Contents

1. Introduction **1**

1.1. Motivation and scope . . . 2
1.2. Background . . . 4
1.3. Research approach . . . 15
1.3.1. Objectives . . . 15
1.3.2. Methodology . . . 16

2. Orbit dynamics and force modelling **19**

2.1. Numerical integration of the equations of motion . . . 20
2.1.1. Prediction . . . 21
2.1.2. Correction . . . 22
2.1.3. Stepsize control . . . 22
2.1.4. Initialization . . . 23
2.1.5. Interpolation . . . 24
2.1.6. Integrator optimization . . . 25
2.2. Coordinate and time systems . . . 26
2.3. Gravitational perturbations . . . 30
2.3.1. Non-spherical geopotential of the Earth . . . 31
2.3.2. Third body gravitational perturbations . . . 35
2.3.3. Tides . . . 36
2.4. Non-gravitational perturbations . . . 38
2.4.1. Atmospheric drag . . . 38
2.4.2. Solar radiation pressure . . . 40
2.4.3. Earth radiation pressure . . . 44

3. Estimation techniques **49**

3.1. Uncertainty propagation . . . 49
3.2. State space representation . . . 50
3.3. The covariance matrix . . . 53
3.4. Differential correction . . . 53
3.4.1. Non-linear least squares . . . 54
3.4.2. Levenberg-Marquardt algorithm . . . 55
3.4.3. Propagation using the State Transition Matrix . . . 57
3.4.4. Process noise . . . 58
3.4.5. Integration example: Neptune . . . 62

4. Methods providing orbit information of predetermined bounded accuracy 65
4.1. Pre-considerations and method requirements . . . 65
4.1.1. Accuracy, precision and trueness . . . 65
4.1.2. Reference orbit . . . 66
4.1.3. Assessing the accuracy relative to a reference . . . 67
4.1.4. Further method requirements . . . 68
4.2. Two-line elements . . . 69
4.3. Orbit information with scaleable accuracy . . . 70
4.3.1. Modifying the geopotential . . . 71
4.3.2. Analysis of method parameters . . . 71
4.3.3. Obtaining the covariance matrix . . . 76
4.3.4. Applying the method to different orbit regions . . . 78
4.3.5. Degradation by adding noise . . . 81

5. Ephemeris compression to provide continuous data 83
5.1. Chebyshev polynomials . . . 84
5.1.1. Chebyshev nodes . . . 84
5.1.2. Chebyshev polynomial coefficients . . . 85
5.2. Ephemeris compression . . . 85
5.2.1. Reference orbits . . . 85
5.2.2. Results . . . 86
5.3. Covariance matrix compression . . . 89

6. Applicability in the operational context 99
6.1. Providing orbit information via standardised data messages . . . 99
6.2. Performance issues . . . 101
6.2.1. Segmentation . . . 101
6.2.2. Data message size and update cycles . . . 103
6.2.3. Covariance envelope interpolation in the operational collision avoidance context . . . 105

7. Conclusion 109

References 123

List of Figures 129

List of Tables 131

List of Symbols 140

List of Abbreviations 146

A. State-of-the-art propagation with the Neptune software **147**
A.1. Units, precision, time, constants and coordinates 147
A.1.1. Units 147
A.1.2. Precision 147
A.1.3. Time 147
A.1.4. Constants 148
A.1.5. Coordinates 148
A.2. Integration 148
A.3. Force model 148
A.3.1. Geopotential 148
A.3.2. Atmospheric drag 148
A.3.3. Third-body gravitation 149
A.3.4. Solar radiation pressure 149
A.3.5. Earth radiation pressure 149
A.3.6. Tides 149
A.3.7. Other 149

B. Numerical integration **151**
B.1. State vector integration using Berry's Störmer-Cowell method 151
B.1.1. Divided differences 151
B.1.2. Predictor 153
B.1.3. Corrector 154
B.1.4. Stepsize control 154
B.1.5. Interpolation 157

C. Conversion between GCRF and ITRF **159**
C.1. Precession and nutation (IAU 2006/2000) 159
C.2. Earth rotation angle 162
C.3. Polar motion 162