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GEOID AFTER THE ERUPTION OF MERAPI IN 2010

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ABSTRACT

Preliminary research to examine the correlation of changes in gravity to geoid has been done by observing the geoid model. Remodeling geoid has been done using gravity data after the eruption of 2010. The eruption of 2010 is the one of great eruption of Merapi volcano, where approximately 150 million m^3 of material removed. The data which used in this study is complete Bouguer anomaly 2011 data of Merapi volcano, elevation data, model of the geoid global data such as DIR 2011 and EGM 96, and also use DEM 2011 with spasial grid 15” x 15”. The method which used to calculate the value of the geoid is using the Stoke’s formula. Geoid value generated in this study is 25.5035 - 27.0835 m while the value of geoid Merapi volcano used data 1998 is 26.00 - 29.91 m. Possible changes that occur due to mass distribution below the surface due to the mass that comes out or change the topography. High value of geoid at north west and lower value at south and south east of Merapi volcano. The high value of geoid is predicted as high density or the reservoir of Merapi.

Key words : the geoid, Merapi, 2010 eruption

INTRODUCTION

One of earth science to determine the size and shape of the earth is geodesy, and geophysics is one of other earth science that to be able to know what lies beneath the earth's surface by observing changes in the value of their physical parameters such as gravity, magnetism, electricity, speed etc. However, in relation to geodesy, the geophysical method that used in geodesy is the gravity method.

The gravity method is a geophysical method that observed changes in the value of gravity at the Earth's surface. The changing of the gravity value can be intepreted as a change in the density (density) as a result of changes of the distribution of rock / mass. The gravimetry in geodesy is the geodetic survey methods relating to the determination of Earth's gravitational field. Usually the gravimetric method is used to determination of the geoid undulation. Geoid is the equipotential field of the Earth. If the earth is a homogeneous body, the equipotential plane will coincide with the earth ellipsoid. Therefore, the earth is not homogeneous so that the geoid field does not coincide with the field of the earth ellipsoid.

Geoid undulation acquired by using gravimetric method that based on measurement of gravity anomaly. There are several approaches that can be used in determining the value of geoid undulation such as Modensky, Stokes etc. Geoid undulation is nessesary to calculation because it is associate with height system network. Ortometric height determination is required in the application fields of engineering, but in the field of geophysics geoid is still a scientific discourse has been no development and application use for interpretation. In orthometric height calculating process value of geoid undulation is needed.

The Merapi is a well-known volcano located at Central Java Island, in the very heart of Java’s myth and cultural growth. The Merapi volcano, one of the most active volcanoes in Indonesia, even the most active in the world. The Merapi volcano lies on the border of Central Java and Yogyakarta (Sparks, 1981, Voight et al, Wahyunto, 2000) attracted the attention of many people of Indonesia and the world both scientifically and culturally. The Merapi volcano as one of about 129 active volcanoes in Indonesia, with some periods of eruption (Wahyunto, 2000; Soebandriyo, 2011). The frequency of its eruption made this volcano become the real and big volcano laboratory. Some eruption that happened which are major eruption by VEI (VEI is a large scale eruptions quantitatively based on the amount of material released and the height of the eruption column) occurred in 1587, 1672, 1768, 1822, 1849, 1872, 1930, 1961 and 2010 (Andreastuti, et al, 2000). Geographically, Merapi's summit located at 7°32'31.2"S and 110°26'31.2"E with height as high as 2985 m above of mean sea level (msl).

The eruption of Merapi in 2010 is estimated as a large eruption. The Merapi volcano erupted more than 18 km^3 materials and cause hundreds of casualties. This eruption might be the worst eruption since 1870. This fact then become either chance and challenge for volcanologist to study Merapi thoroughly. One of many attempts to study this eruption was done by doing gravity study. The changes at topography of the summit and the issuance amount of material that allows for large changes in subsurface structure after the eruption.

This research is pleminary study to determine the influence of gravity changes to the value geoidnya on pre and post-eruption of 2010. The aim of this paper is to calculate the value of geoid undulation by using gravity anomaly after 2010 eruption.

METHODS

The gravity survey was carried out by mapping gravity anomaly above Merapi volcano and area around this volcano. Gravity measurement, which was focused at Merapi volcano, has taken 200 measurement points with area 27 x 27 km^2. The Gravity measurement using LaCoste & Romberg type G1118 gravimeter, equipped with Geodetic GPS Trimble single frequency. Processing gravity and geoid data need some software as Excel, Geosoft, Gravsoft and Mathlab.

The processing flow is quite standard, starting with tidal correction, equipment height and drift correction to acquire g_{OBS} (observed gravity). Complete Bouguer anomaly (g_{CBA}) can be acquired using several additional corrections, which are latitude correction, free-air correction, Bouguer correction and terrain correction. Furthermore, complete Bouguer anomaly result can be projected into horizontal plane using Dampney method (1969). Processing sequence in dataset 2011 use LIDAR 2011 Digital Elevation Model (DEM) which produce by Ministry of public works with spasial grid 15" x 15".

The research of Geoid processing flow is quite standard using Stokes formula there are some steps that have done as compute model geoid global and geoid by using Fast Fourier Transform (FFT) in gravsoft software.

RESULTS AND EXPLAINATION

Gravity data was got same treatment in gravity method as correction for tide, latitude and drift. This is the simplest processing in gravity reduction data sequence the results after drift, tidal corection and mgal convertion process is *g* observation. The results show the value of *g* observation higher in the south than in the north and there are similarities with topographic contours as shown in Figure 1.

Further processing sequence is free-air correction which elevation of each gravity station plays important role in this calculation (Telford, 1990).

$$g_{FA} = 0.3086 \times h \qquad (1)$$

$$\Delta g_{FA} = g_{obs} - g_n + g_{FA} \qquad (2)$$

Where, h is elevation, g_{FA} is free-air anomaly gravity, g_{obs} is observed gravity value, g_n is normal gravity

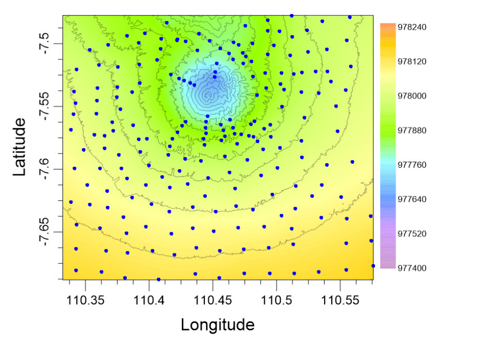


Figure 1. Observed Gravity map on 2011 gravity dataset.

Prior to simple Bouguer correction, Bouguer density need to be defined. Based on a model that has made the density of Mount Merapi is divided into three: around the slopes of Mount Merapi ranges from 2600 kg/m^3, 1800 kg/m^3 in the middle, and in the peak of density 1600 kg/m^3. The model is calculated assuming an average regional density of 2500 kg/m^3. As for the rocks in the summit area is estimated to be sandstone, tuff, fragments of lava, and the lava dome (Arsadi *et al.*, 1995; Setiawan, 2003; Aprillia, 2014). In this case, was used Parasnis method to estimate Bouguer density (Blakely,1996). Bouguer density obtained using least square approach based on Parasnis method. The density was obtained by Parasnis is 2,43 gr/m^3

$$g_B = 2\pi G\rho h \qquad (3)$$

$$\Delta g_B = g_{obs} - g_n + g_{FA} - g_B \qquad (4)$$

Simple Bouguer correction is then can be calculated using equation (3), and can be used to calculate simple Bouguer anomaly using equation (4)

Further processing is terrain correction using Digital Elevation Model (DEM). Terrain correction accounts for variations in the observed gravitational acceleration caused by variations in topography near each observation point. Because of the assumptions made during the Bouguer slab correction, the terrain correction is positive regardless of whether the local topography consist of a mountain or a valley. Terrain correction completely the gravity reduction process to be complete Bouguer anomaly as shown in figure 2.

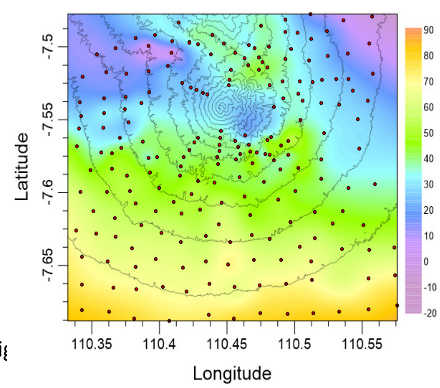


Figure 2. Anomaly Bouguer Merapi volcano based on gravity data 2011

Anomaly Bouguer 2011 is about -20 to 90 mgal with 30 mgal around summit. Commonly it has same trend with anomaly Bouguer before 2011. There are higher anomaly at South and decrease to North, and anomaly at summit of Merapi. Comparing with others data, anomaly gravity at summit in 2011 is higer than anomaly gravity in 1998 and 1988 (Wahyudi 1985, Setiawan, 2003). From visual topographic at summit that show a change of summit feature, some deformation of mass made new feature of Merapi summit. When the mass out during the eruption and deformation on summit, estimated value Bouguer anomaly will drop, but not impaired anomaly. The Bouguer anomaly changes may indicate a large change in the subsurface, surface or both. Increasing the value of Bouguer anomaly may indicate a mass intrution below and added mass on the surface. Probably after the eruption occurred magma intrusion processes.

Measurement of gravity to create a geoid model by means of terrestrial gravity that is a direct measurement of gravity at surface of the earth by using a gravimeter known as geoid gravimetric method. Geoid consists of three kinds of waves there are short wave, medium, and long. Short wave obtained from observational data of gravity, medium wave of terrain correction, and the long wave is a global geopotential model.

Generally modeling local geoid includes three steps, there are a local geoid model is called a gravimetric geoid model contribution, terrain countribution, , and Geoid global contributions.

Processing of geoid gravimetric use two basic formulas, the Bruns and Stokes formula. Bruns formula shows the relationship between potential anomalies and undulations (Vanicek and Krakiwsky, 1982). Determination of the value of the geoid can be done mathematically using Stokes equation. This formula also requires all the masses located outside the geoid is reduced and the reduced gravity anomalies to the surface of the geoid. Assuming that the value of the distribution of density gradient topography and gravity from the ground surface to the geoid is known (Heizkinen & Moritz, 1976).

$$N = \frac{R}{4\pi\gamma_0}\iint \Delta g S(\psi) d\sigma = \frac{R}{4\pi\gamma_0}\sum_{i=1}^{n} \Delta g_i S(\psi) \cos\varphi_i \,.\, \Delta\varphi.\lambda \qquad (5)$$

$$\cos\psi = \sin\varphi \sin\varphi' + \cos\varphi \cos\varphi' \cos(\lambda' - \lambda)$$

$$S\psi = \frac{1}{\sin\left(\frac{\psi}{2}\right)} - 6\sin\frac{\psi}{2} + 1 - 5\cos\psi - 3\cos\psi \ln\left(\sin\frac{\psi}{2} + \sin^2\frac{\psi}{2}\right) \qquad (6)$$

FFT algoritm can is used to estimated the value of gravity anomaly when the value is use as an input data in Stokes formula process.

Residual Terrain Model (RTM) is a terrain contributions due to the influence of topography. Terrain contributions includes two kinds of correction there are terrain and indirect effects. Large terrain correction value is always positive because of the influence topography above and below the reference is considered to contribute positive in gravity reduction process (Wellenhof and Moritz, 2005). Indirect effect is a distance effect between field topography and geoid. Value of indirect effect is used as a geoid correction. Terrain contribution (RTM) method produces three areas topography, ie the reference plane, rough fields, and detail fields. The smaller grid interval will result more detail data. More detail data more accurate, that can minimize the error during the process

Geoid global contribution. Computation of contribution of geoid global data use global gravity coefficients spherical harmonic.There are two kinds of data contribution, the geoid global anomalies and undulation. Equation (7) respectively are used to calculate anomalies (Sideris, 1994).

$$\Delta g_{GM} = g \sum_{n=2}^{n\,max}(n-1)\sum_{m=0}^{n}[Cnm\,cosm\lambda + Snm\,sinm\lambda]Pnm\,(sin\varphi)$$

$$N_{GM} = R \sum_{n=2}^{n\,max}\sum_{m=0}^{n}[Cnm\,cosm\lambda + Snm\,sinm\lambda]Pnm\,(sin\varphi) \qquad (7)$$

Where Δg_{GM} for calculate global anomalies and N_{GM} for calculate undulation with Pnm is constanta in Legende and Cnm, Snm are spherical harmonic constanta with n is degree and m is orde.Figure 3 is geoid global DIR 2011 produce by GOCE.

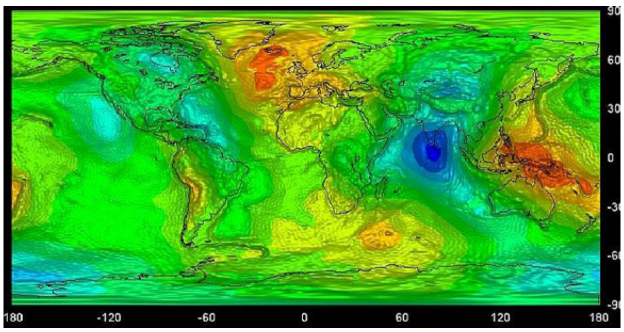
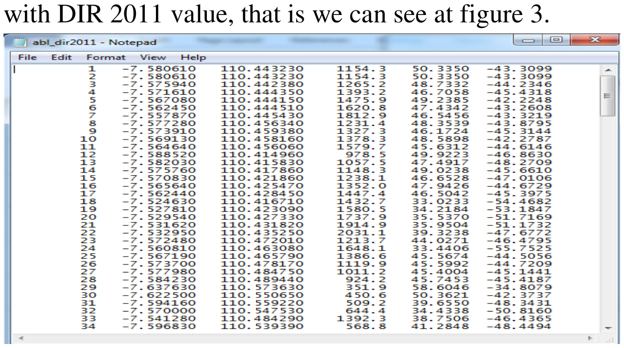


Figure 2. Model Geoid Global DIR 2011.

Some computation by mathlab was used to calculate some value that use in geoid processing. Spherical harmonics calculation is a calculation of the geoid undulation global long wave, in this research use DIR 2011 global geoid model. Computation result combine with Gravsoft software to acqured ABL process with DIR 2011 value, that is we can see at figure 3.



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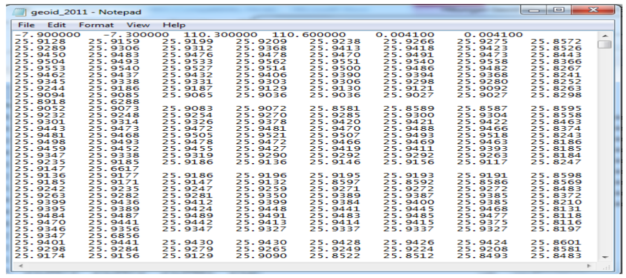
1	-7.580610	110.443230	1154.3	50.3350	-43.3099
2	-7.580610	110.443230	1154.3	50.3350	-43.3099
3	-7.575940	110.442380	1265.2	48.7332	-44.2346
4	-7.571610	110.444350	1393.2	46.7058	-45.4318
5	-7.567080	110.444150	1475.9	49.2385	-42.2248
6	-7.562450	110.444510	1620.8	47.4342	-43.2608
7	-7.557870	110.445430	1812.9	46.5456	-43.3219
8	-7.577280	110.456340	1231.4	48.3539	-43.8795
9	-7.573910	110.459380	1327.3	46.1724	-45.3144
10	-7.569130	110.458160	1378.3	48.5898	-42.2787
11	-7.564640	110.456060	1579.7	45.6312	-44.6146
12	-7.588520	110.414960	978.5	49.9223	-46.8630
13	-7.582030	110.415830	1057.5	47.4917	-48.2709
14	-7.575760	110.417860	1148.3	49.0238	-45.6610
15	-7.570830	110.421860	1238.1	46.6528	-47.0106
16	-7.565640	110.425470	1352.0	47.9426	-44.6729
17	-7.562440	110.428450	1447.4	46.5042	-45.3975
18	-7.524630	110.416710	1432.7	33.0233	-54.4682
19	-7.527810	110.423090	1580.5	34.2184	-53.1847
20	-7.529540	110.427330	1737.9	35.5370	-51.7169
21	-7.531620	110.431820	1914.9	35.9504	-51.1732
22	-7.532950	110.435250	2031.1	39.3238	-47.6772
23	-7.572480	110.472010	1213.7	44.0271	-46.4795
24	-7.560810	110.463080	1648.1	33.4406	-55.7525
25	-7.567190	110.465790	1386.6	45.5674	-44.5056
26	-7.573700	110.478170	1119.9	45.5992	-44.7209
27	-7.577980	110.484750	1011.2	45.4004	-45.1441
28	-7.584230	110.489440	924.2	45.7453	-45.4187
29	-7.637630	110.573630	351.9	58.6046	-34.8079
30	-7.622500	110.550650	450.6	50.3621	-42.3737
31	-7.594160	110.559220	509.2	39.6550	-48.3431
32	-7.570000	110.547530	644.4	34.4338	-50.8160
33	-7.541280	110.484290	1392.3	38.7506	-46.4365
34	-7.596830	110.539390	568.8	41.2848	-48.4494

Figure 3. Result of ABL process with DIR 2011

Processing continue with calculating residual gravity to acquired residual geoid and indirect effect . Lokal geoid value at Merapi volacano base on gravity data of 2011 is 25 m to 27 m (figure 4).



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-7.900000	-7.300000	110.300000	110.600000	0.004100	0.004100		
25.9128	25.9159	25.9199	25.9209	25.9238	25.9266	25.9275	25.8572
25.9289	25.9306	25.9312	25.9368	25.9413	25.9418	25.9423	25.8526
25.9450	25.9483	25.9476	25.9478	25.9470	25.9491	25.9473	25.8443
25.9504	25.9493	25.9533	25.9562	25.9551	25.9540	25.9558	25.8366
25.9553	25.9540	25.9527	25.9514	25.9500	25.9486	25.9482	25.8267
25.9462	25.9437	25.9432	25.9406	25.9390	25.9394	25.9368	25.8241
25.9345	25.9338	25.9331	25.9303	25.9306	25.9298	25.9280	25.8252
25.9244	25.9186	25.9187	25.9129	25.9130	25.9121	25.9092	25.8263
25.9094	25.9085	25.9065	25.9036	25.9036	25.9027	25.9027	25.8298
25.8918	25.6288						
25.9052	25.9073	25.9083	25.9072	25.8581	25.8589	25.8587	25.8595
25.9232	25.9248	25.9254	25.9270	25.9285	25.9300	25.9304	25.8558
25.9301	25.9314	25.9326	25.9378	25.9420	25.9421	25.9422	25.8463
25.9443	25.9473	25.9472	25.9481	25.9470	25.9488	25.9466	25.8374
25.9481	25.9468	25.9505	25.9521	25.9507	25.9493	25.9518	25.8243
25.9498	25.9493	25.9478	25.9472	25.9466	25.9469	25.9463	25.8186
25.9459	25.9452	25.9455	25.9427	25.9419	25.9411	25.9393	25.8185
25.9347	25.9338	25.9319	25.9290	25.9292	25.9292	25.9263	25.8184
25.9235	25.9185	25.9186	25.9136	25.9146	25.9156	25.9117	25.8247
25.9147	25.6617						
25.9136	25.9177	25.9186	25.9196	25.9195	25.9193	25.9191	25.8598
25.9185	25.9171	25.9147	25.9132	25.8597	25.8592	25.8586	25.8569
25.9242	25.9235	25.9247	25.9259	25.9271	25.9272	25.9272	25.8483
25.9263	25.9282	25.9281	25.9350	25.9389	25.9387	25.9385	25.8372
25.9399	25.9436	25.9412	25.9399	25.9384	25.9400	25.9385	25.8210
25.9395	25.9389	25.9424	25.9448	25.9441	25.9445	25.9468	25.8131
25.9484	25.9487	25.9489	25.9491	25.9483	25.9485	25.9477	25.8118
25.9470	25.9441	25.9442	25.9413	25.9414	25.9415	25.9375	25.8116
25.9346	25.9356	25.9347	25.9327	25.9337	25.9337	25.9327	25.8197
25.9347	25.6856						
25.9401	25.9441	25.9430	25.9430	25.9428	25.9426	25.9424	25.8601
25.9298	25.9284	25.9279	25.9265	25.9249	25.9224	25.9208	25.8581
25.9174	25.9156	25.9129	25.9090	25.8522	25.8512	25.8493	25.8483

Figure 4. Value of Local Geoid Merapi volcano based on gravity data 2011

The value of local geoid undulation can be figured as below (figure 5).

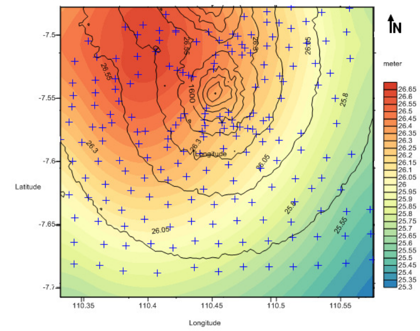

Figure 5. Geoid Lokal Merapi based on gravity data 2011 overlay with topographic map.

The value of local geoid Merapi based on garvity data 1998 is 26 m -29 m (Sunantyo, 2008). Comparing result the geoid value of 2011 with the value of the geoid, 1998 is a decrease value of lokal geoid approximatel 1-2 m. When the value of anomaly gravity increased compared to the value of gravity in 1998, the geoid value should be increase too, but not so. Another research around Merapi, that is Yogyakarta local geoid, the value of local geoid is 21,2 m – 26,6 m (Bagas,2014).

Distribution of the geoid value (figure 5 and 6) appears that high value of geoid on the northwest peak of Merapi and low value of geoid at southeast and south area of Merapi may indicate with high density and low density. Tiede (2005) assumed that geoid at the Merapi volcano was able to be one of the key parameters in volcanic field studies to understand the deeper structures of the volcano. Gerstenecker and Suyanto (1998) states that the computation of an absolute accurate (cm) geoid around the volcanoes Merapi and Merbabu has practical as well as scientific impact. Suyanto (1996) intepreted lower reservoir of Merapi about 2 km from surface.

Another view of the geoid and topography can be seen in Figure 6

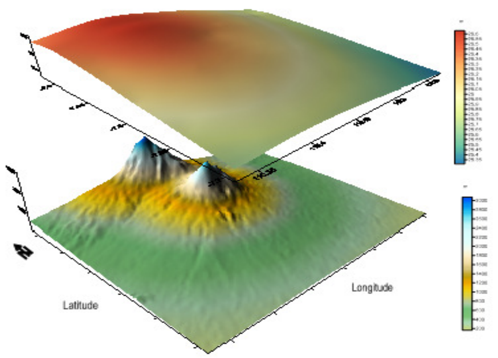

Figure 6. Local Geoid Merapi 2011 overlay with Merapi Topography based on Lidar 2011

In geophysiscal prospecting geoid intepretation can be used to estimed inhomogenities of density (Mariusz, 2008). Geoid data possibly indicate the actual plate boudary (Banarjee, 1999). Study literatur prediction there are a reservoir of Merapi, the reservoir lies in the northwest of Merapi volcano (Aprillia, 2013, Ari 2003). Based on related reseach, the high value of geoid can be predicted as high density. In the gravity subsurface modelling, low value of gravity anomaly inpreted as a resevoir (Aprillia, 2013; Ari 2003; Suyanto, 2000; Wahyudi 1996) and a big reservoir as a recharge of Merapi reservoir in south east of reseach area. The geoid value present of deeper big mass and/or intrusion mass in reservoir than the local deformation on summit.

CONCLUSION

Based on the result and explanation above, it can be concluded that value of geoid undulation of the Merapi volcano based on gravity data after eruption 2010 is about 25.3035 m – 27.000 m. The value of geoid at the summit of Merapi volcano is 26.6505. That is lower than geoid undulation at summit based on 1998 gravity data. The high value of geoid at north-west and lower value at south and south east of Merapi volcano. High value of geoid is predicted as high density or reservoir of Merapi.

BIBLIOGRAPHY

Andreastuti, S.D, Alloway, B.V., Smith, E.I.M. 2000. A detailed tephrostratigraphic frame at Merapi Volcano, Central Java, Indonesia: Implications for eruption prediction and hazard assessment, *J. Volcanology and Geothermal Research.* 100, 51-67

Arsadi, E., Suparta, S., Nishimura, S., 1995. Subsurface structure of Merapi inferred from magnetotelluric, gravimetric and geomagnetic surveys. Merapi Volcano Decade International Workshop, Yogyakarta, October.

Aprillia,N., 2013, Analisis Pergerakan Magma Gunung Merapi dengan Diagram Δg/Δh menggunakan Data Gravitasi, Skripsi , UGM

Blakely, Richard. J., 1996, Potential Theory in Gravity and Magnetic Applications, Cambridge University Press.

Banarjee, Faulger GR, Satyapakarss, Dabral P, 1999, Geoid undulation modelling an intepretation at Ladak, NW Himalaya using GPS and Leveling Data, *Journal og Geodesy*, vol 73 pp 79-86

Bagas, T., Leni, S., Nurohmad, W., 2014, Pemodelan Geoid Lokal D.I. Yogyakarta menggunakan Metode Fast Fourier Transformation dan Least Square Collocation, *Proceding Conference on Geospatial Information*

Dampney, C.N.G., 1969, The Equivalent Source Technique, *Geophysics* Vol. 34, No.1, pp. 39-35.

Gerstenecker, C., Heinrich, R., Jentzsch, G., Kracke, D., Läufer, G., Suyanto, I., and Weise, A. 1998, Microgravity at Merapi Volcano: Results of the First two Campaigns, In: 1. Merapi-Galeras Workshop, June 25, 1998, in Potsdam, Deutsche Geophys. Gesellsch., Sonderband III/1998 (eds.: Zschau, J., Westerhaus, M.), 61-64.

Elevation Model around Merapi Volcano, Java, Indonesia". Natural Hazards and Earth System Sciences. 5, 863-876.

Kahar, Joenil, 2008. Geodesi.. Institut Teknologi Bandung

Kahar, Joenil, Pemanfaatan Anomali Gayaberat Dalam Penyelesaian Geodetic Boundary Value Problem.. Institut Teknologi Bandung

LaCoste & Romberg, Instruction Manual Model G & D Gravity Meters, 2004, Texas, USA

Mariusz, M., Elena, K., Marzena Smarek G, Inpretation of geoid anomalies in the contac zone between East european craton and the Paleozoic Platform, *Oxford Journal* vol 117, pp321 -333

Telford, W. M., Geldart, L. P., Sheriff, R. E., 1990, Applied Geophysics. Cambridge University Press.

Tiede, A. G. Camacho,C. Gerstenecker,J Fernández, I. Suyanto, 2005, Modeling the density at Merapi volcano area, Indonesia, via the inverse gravimetric problem

Sparsk, R., S., J., 1981, Trisgering of volcanic eruption, Natur 290,448 pp

Sideris, M.G. 1994. Geoid and it's geophysical interpretation.In: Vanicek, P. dan Christou, N. T. (eds.) Regional geoid determination.USA: GRC Press.

Setiawan, A., 2003, Modeling of Gravity Changes on Merapi Volcano: Observed between 1997 – 2000, Tesis, Darmstadt: Technischen Universität Darmstadt

Soebandriyo, 2004, *Sejarah erupsi erapi dan Dampaknya bagi Kawasan Borobudur*

Sunantyo, T., A. Computation of Local Geoid around Merbabu – Merapi Adaptive Scheme, 2008.

Vanicek, P., dan Krakiwsky, E.J. 1982. Geodesy: The Concepts.New York, North-Holland Publishing Company.

Voight, B., Constantine, E., K., et.al. , 2000, Historical of Merapi Volcano, Central java, Indonesia, 1768-1998, *Journal of Vulcanology and Geothermal Research Vol 100* p.69-138.

Wellenhof, H. & Moritz, H. 2005. Physical geodesy.Austria, Springer-Verlag Wien

Wahyudi, 1986. Penyelidikan gaya berat di Gunung Merapi. Report of Gadjah Mada Univ., Yogyakarta, Indonesia, 136 pp.