5. Repeated Gravity Measurements at Merapi Volcano

As shown in 2.2 gravity changes in time give information about subsurface mass migration. Such observations try to detect gravity changes in the range of few microgals (µgal) and more with an accuracy of ≥±1 µgal. Therefore such observations are very often called microgravity measurements.

5.1. The Repetition Gravity and GPS-network

Repeated high precision gravity and height measurements are carried out at Merapi volcano. The network consisting of 18 stations was established in August 1997; until August 2000 five further points have been added (fig. 5.1). The net itself consists of three loops at different altitudes: the lowest loop in the elevation range 130-650 m, the second loop between 850 and 1500 m, the third loop at the top (> 2900 m) of Merapi; one profile at the north flank connects the different loops to each other (table 5.1).

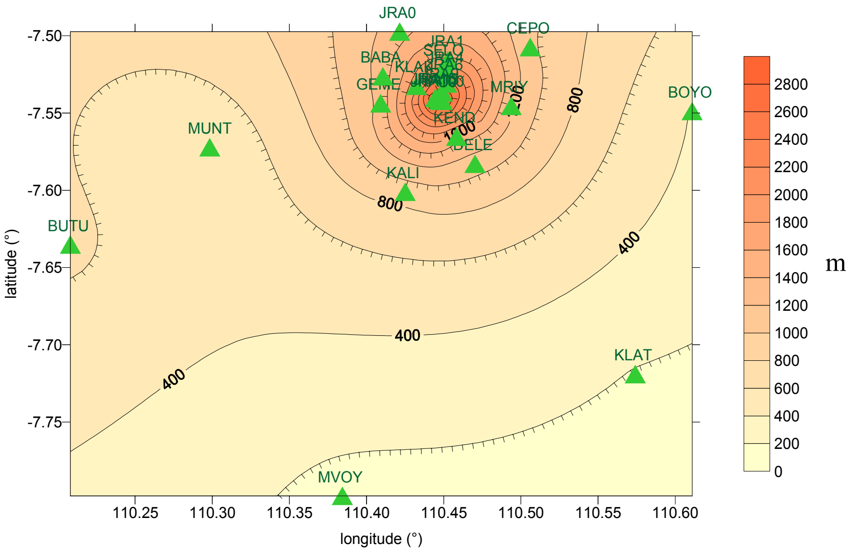

Fig. 5.1. The gravity repetition network loop1 and loop2; interval of height contour lines is 200 m.

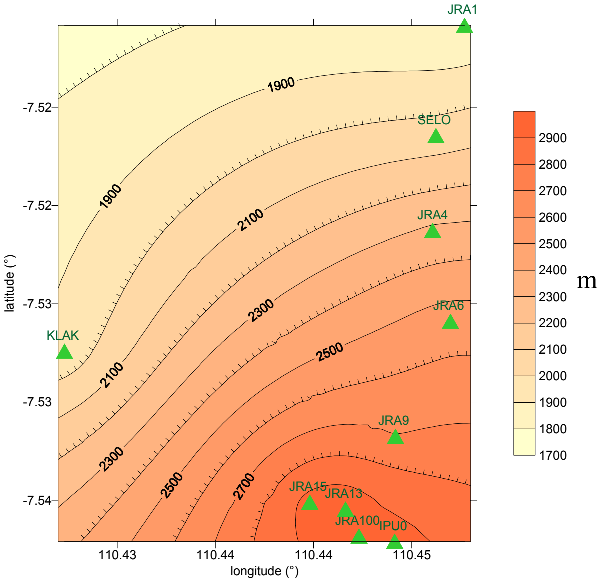

Fig. 5.1b. The gravity repetition network: stations of loop 3 and the profile along the north flank; interval of height contour lines is 100 m.

In the beginning, half-year repetition rates have been planed. Due to missing financial support only yearly repetitions have been possible. Between August 1997 and August 2000 five observation campaigns have been carried out.

Tab. 5.1. Geographical and UTM (zone 49 South) stations coordinates on the WGS84 ellipsoid.

Name of station	Longitude (°)	UTM (m E)	Latitude (°)	UTM (m N)	Altitude (m) above ellipsoid
MVOY	110.384384	432125.106	-7.797882	9137997.338	139.494
KLAT	110.574157	453043.547	-7.719038	9146739.309	190.206
BOYO	110.611036	457093.429	-7.548803	9165563.086	390.732
MUNT	110.298495	422628.639	-7.572217	9162929.660	429.090
BUTU	110.208176	412663.196	-7.635187	9155952.177	648.943
KALI	110.425096	436584.949	-7.601015	9159767.992	878.767
CEPO	110.506124	445514.524	-7.507318	9170137.657	1033.815
DELE	110.470343	441576.639	-7.582912	9161775.655	1091.511
MRIY	110.493872	444167.510	-7.545388	9165927.241	1208.941
GEME	110.409240	434827.545	-7.543729	9166099.193	1266.961
BABA	110.410685	434984.138	-7.526240	9168032.679	1304.273
JRA0	110.421530	436176.412	-7.497321	9171231.322	1318.184
KEND	110.458414	440284.721	-7.565328	9163699.642	1469.807
JRA1	110.452688	439616.724	-7.515833	9169189.239	1810.590
KLAK	110.432320	437372.063	-7.532416	9167353.057	1924.378
SELO	110.451233	439486.553	-7.521444	9168550.120	2045.795
JRA4	110.451064	439438.734	-7.526270	9168035.331	2316.264
JRA6	110.451972	439539.846	-7.530895	9167523.987	2551.680
JRA9	110.449173	439265.486	-7.536748	9167034.206	2699.335
JRA100	110.447320	439028.152	-7.541825	9166315.212	2910.537
IPU0	110.449137	439035.949	-7.542092	9166405.414	2932.344
JRA15	110.444811	438851.044	-7.540101	9166545.232	2935.849
JRA13	110.446633	438952.261	-7.540454	9166466.147	2969.094

5.2. Equipment

For the gravity observations relative spring gravimeters model LaCoste&Romberg G and D were used.

Table 5.2 gives an overview about used gravimeters, observers, number of observations and standard deviations of 1 gravimeter reading.

Table 5.2: Summary of observation campaigns

Date of Campaign	Serial numbers of gravimeter	Observers	Number of Observations	Unit weight error of 1 observation [µgal]
August/September 1997	LCR-D 8	Läufer	199	7.4
	LCR-D38	Gerstenecker	205	6.4
	LCR-G258	Gabriel	178	9.6
	LCR-G979	Kracke	212	7.0
February 1998	LCR-D38	Läufer	239	6.0
	LCR-G79	Heinrich	274	6.2
	LCR-G258	Kracke	269	7.4
	LCR-G979	Suyanto	266	7.4
August/September 1998	LCR-D38	Läufer	330	8.0
	LCR-G85	Snitil	367	5.7
	LCR-G258	Graupner	342	7.6
	LCR-G858	Fischer	330	5.9
August/September 1999	LCR-D38	Läufer	320	8.1
	LCR-G258	Snitil	468	7.1
	LCR-G85	Exss	288	6.6
	LCR-G858	Fischer	391	6.0
August/September 2000	LCR-G85	Gerstenecker	412	7.6
	LCR-G563	Snitil	436	8.1
	LCR-G858	Suyanto	415	6.3
	LCR-G1118	Alex	363	8.5
Total			6307	7.2

The calibration factors of the instruments were controlled by measurements at the gravimeter calibration lines “Harz Mountains” and “Black Forest” (Tab. 5.3).

Tab. 5.3. Calibration factors of gravimeters

Gravimeter	Campaign	Calibration factor
LCR-G258	1, 2, 3, 4	1.000370
LCR-D38	1, 2, 3, 4	0.999800
LCR-G979	1, 2	1.000800
LCR-D8	1	0.999800
LCR-G79	2	0.999920
LCR-G85	3, 4, 5	1.000231
LCR-G858	3, 4, 5	1.000800
LCR-G563	5	1.000457
LCR-G1118	5	1.000659

For the determination of height changes GPS-observations have been carried out in parallel to the gravity measurements. Thereby geodetic 2-frequencies receivers Trimble (4000 SSE and SSi) as well as Leica receivers have been used.

5.3. Processing of the Gravity and Height Observations

The gravity observations were processed with the software packages "FELDGRAV" and "GRAV". “FELDGRAV” reduces the gravity observations, applying different reductions for scale factors, periodic spindulum errors, air pressure, and instrument height. “GRAV” is a program for the least squares adjustment of absolute and relative gravity observations; it is mainly written for observations carried out with LaCoste & Romberg gravimeters (Gerstenecker, 1999).

5.3.1. Theory of “GRAV”

GRAV allows the adjustment of an arbitrary number of observations. However the number of unknowns is limited in the moment to 2000. The adjustment is carried out in following steps:

- construction and storage of design matrix A on hard disc
- computation of normal equation matrix N
- Cholevsky-factorisation of N
- computation of the unknowns x
- computation of the weight unit error m_0
- computation of inverse N^{-1}
- computation of the residuals v
- outlier tests
- computation of variance components
- computation of the standard deviations m_x of the unknowns x
- computation of the standard deviations of the observations m_l and the residuals m_v

The observation equation is formulated for an absolute gravity value G at a particular station.

The most general form of the observation equation is

$$\begin{aligned} v_i = {} & \sum_{l=1}^{3} a_{j,k,l} * t_i^l + dn_{j,k} + \sum_{l=1}^{3} e_{j,k,l} * A_{j,i}^l + \sum_{l=1}^{3} f_{j,k,l} * {F^l}_{i,j} + ta_{j,k} * TA_{i,j} + ti_{j,k} * TI_{i,j} + \\ & \sum_{l=1}^{2} h_{j,k,l} * llev_{j,k}^l + \sum_{l=1}^{2} q_{j,k,l} clev_{j,k}^l + \sum_{p=1}^{6} b_{j,p} * \sin\varphi_{j,p} * \cos\frac{T_p}{2\pi * SKE_{j,i}} + \\ & \sum_{p=1}^{6} b_{j,p} * \cos\varphi_{j,p} * \sin\frac{T_p}{2\pi * SKE_{j,i}} + dg_{i,k} + G_{0_{i,k}} + n_{0_{j,k}} - A_{i,j} \end{aligned} \qquad (5.1)$$

with following notations

i = station index

j = gravimeter index

k = epoch index

l = degree of polynomial (1..3)

p = index of periodic spindulum errors (p = 1..5)

ν_i = residual

$a_{j,k,l}$ = coefficient of the drift polynomial (1..3)

$t_{i,j}$ = Julian time of observation with gravimeter j at station i

$b_{j,p} * \sin \varphi_{j,p} * \cos(T_p / 2\pi * SKE_{j,i})$ = cosine term of the periodic spindulum error

$b_{j,p} * \cos \varphi_{j,p} * \sin(T_p / 2\pi * SKE_{j,i})$ = sine term of the periodic spindulum error

with $b_{j,p}$ = p-amplitude of the periodic spindulum error

$\varphi_{j,p}$ = p-phase shift of the periodic spindulum error

T_p = p-period d of the periodic spindulum error

$SKE_{j,i}$ = counter dial reading of gravimeter j at station i in the instrument units

The periodic spindulum error PSE_p at period p is calculated according

$$PSE_p = b_p * \sin(\frac{T_p}{2\pi * SKE} + \varphi_p) \qquad (5.2)$$

$F_{i,j}$ = feedback voltage of gravimeter j at station i

$f_{j,k,l}$ = calibration coefficient of degree l of feedback voltage of gravimeter j at epoch k

$TA_{i,j}$ = air temperature of gravimeter j at station i

$ta_{j,k}$ = regression air temperature coefficient of gravimeter j at epoch k

$TI_{i,j}$ = temperature of gravimeter j at station i

$ti_{j,k}$ = regression temperature coefficient of gravimeter j at epoch k

$e_{j,k,l}$ = calibration coefficient of degree l of gravimeter j at epoch k

$h_{j,k,l}$ = coefficient of degree l of tilt parabolas of long-level of gravimeter j at epoch k

$llev_{j,k}$ = position of long-level of gravimeter j at epoch k

$q_{j,k,l}$ = coefficient of degree l of tilt parabolas of cross-level of gravimeter j at epoch k

$clev_{j,k}$ = position of cross-level of gravimeter j at epoch k

$dn_{j,k}$ = constant offset of gravimeter j at epoch k

$dg_{i,k}$ = correction of gravity of station i at epoch k

$G_{0i,k}$ = approximate gravity value of station i at epoch k

$n_{0j,k}$ = approximate constant offset of gravimeter j at epoch k

$A_{i,j}$ = reading of gravimeter j at station i in 1 x 10^{-5} m/s^2.

5.3.2. Gravity and height values of five measurement campaigns

The gravity values of all five measurement campaigns are given in table 5.4. The gravity value at the station Merapi Volcano Observatory in Yogyakarta (MVOY), is supposed to be constant with time. Partly large instrumental drift rates, especially at the profile to the top must be taken into account. The reached accuracy of the gravity values of each campaign is around ± 100 $\mathrm{nm/s^2}$ in the lower area around Merapi, increasing to ± 150 $\mathrm{nm/s^2}$ at the profile along the north flank up to the summit of the volcano. That means only gravity changes between two campaigns of at least 300 $\mathrm{nm/s^2}$ at the foot and up to 400 $\mathrm{nm/s^2}$ at the top of volcano can be considered as significant at the 95% significance level.

Tab. 5.4: Gravity value g and standard deviation *s* of the gravity repetition network.

	Campaign									
	Merapi I August 1997		Merapi II February 1998		Merapi III August 1998		Merapi IV August 1999		Merapi V August 2000	
Station	g	*s*	g	*s*	g	*s*	g	*s*	g	*s*
	$\mathrm{nm/s^2}$		$\mathrm{nm/s^2}$		$\mathrm{nm/s^2}$		$\mathrm{nm/s^2}$		$\mathrm{nm/s^2}$	
BABA	9778768308	97	9778768105	74	9778768444	51	9778768385	45	9778768399	51
BOYO	9780684374	86	9780684043	62	9780684263	64	9780684372	74	9780684042	48
BUTU	9780762467	119	9780762509	113	9780762901	82	9780762432	55	9780762021	51
CEPO	9779354147	103	9779354283	67	9779354541	65	9779354473	62	9779354232	56
DELE	9779386101	92	9779385734	65	9779386223	61	9779386417	55	9779386147	80
GEME					9778872752	69	9778872963	57	9778873150	62
IPU0			9774659512	192	9774660190	94	9774660398	112	9774660864	117
JRA0	9778746623	108	9778746224	72	9778746607	56	9778746699	52	9778746721	55
JRA1	9777714700	125	9777714405	79	9777714924	62	9777715157	68	9777715225	75
JRA100	9774729547	189							9774730288	137
JRA13	9774517341	192	9774517076	188	9774517865	89	9774518108	113	9774519128	119
JRA15	9774638837	188					9774639393	113	9774639900	119
JRA4	9776407214	154	9776407178	114	9776408151	76	9776407829	85	9776408632	96
JRA6	9775791541	163	9775790901	153	9775792106	74	9775791680	95	9775792310	102
JRA9	9775417783	176	9775417381	169	9775418186	86	9775418007	101	9775418492	109
KALI	9779922695	54	9779922622	37	9779923025	32	9779922766	32	9779922890	37
KEND					9778546532	53	9778546492	76	9778546875	67
KLAK					9777167969	65	9777168268	65	9777167850	93
KLAT	9781841069	55	9781841062	39	9781841063	41	9781841130	46	9781840833	40
MRIY	9779053986	107	9779053661	75	9779054546	75	9779054177	63	9779054098	73
MUNT	9780973108	63	9780972909	39	9780973089	43	9780972881	34	9780972731	36
MVOY	9782029800	10	9782029800	10	9782029800	10	9782029800	10	9782029800	10
SELO					9777122881	74	9777123009	83	9777123271	84

GPS data processing is done using the commercial software packages GPSurvey 3.5 and SKI 2.1. Baselines are computed with precise ephemeredes, provided by IGS.

Approximate coordinates for each station were calculated in the ITRF (International Terrestrial Reference Frame) 2000 at the WGS84 ellipsoid. As fixed reference points the IGS-Stations BAKO, COCO, DARW and NTUS have been used. Each campaign was adjusted separately. Possible datum shifts and missing points have been balanced using seven parameter (Helmert) transformations whereby all campaign results have been transformed to the epoch August 2000. The ellipsoidal heights h of five measurement campaigns are given in table 5.5

Tab. 5.5 Ellipsoidal heights h and standard deviations *s* of the gravity repetition network.

	Campaign									
	Merapi I Aug. 1997		Merapi II Feb. 1998		Merapi III Aug. 1998		Merapi IV Aug. 1999		Merapi V Aug. 2000	
Station	h	*s*	h	*s*	h	*s*	h	*s*	h	*s*
	m		m		m		m		m	
BABA	1304.223	0.012	1304.272	0.022	1304.212	0.030	1304.245	0.031	1304.273	0.023
BOYO	390.770	0.025	390.772	0.034	390.956	0.042	390.722	0.049	390.732	0.033
BUTU	651.349	0.000	648.848	0.095	648.992	0.058	648.892	0.101	648.943	0.040
CEPO	1033.799	0.011	1033.784	0.028	1033.649	0.039	1033.712	0.050	1033.815	0.021
DELE	1091.496	0.021	1091.513	0.197	1091.442	0.035	1091.515	0.034	1091.511	0.026
GEME									1266.961	0.015
IPU0					2932.257	0.030	2932.385	0.026	2932.344	0.034
JRA0	1318.161	0.006	1318.219	0.019	1318.203	0.024	1318.217	0.027	1318.184	0.018
JRA1	1810.562	0.012	1810.539	0.024	1810.558	0.039	1810.529	0.031	1810.590	0.028
JRA100	2910.524	0.031							2910.537	0.026
JRA13	2969.305	0.017	2968.835	0.046	2969.208	0.081	2969.156	0.200	2969.094	0.031
JRA15	2935.845	0.020	2935.710	0.051			2935.898	0.062	2935.849	0.044
JRA4	2316.075	0.014	2316.011	0.025	2316.024	0.032	2316.156	0.042	2316.264	0.042
JRA6	2551.673	0.013	2551.621	0.026	2551.661	0.037	2551.733	0.045	2551.680	0.026
JRA9	2699.420	0.025	2699.351	0.108	2699.351	0.110	2699.348	0.115	2699.335	0.109
KALI	878.698	0.013	878.656	0.030	878.808	0.037	878.754	0.027	878.767	0.022
KEND							1469.823	0.008	1469.807	0.024
KLAK							1924.391	0.028	1924.378	0.021
KLAT	190.183	0.014	190.207	0.025	190.176	0.041	190.151	0.032	190.206	0.025
MRIY	1208.818	0.031	1208.910	0.098	1208.906	0.032	1208.899	0.032	1208.941	0.056
MUNT	429.253	0.000	429.253	0.000	429.162	0.030	429.110	0.032	429.090	0.041
MVOY	139.532	0.006	139.531	0.018	139.468	0.022	139.562	0.023	139.494	0.018
SELO							2045.851	0.032	2045.795	0.024