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THREE-DIMENSIONAL MAPPING OF STATIC MAGNETIC FIELDS OVER A SEMI-ANECHOIC CHAMBER

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ABSTRACT
The geomagnetic field is a kind of natural potential field in the Earth. A three-year research program for exploration of this field has been conducted in the Lombok Island-Indonesia, where extreme geomagnetic anomalies with two very strong dipolar structures exist. The research aims to construct a system to collect and concentrate geomagnetic fields, in order to possibly use the concentrated fields for geomagnetic power plants or to integrate the system with a field pick-up unit scheme by means of wireless power transfer. The designed geomagnetic concentrator system has been tested in a self-arranged semi-anechoic chamber with a pair of Helmholtz coils, induced with DC currents to simulate the regional ambient static geomagnetic fields. Several tests have proven the performance of the system in one-dimensional space. This paper presents the results of detailed three-dimensional measurements of static magnetic fields in the semi-anechoic chamber. Static magnetic fields over the entire chamber are drawn in their magnitudes and directions, by interpolating data obtained in regular grids of 50cm × 50cm. In specific areas, where the Helmholtz coil is placed, extra grids of 25cm × 25cm are inserted to sharpen the fields' depictions. Results show that by inducing 1 A current on each of coils will produce magnetic fields, concentrated over the surrounding area of Helmholtz coil. The intensities of magnetic fields over this area are about 15,000–45,000 nT, which can be used to model the geomagnetic fields of Lombok Island. Using the results of 3D field mapping, it will be possible to get the optimum placement of the geomagnetic concentrator system when it is tested on the chamber.

Keywords: Anechoic chamber; Geomagnetic fields; Helmholtz coil; Lombok Island

1. INTRODUCTION
The geomagnetic field is a potential field, generated mainly in the outer core, but the fluxes penetrate over the Earth's surface and even to the ionosphere. The studies of the geomagnetic field and its extreme anomalies over the Lombok Island region in Indonesia have been continuously conducted since 2004 by a team of researchers from the Mataram University (Zubaidah et al., 2004; Zubaidah et al., 2005; Zubaidah et al., 2006). The recent survey results, carried out in collaboration with the Deutsches GeoForschungsZentrum (GFZ) Potsdam – Germany, showed a difference in the magnetic intensity of the strongest dipolar structure up to 1,000 nT (Zubaidah et al., 2007; Zubaidah et al., 2010; Zubaidah, 2010; Zubaidah et al., 2014). It will be quite beneficial when we can utilize these high intensity geomagnetic fields as a source of energy.

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Moreover, the geomagnetic fields in the Lombok Island regions can become natural sources of inexhaustible energy, while their source comes from the tectonic settings of this region, which is between two active subductions (Zubaidah, 2010; Zubaidah et al., 2014).

A three-year research program has been conducted to utilize these extreme geomagnetic anomalies as natural energy resources; hence a pioneer technological innovation on the frontier in electromagnetic research is a necessity. The research aims to construct a system to collect and concentrate geomagnetic fields, by firstly getting high intensity-high frequency dynamic magnetic fields. Thereafter, when the static fields can be converted to fields of higher frequencies, it will be possible to use the concentrated fields for geomagnetic power plants or to integrate the concentrator system with a field pick-up unit scheme by means of wireless power transfer.

The previous two-year research program resulted in a self-arranged semi-anechoic chamber and a Helmholtz coil (Zubaidah et al., 2012a), which has been recalibrated in a one-dimensional space (Zubaidah et al., 2012b). A 4-hole geomagnetic flux concentrator has been tested on this chamber, performing with good frequency response, but still only providing quite low efficiency (Zubaidah et al., 2013a). Afterward, a new (larger) chamber has been constructed to accommodate the placing of a larger system and some absorber panels, while its background frequencies have been determined one-dimensionally (Zubaidah et al., 2013b). Since we need to understand the flux concentrator system performance in all directions, therefore we conducted additional detailed three-dimensional measurements, and provided static magnetic mapping of the new semi-anechoic chamber.

2. EXPERIMENTAL

2.1. Design of New Semi-Anechoic Chamber

The anechoic chamber comes from a word of "an-echoic", means free from echo, which is a specific room designed to avoid acoustical or electromagnetic echo. This room is also isolated from outer noise sources. It was Leo Beranek (b.1914), MIT Associate Professor of Communications Engineering and an American expert in acoustics, who had firstly used this term in sound waves. Nowadays, this term is widely used in electromagnetic waves.

The physical attributes of anechoic chamber include a shielded enclosure with the entire inner surfaces covered with a wave absorber to create a non-reflecting environment equivalent to free space. When only some parts of its inner surfaces are covered with an absorber, the chamber is called a semi-anechoic one. An increasing number of low-frequency (30–1000 MHz) electromagnetic anechoic and semi-anechoic test chambers have been manufactured in recent years, due to the rapid growth in the multimedia and telecommunication industries (Chung and Chuah, 2003). Moreover, electronic devices must follow the electromagnetic compatibility (EMC) standards which impose certain conditions on the electronic devices before they can be marketed (Violette et al., 1987). Comprehensive EMC testing of these devices is conducted to determine their emissions and susceptibility levels within specially designed, shielded, reflectionless facilities, that is, anechoic chambers (Iqbal et al., 2014). Hindman and Newell (2006) report that reduced reflections of the near-fields measured data of an EMC test are apparent by using an anechoic chamber.

Figure 1 illustrates the semi-anechoic chamber used in this study, constructed by using aluminium plates as shielding materials. The plates are jointed together with iron structures and are connected by the grounding of iron plates. The dimensions of 6m × 3m × 3m are designed to accommodate the geomagnetic flux concentrator, which will be tested in the next study. The chamber is equipped with FS-400 absorbers, suitable for electromagnetic compatibility tests, ranging from static fields to dynamic fields with a frequency range of 30 MHz–18 GHz (ETS Lindgren data sheet). Figure 2 (a) shows the physical form of this chamber.

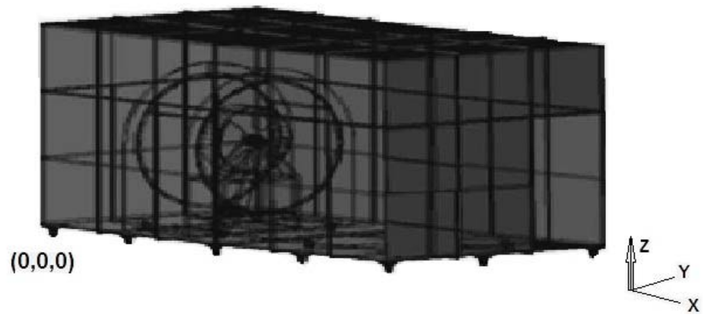


Figure 1 The new semi-anechoic chamber (6m×3m×3m), suitable for electromagnetic compatibility tests, ranging from static to some 30 MHz–18 GHz. A pair of Helmholtz coils is placed inside; its diameter is positioned in line with the y-axis, while Coil-A and Coil-B are exactly on x = 4 and x = 2, respectively.

2.2. Methodology of Fields Mapping

To conduct the static magnetic field measurements, a pair of Helmholtz coils is placed inside the chamber, as depicted in Figure 2 (b). The coils are positioned with their diameters in line with the y-axis (orthogonal to x-axis). Coil-A is exactly on x = 4 (in the front side), while Coil-B is exactly on x = 2 (in the rear side). To generate static magnetic field inductions as synthetic geomagnetic fields, currents of 1 A are driven to each coil from two separate DC power sources.

The complete specifications of coils are as follows:

Type	: Mono-axial
Number of turn per coil	: 100
Wire for coil	: 0.75 mm^2 single bare Copper wire
Total resistance per coil	: 9 ΩDC
Inner diameter	: 200 cm
Total width	: 230 cm
Distance between coils	: 100 cm
Height	: 245 cm
Construction materials	: Wood and Plywood

Five absorber panels are placed behind the measuring equipment (SPECTRAN NF-5035®) for cancellation of any possible echo during the measurements, as depicted in Figure 2 (c). During tests, all electrical parts including the magnetic field measuring equipment are controlled from outside the chamber, and monitored live by two sets of CCTV cameras. Results of the field measurements can be logged or monitored live using a MCS computer program, which can be downloaded from Aaronia AG web page (http://www.aaronia.de/).

Regular grids of 50cm × 50cm are prepared over the entire chamber before measurements. For getting accurate depictions of field's distributions, smaller 25cm × 25cm grids are added in the region between two coils (i.e. from x = 2 to x = 4). It is considered that the designed magneto-static flux manipulator will be placed in this critical region. Set-up of these grids and placement of the measuring equipment are shown in Figure 3.

For each point on the grids, measurements have been conducted for 3D total intensities and 1D component of x-, y- and z-axis. Thirty data points are taken either for the total intensities and each component, with time samplings of 3000–5000 ms, depending on the stability of readings. The readings were done by technicians, who then directly typed the readings to Excel spreadsheets for further processing.

(a) (b) (c)

Figure 2 (a) Physical form of the new semi-anechoic chamber; (b) Positioning of the Helmholtz coils inside the chamber; and (c) Placement of low frequency absorbers behind the measuring equipment (SPECTRAN NF-5035®) for cancellation of echo

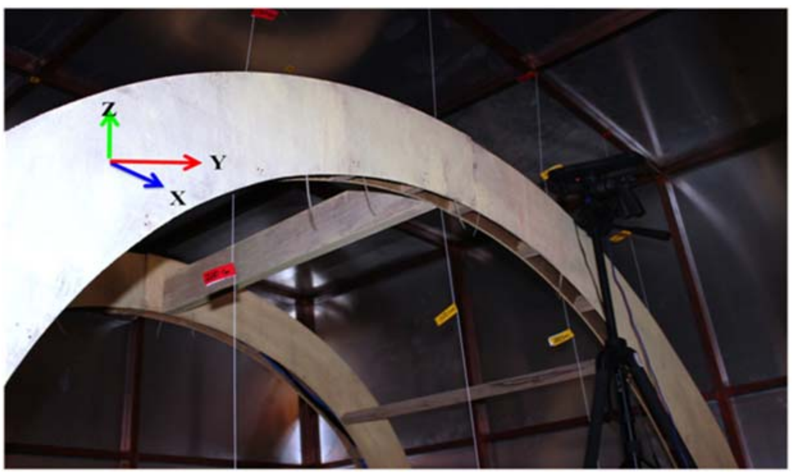


Figure 3 Set-up of regular grids of 50cm × 50cm over the entire chamber and placement of the measuring equipment. Smaller grids of 25cm × 25cm are added in the region between two coils (i.e. from x = 2 to x = 4), for getting accurate depictions of field's distributions where the designed magneto-static flux manipulator will be placed.

The data processing has been done after all measurements have been completed, including filtering the data from the outliers and averaging. The average values are stored as the input of the databases, created on the Oasis Montaj 6.4 (Geosoft Software). 3D grids are generated using Voxel menu. These grids can be expressed in forms of three-dimensional mapping, at 4 levels of each its slices, and on the iso-surface.

2.3. Helmholtz Coil

The Helmholtz coil is a parallel pair of two similar circular coils, spaced at a distance of one radius apart, wound in series such that the current passes in the same direction in each coil. This arrangement of the coil was invented by German physicist, Hermann von Helmholtz, over a century ago. The intensity of the magnetic field is directly proportional to the number of turns and the current through the coil, and which primary component of field is parallel to the axis of the coil. The uniform field within the two coils is derived from the summation of fields parallel to the axis and the difference of the vertical component fields (Gyawali, 2008).

Figure 4 schematically shows the magnetic fields induced by each of the Helmholtz coils and the corresponding total fields, which are the sum of the fields induced by each individual coil. In the region between two coils, the total magnetic fields should be uniformly distributed along the coil axis.

Detailed equations to get the magnetic fields induced by the Helmholtz coils have been derived in research by Trout (1988) and Zubaidah et al. (2012a), which can be summarized below. If a is the radius of these coils in metres, and the coil are separated by a distance of 2d metres, while N is the number of turn of each coil, the total fields along coil axis (in this case is in the direction of x-axis) will be,

$$\mathbf{B}_x = \frac{\mu_0 a^2 IN}{2}\left[\frac{1}{(a^2+(d-x)^2)^{3/2}} + \frac{1}{(a^2+(d+x)^2)^{3/2}}\right] \text{ T} \qquad (1)$$

For the centre point of coil (when x = 0), the fields are maximum, and the equation becomes,

$$\mathbf{B}_x = \frac{8\mu_0 IN}{5^{3/2}a} \text{ T} \qquad (2)$$

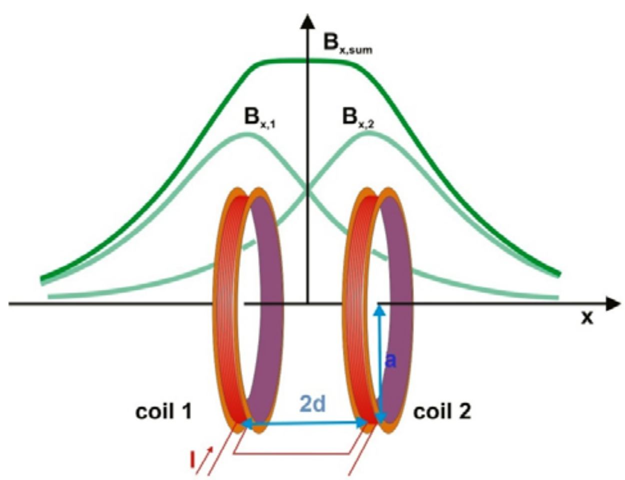


Figure 4 Schematical of magnetic fields induced by each of Helmholtz coils and the corresponding total fields. In the region between two coils, the total magnetic fields should be uniformly distributed along the coil axis. (Source: http://www.emf-portal.de/)

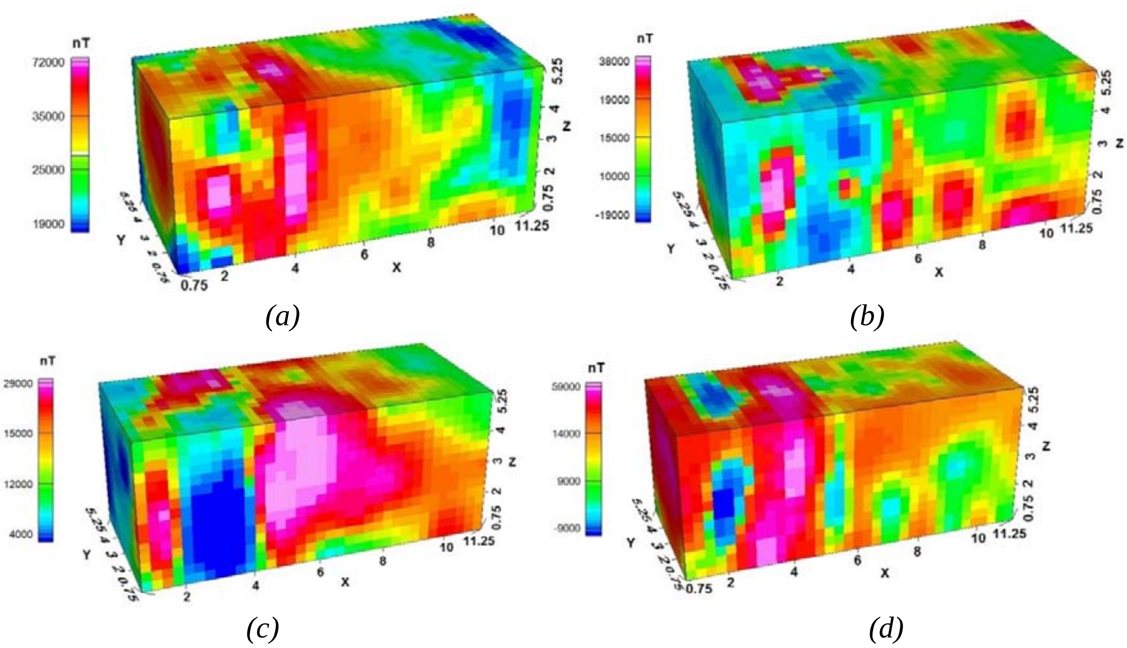
3. RESULTS

The results of three dimensional measurements of static magnetic fields over the new chamber are mapped as shown in Figure 5. As theoretically expected (EMC Test System, 2001), the maximum and homogenous distributions of the 3D total intensities are found in the region between two coils, as shown in panel (a). The other three panels show the 1D field's distributions measured along x-, y-, and z-axis. However, it is still difficult to say about the dominant components of the total fields. The slices of this 3D mapping are indeed quite helpful to determine the dominant components.

Four panels in Figure 6 respectively show the slices of three-dimensional mapping of static magnetic fields over the new chamber for measurements results of 3D total field intensities, and measurements along x-, y-, and z-axis. These slices obviously show that the maximum and homogenous distributions of the total fields are found in the region between two coils, as expected.

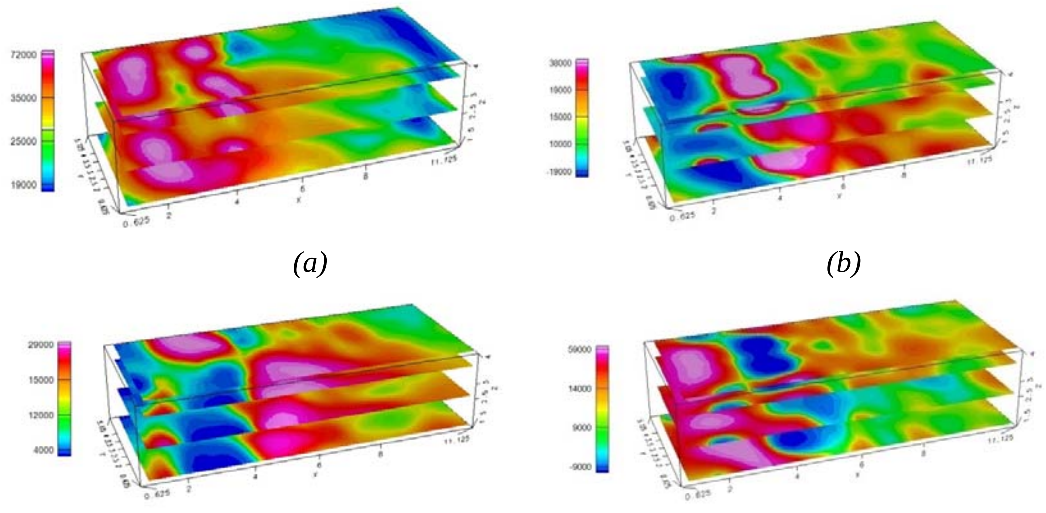
The field intensities of each component in the direction of x-, y-, and z- axis are all in agreement with theories (EMC Test System, 2001). Moreover, they show that the total fields from the centre of two coils towards the Coil-A (in the front side) are actually dominated by fields in the x-direction. Contrarily, the total fields from the centre of two coils towards Coil-B (in the rear side) are actually dominated by fields in the z-direction. The fields in the y-direction are quite minor compared to the other directions, and with only positive values. It is because, in this direction, the fields induced by each coil of a pair Helmholtz coils cancel out each other.

Furthermore, three-dimensional iso-surfaces give a clearer depiction of field distributions along each axis. Figure 7 shows these iso-surfaces of 3D total intensities and along the three axes. The surfaces of 3D total intensities obviously show that the maximum and homogenous distributions of the total fields are found in the region between the two coils, as theoretically expected. Fields in the directions of the x- and z-axis are complementary of each other, to give the total intensities' values; while fields in the direction of y-axis are less significant compared to the other two directions.



(a) (b) (c) (d)

Figure 5 Three dimensional mapping of static magnetic fields over the new chamber for measurements results of: (a) 3D total intensities; (b) along the x-axis; (c) along the y-axis; and (d) along the z-axis. Scales of magnetic intensities are in nT, while all distances are in 0.5 meters. The maximum and homogenous distribution of the total fields are found in the region between the two coils, as expected (EMC Test System, 2001)



(a) *(b)*

(c) *(d)*

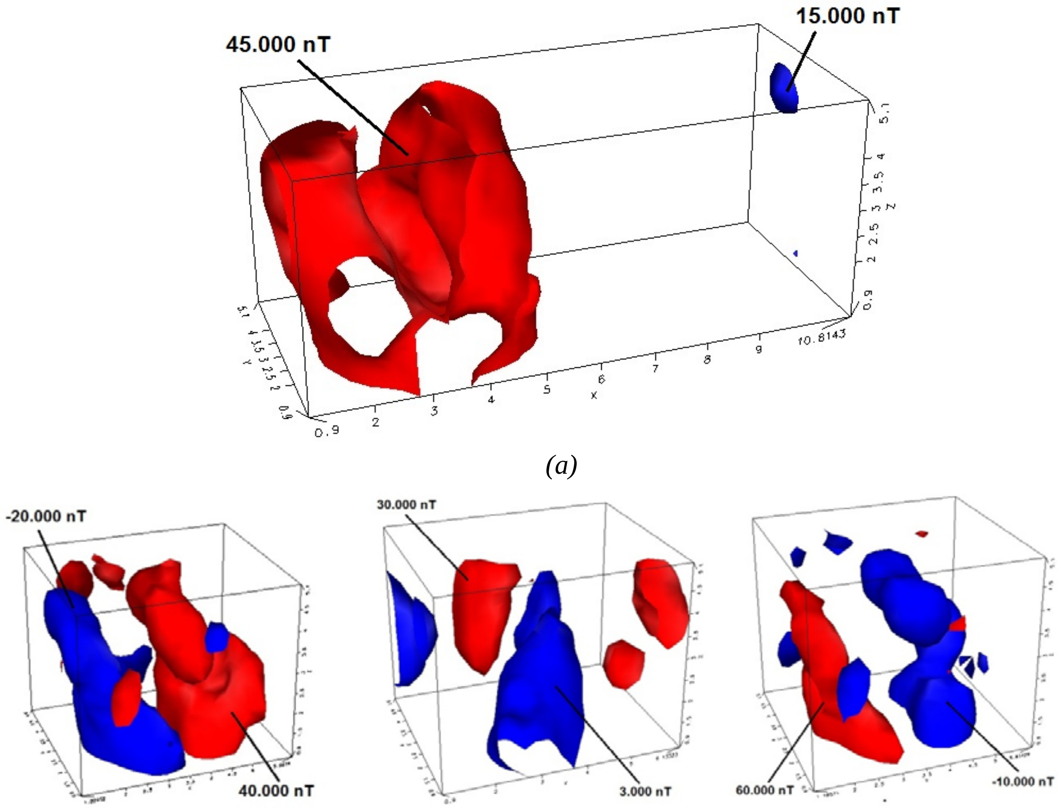
Figure 6 Slices of three-dimensional mapping of static magnetic fields over the new chamber for measurements results in: (a) 3D total intensities; (b) along the x-axis; (c) along the y-axis; and (d) along the z-axis. Scales of magnetic intensities are in nT, while all distances are in 0.5 meters. These slices obviously show that the maximum and homogenous distribution of the total fields are found in the region between the two coils, as expected. Field intensities of each component in the direction of the x-, y-, and z- axis are in agreement with the theories (EMC Test System, 2001)

4. DISCUSSION

The Helmholtz coils and the new chamber perform nearly uniform field distributions, with maximum total intensities of 45,000 nT, found in the region between two coils. These results are satisfactory, when compared to the ambient geomagnetic fields. Therefore, these results make this new chamber and the Helmholtz coils quite a realistic choice to be used to model the geomagnetic fields of the Lombok Island regions.

To be used for the testing of the designed geomagnetic flux concentrator, the system should be placed orthogonally to the x-axis, since the direction of the Helmholtz axis is parallel with this direction. Regarding the field distributions in this direction, the best placement of concentrator is much closer to Coil-A (in the front side) and far away from Coil-B (on the rear side); it also should be placed not exactly in the middle distance between the two coils where the values of total intensities are actually zero.

As previously studied (Zubaidah et al., 2012a; Zubaidah et al., 2013a), it was found that efficiency of the flux concentrator is quite low (only within 0.16%). We now are arguing that this low efficiency is likely because of mis-placement of the concentrator, which was placed exactly in the middle of the Helmholtz coils. Using the results of current study, it will be possible to get the optimum placement of the geomagnetic concentrator system in the chamber.



(a)

(b) (c) (d)

Figure 7 Three dimensional iso-surface of static magnetic fields over the new chamber for measurements results of: (a) 3D total intensities; (b) along x-axis; (c) along y-axis; and (d) along z-axis. Scales of magnetic intensities are in nT, while all distances are in 0.5 meters. The surfaces of (a) obviously show that the maximum and homogenous distribution of the total fields are found in the region between two coils, as expected (EMC Test System, 2001). The maximum total intensities of 45,000 nT makes this new chamber and the Helmholtz coil quite realistic to be used to model the geomagnetic fields of the Lombok Island regions.

5. CONCLUSION

Three-dimensional mapping over the new semi-anechoic chamber has been completed with the primary results being as follows:

1. The Helmholtz coil can induce static magnetic fields with total intensities of 15,000–45.000 nT. These values are much more suitable for modelling geomagnetic fields of the Lombok Island regions.
2. The maximum and homogenous field distributions are found in the region between two coils, however the fields in the direction of Helmholtz axis are mainly found in the area closer to Coil-A (on the front side).
3. The best placement of concentrator is much closer to Coil-A (on the front side) and far away from Coil-B (on the rear side); it also should be not exactly in the middle distance between the two coils where the values of total intensities are actually zero.
4. Getting the best placement of the concentrator will increase system efficiency.

6. ACKNOWLEDGEMENT

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