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Research Paper

A Study on Airborne LiDAR Calibration and Operation Techniques for Bathymetric Survey

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Abstract

The necessity of maritime sector for continuous management, accurate and update location information such as seabed shape and location, research on airborne LiDAR bathymetry surveying techniques are accelerating. Airborne LiDAR systems consist of a scanner and GPS/INS. The location accuracy of 3D point data obtained by a LiDAR system is determined by external orientation parameters. However, there are problems in the synchronization between sensors should be performed due to a variety of sensor combinations and arrangement. To solve this issue, system calibration should be conducted. Therefore, this study evaluates the system verification methods, processes, and operation techniques.

Keywords : Airborne LiDAR, LiDAR Calibration, Bathymetric Survey, GPS/INS

1. Introduction

In Korea, currently multi beam, single beam, and side scan sonar measurements are being used to obtain data for the purpose of determining sea bed shapes and locations. In mixed areas of coastal landward boundaries with many rivers, wetlands, coral reefs, and fringing reefs and waters, surveying is impossible due to the difficulty of operating data collection vessels. In areas where fishing activities are performed, bathymetry surveying is limited. Hence, advanced countries are using airborne LiDAR bathymetry surveying tools for depth-sounding to prevent marine disasters coupled with maritime safety, marine territory management, and climate change considerations.

Airborne LiDAR is equipment designed to obtain 3D location data from the ground and the ocean floor rapidly and accurately using aircrafts equipped with GPS/INS and laser scanners (Choi et al., 2005). The advantage is possibility to obtain data regardless of climate or time of day. Additionally, high precision 3D location information can be obtained rapidly and accurately, as it is possible to calculate the exact distance to the ground. In particular, it can be used effectively to obtain 3D location information and marine charts for submarine topology in locations that are difficult for vessels to approach.

The location accuracy of 3D point data obtained by airborne LiDAR systems is determined by the external orientation parameters of the equipped scanners and GPS/INS. Therefore, prior to the use of a LiDAR system, system calibration to identify and resolve factors that can cause errors in GPS/INS and laser scanner data should be performed.

This study examined airborne LiDAR calibration related theoretical backgrounds and operation plans in bathymetry surveying with airborne LiDAR.

2. Calibration Method

Airborne LiDAR scanning is a surveying technique used to calculate location at reflection points and extract geographic information on the surface of the earth. This is accomplished by mounting a LIDAR system on an aircraft, with the laser pulse directed toward the ground. The time of arrival for the reflected laser pulse is measured. The flow chart for

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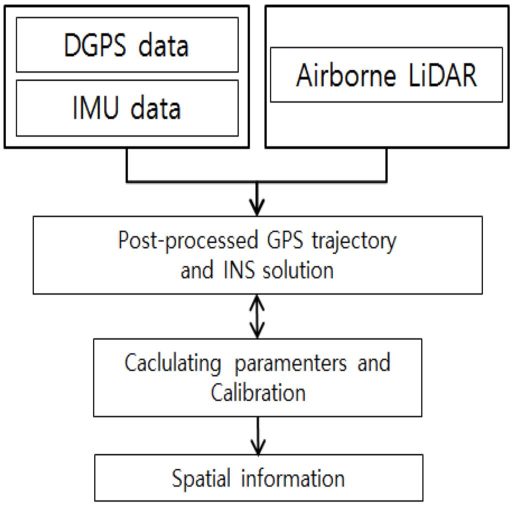

Figure 1. Flow chart for the airborne LiDAR Calibration method

the airborne LiDAR calibration method is shown in Fig. 1. To use an airborne LiDAR system, a calibration process to identify and remove factors that can lead to errors in the GPS/INS and laser scanner data should be performed. Here, calibration is the process of comparing a certain equipment or measuring instrument with a standard equipment or instrument whose accuracy has been verified, to determine the differences in accuracy, correlation, and recording, and to eliminate the identified differences . In other words, it can be termed an essential process to correct errors in equipment, minimizing the errors, and increasing the accuracy of data. The advantages of calibration lie in obtaining reliable measuring equipment and results, determining and correcting systematic errors in the equipment used, calculating necessary factor coefficients for data correction, predicting the accuracy of a theory, and confirming the operating functions in equipment specifications. The factors that cause errors in airborne LiDAR systems are largely divided into mechanical errors and accidental errors (Table 1). Among mechanical errors, major causes originate from the GPS/INS system. The location determination accuracy of a laser scanner equipped with GPS/INS has a large influence on the final measurement accuracy (Choi et al, 2005). Therefore, it can be said that the largest error factor is a difference in rotation between the laser scanner and the INS in a coordinate system. Mostly, calibration is conducted in various 3D planimetric features with a combination of wide flat roofed buildings, large parking lots, valleys, forests, roads, and small buildings (National Geographic Information Institute, 2002). In Fig. 2, the top figure presents the data obtained before calibration while the bottom one presents data after calibration. Data without

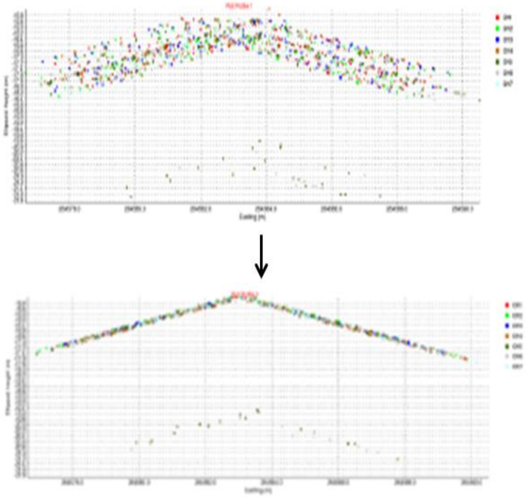

Figure 2. Data before and after calibration

Table 1. Factors that cause errors in airborne LiDAR systems

Mechanical errors	Accidental errors
Laser scanner mechanical error	Detection of pulse
Delay of laser pulse	Point jitter
INS misalignment and gyro drift	INS
GPS baseline distance (when baseline distance is more than 30km)	GPS
Delay effect of GPS signal in troposphere	tough terrain
Terrain gradient and plant species	reflectivity

calibration cannot be used. If calibrations were corrected in the three-dimensional X, Y, or Z axis, exact results can be obtained. Calibration can largely be divided into system calibration and field calibration. System calibration is a self-discrimination and correction process within a system, for example, the arrangement of the laser, correction of the scanner angle, correction of the signal delay, and correction of the absolute range. Field calibration is the process of correcting Roll, Pitch, and Heading errors that occur when the equipment is mounted on a new aircraft.

2.1 Geometrical Theory

2.1.1 Difference in Amount of Rotation between INS and LiDAR

In airborne LiDAR systems, navigation equipment such as GPS antennas and INS sensors are separate. The GPS antenna is located at the upper part of the aircraft, whereas the INS sensor is located within the lower LiDAR system. The relationship between the two should be highly accurate and maintaining this relationship is very important. If the geometrical structure of the sensors changes, general errors will occur in the system model, The position of the lasers determines the position and vector of orientation. The coordinates are nonlinear. In particular, the adjustment process for each factor is very complex. The relational expression is shown in Eq. (1).

$$P_{Loc} = R_{Att} \cdot (R_{mis} \cdot R_{sca} \cdot r_{las} + \triangle f_{lev}) + APC_{loc} \tag{1}$$

$P_{loc(Local)}$is 3D coordinates of a laser point in the local mapping frame;

$R_{At(Attitude)}$is the rotation matrix between the INS frame and mapping frame, measured by GPS and INS;

$R_{mis(misalignemnt)}$is boresight matrix between the laser frame and INS frame;

$R_{scan(scanangle)}$is the transformation matrix from laser range to laser frame with scan angle;

$r_{las(laserrange)}$is the laser range from fired point to target;

$\triangle f_{lev(levelarm)}$is offset between laser fire point and GPS antenna phase center in body frame;

$APC_{loc(loclocal)}$is the 3D coordinates of GPS Antenna Phase Center in the local mapping frame.

2.1.2 Influences of Roll

Errors in the Roll are shown in Fig. 3. If the laser pulse in a horizontal plane is directed left and right orthogonal to the flying direction at a certain width, the three-dimensional location of the laser pulse is greatly influenced by changes in the rotation in the X-axis. In other words, the actual location of a building and the LiDAR data can change at regular intervals orthogonal to the flying direction. This phenomenon indicates that errors exist in X-axis.

The relational expression of Roll is expressed as shown in Eq. (2). Here, $Z_L - Z_R$ is the difference between the height of the right-most point coordinate and the height of the left-most point coordinate in a horizontal plane. H is the average flying height and $\theta_{\max}$ is the maximum look angle of the scan system.

Table 2 represents errors in the Roll depending on the difference in height at both ends of the horizontal plane at a certain altitude. Each time the heights of both ends differ by about 2 meter, $\triangle R$ increases by 0.5 unit.

$$Z_L - Z_R = 2H\tan\theta_{\max} \cdot \quad \triangle R \quad ; \triangle R = \frac{(Z_L - Z_R)}{2H\tan\theta_{\max}} \tag{2}$$

Table 2. Rolling angle deflect the horizontal surface

H(m)	200				
$\theta_{\max}$(°)	30				
$Z_L - Z_R$ (m)	0	2.02	4.03	6.05	8.06
$\triangle R$	0	0.5	1	1.5	2.0

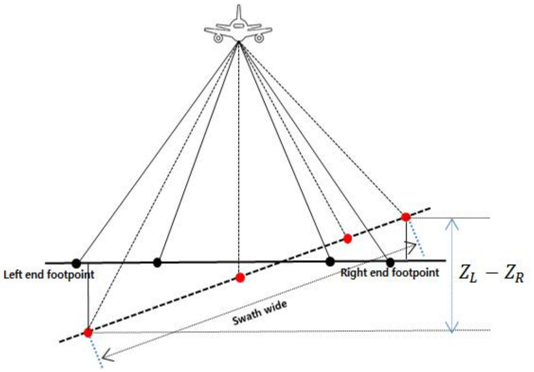

Figure 3. Rolling misalignment deflects the horizontal flat surface and shifts the feature position simultaneously

2.1.3 Influences of Pitch

Errors in pitch are shown in Fig. 4. Although the laser data reflected by the building and the laser data reflected by the ground should be exactly identical to the outline of the building obtained by actual measurement, the real data obtained are expressed twice in terms of the angle of the building measured in the field and the airborne LiDAR data. The relational expression of Pitch is expressed as shown in Eq. (3). D is the distance between points by normal direction flying vs. by reverse direction flying, H is the average flying height, and $\theta_{\max}$ is the maximum look angle of a scan system.

Table 3 presents errors in Pitch depending on the distance between points in normal direction flying vs. in reverse direction flying. Each time the difference in distance from the center in the normal direction flying vs in the reverse direction flying differs by about 4 meters, $\triangle P$ increases by 1 unit.

$$D = 2H\tan\theta_{\max} \cdot \ \triangle P \quad ; \quad \triangle P = \frac{D}{2H\tan\theta_{\max}} \qquad (3)$$

Table 3. Pitching angle shift the horizontal position along the flight direction

H(m)	200				
$\theta_{\max}$(°)	30				
D(m)	0	2.02	4.03	6.05	8.06
$\triangle P$	0	0.5	1	1.5	2.0

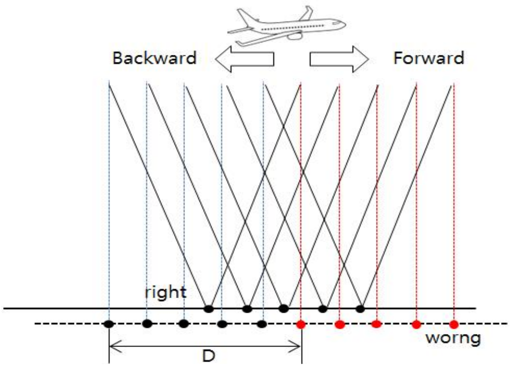

Figure 4. Pitching misalignment shifts the feature position mainly along the flight direction

2.1.4 Influences of Heading

Errors in heading are shown in Fig. 5. If the rotation angle of axis Z in the INS coordinate is not identical to that in the laser equipment coordinate, the location of a building is not identical at the point where the flying directions cross. To make the location identical, the heading should be corrected. Heading can be drawn by comparing it with airborne LiDAR data at the point where flying directions cross.

The relational expression of Heading is shown in Eq. (4). S is the mean distance between building point groups in normal direction flying vs. in the reverse direction flying, H is the average flying height, and D is the distance between vertical lines of the building and aircraft.

$$S = D \cdot \ \triangle H \quad ; \quad \triangle H = \frac{S}{D} \qquad (4)$$

Table 4 presents errors in Heading depending on the mean distance between point groups in the flying direction. Each time S increases by about 1.7 meter, $\triangle H$ increases by 1 unit.

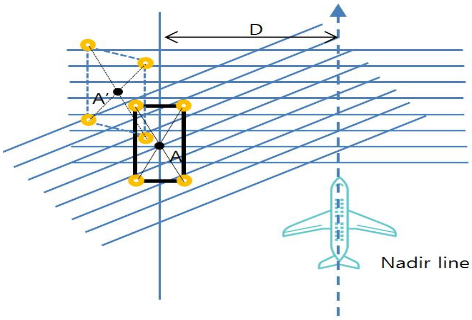

Figure 5. Positioning error from heading misalignment in both along and across flight direction

Table 4. Heading angle shifts the horizontal position

D(m)	100				
S(m)	0	0.873	1.745	2.619	3.492
$\triangle H$	0	0.5	1	1.5	2

3. Data Acquisition and Adjustment Factor Calculation

3.1 Area of Study, Equipment and Data

For calculation of the airborne LiDAR bathymetry surveying calibration adjustment factor, Muan International airport was selected as the inland calibration area. The flight was divided into two parts: inland and sea. In the inland test station, an area with a wide area containing buildings was selected and the flight occurred lengthwise and breadthwise. CZMIL has a laser pulse scanning rate of 70kHz inland and 10kHz at sea, with a point density of 2m×2m(0.25pt/㎡)(Table 5). In particular, it has a nonhomogenous scan pattern as a circular scanner. In both ends of the aircraft, the laser scanning results are relatively richer than SHOALS 3000, with an arc-shaped scan pattern. This pattern influences the point density, and the point density of CZMIL is higher than that of SHOALS at the same altitude.

3.2 Adjustment Factor Calculation

As shown in Fig. 6, to extract Pitch, Roll, and Heading factors from the selected site for calibration (Muan International Airport), cross shooting was executed and the test station flight trajectory (.sbet), shooting plan (.xml) file, and LiDAR source data (RAW) were used. To check correction values, blocks were set in the parts where each course was overlapped as shown in Fig. 7 and then the test was conducted.

It was found that when data were extracted as primitive parameter values, 3-dimensional coordinates were incorrect as shown in Fig. 8.

Figure 6. Area of study and route of calibration

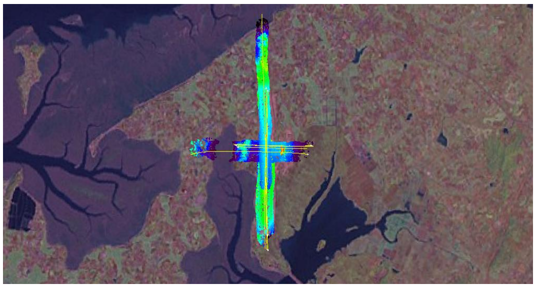

Figure 7. Calibration source data extraction

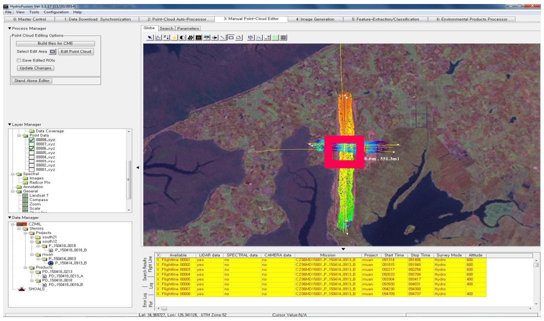

Figure 8. Pitch, Roll, and Heading adjustment factor verification

The final results were observed in profile by adjusting the calibration adjustment factor values (Parameter) and the parameters were obtained before correction(Fig. 9). The parameters were applied and after checking the profile, the difference in data performance between the imported las files were analyzed in Table 6.

Table 5. CZMIL specification

Equipment	Item	Specification
	Manufacturer	Optech
	Standard	CZMIL
	Altitude	400m
	Underwater laser repetition rate	10 kHz
	Inland laser repetition rate	70 kHz
	Resolution	2m×2m nominal
	Angle of scan	20°
	Scanning range	291m nominal
	Classification of laser	Class 4 laser product

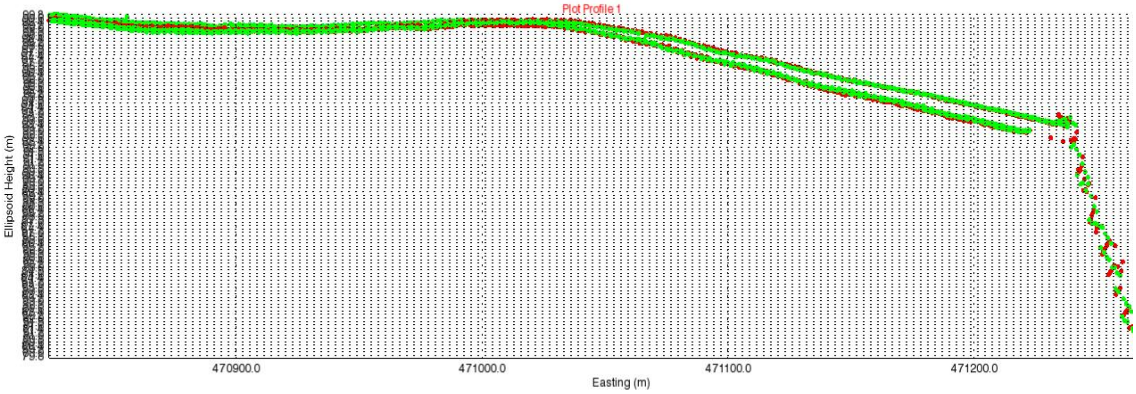

Figure 9. Overlap course Roll adjustment factor verification

Table 6. Comparison of calibration parameters

Correction factor	Before correction		After correction	
SBF-IMU Misalignment(X)	0.000000		-0.01000	
SBF-IMU Misalignment(Y)	0.000000		-0.02600	
SBF-IMU Misalignment(Z)	0.000000		0.00000	
angular_misalignment_scanner_fresnel_x	0.000000		0.00000	
angular_misalignment_scanner_fresnel_y	0.000000		0.00000	
Scanner Angle Origin Offset	0.000000		2.5000	
Fresnel Element Slope	39.1500		39.15000	
Range Offset	CH1	0.0000	CH1	-0.35000
	CH2	0.0000	CH2	-0.50000
	CH3	0.0000	CH3	-0.43000
	CH4	0.0000	CH4	-0.47000
	CH5	0.0000	CH5	-0.47000
	CH6	0.0000	CH6	-0.35000
	CH7	0.0000	CH7	-0.35000
	IR	0.0000	IR	-1.58000
	DeeP	0.0000	DeeP	-0.41000

4. Planning and measurement of calibration site for each sea

Airborne LiDAR bathymetry surveying employs different calibration methods depending on equipment specification, turbidity of seawater, tidal current, tidal conditions, and climatic elements (wave, wind, etc). In particular, as a result of Secchi depth, it was found that calibration of the depth-of-water data was possible for depths greater than 3m (Baltsavias, 1999). Therefore, for airborne LiDAR bathymetry surveying in coastal areas, calibration adjustment factors as mentioned in Section 2 should be checked in advance so that optimal depth-of-water data calibration can be executed.

Additionally, permanent calibration sites have not yet been installed according to sea sectors in Korea. This is why temporally installed reference points are used if necessary to test sensors for aircrafts, which leads to an economic burden and lack of consistency and reliability. Also, Korea has distinct characteristics according to the sea sector, specifically the sea surface in the East Sea, the South Sea, and the Yellow Sea and underwater turbidity. In particular, the underwater turbidity of the West Sea changes dynamically in real time. So, it is necessary to establish plans depending on the underwater environment according to the sea sector during

Table 7. Considerations in establishing calibration sites

Class	Conditions	
Installation of calibration sites	Location	- Areas that are adjacent to operating agencies for operation and management - Places where there are no variations in topography/planimetric features - Government owned lands or public institution owned lands to avoid land disputes - Places where there is no GPS data reception failure - Places where there is no hindrance to flying
	Size	- Consider distance to reference point, distribution, and redundancy, etc - Considering foreign cases, 3km x 3km is an appropriate size.
	Distribution and installation of standard point	- Analogue and digital data can be combined. - Scale and resolution power should be considered before manufacturing at the size of the reference point for multiple purposes with one target. - Reference point that can be verified by both airborne sensor and satellite sensor should be installed. - Should be implemented according to current aerial internal rules.

airborne LiDAR bathymetry surveying.

4.1 How to Establish Calibration Sites by Sea Sector

The West Sea has a large tidal range and developed mud flat. The South Sea has a complex coastline. The East Sea has deep water and many rocks are covered and uncovered along the coast. Therefore, it is necessary to install calibration sites at a representative area by each sea sector and establish calibration sites that satisfy various conditions. This is why in Korea, various aircraft sensors are increasingly introduced and generalized. At this point in time, plans for standardization of the methodology for establishing test fields at the national level, system verification, data processing, and result calculation are required.

The most important considerations before establishing calibration sites in Korea are optimal locations and size. In foreign countries, calibration sites are above 6km×6km. However, in Korea, considering domestic topographic conditions and social conditions, a 3km×3km, 1/4 area seems appropriate. Also, selecting areas that are adjacent to operating agencies (National Geographic Information Institute, public institution, etc) for operation and management would be ideal. Currently, the Korea Ocean Research Association is analyzing optimal sites for field calibration with multi beam and single beam and drawing up measures for multi beam calibration sites. Finally, it is necessary to establish actual sea sector calibration sites and install artificial structures to enable verification in various environments.

4.2 Measurement according to Underwater Environment by Sea Sector

Airborne LiDAR bathymetry surveying is a laser-based surveying method and due to the nature of lasers, its reflectance depends on the materials reflected. The results of measurement should be based on the reflectance of sand, mud flats, and rocks. In particular, aerial surveys need to be conducted for the existing single beam sea areas to improve precision. CZMIL survey results including depth-of-water and height are considered to provide precise information on rocks, bathing resorts, fish farms, and fishing area, which is lacking currently, and to help alleviate safety issues related to vessels and close surveying.

However, CZMIL is based on a circular laser scanning method. Thus, it is impossible to measure if there is water in a breaking wave zone. Error in CZMIL is ±5cm. To satisfy IHO-1(a) and improve accuracy, it is necessary to shoot simultaneously with a digital camera, compare and verify the obtained data, continuously upgrade the equipment and constantly monitor domestic coastal environments.

5. Conclusion

Calibration work is essential for performing airborne LiDAR measurement. Among the factors that cause errors, the largest is the difference in rotation between INS and LiDAR. Therefore, when testing LiDAR systems, the test should be conducted in structures with large relief displacement, like floating structures or roofs on a building. This study examined the calibration methods for airborne LiDAR bathymetry surveying and derived the following conclusions.

First, it was found that whenever the error in Roll depending on differences in the height in both ends of a horizontal plane differs by about 2 meter, $\triangle R$ increases by 0.5 unit. Additionally, whenever the distance for normal direction flying and reverse direction flying differs by about 4 meter, $\triangle P$ increases by 1 unit. Finally, whenever the mean distance between building point groups in normal direction flying vs. in reverse direction flying increases by about 1.7 meter, $\triangle H$ increases by 1 unit.

Second, bathymetry surveying by using airborne LiDAR, enables the establishment and utilization of coastal management based on scientific data. And also, a systematic management of disasters and accidents in coastal areas is considered to be possible. To this end, it seems to be necessary to install fixed calibration sites suitable for each of the Yellow Sea, the South Sea, and the East Sea in Korea. It also seems necessary to carry out further research on how to obtain data appropriate for the domestic environment, with utilization and management plans for the data obtained. Also, rules regarding airborne LiDAR bathymetry surveying wroks need to be made by analyzing the maximum depth of water acquired according to the turbidity of the sea surface according to the sea sector, tidal current, tidal conditions, and weather conditions.

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