Mapping of archaeological structure along east-coast of Aceh Besar District, Indonesia based on total magnetic field anomalies

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Abstract. The coast of Aceh along the northern tip of Sumatra had an important role since the beginning of the first millennium AD. The area was used as a transit point for the maritime silk road of the gate of the Malacca Strait. Many old settlements and ancient fortresses were found on the area. One of them is Indrapatra fortress. At present, the Indrapatra fortress has been slowly damaged by weathering and was also hit by disasters. Parts of the main building is still intact, while the other parts have been damaged and buried by sand deposits. In order to preserve the building, some actions need to be taken such as re-mapping the existence buildings and the buried parts as well. For this reason, a geomagnetic survey has been conducted to delineate the remains of the building at the subsurface. Data of total magnetic field intensity were acquired in an area of 31,255 m\textsuperscript{2} with a grid of 3 meters for each station so that the measurement covered the whole area of the target site. Total magnetic field anomalies were calculated using diurnal and International Geomagnetic Reference Field corrections. The obtained anomalies represent magnetic objects (archaeological structures) which buried beneath the surface. To obtain a more detailed form of anomalies several transformations, such as analytic signals, tilt derivatives, and horizontal derivatives were applied. The results of the transformations show several circular and elongated anomalies. The circular forms of anomalies are considered as buried wells, and the elongated forms are considered as channels which presumed connected the buildings in the area. The data showed that there are also foundations of the buildings made of stone structures cemented with lime plats.

1. Introduction

Many archeological structures are found along the east coast of Aceh Besar Regency of the Aceh province, Indonesia. The large number of archaeological sites have proven that the coastal area of Aceh was an important part of the maritime silk road in Southeast Asia in the past. One of the structure is the Indrapatra archeological site, which is alleged to have been used as a fortress and trading center located at the gate of the Malacca Strait. The Indrapatra site is situated near the beach of Ujong Batee, Ladong Village, Masjid Raya Sub-district. Today, the structure has been damaged because of weathering, seawater intrusion and natural hazards (e.g earthquakes and tsunamis). Some buildings in the area have been damaged and buried by sand deposits [1]. In order to preserve the archeological site, the damaged and buried buildings need to be reconstructed. The reconstruction process can be done if the location
and shape of the building structure in the area are known thoroughly. Archeological research needs to be carried out for the reconstruction processes.

In archaeological studies, archaeologists usually use excavation method. This method will be time-consuming, expensive, and ineffective [2]. This happens because the location of the buried structure cannot be identified properly, so the excavation is not always carried out in the precise location. Therefore, the geophysical method should be carried out as a reference to choose right excavation sites in the area [3]. Geophysical methods are able to specify the location of structures below the surface very easily. Moreover, the method is one of nondestructive method [4, 5]. So that this method can be used as an initial stage in archeological studies. Geophysical methods can map structures based on anomalies derived from objects on the site [6]. Information obtained from this method can be used as a reference in carrying out excavations. One of the effective geophysical methods used to identify ancient objects is the magnetic method [7, 8].

Magnetic methods are often applied in archaeological studies [9, 10, 11, 12]. This method is beneficial for large areas because the measurement process can be performed rapidly. In addition, to map the subsurface structure with this method, a qualitative interpretation is sufficient. The interpretation process can be done quickly and the results are able to delineate subsurface structures. The qualitative interpretations which suitable to determine the location of an object are derivatives calculations, such as horizontal derivative and tilt derivative [13, 14]. Calculation of these derivatives can sharpen the edge pattern of objects which are under the surface [15]. In addition, further image processing methods can be used to obtain a better map [16]. The position of the obtained structure will be compared to the results of mapping using aerial photographs.

![Image](image_url)

**Figure 1.** Map area of study overlaid with Unmanned Aerial Vehicle (UAV) imagery. Parts of the fortress structures that are still visible in the middle (A), east (B), southeast (C) and northwest (D). The inset image on the right is the city of Banda Aceh (top) and Sumatra (bottom), the location of the research is indicated by the red dot on the map Banda Aceh. Grid points in UAV images represent the distribution of measurement stations.

### 2. Materials and Methods

Aerial imagery obtained from Unmanned Aerial Vehicle (UAV) has been used to obtain an overall view of the area of the study (Figure 1). Some buried structures were expected at western and southern part of the fort A. Measurement stations were designed based on the aerial photograph.
Figure 2. Total magnetic field anomaly map (a) after analytic signal transformation (b), tilt derivative (c), and horizontal derivative (d) calculations. Existing structures and predicted archaeological object are indicated by red and white dashed rectangle, respectively. The measured data do not reflect the existence of archeological objects near the surface directly. The Magnetic field data from subsurface structures was obtained by reducing measured data with magnetic field influences from diurnal and International Geomagnetic Reference Field (IGRF). Corrected data should be able to show subsurface anomalies, but for low-magnetized areas such as Aceh requires further data transformation processes. The transformation process applied in this case including analytic signals [17], horizontal derivatives [18], and tilt derivative to change the magnetic dipole properties to monopole. The horizontal derivative [19] and tilt derivative [20] are able to show the form of anomalies from the edges of objects below the surface.
The magnetic method works with the principle that each sub-surface and object has magnetic interference. Based on this principle, this method does not only measure the influence of magnets from the structure but also responds to all magnetic effects in the area. Thus, to obtain a clear magnetic response from archaeological objects, measurements were made using equipment that has high accuracy and the distance between measurement stations were designed more closely. Total magnetic field anomaly data were collected using Proton Precession Magnetometer (PPM). The instrument has a sensitivity of 0.1 nT, therefore it is suitable to probe archaeological objects that are buried near the surface. The data were collected sequentially from the west to east sides of the fort with a distance of 3 m between stations (Figure 1). The total stations were obtained 4010 points with an area of 31,255 m².

3. Results and Discussion
The total magnetic field anomaly map clearly illustrates the position of fortress A (Figure 2 (a)). The map is in agreement with UAV image (Figure 1), the position of the A fort anomaly is in the exact same position. It means the data able to delineate the structure of the fort. The magnetic field obtained shows high values on the walls of the fort. However, the data does not show the same pattern on the northwest and southeast side of A fort anomaly, which are the C and D fort. The anomaly pattern at both forts do not explain the existence of the fort on the spot. This difference in the pattern of magnetic anomalies may be due to the state of the fortress. Based on the position of the two fortresses, there are canals around the buildings. Water intrusion from canals can damage the composition of the building. If the composition of the building changes, the magnetic field response obtained is also different. In addition, the pattern of anomalies in the two fortresses is not visible because the data are in dipole effect. Anomalous patterns around Fort A also look very abstract, which might also be caused by dipole effect of magnetic field. Maximum total magnetic field anomaly measured at low geomagnetic latitude does not directly indicate the position of the anomalous object because of the dipole effect. This effect was overcome by using analytical signal calculations.

The result of the analytic signal shows the condition of the fort A more clearly (Figure 2 (b)). In addition, abstract patterns around Fort A are neater. Analytical signal data shows a new anomaly in the south of fort A. The values obtained generally are low, but there are several anomalous distributions that have high values at the south. The anomalies with high magnetic values mean that objects under the surface have high magnetic properties. Thus, the object may be a structure. However, to show an anomaly was a structure, it was necessary to know the shape of the object. The same case also occurred anomalous patterns in the C and D fortresses. In both areas, there is an unclear pattern of anomalies. In the C fort area, unclear anomalous patterns can be caused by vertical anomalies. However, the shape of the structure shown by the anomaly will be clearer after the data were applied to the horizontal and tilt derivative filter.

The tilt analysis results show clearly the structure shape below the surface (Figure 2 (c)). The results of this filter have a value between -1.4 and 1.4. This value indicates that the area of -1.4 rad (greenish) and 1.4 rad (bluish) is an area with a surface layer having different magnetic properties from each other. Based on this difference in value, the boundary formed by the two surface layers is not the effect of the structure of the building. The results of this filter also show other structures in the research area. Other structures found in this area are circular and elongated. This circular structure is considered as an anomaly of wells below the surface, while the elongated form is a channel shape. The structure of some parts is not clearly visible because of the effect of changing the nature of the surface magnet. The invisible structure was properly mapped by the Horizontal derivative filter (Figure 2 (d)).

Horizontal derivative filters indicate anomalies based on the boundary of a structure. The results of this filter show the locations where buildings C and D (Figure 2(d)). In addition, this filter shows other abstract patterns within the fort area, which indicate other structures in the building. Horizontal derivative data also shows the existence of other wells in the south-eastern part of the study area. The location of the well is right at the location of the well found from the excavation [1]. Based on historical information, there were many distributed wells in the Indrapatra site area. The wells were water source
in this area. In addition, abstract patterned structures in the data do not look like structures formed by natural activities. Therefore, the structure is assumed to be part of a buried building.

4. Conclusion
The current state of the Indrapatra cultural heritage site is different from the real form in the past. At present, there are only a few buildings exist in the area. The magnetic field anomalies successfully located other structures buried on this site. These buried structures are ancient wells, channels and the remnant of buildings. These buried structures need to be excavated and repaired because they are located on the shore which flooded during a high water, so that the rescue of this site must be a priority. The intrusion of the sea water will cause damage to the buildings.

The similar threat also applies to other ancient buildings located along other coastal area and similar magnetic interpretation procedures can also be applied. This magnetic interpretation process is qualified to map similar subsurface structures, especially in the coastal areas of Aceh.

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