

Table of Content

Abstract.....	ii
Resumen.....	iv
Resum	vii
Acknowledgments.....	x
Table of Content	xi
List of Figures	xix
List of Tables	xxv
Abbreviations.....	xxxii
Chapter 1 Thesis Introduction.....	1
1.1 Introduction.....	1
1.2 Research aim, objectives, and research hypothesis	11
1.3 Thesis organization	12
Chapter 2 GNSS Background	15
2.1 Satellite navigation systems and signal spectrum.....	15
2.1.1 Global Positioning System.....	15
2.1.2 GLONASS	18
2.1.3 Galileo.....	20
2.1.4 BeiDou Navigation Satellite System	22
2.1.5 Regional Navigation Satellites Systems (RNSS).....	24
2.1.6 Augmentation system.....	25
2.1.7 Summary of GNSS systems.....	27
2.2 Geodetic reference systems and frames.....	30
2.2.1 Conventional celestial reference system	30
2.2.2 International earth rotation and reference systems service	30
2.2.3 Conventional terrestrial reference system.....	31

2.2.4 Reference system and international terrestrial reference frame.....	31
2.3 GNSS Reference Frames	34
2.3.1 GPS Reference Frame WGS-84.....	34
2.3.2 GLONASS Reference Frame PZ-90.....	34
2.3.3 Galileo Reference Frame (GTRF)	35
2.3.4 BeiDou reference frame.....	35
2.4 GNSS error sources.....	35
2.4.1 Satellite clock errors	35
2.4.2 Receiver clock errors	36
2.4.3 Satellites orbital errors	36
2.4.4 Satellites wind-up error.....	38
2.4.5 Satellites antenna phase center error.....	38
2.4.6 Receiver antenna phase center error	39
2.4.7 Multipath error	40
2.4.8 Atmospheric delay	41
2.4.9 Cycle slip	46
2.4.10 Relativistic effect	47
2.4.11 Instrumental delay.....	48
2.4.12 Receiver clock jumps.....	48
2.4.13 Satellites eclipse periods.....	48
2.4.14 Satellite problems.....	49
2.4.15 Additional GNSS error sources	49
2.5 International GNSS Services (IGS)	50
2.5.1 IGS working groups.....	54
2.5.2 Main international GNSS Services analysis centers	54
2.5.3 The Multi-GNSS Experiment (MGEX).....	61

2.6 Other regional and continental projects	62
2.6.1 The EUREF	62
2.6.2 European Plate Observing System (EPOS)	63
2.6.3 Sirgas.....	63
2.6.4 Asia-Pacific Reference Frame (APREF)	64
2.6.5 The African Geodetic Reference Frame (AGRF)	64
2.6.6 The North American Reference Frame (NAREF)	65
2.6.7 Japanese Geodetic Datum 2011 (JGD2011).....	65
Chapter 3 Precise Point Positioning Technique.....	67
3.1 Introduction.....	67
3.2 Precise point positioning.....	68
3.2.1 RT double differences approach versus RT-PPP approach	74
3.2.2 Linear observation model and mathematical model for precise point positioning	75
3.2.3 Precise point positioning modelling components	78
3.3 Real-time precise satellite clock and orbital products and formats	80
3.3.1 Real-time precise satellite orbits and clocks	80
3.3.2 State Space Representation (SSR)	82
3.3.3 Current real-time state space representation products at IGS and analysis centers	85
3.4 Current tools for real-time precise point positioning.....	89
3.4.1 BNC	90
3.4.2 RTKLIB	91
3.4.3 PPP-WIZARD.....	92
3.4.4 gLAB.....	93
3.4.5 GipsyX	93
3.4.6 GMV MAGIC-PPP	94
3.4.7 G-Nut/Geb.....	94

3.4.8 Bernese tool	95
3.4.9 Other tools.....	95
3.5 Current limitations of precise point positioning and real-time precise point positioning...	95
3.5.1 Ambiguity resolutions.....	95
3.5.2 Initialization period and noise of ionosphere-free combination	97
3.5.3 Latency.....	99
3.5.4 Availability and the quality of state space representation corrections.....	100
3.5.5 The effect of tropospheric and ionospheric layers on the precise point positioning performance	102
Chapter 4 Early Warning System	106
4.1 Introduction.....	106
4.2 The changing shape of the earth: natural land deformation.....	107
4.2.1 Earthquakes activities	107
4.2.2 Tsunami activities	110
4.2.3 Landslides activities.....	110
4.2.4 Volcanic activities.....	114
4.3 The behavior of structures under load: structural deformation.....	114
4.4 The necessity of an early warning system to prevent risks and natural hazards.....	117
4.5 Earthquakes, tsunamis, landslides, and volcanic early warning systems	122
4.6 Early warning system methods	125
4.7 Examples of current DGNSS-based early warning systems.....	126
4.7.1 Pacific Tsunami Warning and Mitigation System (PTWS).....	126
4.7.2 ShakeAlert earthquake early warning system for the west coast of the United States	127
4.7.3 TRUAA early warning system.....	127
4.7.4 GNSS-based Upper Atmospheric RT Disaster Information and Alert Network (GUARDIAN).....	128

4.7.5 GNSS/LPS/LS-based online Control and Alarm System (GOCA)	128
4.7.6 Japan's early warning system.....	129
4.7.7 GeoNet.....	129
4.7.8 Indonesia Tsunami Early Warning System (InaTEWS).....	129
4.7.9 Early-Warning and Rapid Impact Assessment with real-time GNSS in the Mediterranean (EWRICA).....	130
4.7.10 Local landslides early warning systems.....	130
4.7.11 Precise point positioning deformation studies	131
Chapter 5 Machine Learning	136
5.1 Introduction.....	136
5.2 Supervised Learning	137
5.3 Unsupervised learning	138
5.4 Reinforcement Learning	138
5.5 ML classification and regression models.....	139
5.5.1 Linear model	139
5.5.2 Logistic model	139
5.5.3 Polynomial model.....	140
5.5.4 Decision tree	140
5.5.5 Random Forest (RF)	142
5.5.6 Extreme Gradient Boosting (XGB)	144
5.5.7 K Nearest Neighbours (KNN)	144
5.5.8 Support Vector Machine (SVM).....	145
5.5.9 Autoregressive integrated moving average.....	146
5.6 Python ML libraries	148
5.7 Metrics and models accuracy assessments	149
5.7.1 R ² for the goodness of fit	150
5.7.2 Root Mean Squared Error (RMSE).....	150

5.7.3 Mean Absolute Error (MAE)	151
5.7.4 Prevalent employed performance indicators regarding the confusion matrix	151
5.7.5 Receiver Operating Characteristics (ROC).....	153
5.7.6 Area Under Curve (AUC).....	153
5.8 GNSS ML applications	154
5.9 Harnessing the power of machine learning in establishing robust early warning systems	157
Chapter 6 Research Methodology.....	159
6.1 Introduction.....	159
6.2 Research methodology concerning the reduction of latency impact of GNSS products in real-time precise point positioning technique	161
6.2.1 Work package 1 (RT-PPP data acquisition)	163
6.2.2 Work package 2 (BNC configurations)	165
6.2.3 Work package 3 (ML training and clock correction analysis).....	166
6.2.4 Work package 4 (ML prediction/implementation)	168
6.2.5 Work package 5 (Prediction and solution creation).....	171
6.2.6 Work package 6 (RT-PPP coordinates assessment)	172
6.2.7 Work package 7 (Data interpretation).....	173
6.3 Research methodology regards establishing RT-PPP early warning system.....	173
6.3.1 Work package 1 (Selecting the study reference station).....	176
6.3.2 Work package 2 (RT-PPP coordinates quality investigations).....	181
6.3.3 Work package 3 (BNC configurations)	181
6.3.4 Work package 4 (Research variables investigation)	182
6.3.5 Work package 5 (Description of proposed engines).....	187
6.3.6 Work package 6 (Ranges of deformation and subsidence, time span)	192
6.3.7 Work package 7(Experiments implementations).....	195
6.3.8 Work package 8 (Machine learning implantation and assessments)	200
6.3.9 Work package 9 (Data interpretation).....	205

6.3.10 Work package 10 (Azure platform)	206
Chapter 7 Results and Discussions	207
7.1 Introduction.....	207
7.2 Latency results	208
7.2.1 ML prediction models' assessment regards the latency issues.	211
7.2.2 Coordinates assessment regarding the latency issues.	224
7.3 RT-PPP EWS results.....	230
7.3.1 Selection of noise-free measurements with satellite elevation angle.....	237
7.3.2 RT-PPP early warning system assessment results	248
7.3.3 Simulated land subsidence and land-uplifting results.....	253
7.3.4 Simulated horizontal deformation results	257
7.3.5 Simulated 3D deformation monitoring results.....	261
7.3.6 Summarizing the results.....	264
7.4 Generic model Azure analysis	267
7.5 Feature importance and feature selection	271
7.6 Generic model.....	273
7.7 Summary.....	278
Chapter 8 Conclusion, Discussions, and Future Works.....	280
8.1 Conclusions and discussions.....	280
8.2 Research main finding	283
8.3 Research novelty and main contributions	286
8.4 Future works	288
8.5 Challenges.....	288
Appendix.A Ph.D. activities.....	290
Appendix.B Exploring Research Latency Results: A Compilation of Statistical Summaries	292

Appendix.C Analyzing RT-PPP EWS Research Experiment Comprehensive Statistical Summaries.....	319
References.....	353
