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Absolute length measurement using multiple-wavelength phase-stepping interferometry

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ABSTRACT

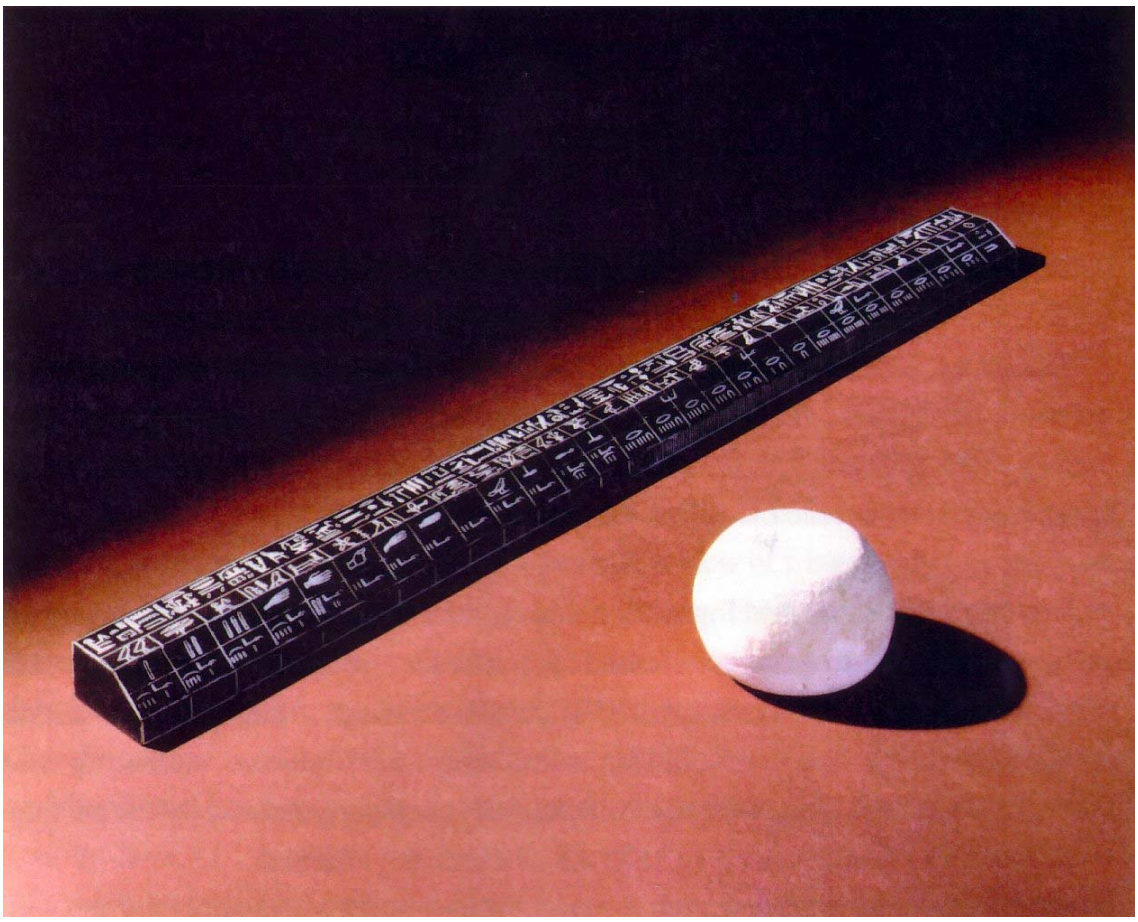
This thesis describes the design, construction, commissioning and testing of a new interferometer for the absolute measurement of length standards. The thesis starts with an introduction to the subject of length standards and length measurement by interferometry before considering various designs of interferometer. The design of the new interferometer is given in detail, including the operation of the lasers used as light sources. The alignment of the interferometer and the effects of incorrect alignment and collimation on the measured length are examined. A review of fringe analysis techniques is given, with an emphasis on phase-stepping algorithms. The 5-position algorithm used in the new interferometer is examined in more detail together with the phase-stepping actuator and its advantages over other devices. The data processing of images digitised in the interferometer is described, including the techniques developed for discontinuity removal and surface fitting. The measurement of the flatness and parallelism of the measuring faces of the length standards is described. The automated method of exact fractions is used to combine phase measurements at three wavelengths to allow accurate calculation of the length of the measured object, with a larger range than one or two-wavelength techniques. The techniques used for compensating for the refractive index of the air inside the interferometer chamber are summarised, with a comparison of calculated and directly-measured refractive index values, measured with a specially constructed refractometer. The thermal control of the interferometer is presented, including the use of the instrument to measure the thermal expansion coefficient of length standards, by measuring their lengths at different temperatures. Example results of length, flatness, parallelism, and thermal expansion are given for various sizes of length standard. A full uncertainty budget is calculated, allowing critical examination of the performance of the instrument. A chapter on conclusions is followed by several appendices.

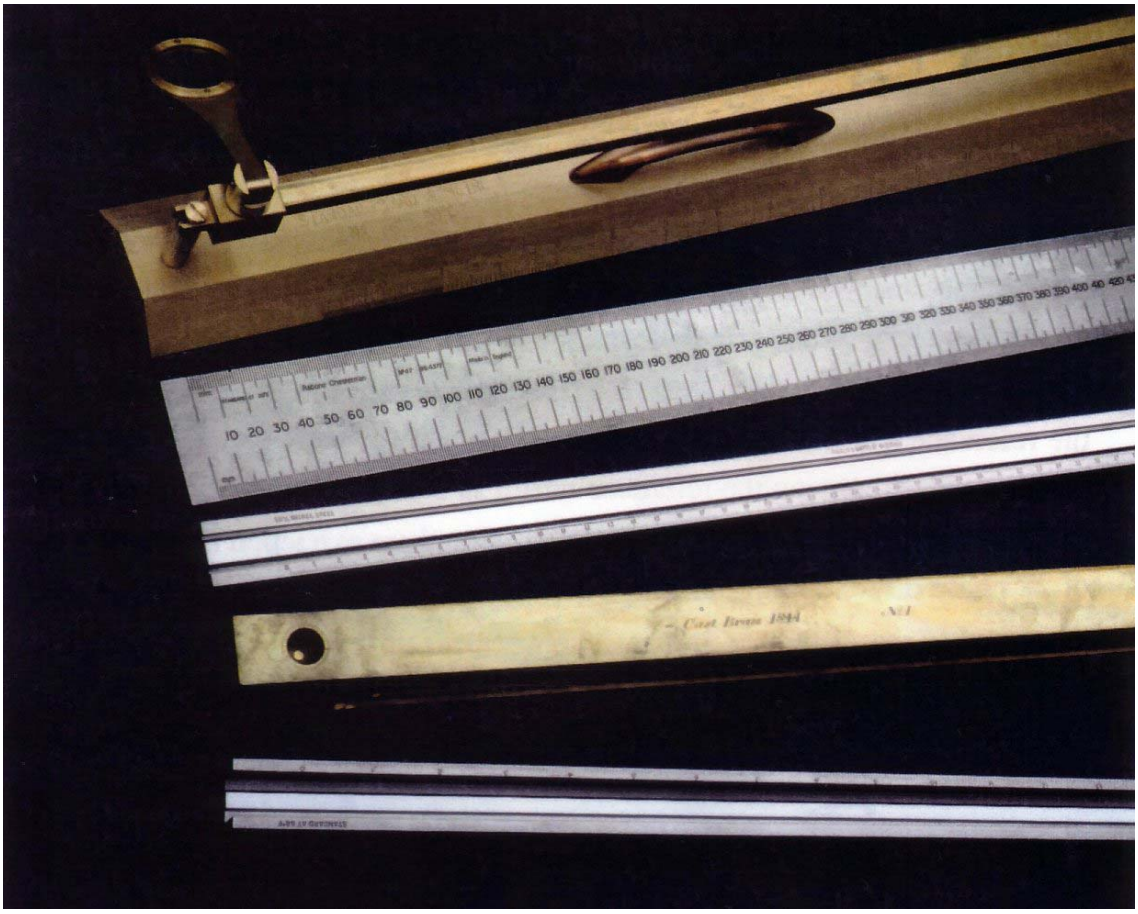
PREFACE

This thesis describes the design, construction, commissioning and testing of a new multiple-wavelength phase-stepping interferometer for the measurement of length bars. This interferometer is called the NPL National Primary Length Bar Interferometer, or Primary Length Bar Interferometer (PLBI) for short. The instrument was designed and built at the National Physical Laboratory (NPL), Teddington. NPL was founded in 1900 and is the focus for the UK's National Measurement System.

The PLBI has been developed as a link between the realisation of the metre as a wavelength of a frequency-stabilised laser and the use of secondary length standards known as length bars, which are used as transfer standards to calibrate other standards or to verify the performance of instruments such as co-ordinate measuring machines (CMMs). The operation of the PLBI is described in a paper published by the author, which is reproduced in Appendix F (p 317). An overview is given here.

The PLBI is an interferometer of a modified Twyman-Green design, which measures the length of a bar in terms of the wavelength of the light emitted by calibrated frequency-stabilised lasers. The length, L, is calculated from the equation $L = (n + f)\lambda / 2$ where n is an integer (fringe order) and f is a fraction. In the interferometer, f is measured as a fringe fraction but n is initially unknown. The PLBI uses 3 wavelengths and measures a fringe fraction for each wavelength. The method of exact fractions is used to combine these 3 fractions with an estimate for L (within ± 9 μm) to calculate L more accurately. In order to measure the fringe fractions with sufficient accuracy, Phase Stepping Interferometry is used to measure the fractions in terms of the phase difference between the reference and measurement beams. A 5-position phase-stepping algorithm is used which involves moving the reference mirror in 5 steps of size $\lambda/8$ for each wavelength and digitising the image at each step. Point-wise phase extraction is followed by removal of 2π phase discontinuities at fringe boundaries. After tilt removal, fringe fractions are measured as the difference in phase between pixels at the centre of the bar and those corresponding to the platen surface, in the 3 phase maps.





Egyptian Cubit (& mass standard) and more modern line standards of length

To my parents ...

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