),Z(2,0),Z(2,2),Z(3,1) Z(3,3),Z(4,0) removed

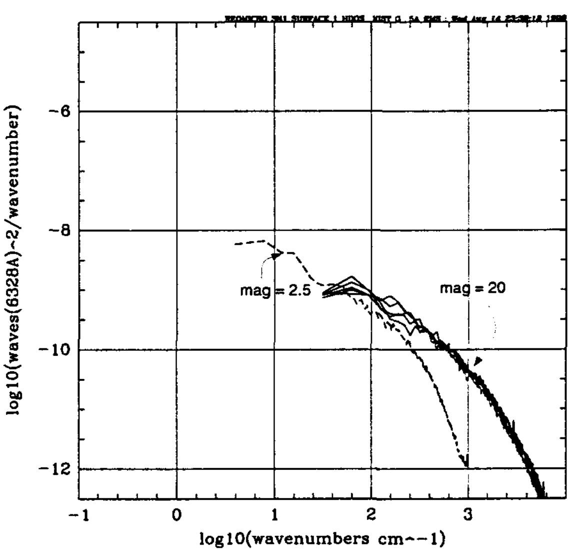
h = long dash = CSIRO surface 2 #2
j = short dash = HDOS serial04 side 2
k = dots = CSIRO surface 2 #6
m = solid = GO

Figure 2: Comparison of Flat surfaces as measured at NIST

increase the surface amplitude variations at low frequency. This also adds credence to their claim that more time on the large lap might have brought the surfaces to within the specification. The CSIRO flats are also shown to be quite similar, demonstrating the claim of repeatability which was compromised by the necessity of polishing the SN 002 curve on a smaller lap.

6.2. Microroughness

Figures 3, 4 and 5 show the microroughness, as measured at REO. The measurements of the HDOS, CSIRO, and GO substrates are shown respectively. Each plot shows the several measurements which were taken at different locations on each surface. While CSIRO does slightly better than HDOS, it is clear overall that the GO process provided a much smoother surface. The odd shape of the GO curves is attributed to roll off of the instrument. It should be noted that HDOS did not, due to schedule, make any attempt at supersmoothing. CSIRO was within the spec by 25 to 30 percent and was not aware that smoother surfaces would be of interest to LIGO.



FILES:
111,112,113,114,115,116

sn1 surface 1 HDOS NIST G 3A rms

Figure 3: REO measurement of HDOS microroughness

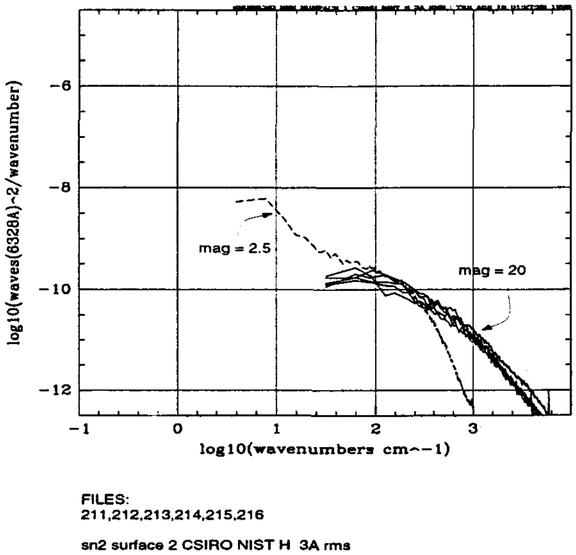


Figure 4: REO measurement of CSIRO microroughness

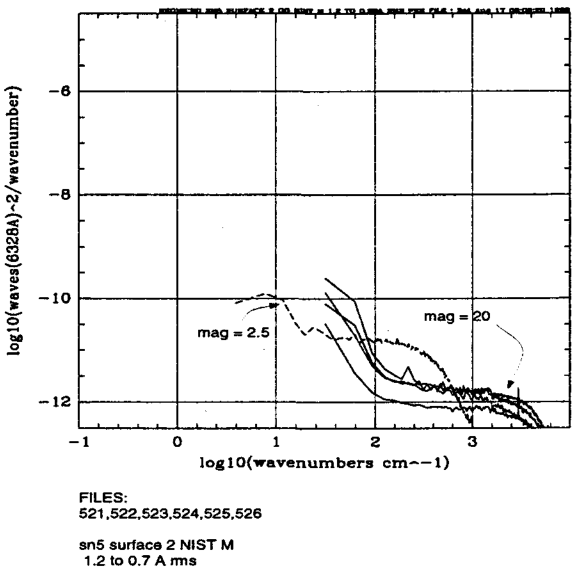


Figure 5: REO measurement of GO microroughness

7 SUMMARY

Overall, the substrate polished by GO was superior to the others. Of the two remaining, CSIRO did the better job at polishing. It is not known how much better HDOS could have done had they been given more time. The Calflat data implies that they have, at least once, polished to the level of our central 8 cm Surface Error requirements. Of all the metrology performed during this program the HDOS metrology had the fewest anomalies. All metrology was found to be sufficient for our purposes.