Utilization of Airborne Topo-Bathymetric LiDAR Technology for Coastline Determination in Western Part of Java Island

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Abstract. Indonesia is the largest archipelagic country consisting of 17,504 islands which have 99,093 km of coastline. From the total, approximately only 10% had mapped. The coastline is essential for several applications such as topographic height reference, a reference in the delimitation of the marine management area, coastal boundaries, etc. Law number 4 of 2011 (UUIG), in article 13 paragraph 2 concerning Geospatial Information, mentioned three types of coastlines, namely: (a) the lowest astronomical tide, (b) the highest astronomical tide, and (c) the mean sea level. The existing method for determining the coastlines is observing a tide gauge over a long period at several places, then densify the point height by levelling method. This method is less effective due to time, cost, and amount of sample points. This paper presents our experience on coastlines determination by extracting it from a digital terrain model (DTM). The Airborne Topo-Bathymetric LiDAR technology is utilized to provide DTM that covers land and seabed. The points cloud, which is the output of this technology, was transformed to the geoid and corrected by tidal datum before those three types of coastlines were determined and delineated. The Western Part of Java Island is a study area. The project covers 1,000 km of coastline. The DTM quality was validated using several independent check-points along the coastline and hundreds of shorelines transect points at two locations. The result shows that vertical accuracy within the decimeter level.

1. Introduction

Indonesian Geospatial Information Agency (BIG) is a non-ministerial institution assigned to provide geospatial information for policy formulation, decision making, or implementing activities related to spatial utilization. As part of the institution, the Marine and Coastal Environment Mapping Centre (PKLP) has one of the tasks to provide a bathymetric map. Periodically, traditional bathymetric surveys are carried out to fulfill these products. One of the map’s essential elements is a coastline and, by definition, is a line that forms the boundary between the land and the water body. This element has an important role; it is used to determine sea area boundaries, topographic height reference, a reference in the delimitation of the marine management area and coastal boundaries, a basis point for maritime boundary determination, etc. From the total 99,093 km, approximately less than 10% had mapped. The traditional method of coastline determination is less effective due to time, cost, and amount of sample points, so it needs another approach to accelerate it. PKLP has recently started to utilize Topo-Bathymetric LiDAR technology for 1,000 km coastline determination.

The coastline can be determined when a digital terrain model (DTM) that represents the seamless terrain profile of land to the seabed and a sea surface dynamics model (tidal datum) is available. A bathymetric map is currently produced by a single/multibeam echo-sounder mounted on the vessel. A
topographic map obtained from the digital photogrammetric technique, or topographic LiDAR system mounted on the airborne platform. These two mapping techniques have limitations in the coastal area due to the shallow water. The vessel cannot go through to this area, and the wavelength used for the sensor system in Photogrammetry (visible light) or Topographic LiDAR (near-infrared) is not suitable for seabed mapping. The additional LiDAR sensor at the green wavelength, which can penetrate the water column, is then employed to overcome this problem. How deep it can go through will depends on the water clarity and ripple of the water surface. Combining two sensors at near-infrared and green wavelength, Global Positioning System (GPS) and Inertial Measurement Unit (IMU), in one platform is becoming a new solution for mapping in the shallow water area. This system can be called as Topo-Bathymetric LiDAR system. As a complement, a digital camera integrates with the system to provide mosaic photos which are useful for the points classification.

In general, the system works in the following way. The technology uses an active remote sensing system approach. It utilizes two sensors for range measurement, emitting and recording reflected electromagnetic waves from an object on the earth's surface at the narrow footprint. The two laser sensors emitted light at the same time. The near-infrared signal returns to the system when it hits a water surface, which provides the aircraft's height above the water surface. The green signal continues to travel through the water column to the seabed. Depth measurements are based on the differential arrival times of the reflection of the laser beam from the air/water interface or "surface" and the seafloor "bottom" [1]. The system records the time difference of emission and return signal. The distance between the sensor and reflecting objects can be calculated by multiplying it by the speed of light. The GPS and IMU devices are used to determine the 3D position and orientation of the laser sensor at each signal transmission. The reflecting object position is then computed from this three information. The LiDAR measurement provides a three-dimensional point position that contains the planimetric location and elevation of reflecting objects. This data is usually called a point cloud. Digital terrain model and seabed profile or other objects such as buildings, trees, sea plants, underwater objects, etc., extracted from points cloud. Often, a point does not represent a necessary object, so it should be filtered out. The energy decreases when the signal goes through due to refraction, scattering, and absorption, which attenuate the return signal. It can be run out of energy before reaching the seabed floor. This condition limits signal depth penetration. In addition, other disturbances that affect the quality of the data is suspended particle or material in the water column that reflects the signal like it comes from the seabed.

2. Data and procedure

2.1. Project area and equipment
The project is located at two different islands around the Sunda Strait, one in Java Island on the west and south coast, and the other in Sumatera Island on the southeast coast, as shown in red marking on figure 1. The data acquisition survey started on 24 Oct 2020 and finished on 26 Dec 2020. The data processing plan is to finish at the end of 2021. The workflow starts from the data acquisition to coastline delineation, as shown in Figure 2 with its explanation in section 2.2. The main characteristic of these coastal areas is shallow water with relatively gentle waves and some estuary [2]. The coastal morphology consists of plains, hilly and mountainous with ramp slopes, wavy to steep. Most of it is coastal plains, and some are alluvial.

The Topo-Bathymetric survey equipment uses a Leica DragonEye system modified with an additional green wavelength laser sensor and camera RCD30 integrated as one platform equal to Leica Chiroptera II. This system was installed on PAV 100 Gyro Stabilizer Mount in single-engine Grand Caravan Aircraft fuselage. The system produces points cloud, aerial digital photographs, including trajectory and exterior orientation. The GNSS dual-frequency system uses to determine check and control point coordinates. Lever arm or offsets a center of the sensor determines using total station measurement. Computers with high processing capability and ample storage are employed to handle various and massive amounts of data. Data processing utilizes Leica Survey Studio, Hxmap, Inertial Explorer, and Terrasolid software.
2.2. Procedure

This section explains the process steps of making DTM that covers land and seabed by utilizing airborne topo-bathymetric LiDAR technology for coastline determination. The workflow can be seen in figure 2. A preliminary survey was conducted to ensure the field conditions were suitable for project execution. In the preparation stages, activity started in administration matter and continues to technical plan comprise of flight index, distribution locations of a base station, Secchi depth, boresight calibration area, check, and control points.

Data acquisition can be divided into three main activities: Secchi depth measurement, point positioning, and airborne Topo-Bathymetric LiDAR survey. Secchi depth is a measure of water transparency. It correlates with the effectiveness of laser beam penetration and is represented as a number. A small value means low penetration results in difficulties on seabed identification. The airborne survey considers this information to avoid getting bad data. A lever arm measurement and boresight calibration were done before airborne data acquisition. The lever arm is defined as the differences of Inertial Measurement Unit (IMU) center, Global Navigation Satellite System (GNSS) phase center, and sensor (camera & LiDAR) center. Boresight calibration is a process of determining differences in the rotations of the sensor rotational axes and the rotational axes of the IMU. These correction values, along with GNSS and IMU data recorded during airborne data acquisition and base-station data observation, are used in the trajectory data processing. The laser range information combines with the trajectory data produces a georeferenced point cloud. The digital photo obtained from an aerial camera, injected with exterior orientation extracted from the trajectory, produces mosaic photos.

The georeferenced point cloud consists of topography and bathymetry region. The data on the topography region is filtered to eliminate noise and classified the points representing the ground surface. The bathymetry data process starts with optimizing a sea surface, and the depth estimation is determined from this information. The point cloud, which represents the object under the sea, is extracted from waveform signal processing. The way of deducing water depths of bathymetric LiDAR data is to calculate the time difference between the surface and the bottom returned energy peaks [3]. Sometimes many points cloud does not represent the seabed, usually occurs in the turbid water area, and this thing is reduced/eliminated by applying turbidity removal algorithm. Afterward, the data is filtered and cleaned from points that do not represent a seabed. The two datasets then merge to produce seamless topo-bathy data. The coastline is delineated from this dataset after it transforms into geoid and tidal datum correction applied.
Figure 2. Workflow of Topo-Bathymetric LiDAR processing for Coastline Determination
2.3. Data Acquisition

There are three parallel activities of data acquisition that are done parallelly [5]. First, the aerial survey started with the boresight calibration. The survey was carried out at two different locations, Bekasi and BSD Tangerang. For this purpose, the aircraft have flown in two sets of a line perpendicular to each other. The footprint overlap between lines is 30%. The GCP is distributed at the cross-region of the line perpendicular, the end, and along the line. Lever arm measured in the airport to obtain offset correction value. Afterward, the airborne data acquisition survey started from a coastal area in the western part of Java Island which belongs to the Banten Province that covers Merak, Anyer, Tanjung Lesung, Ujung Genteng up to Pelabuhan Ratu. This area finished in 31 days. The survey then continues to Lampung Bay and a small portion in Semangka Bay that belong to Lampung Province at the southern part of Sumatra Island that finished in 21 days. The aircraft has flown at 600 m above the terrain with constant altitude flying mode. The flight line direction is parallel to the coastline and adapted to the shape of the coastline. The sample of the flight line is illustrated in figure 3. The coverage varies in width between 0.5 – 6 km. The average LiDAR data density is more than 10 ppm for land area and 1 to 4 ppm for seawater areas. The aerial photo ground sampling distance was 8 cm with 60% overlap and 25% side overlap. The aerial data acquisition was completed in 52 days, taking 168.85 flying hours with 9,506.66 km in 573 flight lines.

Second, the Secchi depth measurement was conducted in several places along the coastline. This survey identifies a location with turbid water or other suspended material in the seawater column and makes sure the water is clear enough for light penetration. The sample is taken from a location close to a seashore, port, or jetty. The distribution is shown in figure 4. The Secchi depth value varies from less than 1m, 2m, 3m up to more than 3 for each location.

Third, the determination of ICP coordinate and base station observation. The GNSS dual-frequency is used for this purpose. The ICP was calculated to nearest Continuously Operating Reference Stations (CORS) with radial network and differential static post-processing. The time observation for ICP determination is around 1 hour. The ICP was placed along the coastline at unequal intervals. The data of base station observation was used for trajectory adjustment. Every flight line of the aerial survey is within a 40 km radius from a base station. There are a total of 6 base-station and 57 ICP distributed within the project area, the overview shown in figure 5. In addition to ICP, there is 271 transect shoreline in Mutun Beach the Lampung. The point distribution and survey activity are illustrated in figure 6.
2.4. Data Processing

The trajectory is essential data; it provides the position and orientation of a sensor while measuring a range between sensor and reflected object. Improper trajectory processing leads to the inaccurate point cloud. The trajectory processing and refinement use Inertial Explorer software. The input is data from the IMU and GNSS system included base-station observation. A single base-station differential processing method with an elevation mask within 10° to 15° and a Tightly Coupled (TC) option are chosen [6]. The sample overview of trajectory data quality is shown in figure 7. It provides accuracy within 10 cm. The refined trajectory and laser range data is used as an input for point cloud generation in the Leica LiDAR Survey Studio (LSS) software, as shown in figure 8.

![Figure 7. Trajectory data quality overview](image)

![Figure 8. Point cloud in sea region, (a) top view, (b) cross-section view, and (c) point view](image)

The data is processed each flight line for editing and waveform analysis. Figure 9(a), showing a schematic green waveform (in red) from the bathymetric sensor, the first peak on the left represents surface return equal to the sea surface and the other second-best peak on the right representing bottom return equal to the seabed [1]. There are four parameters for waveform data analysis, as shown in figure 9(b), which are the backscatter threshold (A), backscatter threshold slope (B), maximum amplitude threshold (C), and minimum amplitude threshold (D). These parameters should be determined in such a way so that the threshold passes through the first peak and cuts off at the best second peak, as shown in figure 9(c). For example, the threshold value can be changed when the default parameter value doesn't provide LAS Shallow 4X, or the data result is too sparse in a
particular area. Four parameters with a certain threshold value are used to find the best result. The parameters are a backscatter threshold value within 3,000 to 1,500, the backscatter threshold slope value within -5 to -25, the minimum amplitude threshold value within 500 to 350, and the max amplitude value within 3,000 to 750. The process runs iteratively to provide a result [6].

![Image](a)

![Image](b)

![Image](c)

**Figure 9.** The waveform graphic overview

Figure 10 illustrates a generated point cloud from the two different threshold values. Figure 10(a) shows a point cloud generated from the default parameter value, and figure 10(b) is generated from the adjusted parameter value. The total amount and point cloud density are increased, but the adjusted result produces quite a lot of noise in the water column. Thus, the proper value parameter needs to be determined to produce the best data. The bathymetric point cloud is then produced based on this parameter value. The water refraction index is essential for a bathymetric sensor; it is used to compensate for the coordinate displacement due to water and calculated from water temperature, water salinity, and laser wavelength. LSS provides a calibration and matching tool used to correct errors in the sensor mirror and roll, pitch, yaw sensor orientation [6].

![Image](a)

![Image](b)

**Figure 10.** Cross-section view of LiDAR data, (a) default, (b) adjusted.

The process then continues to the point cloud data classification. Ground and seabed points are identified and extracted from the dataset separately. Adaptive TIN was applied for automatic ground points classification after the noise had been filtered. The manual classification was conducted to cleaning both data and then merge them. Figure 11 illustrates a sample overview of green waveform data, generated point cloud, and aerial photos of the same area. The mosaic photo is obtained from georeferenced aerial photos. The photo exterior orientation is extracted from the trajectory data; till this stage, all the data is processed in the ellipsoid reference system.

For the coastline determination, the process started from DTM transformation to model geoid EGM 2008 then apply tidal datum correction. The tidal datum reference is calculated based on the ocean model simulation adjusted to the local tide station. The DTM with zero height value obtained from this process is a Mean Sea Level (MSL). The Lowest Astronomical Tide (LAT) and Highest Astronomical Tide (HAT) are determined using the same approach. The coastline of those three was then delineated.
accuracy assessment was conducted on the data by looking at the difference with ICP, including the transect shoreline.

Figure 11. Data overview, (a) waveform, (b) point cloud, and (c) aerial photo.

3. Result
The vertical accuracy assessment of DTM produced from topo-bathymetric LiDAR technology is conducted on three different groups [4]. Two groups are in the land region consisting of 16 ICP and 12 ICP and one group in the shallow water area, consisting of 271 transect points. The result is shown in table 1. A sample overview of DSM and DTM profile is shown in figure 12, a sample of coastline overview is shown in figure 13 and figure 14, and a sample of photo mosaic is shown in figure 15.

| Group | Number of points | RMSE  | LE 90 |
|-------|-----------------|-------|-------|
| 1     | 16              | 0.127 | 0.21  |
| 2     | 12              | 0.154 | 0.25  |
| 3     | 271             | 0.237 | 0.39  |

Table 1. Vertical accuracy assessment result

Figure 12. DSM profile (a), (c), (e) and DTM profile (b), (d), (f).
Figure 13. Coastline, (a) LAT, (b) MSL, (c) HAT and (d) Combination of Three

Figure 14. Three types of coastlines (LAT in blue, MSL in purple, and HAT in green)
4. Conclusion
The three types of coastlines (HAT, MSL, and LAT) can be determined from the Airborne Topo-Bathymetric LiDAR point cloud data with provided workflow. The accuracy assessment shows that vertical accuracy LE90 is between 0.21 – 0.39 m, which met national map standard PerBIG No. 1 Tahun 2020, for large scale map.

5. Acknowledgment
The authors gratefully acknowledge to Marine and Coastal Environment Mapping Centre – Geospatial Information Agency for the data and information used in this paper. We would also like to thank our colleagues in this institution for their support, especially for the center head, Mr. Y. D. Sigit Purnomo.

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