CHAPTER 11

CONCLUSIONS

"I never think of the future, it comes soon enough"
A Einstein

11.1 CONCLUSIONS

1 The first conclusion must be that the instrument works, and meets its design criteria, namely to offer: improved accuracy calibrations of length bars over 100 mm with an easy to use interface, measurement of flatness and variation of measurement faces, and measurement of thermal expansion.

2 The spread in the measurements and deviations from the results of other instruments are within the uncertainty budgets of the instruments concerned.

3 The extra option for double-ended measurement offers potential for measurement of length bars without wringing.

4 The automation of the instrument not only reduces the required skill level of potential operators, but has the advantages of an objective measurement compared to the subjective measurement of instruments requiring manual operation.

5 It is therefore hoped that this instrument may be commercialised. This will complete the cycle of development of measurement techniques noted in § 1.3.7, bringing a new level of accuracy to commercial measurements and initiating the search for the next level of measurement accuracy which will be required from national standards laboratories in the future.

6 A particularly useful feature of the instrument is the ability to measure not only length bars, but also gauge blocks, allowing comparison with other instruments such as the Gauge Block Interferometer and the Gauge Block Dilatometer which is being developed.

7 Apart from the lower accuracy measurements of bar diameter and straightness which are measured using calibrated micrometers, the interferometer can be used to measure all the dimensional aspects of length bars, according to the relevant standards.

8 A single measurement on the interferometer takes under 2 minutes to complete, and gives not only length measurement, but also flatness and parallelism. This compares favourably will the 30 minutes to perform a measurement on the Kösters-Zeiss (length of one bar per loading), or approximately 3 minutes for the NPL Length Bar Machine (central length only, 5 bars per loading, with larger uncertainty).

9 Thermal expansion measurements can be performed in one week, with measurements at 5 temperatures over the range 20 °C - 30 °C.

10 The ability to leave the interferometer running, making repeated measurements gives increased confidence in the results obtained, because of the small spread in the results.

11 One important factor throughout the whole of the interferometer design has been the small source size, and accuracy of placing the source on the axis of the interferometer. The alignment inaccuracy is one of the drawbacks of the Length Bar Machine, which has a smaller laser beam which is not so easy to align, since no large field interference pattern can be viewed, nor a return spot smaller than 2 - 3 mm diameter. The small source size of the interferometer is also important for the coherence exhibited by the interferometer, particularly in double-ended mode, and for the good fringe contrast at large path differences and the good depth of focus.

12 This work has shown that it is possible to combine multiple-wavelength interferometry with phase-stepping interferometry over long path lengths to achieve accurate length measurement.

13 As shown in chapter 10, much of the measurement uncertainty is due to factors other than the multiple-wavelength phase-stepping interferometry which is a powerful technique which is theoretically capable of high accuracy measurement. With careful control and accurately known chosen wavelengths, it should be possible to build a three-wavelength interferometer with a multiple-wavelength repeat distance of up to 0.5 mm using the three wavelengths used in this work, accurate refractive index determination and fringe fraction measurement of better that ± 0.015 fringes over long path lengths.

11.2 PROPOSALS FOR IMPROVEMENTS

The measurement or calculation of refractive index is of vital importance to measurements of length made in the interferometer. There is no doubt that by operating in a vacuum, the problem of refractive index determination would be removed. A vacuum though poses other problems (as mentioned in chapters 3 & 7) and may not prove more accurate overall. Perhaps the best technique would be to incorporate a refractometer inside the interferometer, either simply inside the chamber, or directly in the measurement beam (as is the case in the Kösters-Zeiss). This would require further piping to allow evacuation of the refractometer cell inside the chamber, and possible reduction in the beam area available for measurements. One way of making sure of having a cell of well-determined length would be to use accurately measured length bars as dimensional structures in the refractometer, with accurately measured expansion coefficients. Rather than use quadrature fringe counting, which is prone to offset and gain errors, the fringe order of the refractometer could be determined approximately by Edlén calculations, and the fractional fringe order measured by phase-stepping interferometry.

For the ultimate accuracy, the Zeeman stabilised lasers could be replaced directly with iodine-stabilised lasers, with much better frequency stability, allowing a larger uncertainty in the initial estimate of the length of the bar. Adding another wavelength would also increase the allowable initial length uncertainty by extending the range of the multiple-wavelength technique. Alternatively, selecting a different wavelength may increase the range of the three-wavelength technique, though the laser would still have to be frequency-stabilised.

On a professional note, some of the optical mounts used in the interferometer are not fully kinematic. Before the instrument is commercialised it would be useful to design some proper kinematic mounts for the optics such as the beamsplitter and the collimator mirror which have repeatable positioning and are not over-constrained.

The choice of computer system was rather limited at the time of purchase, since only the IBM PC-compatible market had interface cards that were needed for the instrumentation, and a seemingly-suitable language for the programming. Given the choice at the present time, perhaps a more powerful computer would be chosen, either a Hewlett-Packard workstation or a top range Macintosh, such as a Quadra. These machines have no imposed 640 K memory restrictions and have very good programming languages and interfaces. For programming language, any well-structured, easy to read language will suffice - Pascal, C, or one of the better implementations of BASIC, such as HP Basic, so long as it can be used to drive the interfaces and access large arrays.

On the subject of thermal control, recent work at NPL on the Gauge Block Dilatometer has shown that individually controlled heating panels, using electric resistive heating can be used to control a small volume of air very uniformly. Perhaps this technique could be expanded to the scale of the PLBI thus decreasing temperature gradients even further. A disadvantage is the lack of cooling, so this would require a room at a temperature below 20 °C in order to be able to make measurements at temperatures below 20 °C or to stabilise under active control at 20 °C.

It would be useful to include more PRTs inside the chamber, particularly when measuring thermal expansions, to check temperature gradients along the bars. The data could enable finer adjustments to be made to the heating system (particularly in the case of individual panels, as described above) to decrease thermal gradients in the bars. This would require further channels on the Tinsley resistance bridge selector switch and longer measurement time, though once proper temperature uniformity had been achieved, only one or two PRTs would be needed for the measurement of temperature during a ‘real’ measurement.

Another possibility, which was considered at the design stage, would be to fill the chamber with a gas other than air. Nitrogen or helium are good candidates as they are both inert. Helium offers two advantages: it is less dense than air or nitrogen so its refractive index is less sensitive to pressure changes and it has approximately 6 times the thermal conductivity of air, which would result in lower temperature gradients and decreased stabilisation times. However accurate knowledge of the refractive index of helium would be required and it is difficult to use with many pressure transducers because its density is different to air (some transducers work by measuring density) and it would leak into any reference vacuum compartments found inside other transducers. Venting a chamber of helium to atmosphere after an experiment would be interesting for any observers in the room at the time!

In § 9.8 it was stated that the accuracy of the fringe fraction measurement is limited by the data fitting of the phase data on the platen surface in the case where the platen is not flat. This can be improved in two ways. Firstly, a 2nd order polynomial surface fitting should give a better result than the best fit plane and Chebychev techniques. Secondly, platens with flatter surfaces would allow more accurate data fitting, although there is the limitation that when bars are wrung to the platens, the wringing forces can distort the platen surface in attempting to reach closer contact with the bar. These effects have been observed when wringing gauge blocks, at PTB, Germany.

Although this thesis has presented some work on the use of double-ended interferometry, it must be remembered that this was designed as an add-on to the main interferometer and so could be improved. For instance, the use of a compensator plate would be of a great advantage to both the double-ended work and the mainstream use of the interferometer by removing the dispersive effects of the wedged beamsplitter and allowing almost perfect alignment of the reference beam to be maintained for different wavelengths. The collimated beam diameter was designed to be sufficient for single-ended measurement but is not really large enough for double-ended use. The double-ended analysis requires more data in the background region for more accurate data fitting. At present there is only a limited amount of data and the results are inaccurate. Increased spatial coherence is also needed to improve the fringe contrast in the background area (and on the rear face of the bar) to further decrease fringe fraction measurement errors. With better data, proper results for flatness and parallelism can be calculated.

Least-squares planes would be fitted to the phase data for each of the faces, to determine individual flatness and variation results. The images of the bar faces are both horizontally inverted in the camera image, *i.e.* each is the view one would obtain by eye, looking at each end of the bar separately, but flipped left-to-right. However, to compare the results so that mutual parallelism or variation may be measured, one phase map must be horizontally inverted. The parallelism would then be obtained as the sum of the two phase maps - the parallelism of the rear face with respect to the front face is already inverted because of the double-ended configuration, so the phase maps would be added rather than subtracted, to get mutual parallelism.

11.3 ACKNOWLEDGEMENTS

Firstly I would like to thank the Director of the National Physical Laboratory (where this work was performed) for allowing me to submit this work for my Doctorate thesis and for letting me study at Imperial College.

I am very grateful to my supervisors for their precious time and effort in seeing this work through to its conclusion. At NPL: David Pugh for his enthusiasm, knowledge and interest in this work; Keith Jackson for his knowledge, experience and humour. At Imperial College: Jonathan Maxwell for his time, observations and comments.

I would also like to acknowledge the craftsmen, designers and engineers of NPL's Engineering Services and Optical Workshop for turning my (somewhat unconventional) designs into reality - much of what the interferometer contains has been manufactured by them.

I am grateful to the staff of End Standards Section, NPL, for putting up with me 'going virtual' on Friday afternoons (and other times !) and laying claim to the Macintosh for hours at a time. I am also grateful to Ben Hughes and Richard Leach for the many discussions on aspects of this work and for the encouragement and enthusiasm of other colleagues at NPL. Thanks also to Dr Graham Peggs for the use of his scanner.

I would also like to put in a brief thank you to my friends from Cambridge and Leicester for their help and advice during my 3 years as a 'real' student.

Finally, the biggest thank you, for everything else, to my parents.

"Original ideas are exceedingly rare and the most that philosophers have done in the course of time is to erect a new combination of them"
G Sarton