Contents

List of Abbreviations xiii

List of Symbols xvii

Abstract xix

Zusammenfassung [German Abstract] xxi

1. Introduction 1
- 1.1. Space Debris . . . 2
- 1.2. Scope of Work . . . 5
  - 1.2.1. Computational Models for Orbital Propagation . . . 5
  - 1.2.2. Use Cases . . . 5
- 1.3. Outline . . . 8

2. State of the Art 9
- 2.1. Orbital Physics and Propagation . . . 9
  - 2.1.1. Perturbation Forces . . . 10
- 2.2. GPU Computing . . . 18
  - 2.2.1. A Short History of Graphics Processors . . . 18
  - 2.2.2. General Purpose GPU Computing . . . 24
  - 2.2.3. CUDA . . . 25
  - 2.2.4. Alternative Parallel Programming APIs . . . 32
  - 2.2.5. GPU Computing in Space Research . . . 32
- 2.3. Software Architecture and Development . . . 33
  - 2.3.1. Object-Oriented Programming Techniques . . . 33
  - 2.3.2. Design Patterns . . . 35

3. A Software Framework for Orbital Propagators 37
- 3.1. Properties of Orbital Propagators . . . 37
  - 3.1.1. Complexity . . . 37
  - 3.1.2. Modularity . . . 37
  - 3.1.3. Eligibility for Parallelization . . . 37
- 3.2. Orbital Propagation Interface . . . 38
  - 3.2.1. Overview . . . 38
  - 3.2.2. Concept . . . 39
  - 3.2.3. Data Types . . . 43
  - 3.2.4. Host Interface . . . 45
  - 3.2.5. Plugin Interface . . . 46
  - 3.2.6. PropagatorProperties . . . 50
  - 3.2.7. CUDA Support . . . 53
  - 3.2.8. Multi-Language Support . . . 54

3.2.9. Collision Detection . . . 54
3.3. Propagator Implementation Guidelines . . . 55

4. High-Performance Analytical Propagation **61**
4.1. FLORA . . . 61
4.1.1. Overview . . . 61
4.1.2. Atmospheric Model . . . 62
4.1.3. Third Body Perturbations . . . 62
4.1.4. Solar Radiation Pressure . . . 63
4.1.5. Zonal Harmonics . . . 63
4.1.6. FLORA as an OPI Plugin . . . 63
4.2. Ikebana - A Parallel CUDA Propagator . . . 64
4.2.1. Overview . . . 64
4.2.2. Ikebana::Ikebana . . . 65
4.2.3. Ikebana::PMMeanMotion . . . 67
4.2.4. Ikebana::PMZonalHarmonics . . . 69
4.2.5. Ikebana::PMLuniSolar . . . 71
4.2.6. Ikebana::PMSolarRadiation . . . 72
4.2.7. Ikebana::AtmosphericData . . . 74
4.2.8. Ikebana::PMAtmosphere . . . 75

5. Performance Analysis **77**
5.1. Reference Population . . . 77
5.2. Accuracy . . . 78
5.2.1. Floating Point Considerations . . . 78
5.2.2. Accuracy Dertermination . . . 80
5.2.3. Individual Model Accuracy . . . 81
5.2.4. Total Accuracy Results . . . 96
5.2.5. TLE Data Comparison . . . 107
5.3. Speed . . . 109
5.3.1. Runtime Evaluation . . . 109
5.3.2. Benchmarking . . . 110
5.3.3. Performance Evaluation Setup . . . 111
5.3.4. Performance Results . . . 113
5.3.5. CUDA Runtime Analysis . . . 114
5.4. Double Precision Comparison . . . 118
5.5. Summary . . . 126

6. Use Case Study: Space Debris Visualization **127**
6.1. Overview . . . 127
6.2. Classes . . . 128
6.2.1. DOCTOR::DOCTOR . . . 128
6.2.2. DOCTOR::SpaceObject . . . 129
6.2.3. DOCTOR::Debris . . . 130
6.2.4. DOCTOR::TimeMachine . . . 130
6.2.5. DOCTOR::GuiWrapper . . . 130
6.2.6. DOCTOR::ScriptEngine . . . 130
6.2.7. Auxiliary Classes . . . 132
6.3. Propagation . . . 132

6.3.1. GPGPU Approach . . . 132
6.3.2. OPI Approach . . . 133
6.4. Performance . . . 135

7. Conclusions and Further Research **137**
7.1. OPI . . . 137
7.2. Ikebana . . . 138

8. Outlook **141**
8.1. GPU Computing . . . 141
8.2. Numerical Propagation . . . 141

A. CUDA Profiler Report for the Atmospherical Model **143**
A.1. GeForce GTX 860m . . . 143
A.2. GeForce GTX 960 . . . 152
A.3. Tesla K20c . . . 161

B. Individual Error Rate Plots **171**

C. Ikebana Class Headers **177**
C.1. Ikebana::Ikebana . . . 177
C.2. Ikebana::PMMeanMotion . . . 181
C.3. Ikebana::PMZonalHarmonics . . . 182
C.4. Ikebana::PMLuniSolar . . . 183
C.5. Ikebana::PMSolarRadiation . . . 185
C.6. Ikebana::AtmosphericData . . . 187
C.7. Ikebana::PMAtmosphere . . . 190