Contents

List of Figures ix
List of Tables xiii
List of Symbols xv

I Introduction 1
1 Scope of this Work and Summary of Results 3

II Groundwork: ‘Identifying the Problem’ 7
2 State of the Art 9
2.1 Interferometry 9
  2.1.1 Measurement Principle 9
  2.1.2 Sample Implementations 11
2.2 Deflectometry 12
  2.2.1 Measurement Principle 13
  2.2.2 Sample Implementations 16

3 Comparative Assessment 21
3.1 Information Theory as Classification Criterion 21
3.2 Analysis of Probing Mechanisms 22
  3.2.1 Primary Measurand of Interferometry 22
  3.2.2 Primary Measurand of Deflectometry 23
  3.2.3 Etalons 25
  3.2.4 Summary of Probing Mechanisms 25
3.3 Fundamental Considerations 26
  3.3.1 Information Theoretical Aspects of the Source Encoding 26
  3.3.2 Types of Errors 28
  3.3.3 Random Errors in Interferometry: Phase Noise 29
  3.3.4 Random Errors in Deflectometry: Uncertainty Relations 29
  3.3.5 Semi-Random Errors: Coherence and Speckle Contrast 34
  3.3.6 Semi-Random Errors: Quantization, Linearity and Phase Shift 38
    Quantization Errors 38
    Signal Nonlinearities 40
    Phase Step Errors 40
  3.3.7 Systematic Errors: Retrace Error and Object Position 41
  3.3.8 Systematic Errors: Reference and Null Test 42
  3.3.9 Local vs. Global Accuracy 43
  3.3.10 Sensitivity to Disturbing Environmental Influences 44
    Contamination and Partial System Damage 45
Fluctuations of the Environmental Conditions .................. 45
Vibrations ......................................................... 46
Conclusion .......................................................... 47

3.3.11 Angular Dynamical Range: The Aperture Problem .......... 47

3.4 Summary: Strengths and Weaknesses .......................... 49

4 Limitations of Classical Deflectometry .......................... 51
4.1 Types of Limitations .......................................... 51
4.2 Principal Limitations .......................................... 52
4.2.1 Types Of Objects ........................................... 52
Surface Properties ............................................... 52
Shape ............................................................... 54
Transparency ...................................................... 54
4.2.2 Measurement Accuracy ..................................... 55
4.3 Technical Limitations ......................................... 55
4.3.1 Measurement Range ......................................... 56
4.3.2 Efficiency .................................................. 56
4.3.3 Environmental Conditions ................................ 56
4.3.4 Usability .................................................... 57
4.4 Summary of Critical Limitations ................................ 57

III Advanced Methods: 'Attacking the Problem' .................. 59

5 Back Side Reflex .................................................. 61
5.1 Problem Definition and Analysis ................................ 61
5.1.1 Statement of the Problem .................................. 61
5.1.2 Mathematical Model ........................................ 62
Coherence ......................................................... 62
Signal Definition and Mindset .................................... 62
Some Notational Issues ........................................... 63
Mathematical Structure of the Signal ............................. 63
Transition to a Complex Notation ................................. 64
Comparison with Interferometry .................................. 65
5.1.3 Quantification of the Effect ................................ 65
5.1.4 Assessment of the Severity ................................ 67
5.2 Possible Solutions ............................................. 68
5.2.1 Starting Points .............................................. 68
Observation Aperture ............................................. 68
Signal Modulation ................................................ 69
5.2.2 Existing Solutions and Approaches ....................... 69
5.2.3 Solution Categories ........................................ 71
Signal Suppression ................................................. 71
Signal Separation prior to Recording ............................. 71
Signal Separation after Recording ............................... 72
5.3 Algorithmic Solution .......................................... 73
5.3.1 Principle of the Multifrequency Technique ................. 73
5.3.2 Brute Force Evaluation ..................................... 75
5.3.3 Pattern Coordinate as a Frequency ......................... 77
5.3.4 Evaluation Options .................................................. 79
Fourier Approach: Periodogram Estimator .......................... 79
Criteria to classify the Problem ........................................ 81
Iterative Fit on a Refined Model ....................................... 82
Phase Slope Fit ........................................................... 84
5.3.5 Pathological Lines ................................................... 87
Local Ill-Conditioning .................................................... 87
Geometrical Considerations ............................................ 88
5.3.6 Results of the Algorithmic Solutions ........................... 91
5.4 Line-Shift-Deflectometry ............................................. 93
5.4.1 Measurement Principle ............................................ 94
5.4.2 Fundamental Limits ............................................... 95
Modeling the Signal Generation ...................................... 97
Derivation of the Uncertainty Relation ............................... 100
Summary and Appraisal .................................................. 104
5.4.3 Technological Limitations ........................................ 105
5.4.4 Information Efficiency ............................................ 109
5.4.5 Pathological Lines ................................................ 110
5.4.6 Final Assessment ................................................... 113
5.5 UV-Deflectometry ..................................................... 116
5.5.1 Measurement Principle ............................................ 116
5.5.2 Technical Realization ............................................. 117
Light Source .............................................................. 117
Camera .................................................................. 117
Pattern Generation ...................................................... 118
Axis System .............................................................. 119
Mask Layout ............................................................. 120
Base Frame ............................................................... 121
5.5.3 Measurement Examples ........................................... 121
5.6 Final Assessment of the Back Side Reflex ....................... 125
6 Measurement Accuracy ................................................ 127
6.1 Local and Global Accuracy ......................................... 127
6.1.1 Error Distribution in Fourier Space ........................... 128
6.1.2 Impact of Correlated Errors on the Global Accuracy ....... 129
6.2 System Calibration .................................................... 132
6.2.1 Prior Art Calibration Procedure ................................. 132
6.2.2 Shortcomings of the Existing Concept ......................... 134
6.2.3 New Holistic Calibration Approach ............................ 135
6.3 Further Systematic Errors .......................................... 140
6.3.1 Geometrical Errors due to an Inadequate Model ............ 140
Shape Distortion of the Circle of Confusion ....................... 140
Image Shift .............................................................. 142
6.3.2 Angular Dependence of the Linearity of the Screen Luminance .... 143
6.3.3 Phase-related Wavelike Artifacts .............................. 145
6.4 Improvements ......................................................... 146
6.4.1 Results of the New Calibration Approach .................... 146
6.4.2 Suppression of Wavelike Artifacts by the Multifrequency Method .... 148
6.5 Final Assessment regarding Measurement Accuracy .......... 150