Comparison of Airborne Electromagnetic and Ground-based Resistivity Observations: Case Study Banda Aceh Basin

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Abstract. Airborne measurements are very useful to cover very large areas. Nine month after the Aceh Tsunami and Earthquake in 2004, BGR (Federal Institute for Geoscience and Natural Resources) conducted a fresh water supply exploration survey within a project called Helicopter Project Aceh (HELP ACEH). The helicopter-borne electromagnetic (HEM) device operates at five frequencies. The HEM can estimate the 1D resistivity models down to a depth of 150 m for the high electrical resistivity areas and 50 m for low electrical resistivity areas. In this paper, the airborne data of 2005 are compared with resistivity data acquired in Banda Aceh basin in 2018. The HEM output consists of 1D resistivity models derived by inversion of the processed data. These 1D resistivity models are compared with the 2D resistivity models derived from ground-based resistivity measurements. However, the 2D models on the ground are transformed into 1D resistivity models so it can be used for comparison. The transformation is conducted by averaging the resistivity values in the each layer, so every layer only has one resistivity value. Both methods are influenced by many factors. For example, resistivity on the ground is affected by local conditions. The airborne measurements are also influenced by objects that are at the surface of the ground. In some cases, the airborne resistivity models have some differences in absolute resistivity values, but they often have the same structural pattern compared with the ground-based resistivity models.

1. Introduction
Geophysical parameter measurements can be carried out on surfaces, move on surface, above surfaces, and in the subsurface by ground-based, vehicle-based, airborne and borehole measurements, respectively. A common ground-based method to derive the resistivity of the subsurface is direct-current geoelectrics with all its variants, which require current injections into the earth and voltage measurements at the surface. Measurements that are not in direct contact with the surface are very useful because there are less logistical problems. Vehicle-based measurement such as VLF [1] can cover very long route from in tens to hundreds km in short time. Airborne measurements such as helicopter-borne electromagnetics (HEM) [2] can cover very large areas in short time. Such airborne electromagnetic measurements have been carried out in the Banda Aceh basin between August 23 and September 12, 2005, within the HELP ACEH (Helicopter-Borne Geophysical Investigations in the Aceh Province, Indonesia) project, which was able to cover an area of approximately 1000 km² [3][4].
HELP ACEH covered three quite extensive areas, Banda Aceh basin which included the City of Banda Aceh and the Aceh Besar District, Calang–Meulaboh[3] and Sigli [5]. The purpose of the survey was to find areas with potable water after the tsunami 2004. Therefore, the studies focussed on hydrogeology for subsurface water mapping. However, the large dataset of the covered areas, which also include magnetic and radiometric data, might be very interesting, when used for other applications [6], such as determining soil liquefaction conditions, carrying capacity of the soil, bed rock mapping [7], determining Vs30 for shakemap [8], and structural sediment for Neo-Deterministic Seismic Hazard Analysis (NDSHA) [9]. It might be also used to determine active faults around Banda Aceh Basin [10][11]. In this paper, we discuss a comparison of airborne and ground-based resistivity models.

2. Methodology
HEM resistivities are derived from measured secondary electromagnetic fields caused by the induction of primary fields, which interact with ground material of earth’s subsurface as shown in Figure 1a. Each primary electromagnetic field is generated at a discrete frequency by a transmitter coil (T), and a receiver coil picks up the secondary electromagnetic field [12]. A bucking coil cancels out the direct primary field at the receiver and a calibration coil helps to get accurate data. All coils are installed in a tube (“bird”) with a length of about 10 m and a diameter of 0.5 m. The shell of the bird is made of Kevlar, a material that has extremely high mechanical stability and poor electric conductivity. This system (Resolve) was manufactured by Fugro Airborne Surveys (FAS), Canada [12] The digital electromagnetic system in horizontal-coplanar coil configuration is operated at five discrete frequencies as shown in Table 1.

| Frequency  | 387 Hz | 1820 Hz | 8225 Hz | 41.550 Hz | 133.200 Hz |
|-----------|--------|---------|---------|-----------|------------|
| Wavelength| 775km  | 164.8km | 36.47km | 7.22km    | 2.25km     |
| Band name | ULF    | ULF     | VLF     | LF        | LF         |

The bird is connected with the helicopter by a cable of approximately 45 m in length and towed about 41 m beneath the helicopter, depending on the flight speed. This length of cable is chosen to largely reduce the influence of the helicopter on the highly sensitive magnetic and electromagnetic sensors. The average flight altitude of the HEM sensor was 60 m above ground and the normal survey speed was 110–165 km/h.

Three altimeters (radar, laser, barometric altimeter) are used. The radar altimeter is installed beneath the nose of the helicopter to get the distance of the helicopter to the surface. Besides, the laser altimeter is used for getting the altitude of the bird above the ground. The barometric altimeter is used for correction of GPS elevation data and to get air-pressure values. GPS systems are in both the helicopter and the bird to get precise navigation and position data.

The 20 km x 50 km survey area between 95°13'E to 95°44'E and 5°13'N to 5°37'N covers Banda Aceh as well as the valley of Krueng Aceh river,. A flight-line map of the northwestern portion of the survey area is shown in Figure 1a. There are 163 profile lines (red lines) in SW–NE direction and 24 tie–lines flown (green lines) in SE–NW in the entire survey area. The total length of the profile lines is about 3960 line-km [14].

The airborne electromagnetic data are stored per site along the survey lines as shown in Figure 1b. The inversion calculation is done per point providing inverse 1D models by using Levenberg-Marquardt inversion [15][16][17]. The data file with the inversion models [14] contains more than 900,000 1D resistivity models, so it has been necessary to create an AWK [18] script to retrieve the closest 4 sites to the sites on the ground which check for all profile and tie-lines. All four 1D profiles are plotted using gnuplot [19] together with a ground-based resistivity model as seen in Figures 3,4 and 5.
ERT (electric resistivity tomography) or direct-current geoelectrics is a standard method for resistivity measurements directly at the surface of the earth by injecting an electric current and installing other electrodes to measure the subsurface voltage [20]. The data acquisition in the field is carried out using SuperSting R8/IP resistivitymeter (Figure 2a) with Wenner-Schlumberger array. The data are obtained from SuperSting R8/IP are saved to the computer and converted for inversion with res2dinv [21]. An example is shown in Figure 2b. The output is a 2D resistivity model that is converted into an averaged 1D model using an AWK script as shown in Figure 2c. In this paper, 9 ground-based resistivity datasets are discussed as shown in Table 2 which will be compared with the inversion results of helicopter-borne electromagnetic resistivity results.

**Figure 1.** (a) BGR’s airborne geophysical survey system [14] (b) HELP ACEH airborne flight lines for Banda Aceh basin overlaid with the sites of the resistivity measurements on ground.

**Figure 2.** (a) Resistivity measurement at the KRA site. (b) Processing the resistivity data using res2dinv software generates 2D profiles. (c) 1D resistivity model derived from 2D model.
Table 2. Location of ground-based resistivity measurements

| No | Site Label | Longitude   | Latitude   | Note       |
|----|------------|-------------|------------|------------|
| 1  | LNY1       | 95.36052    | 5.57290    | Lamyong Bridge |
| 2  | LNY2       | 95.36004    | 5.57261    | Lamyong Bridge |
| 3  | KRA        | 95.39887    | 5.52852    | Cave Bunker |
| 4  | JLK1       | 95.34335    | 5.57856    | Jeulingke |
| 5  | JLK2       | 95.34235    | 5.58226    | Jeulingke |
| 6  | JLK3       | 95.34104    | 5.58896    | Tibang |

3. Result and Discussion

This paper shows the comparison of ground-based resistivity models using direct-current resistivity methods and resistivity models derived from airborne electromagnetic measurements. Figures 3 and 4 show overlaid sections of ground-based and airborne resistivity models (taken from closest four locations).

![Figure 3](image)

Figure 3. Plotting the ground-based (Terrain) and airborne resistivity models (Airborne1-4) for Lamyong Bridge at sites (a) LNY1, (b) LNY2, and Japan’s Bunker Cave at site (c) KRA.

In Figures 3a and 3b, a comparison is shown for the Lamyong Bridge site and in Figure 3c for the Cave Bunker site. The point measurement is near enough, where an airborne profile is fluctuating. The layers have some differences, but the fluctuation of the airborne resistivity is around the value of ground-based resistivity. The penetration of ground-based values can exceed 40 m, but this is not plotted to focus more on the penetration of the airborne data, which is limited here to less than 40 m.

Figure 4 shows a comparison for locations that are relatively close at Lingke area. There, the penetration of airborne data is limited to about 10 m depth due to very low (< 1 Ωm) resistivities caused by salt water. Because of the skin depth effect, the airborne electromagnetic method did not successfully probe the area below the surface, so it was clear that the airborne resistivity value was relatively smaller than the value of terrain resistivity. Especially for the JLK2 site, there seems to be a bit of a curve in the pattern formed.

Generally, the comparison shows that the models are relatively close at all sites. Figure 3c shows high resistivity values, because the measurement area of the ground-based measurement is just above the bunker cave. Thus, the local conditions greatly influence the results of the ground-based resistivity measurement, while the airborne resistivity is derived from a larger area.
4. Result and Discussion

The resistivity distribution in the subsurface, particularly at shallow depth, determines the penetration depth of airborne electromagnetic fields. If the resistivity value at shallow depth is low, then the skin depth effect will inhibit the electromagnetic fields from deep penetration and, thus, the results of inversion will produced shallow models. However, if the shallow resistivity values are high, electromagnetic fields can get deeper into the earth and the inversion will resolve deeper parts. The opposite effect is observed for the results of the ground-based resistivity method as low shallow resistivities still enable deep penetration, but high resistivities are problematic. This finding confirms that electromagnetic methods are sensitive to conductivity and direct-current geoelectric methods to resistivity. Local resistivity variations affect ground-based measurements stronger than airborne measurement due to the generally larger footprint of airborne measurements. On the other hand, electromagnetic measurements are always affected by anthropogenic installations containing highly conductive material (metals) such as buildings, fences, power lines, or roads tracks. This cultural noise can be excluded (and interpolated) during HEM data processing, but this was not done in 2005. Geoelectric methods are less sensitive to such anthropogenic effects. In this study, the number of measurement on the ground was limited and needs to be expanded to more sites for a better comparison. Furthermore, one has to pay attention to rainfall factors or ground moisture and differences due to near-surface saltwater effects caused by the tsunami of 2004.

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