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Airborne Gravimetric Survey of Switzerland

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In einem gemeinsamen Forschungsprojekt mit der Firma LaCoste & Romberg hat das Institut für Geodäsie und Photogrammetrie (IGP) im November und Dezember 1992 in einer Höhe von 5200 m flugzeuggestützte Schwerefeldmessungen in der ganzen Schweiz vorgenommen. Das Flugzeug, eine Twin Otter der Vermessungsdirektion, war mit drei GPS Empfängern ausgerüstet, einerseits zur Navigationsunterstützung, andererseits zur Bestimmung der Flugtrajektorien und der Beschleunigungen. Für die Schweremessungen wurde ein modifiziertes LaCoste & Romberg S114 Gravimeter mit einer Abtastrate von 1 s eingesetzt. Die Instrumentierung und Datenanalyse werden beschrieben. Als erstes vorläufiges Resultat wird eine Bouguer-Schwerekarte präsentiert und mit derjenigen aus terrestrischen Messungen erhaltenen verglichen. Die Vergleiche zeigen, dass Genauigkeiten unter 10 mgal mit der Airborne Gravimetrie erreichbar sind.

Dans le cadre d'un projet de recherche commun avec la firme LaCoste & Romberg, l'Institut de géodésie et de photogrammétrie (IGP) a procédé en novembre et en décembre 1992, dans toute la Suisse, à des mesures du champ de gravitation à partir d'un avion volant à 5200 m d'altitude. L'avion, un Twin Otter de la Direction fédérale des mensurations, était équipé de 3 récepteurs GPS, d'une part pour l'assistance à la navigation et d'autre part pour la détermination des trajectoires de vol et des accélérations. Pour les mesures de gravitation on a eu recours à un gravimètre S 114 modifié de LaCoste & Romberg permettant une mesure toutes les secondes. Les auteurs décrivent l'instrumentation et l'analyse des données. Comme premier résultat provisoire il présente une carte des gravitations du type Bouguer et la compare à celle issue de mesures terrestres. Les comparaisons montrent que les précisions obtenues par gravimétrie aéroportée sont inférieures à 10 mgal.

Nei mesi di novembre e dicembre 1992, l'Istituto di geodesia e fotogrammetria (IGP), in un progetto di ricerca congiunto con la ditta LaCoste & Romberg, ha effettuato in tutta la Svizzera delle misurazioni aeree dei campi gravitazionali da 5200 m di altezza. Il velivolo, un Twin Otter della Direzione delle misurazioni, era dotato di 3 ricettori GPS, da una parte come appoggio per la navigazione e dall'altra per la determinazione delle traiettorie di volo e delle accelerazioni. Per le misurazioni è stato impiegato un gravimetro modificato S114 LaCoste & Romberg con una frequenza di rilevamento di 1 s. In seguito è stata effettuata una descrizione degli strumenti e un'analisi dei dati. Il primo risultato provvisorio è presentato su una carta gravitazionale Bouguer e raffrontato a quello comprendente le misurazioni terrestri. Tali confronti dimostrano che con la gravimetria Airborne sono raggiungibili precisioni inferiori a 10 mgal.

1. Introduction

Knowledge of the earth's gravity field is of great importance for geodesy and geophysics. Typical applications are the determination of the geoid, the reduction of levelling data for the determination of orthometric heights, the determination of the density distribution inside the earth, and the detection of secular gravity changes coupled with geodynamic processes.
In geodesy, the measurements are linked to geopotential surfaces and gravity lines. Measurements carried out at the surface of the earth are strongly perturbed by the effects of local inhomogeneities and therefore have to be corrected for. In spite of sophisticated interpolation and regularization methods, the errors introduced by local effects are not completely eliminated and affect the results of computations.

In geophysics the gravity method is important for studying the earth's interior. This method provides information complementary to seismic data, and enables a quasi-continuous determination of the density at depth.
In the classical terrestrial gravity method the costs and time necessary for measurements are extremely high. Because the measurements are not made on a horizontal surface, they are strongly influenced by local density anomalies and time consuming algorithms have to be applied during data reduction.
For geodesy as well as for geophysics, measurements made on a horizontal surface located above the topography would be an ideal solution. The interpretation can be performed directly on the measurement surface and all the potential field transformation methods, based on the Fourier transformation, can be applied without restriction.
In order to obtain data smooth enough at large scale it is tempting to determine the gravity field from space. By means of measurements of satellite orbit perturbations it has become possible to determine the long wavelength components (λ > 1000 km) of the gravity field with sufficient accuracy. Unfortunately, however, these wavelengths are not suitable for the determination of the geoid at local or regional scale, like for the Alpine region. Recently the European Space Agency (ESA) has proposed a geodetically dedicated mission called ARISTOTELES in which a satellite with a two-component gravity gradiometer should allow the determination of the earth's gravity field in the range of wavelength between 100 and 1000 km.
Apart from the fact that this mission will not be pursued in the future for financial reasons, the expected results would also suffer from the disadvantage that the minimal wavelength of the gravity field is too large. With such kind of data Switzerland would be covered, in the most optimistic case, by only twenty values.
In order to fill the gap between the very short wavelength information (λ < 10 km) obtained from ground measurements and the actual and in the future available long wavelength information (λ > 1000 km) the IGP of the ETH Zurich decided in 1990 to work out strategies for performing airborne gravimetric surveys in Switzerland.

Until now only few experiments have been carried out for the development of airborne gravimetric measurements for geodetic and large-scale geophysical purposes, particularly because of the problem to determine the relative position of the aircraft with very high accuracy. This accuracy (mm range) is necessary for computation and removal of disturbing accelerations (non-gravitational accelerations). Systems for measuring gravity in dynamic mode were mostly used in marine applications with low-dynamic behaviour and in few cases for airborne gravimetric tests (LaCoste, 1967; Bell et al., 1991; Brozena and Peters, 1984; LaCoste et al., 1982; Brozena et al., 1989; Bell et al., 1994).
After some discussions during 1991 it appeared that this project would be a good opportunity for LaCoste and Romberg Gravity Meters Inc. (Austin, Texas) to modify and improve their Model S Marine gravimeter in order to make it a real and commercial airborne system. Therefore the ETH and LaCoste and Romberg decided to join their efforts for the realisation of this project. At the same time the «Eidgenössische Vermessungsdirektion» (V+D) expressed interest to participate in this project by placing its aircraft, their pilots and navigators at disposition for the survey.

2. Instrumentation

2.1 The Aircraft

The survey was performed with a DeHavilland Twin Otter aircraft owned by the «(V+D)» Ministry of Justice, and operated by pilots of the «Bundesamt für Militärflugplätze». The aircraft is equipped with an automatic pilot, Collins type AP 106 and with a GPS/LORAN receiver Trimble 2000 for navigation purposes.

2.2 Gravimeter and Stabilised Platform

The LaCoste and Romberg Model S Marine gravity meter consists of a heavily damped zero length spring gravity meter element mounted in a gyro-stabilised platform. Two horizontal accelerometers on the platform are used to keep the platform in a vertical position. Details of the marine gravity meter and stabilised platform have been described previously (LaCoste, 1967; Bell et al., 1991; Brozena an Peters,1988; Brozena,1984; LaCoste et al.,1982).

In order to produce a prototype Model SA airborne gravity meter, the following major modifications were carried out:

A D.C. servo motor was substituted for the existing stepper motor to permit rapid adjustment of the Spring Tension at the end of each line.

A 24-bit absolute shaft encoder (4096 turns by 4096 bits per turn) was added to ensure that a correct Spring Tension information was recorded despite the high slewing rates.

The existing marine gravity «SEASYS» software was used only to control the stabilised platform and to compute and record cross coupling values. The platform period was set to 4 minutes.

A second data acquisition system was installed with LabView software and data acquisition hardware.

A timing signal was generated by the LabView software each minute and sent to the GPS system for synchronisation between the gravity and positioning systems. Three extra channels of analogue input were provided by the gravity meter system to digitise and record pitch, roll and barometric altitude.

A signal conditioning module with 3-Hertz Low-Pass Filters was placed in line with the Beam Position output and both horizontal accelerometers in order to prevent aliasing upon digitisation.

The three on-off heating circuits in the marine gravity meter (for the gravity meter heater box and two gyros) were replaced by proportional heater systems in order to avoid transient current in the beam position signal.

On the stabilised platform frame an attitude gyroscope was mounted for measuring pitch and roll of the aircraft. This information was registered with the gravimeter data.

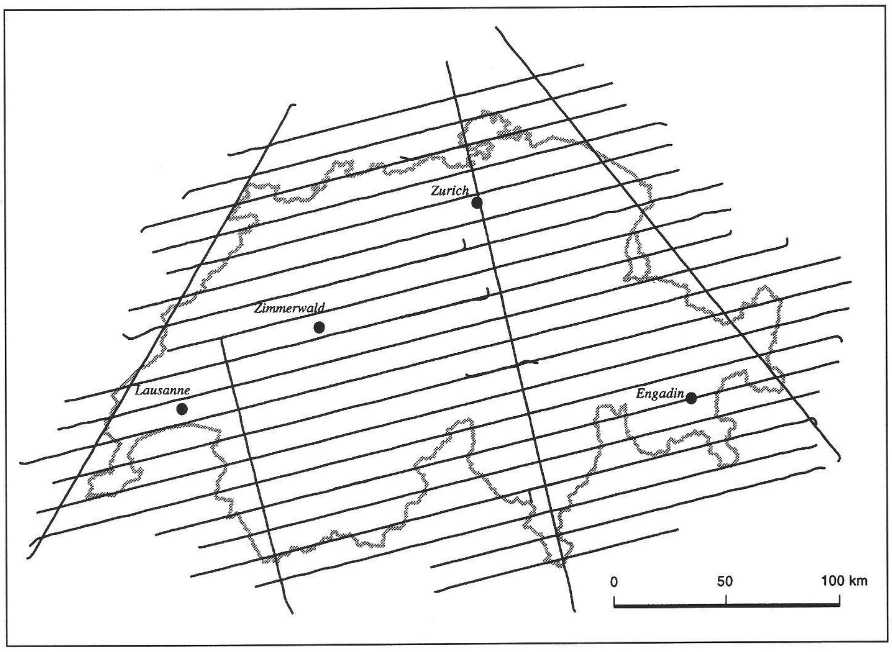

Fig. 1: Flight trajectories of the whole survey computed from GPS observations, and locations of the GPS base stations.

2.3 GPS Receiver

For the flights, six GPS-receivers TRIMBLE SST were used, two of them were installed in the aircraft and four were deployed at ground to serve as base stations. The locations of these base stations were: Astronomic Observatory of Zimmerwald (BE), ETH-Lausanne (VD), ETH-Hönggerberg (ZH) and Samedan Airport (GR).

The measurements were collected at a sampling rate of two Hz (one block of measurements every 0.5 sec). The durations of the flights were about five hours. Since the capacity of the internal memory of the receivers was too small, the data were directly transferred to two laptop computers using Trimble software. The entire data set was then transferred to a large PC-computer. The binary data were converted to a receiver independent ASCII-format (RINEX).

2.4 Survey

Eight night flights were performed between November 24 and December 11, 1992, at a barometric altitude of 5200 m. A total of 24 lines of data were acquired, including 4 cross-lines.The orientation of these lines is given on Fig. 1. Flight operations were generally limited to the period between midnight and 5 am on weekdays due to a combination of air traffic restrictions, GPS satellite geometry and selective availability.

A table of expected gravity values was computed for a grid of points covering the survey area, with heading and aircraft speed as variables. The operator adjusted the spring tension to the expected value for the starting point on the next line. Once the aircraft was on line and level for about five minutes, the operator unclamped the meter and began recording.

3. GPS Positioning by Phase Measurements

Before processing the flight data, the co-ordinates of all reference stations were determined. The stations Zürich, Lausanne and Engadin were connected to the permanent station Zimmerwald, using the ionosphere free L3 combination of the phase measurements and holding the co-ordinates of Zimmerwald fixed. This was done by processing the static data using the «Bernese software». This procedure permitted the determination of a set of co-ordinates for the reference stations with an accuracy of a few centimeters. They were then used as reference co-ordinates for the kinematic processing.

For the computation of the kinematic GPS data an approach using code and phase measurements simultaneously in a differential mode was adopted. The corresponding observation equations of the single difference code measurements are:

$$\Delta\rho^i_{jk} = \rho^i_k - \rho^i_j = d^i_k - d^i_j + \Delta cl_{jk}$$

and for the single difference phase measurements:

$$\Delta\phi^i_{jk} = \phi^i_k - \phi^i_j = d^i_k - d^i_j + \Delta cl_{jk} + \lambda\Lambda^i$$

where

- ρ: pseudo-range measurement
- ϕ: phase measurement
- d: distance between satellite and receiver
- A: ambiguity related to the phase measurement
- Δcl: differential synchronisation error of the receiver
- λ: wavelength of carrier phase

The superscripts i designate the satellite. The subscripts j and k are related to the reference station and the aircraft antenna, respectively. The clock and the position of the satellite, as they are given by the broadcast ephemeris, are supposed to be known and are, therefore, not included in the observation equations.

An a priori accuracy for the measurements is assigned to the phase- and code-differences. These values may be quite different depending on the quality of the receiver. Typical values for the a priori RMS for different types of observations are: Phase 2–5 mm; C/A-code 1–5 m; P-Code 0.2–0.8 m.

The processing was performed according to the procedure described below (Cocard, 1994):

In a first step, the time-invariant parameters were determined. Parameters which are considered invariant are the ambiguities and the co-ordinates at rest before and after the flight. For each epoch, a normal equation system (NES) was established. This was done by regrouping the co-ordinates and the clock information of the moving receiver as well as the ambiguities of the phase-measurements as unknown parameters. All time-variant parameters were then eliminated from the normal equation system and the reduced NES were accumulated over the total time span. By inversion the floating point solution for the ambiguities was obtained.

In a second step, the values for the ambiguities obtained from the previous step were used to calculate the co-ordinates of the moving receiver for every epoch.

At first the Zimmerwald station was used as reference station and a floating point solution was calculated from C/A code and L1-phase measurements.

The quality of the absolute co-ordinates of the flight track is in the order of 1-2 meters. The differences of the co-ordinates between epoch to epoch over small time intervals is on the order of some few mm, but strongly depend on the quality of the GPS constellation. It has to be pointed out that, over the whole data set, there are large variations in the quality of the GPS constellation with the GDOP ranging from 2 to 25. Fig.1 shows an overview of the trajectories deduced from the GPS-solution. The longest line is about 400 km. It was flown over a period of 1.5 hours.

4. Data Processing

In the method of computing g, only three types of information were taken from the gravimeter-platform system: The cross-coupling corrections, the raw beam positions and the raw spring tensions.

The first step of the gravity computation consisted in filtering the last two values by means of a cascade of filters of different kinds. These filters were running median, running mean, transverse and RC recursive filters. For the data presented here only RC filters were used.

The differential equation of a RC filter can be written as follows:

$$\frac{dy}{dt} + \frac{1}{T}y = \frac{1}{T}x$$

where y(t) is the filtered value, x(t) is the unfiltered value and T is the time constant of the filter.

In digital form this equation can be written:

$$\frac{y_n - y_{n-1}}{t_n - t_{n-1}} + \frac{1}{T}y_n = \frac{1}{T}x_n$$

For a interval of 1 sec, this equation becomes:

$$y_n = \frac{T}{T+1}y_{n-1} + \frac{1}{T+1}x_n$$

The filtered beam positions were then used for the computation of the beam velocities by means of a seven point Lagrange differentiation operator. These values were multiplied by the so-called «K-factor», and then added to the filtered spring tension. The K-factor multiplication serves to transform the beam velocity into counter units which are the units of the spring tension. This sum was finally multiplied by the gravimeter factor to obtain a g value in mgal (10-5 ms-2), which compared to the known gravity value at the airport, yields the instantaneous absolute gravity value at the measurement point.

Parallel to this procedure, the GPS data containing the time of measurement, the three co-ordinates of the aircraft, the flight azimuth and the distance to the earth's center, were used to compute the vertical accelerations of the aircraft. During this procedure the same kind of filters and the same filtering parameters as those employed for the raw spring tension and the raw beam position were used.

The vertical GPS accelerations were computed by double differentiation of the vertical positions of the aircraft. Some filtering procedures (on positions and velocities) were also necessary before and between these two differentiations. This filtering must be used with great care because the choice of the parameters is not obvious and the criteria for their choice are often subjective.

Both vertical accelerations (from GPS and gravimeter) were introduced into a cross correlation computation in order to detect time differences between the data sets. When necessary, both times were synchronised by adding a constant or variable value to the gravimeter time. From this last computation step it was possible to determine the necessary time shift and also the best possible filtering procedures and parameters. After all these parameters were determined the GPS data (co-ordinates, flight azimuth, distance to the earth's centre), the raw beam and raw

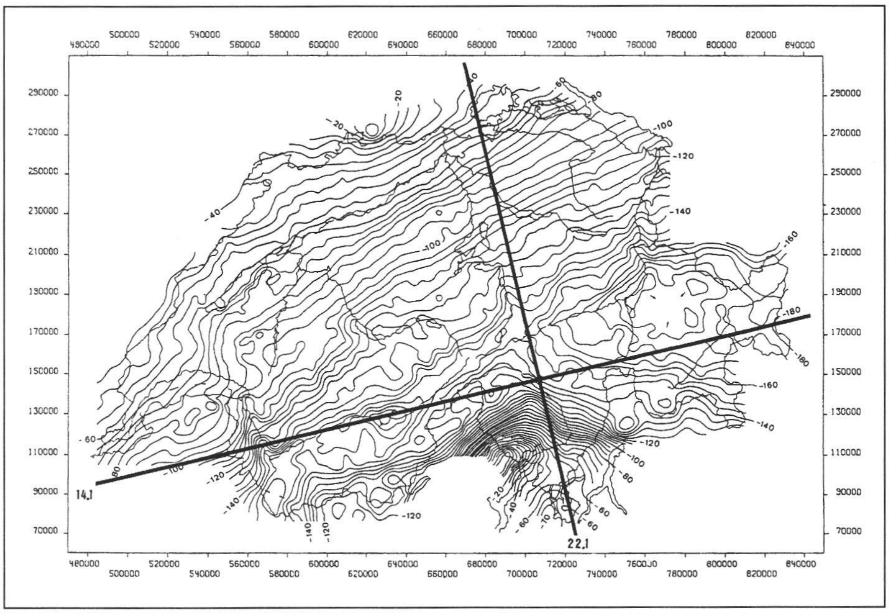

Fig. 2: Ground Bouguer anomaly map after Klinglé and Olivier (1982) with the locations of the two lines 14.1 and 22.1 used for quantitative evaluation of the survey accuracy.

spring tension data and the cross-coupling corrections were introduced into another program. It recomputes the vertical accelerations of the aircraft, the filtered value of g and applies cross-coupling corrections to the previous value of g. It also computes the Eotvös effects and subtracts them from the g values. For this computation the horizontal position of the aircraft, the flight altitude and the distance to the earth's centre were used. For the computation of the Eotvös effect (vertical component of the Coriolis acceleration) the formula given by Harlan (1968), taking into account the flattening of the earth was used. This expression is given by:

$$\Delta g_e = \left(1+\frac{h}{a}\right)\left(2\omega v\cos\phi\sin\alpha+\frac{v^2}{r}\right)-f\frac{v^2}{a}\left(1-(\cos\phi)^2\left(3-2(\sin\alpha)^2\right)\right)$$

with:

- h: Altitude above the ellipsoid
- a: Earth's semimajor axis
- f: Earth's flattening
- ω: Earth's angular velocity
- v: Ground velocity of the aircraft
- ϕ: Latitude
- α: Flight azimuth
- r: Radial distance to geocenter

First the horizontal velocity was calculated by means of the same differentiation operator as used for gravity and aircraft vertical acceleration computations.
Optionally the corrected g values can be reduced to the nominal flight altitude by multiplying the local vertical gradient with the difference between the real and the theoretical flight altitude. The local gradient was calculated with a formula for a series expansion of the theoretical gravity field with earth parameters corresponding to the World Geodetic System 1984 (WGS 84).
Finally, the free-air anomaly was computed for every point by subtracting the theoretical value of g from the measured one.
In our case the topographic effects were computed by numerical integration using different terrain models. The first model consists of altitude cells of 250 m by 250 m covering all of Switzerland and extending into Austria, France, Germany and Italy up to 100 km. This model was used for the topographic corrections around the measurement point from 0 to 15 km. The calculation was performed by the line-of-mass formula. In order to reduce the computing time the original cells were combined to form larger cells of 1 km by 1 km. This size was determined after calculations were performed to find the largest possible mesh size of the topographic cells which give a reasonable accuracy.
The second model was formed by altitude cells of 3' by 3', covering almost all of continental Europe. Here also the computation was done with the line-of-mass formula.
The last procedure consisted of subtracting the topographic effects from the free-air anomaly; this gives the full Bouguer anomaly. It is worth noting that the Bouguer anomaly can also be filtered with the same filters which can be applied to GPS, gravimeter data and free-air anomalies.

5. Results

The data acquired were used to produce a colour Bouguer gravity map. This map was produced for a qualitative comparison with the already existing gravity map of Switzerland (Klingelé and Olivier, 1980). No equalisation procedure has been applied and the lines flown at different altitudes were upward continued to 5200 m

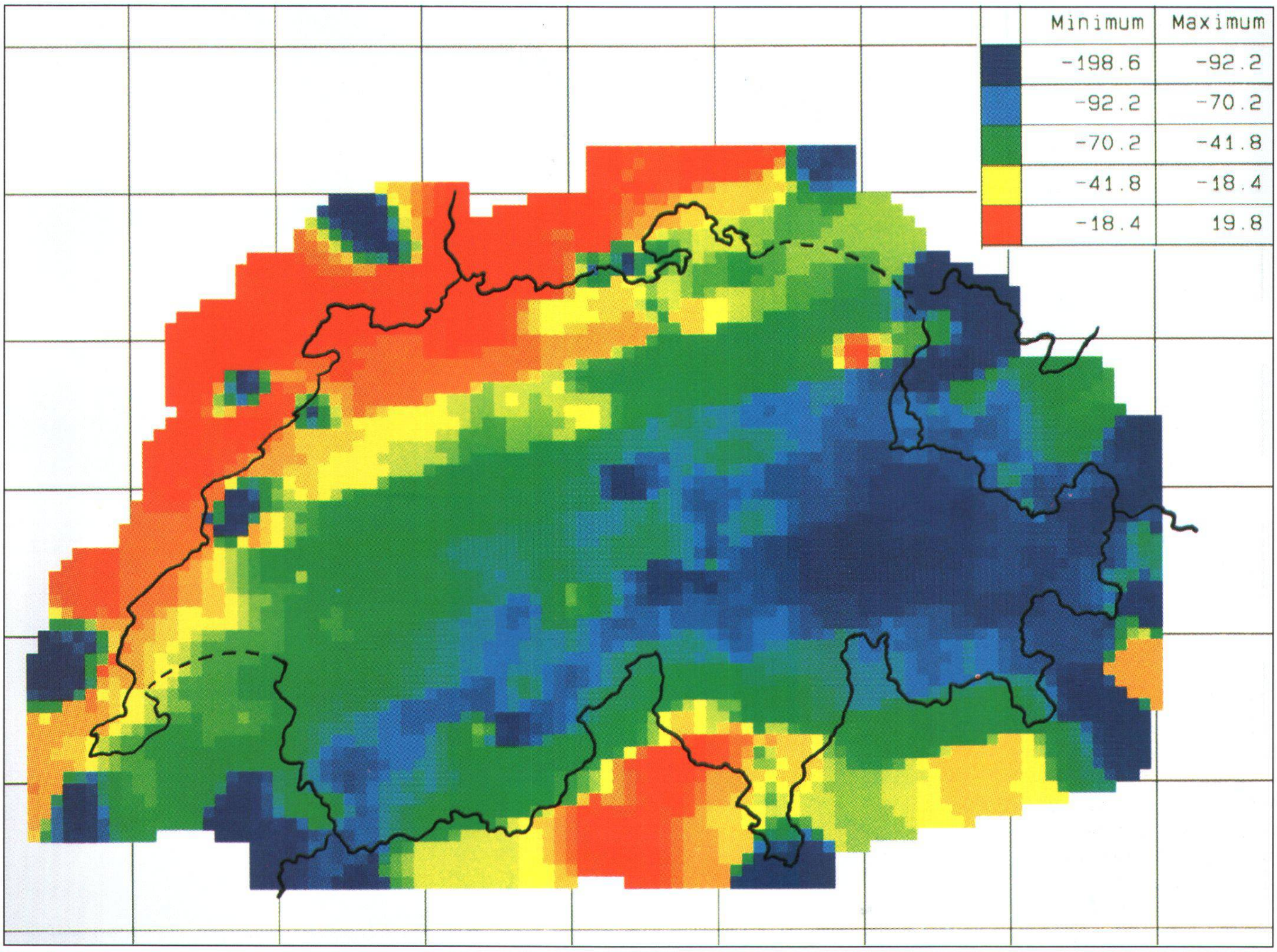

Fig. 3: Airborne Bouguer anomaly map at 5200 m altitude, produced with the data measured during the campaign of November–December 1992. Units are in mgal.

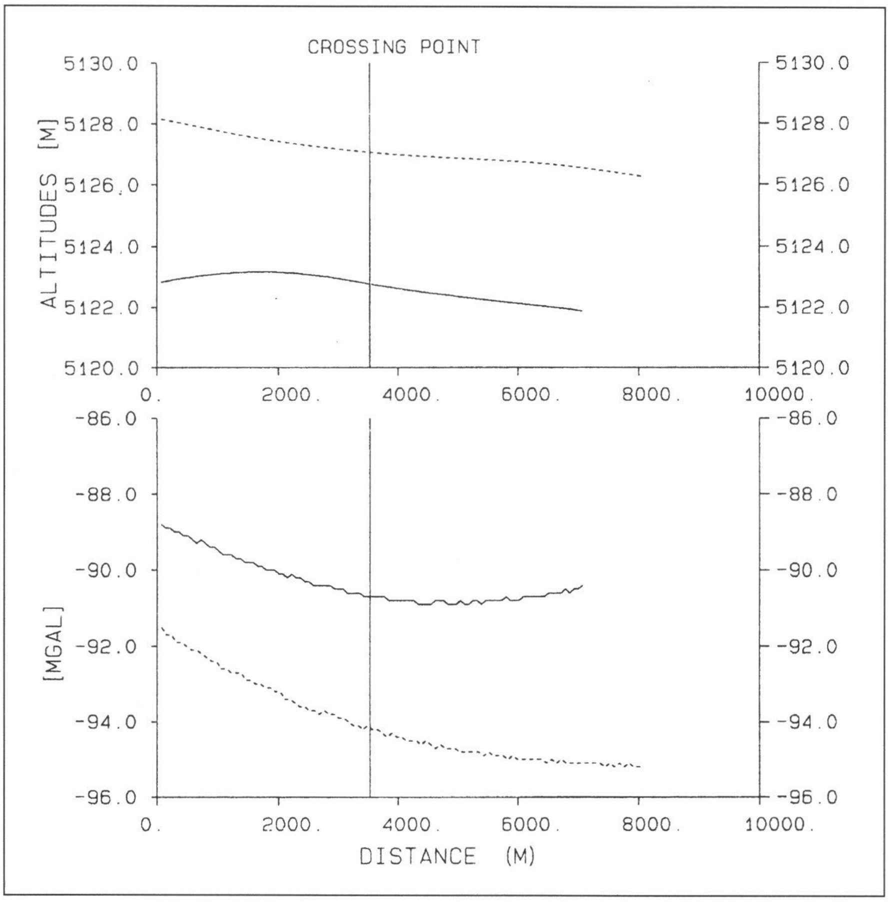

Fig. 4: Gravity values (lower diagram) and altitudes (upper diagram) around the crossing point between line 14.1 and 22.1. The difference in altitude is 4.2 m and gravity difference 3.56 mgal. The theoretical difference obtained by using a standard vertical gradient of -0.3086 mgal/m is 2.26 mgal.

with a three stage RC filter of 30 seconds time constant(3.1.30), before the computation of the vertical accelerations. The same procedure was applied to the computed Eotvös accelerations and to the vertical accelerations of the aircraft. After the computation of g a three stage, thirty seconds, back filter was applied (3. -1. 30). The free-air anomaly was then computed by subtracting the filtered g values from the theoretical gravity values computed according to WGS84.

Fig. 2 and 3 show the two maps plotted at the same scale. The airborne map shows all the important features appearing on the ground map, like the negative anomaly of «Graubünden», the positive anomaly corresponding to the eastern end of the Ivrea body, the general NW-SE trend and the S-shaped isolines of the western part of the country (compare fig. 2). Some very small and sharp anomalies can be seen only in the airborne map. These anomalies are produced by the differences at the crossing point between NS and EW lines. These differences should disappear after the equalisation procedure has been applied. An evaluation of the quality of the survey can be made by looking at the crossing points between lines flown at comparable altitudes. For this evaluation lines 14.1 and 22.1 were chosen because they cross each other at altitudes differing by only four meters. This very small altitude difference allows a significant comparison between the measured g values at the crossing point without any hypothesis about by using a standard vertical gradient of –0.3086 mgal/m. Both sets of data were corrected for the effect of topography to a distance up to 167 km with a density of 2670 kg/m³. The ground anomalies refer to the 1930 Potsdam system whereas the airborne data are referenced to WGS84.

All the computations were carried out only with the GPS data provided by the rear antenna of the aircraft and by the ground base station located at Zimmerwald.

For data processing the beam positions and the spring tension data were filtered

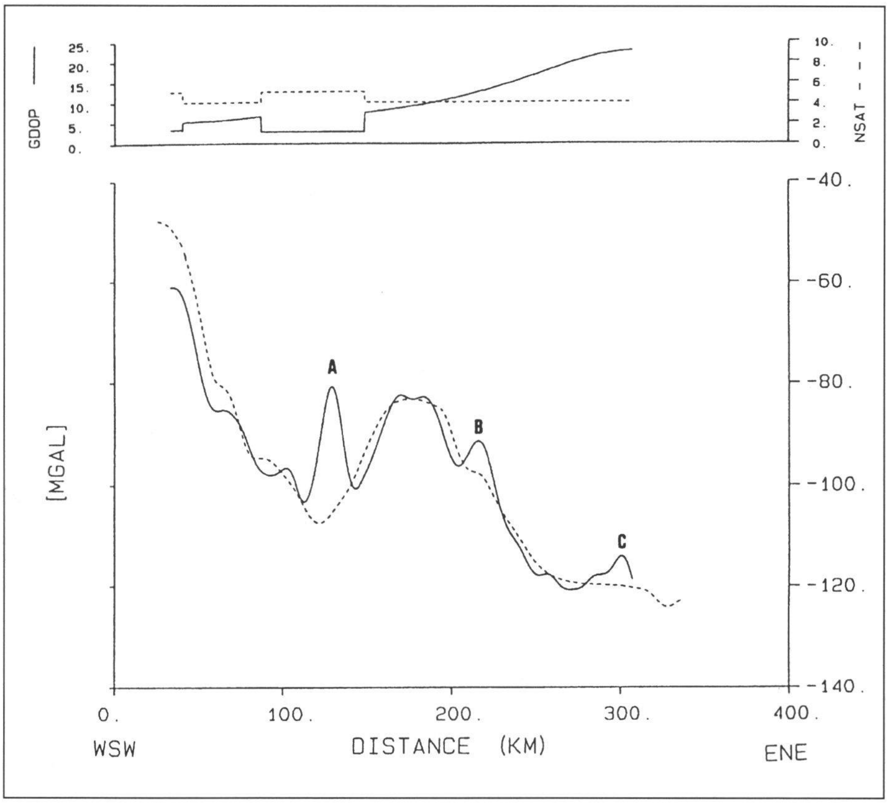

Fig. 5: Bouguer anomaly at 5120 m along line 14.1 computed from airborne data (continuous curve) and ground anomaly upward continued at the same altitude (dashed curve). The RMS difference between the two anomalies computed for 620 points is equal to 6.3 mgal. The anomalies denoted A,B and C are not yet explained. The upper diagram shows the number of available GPS satellites and the GDOP of the constellation during the measurements.

the vertical gravity gradient. The results of this comparison are presented in Fig. 4. In this figure the measured g values along the flight lines, approximately three km before and after the crossing point (lower diagram) and the flight altitude for the same portion of the flight line (upper diagram), are shown. A good evaluation of the accuracy of the result can be made by considering the difference at the crossing point after the data have been reduced to the same altitude by using a normal gradient. This comparison gives a difference of 2.26 mgal.

Another quantitative comparison has been performed between ground and airborne data along the same flight lines. For this purpose data were extracted from the gravity map of Switzerland at scale of 1/500000. by picking the positions of the isolines along the two profiles (Fig. 2). These data were then interpolated with a sampling interval comparable with that of the airborne data. Finally the anomalies were upward continued along the profiles by means of an integration algorithm (Dirichlet integral). The ground and airborne Bouguer anomalies are presented in figs. 5 and 6. The RMS difference between the two anomalies computed for 437 points along line 22.1 gives a value of 6.3 mgal and for 643 points along line 14.1 a value of 6.4 mgal. It is worth noting that small differences remain between the two kind of anomalies due to the different reference system used for the computations. Also, one has to remember that the airborne data are much more detailed than the ground data (one ground measurement for 15 km², one airborne value every 100 meters along the profile). Therefore, it is difficult to define which data have to be taken as reference. The airborne Bouguer anomaly of line 14.1 shows three sharp anomalies (noted A, B and C on figure 4) which cannot be easily attributed to geological disturbing bodies. Further processing with different filtering parameters, correlation techniques and geological analysis may help to decide if these anomalies are real or artefacts.

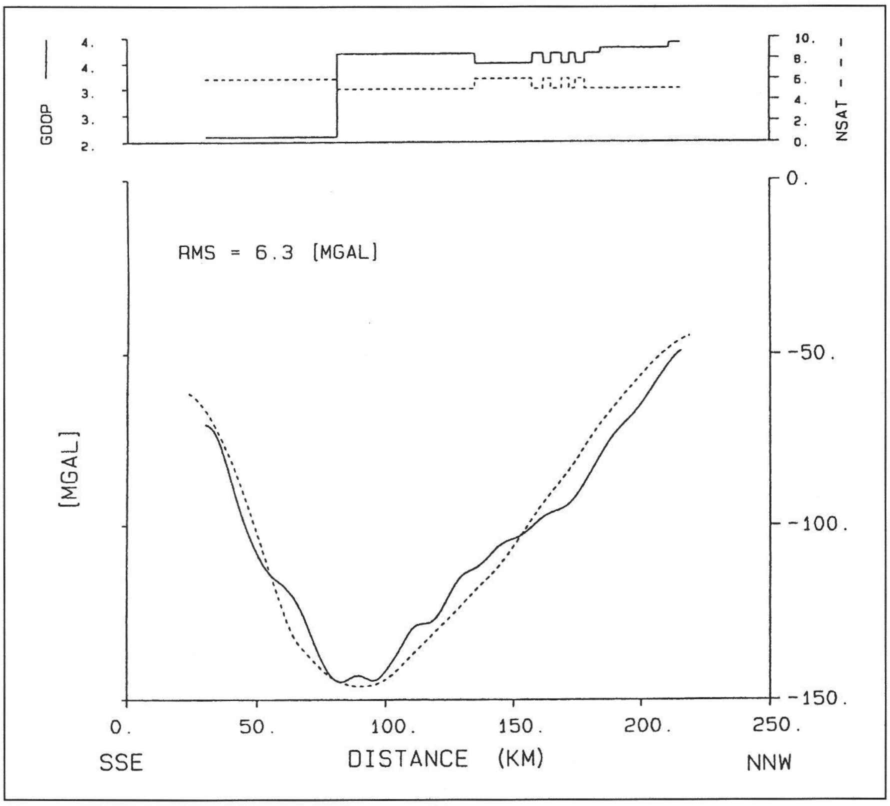

Fig. 6: Same as in figure 5 for line 22.1. The RMS difference between the two anomalies computed for 427 points is equal to 6.4 mgal.

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References:

Bell, R.E., Coackley, B.J., Stemp, R.W., «Airborne Gravimetry from a Small Twin Engine Aircraft over the Long Island Sound», Geophysics, Vol. 6, Nr. 9, 1486-1493, 1991.

Bell, R.E., Coackley, B.J., Blankenship, D.D., Hodge, S.M., Brozena, J.M. and J. Jarvis, 1992. Airborne Gravimetry from a light Aircraft: CASERTZ 1990-1991., Recent Progress in Antartic Earth Science: Y.Yoshida et al. Editors. Terra Scientific Publishing Company, Tokyo,1992.

Brozena, J.M., «A Preliminary Analysis of the NRL Airborne Gravimetry System 1984», Geophysics, Vol. 49, Nr. 7, 1060-1069, 1984.

Brozena, J.M., Peters, M.F., «An Airborne Gravity Study of eastern North Carolina», Geophysics, Vol. 53, Nr. 2, 245-253, 1988.

Brozena, J.M., Mader, G.L. and M.F. Peters, 1989. Interferometric GPS : 3D positioning source for Airborne Gravimetry. J. Geophys. Res., 94, B9: 12153-12162.

Cocard, M.,1994. High Precision GPS-Processing in Kinematic Mode. Diss. ETH, No 10874.

LaCoste, L.J.B., «Measurement of Gravity at Sea and in the Air», Reviews of Geophysics, Vol. 5, No. 4, pp. 477-526, November 1967.

LaCoste, L.J.B., Ford, J., Bowless, R., Archer, K., «Gravity Measurements in an Airplane Using State-of-the-Art Navigation and Altimetry», Geophysics, Vol. 47, Nr. 5, 832-838, 1982.

Harlan, R.B., «Eotvos Corrections for Airborne Gravimetry», JGR, vol. 73 Nr. 14, pp. 4675-4679, 1968.

Klingelé, E.E., Olivier, R., «La Nouvelle Carte Gravimétrique de la Suisse. Matériaux pour la Géologie de la Suisse», Série Géophysique, 96 Pages, 9 Figures, 4 Tables, 1 Carte, 1980.

Valliant, H.D., «The LaCoste and Romberg Air/Sea Gravity Meter: An Overview», Geophysical Exploration at Sea, 2nd Edition, Vol. 1, pp. 141-176, December 1991, ISBN 0-8493-4252-X.

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