

# Geodätisch-geophysikalische Arbeiten in der Schweiz

(Fortsetzung der Publikationsreihe  
«Astronomisch-geodätische Arbeiten in der Schweiz»)

herausgegeben von der

Schweizerischen Geodätischen Kommission  
(Organ der Akademie der Naturwissenschaften Schweiz)

Neunundsiebziger Band  
Volume 79

## In-flight Quality Assessment and Data Processing for Airborne Laser Scanning

Philipp Schaer

2010

ULB Darmstadt



17478010

# Contents

<b>1</b>	<b>Introduction</b>	<b>1</b>
1.1	Context . . . . .	1
1.2	Research Objectives . . . . .	3
1.3	Methodology . . . . .	3
1.4	External Contributions . . . . .	5
1.5	Thesis Outline . . . . .	5
<b>2</b>	<b>ALS Enabling Technologies</b>	<b>7</b>
2.1	Airborne Laser Scanning . . . . .	7
2.1.1	History of ALS Technology . . . . .	7
2.1.2	Current in-flight QA/QC Capabilities . . . . .	8
2.1.3	Trends in ALS . . . . .	9
2.2	Direct Georeferencing: Basic Relations . . . . .	9
2.2.1	Direct Georeferencing for ALS . . . . .	9
2.2.2	Used Reference Frames . . . . .	10
2.2.3	ALS Observation Equation . . . . .	13
2.3	Laser Scanner Technology . . . . .	14
2.3.1	Laser Ranging . . . . .	14
2.3.2	Intensity Measure . . . . .	15
2.3.3	Scanning Patterns . . . . .	17
2.4	Positioning Technology . . . . .	19
2.4.1	GNSS Systems . . . . .	19
2.4.2	GPS Signal . . . . .	20
2.4.3	GPS Positioning Modes . . . . .	20

## Contents

---

2.4.4	GPS Quality Monitoring Techniques . . . . .	21
2.5	Integrated Navigation Technology . . . . .	25
2.5.1	Inertial Measurement Units . . . . .	25
2.5.2	GPS/INS Integration . . . . .	27
2.5.3	IMU Alignment . . . . .	28
2.5.4	GPS/INS Quality Monitoring . . . . .	29
<b>3</b>	<b>ALS System Calibration and Point-cloud Processing</b>	<b>31</b>
3.1	System Calibration . . . . .	31
3.1.1	Boresight Calibration . . . . .	32
3.1.2	Leverarm Calibration . . . . .	34
3.2	Strip Adjustment . . . . .	35
3.3	ALS Point-cloud Data Processing . . . . .	37
3.3.1	Spatial Data Indexing . . . . .	37
3.3.2	Co-registration . . . . .	38
3.3.3	Point-cloud Geometry Analysis . . . . .	39
3.3.4	Point-cloud Filtering and Classification . . . . .	41
3.4	Digital Elevation Models . . . . .	42
3.4.1	Triangulation . . . . .	42
3.4.2	Elevation Raster . . . . .	43
3.4.3	DEM Analysis . . . . .	44
<b>4</b>	<b>Point-cloud Quality Assessment</b>	<b>47</b>
4.1	Overview of ALS Error Sources . . . . .	47
4.2	ALS Navigation Errors . . . . .	47
4.2.1	Trajectory Positioning Errors . . . . .	47
4.2.2	Trajectory Orientation Errors . . . . .	49
4.3	ALS System Errors . . . . .	50
4.3.1	Range-finder and Scanner Errors . . . . .	50
4.3.2	Calibration errors . . . . .	50
4.4	Assessment of ALS Target Accuracy . . . . .	51
4.5	Assessment of Scanning Geometry . . . . .	53

4.5.1	Laser Beam Power Distribution . . . . .	53
4.5.2	3D Footprint Computation . . . . .	54
4.6	Single Point Quality Indicator . . . . .	56
4.6.1	Removal of non-ground Points . . . . .	56
4.6.2	Workflow for Q-indicator Computation . . . . .	56
4.7	Error Budget Evaluation . . . . .	57
4.7.1	Theoretical Analysis . . . . .	58
4.7.2	Error Budget for long-range ALS system . . . . .	61
4.7.3	Error Budget for short-range ALS System . . . . .	64
4.8	Use of Quality Indicators in Point-cloud Processing . . . . .	66
4.8.1	Metadata Generation . . . . .	66
4.8.2	Strip Adjustment . . . . .	66
4.8.3	Ground Classification and DTM Generation . . . . .	66
<b>5</b>	<b>Surface Quality Assessment</b>	<b>69</b>
5.1	Data Coverage Analysis . . . . .	69
5.1.1	Factors influencing the Point Density . . . . .	69
5.1.2	2D Point Density . . . . .	70
5.1.3	3D Point Density . . . . .	71
5.1.4	Data Extent and Gap Analysis . . . . .	71
5.2	Internal Data Accuracy . . . . .	72
5.2.1	Strip Difference Map . . . . .	73
5.2.2	Translation and Rotation Detection by ICP . . . . .	74
5.3	Height Model Data Accuracy . . . . .	76
5.3.1	Factors influencing DTM Accuracy . . . . .	76
5.3.2	Empirical DTM Quality Assessment . . . . .	78
5.3.3	Automated DTM Quality Assessment . . . . .	79
<b>6</b>	<b>Implementation</b>	<b>83</b>
6.1	Handheld Airborne Mapping System . . . . .	83
6.1.1	History of Scan2map . . . . .	83
6.1.2	Concept . . . . .	84

## Contents

---

6.1.3	Hardware System Architecture . . . . .	85
6.2	Flight Preparation . . . . .	86
6.2.1	Flight-plan . . . . .	86
6.2.2	Analysis of GPS Constellation . . . . .	87
6.3	In-flight Quality Assessment Tool (IQUAL) . . . . .	88
6.3.1	General Strategy . . . . .	88
6.3.2	Communication . . . . .	89
6.3.3	Software Modules . . . . .	89
6.3.4	Inter-modular Communication . . . . .	90
6.4	GPS Quality Analysis Module (GPSQUAL) . . . . .	91
6.4.1	Quality Indicators . . . . .	92
6.4.2	Quality Flags . . . . .	93
6.5	RT GPS/INS Integration Engine (GIINAV) . . . . .	93
6.5.1	Integration Strategy . . . . .	93
6.5.2	IMU Alignment . . . . .	94
6.6	RT ALS Georeferencing Engine (LIEOS) . . . . .	95
6.6.1	Configuration . . . . .	96
6.6.2	Georeferencing Algorithm . . . . .	96
6.7	LiDAR Quality Analysis Module (LIAN) . . . . .	97
6.7.1	Concept . . . . .	97
6.7.2	Configuration . . . . .	98
6.7.3	Data Filtering . . . . .	99
6.7.4	Strip Overlap Control and Zone Handling . . . . .	100
6.7.5	Extent and Gap Detection . . . . .	101
6.7.6	DSM and Hillshade Generation . . . . .	102
6.7.7	Image Footprint Computation . . . . .	103
6.7.8	Ground Classification . . . . .	103
6.7.9	Error Propagation . . . . .	104
6.7.10	DTM Generation . . . . .	106
6.8	Flight Management and Monitoring Module (HELIPOS) . . . . .	107
6.8.1	Concept . . . . .	107
6.8.2	Communication with other Modules . . . . .	109
6.8.3	Pilot Guidance . . . . .	111
6.8.4	In-Flight Quality Data Display . . . . .	112

<b>7 Results and Performance Analysis</b>	<b>115</b>
7.1 RT Trajectory and Point-cloud Accuracy . . . . .	115
7.1.1 Single Point Positioning (SPP) . . . . .	115
7.1.2 RTK . . . . .	118
7.1.3 Summary of RTK Performance . . . . .	120
7.2 Trajectory Quality Analyses (GPSQUAL) . . . . .	122
7.2.1 Application Example . . . . .	122
7.2.2 General Validity of Quality Flags . . . . .	124
7.3 ALS Point-cloud Quality Analysis (LIAN) . . . . .	124
7.3.1 Data Extent and Gap Polygons . . . . .	124
7.3.2 Point-cloud Quality Map . . . . .	125
7.3.3 Ground Classification and DTM Generation . . . . .	128
7.4 Computational Performance . . . . .	130
7.4.1 RT Computations . . . . .	130
7.4.2 Strip-wise Computations . . . . .	131
<b>8 Conclusion and Perspectives</b>	<b>137</b>
8.1 Summary of Contributions . . . . .	137
8.2 Conclusions . . . . .	139
8.3 Perspectives . . . . .	141
<b>Bibliography</b>	<b>142</b>
<b>A Derivation of Sub-matrices</b>	<b>157</b>
<b>B Computation of 3D Laser Footprint</b>	<b>163</b>
<b>C Comparison RT - PP</b>	<b>165</b>