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Regional geoid determination in Tierra del Fuego including GPS levelling

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ABSTRACT

A regional geoid model for the Argentine part of the Isla Grande de Tierra del Fuego, established in previous works on the basis of GPS levelling, suffers a lack of observation data in the remote south-western investigation area. In order to improve the data distribution in this region, the mean lake level of Lago Fagnano has been regarded as a natural indicator for the local geoid. Using a GPS buoy and pressure tide gauges, a method to determine the mean lake surface topography with respect to the ellipsoid has been developed. It is shown that the obtained lake level geometry is essentially controlled by the regional gravity field. The derived information on the mean lake level has been included in the geoid model, which results in a more detailed and plausible representation of the regional geoid.

KEYWORDS **Geoid. Mean lake level. Equipotential surface. GPS Buoy. Tierra del Fuego.**

INTRODUCTION

In recent years, the accuracy of global geoid models has been remarkably improved. A number of observation techniques has become applicable for refined regional geoid determinations. However, in many remote areas our knowledge about the geoid still does not reach the increasing demands related with the use of the Global Positioning System (GPS) for all geodetic purposes

For the Argentine part of Tierra del Fuego, gravimetric field observations, precise levelling measurements, as well as GPS positioning on levelling lines along main roads carried out in 1998 and 1999, have been used to determine a regional geoid model. The resulting regional model has been compared with the global geoid model EGM96 (Lemoine et al., 1998).

Another approach consists on using a natural water surface as a local indicator for an equipotential surface. In

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the case of Tierra del Fuego, the level of the Fagnano lake, with an East-West extension over 100 km, might be appropriate for the detection of the local geoid shape and gradients. The main interference can be expected from hydrodynamical effects producing a deviation of the lake surface from the undisturbed equilibrium state, which would reflect pure gravitational forces.

Measurements with a GPS buoy were carried out at more than 70 locations on Lago Fagnano in 2003, 2004 and 2005. The kinematic processing of the GPS observations allowed the determination of ellipsoidal lake-level heights. Tide gauge measurements are available in order to correct the observed instantaneous lake-surface topography for disturbing external effects.

In the present contribution, the analysis and combination of these observations are shown. The consistency of the obtained results with measurements by different methods and the feasibility of the proposed approach are discussed.

PREVIOUS SITUATION

In 2001 a geoid model for Tierra del Fuego, Argentina (Fig. 1), was determined from GPS measurements on levelling points along 420 km of the main roads of the region (Del Cogliano et al., 2001). In a first step, the levelling line along the Ruta Nacional 3 from Ushuaia to the north of the island has been observed with GPS. The height measurements of both techniques have been analysed and combined in order to derive precise geoid heights. The first results were promising, but the data distribution was too poor for representing the regional geoid of Tierra del Fuego.

Therefore, in a joint effort of UNLP (La Plata National University) and IGM (Military Geographic Institute), further GPS levellings have been carried out along some of the few secondary roads. In addition, GPS and levelling observations from the Argentine mainland as well as from Chile have been incorporated.

A further improvement of the obtained geoid model requires an increased number and a better geographical distribution of observations. In Fig. 1 this becomes especially evident for the south-western part of Argentine Tierra del Fuego. This remote area, however, is not accessible for a classical GPS levelling due to the lack of roads.

THE GOAL

Today, in sparsely populated regions like Tierra del Fuego, geodetic surveys for both administrative and scientific purposes rely essentially on the GPS technique. GPS provides very effective 3D coordinates related to a mathematic reference surface, the ellipsoid. For practical applications, however, heights that refer to a natural, i.e. physical reference surface, the geoid, are usually needed. Ellipsoidal heights obtained from GPS measurements can

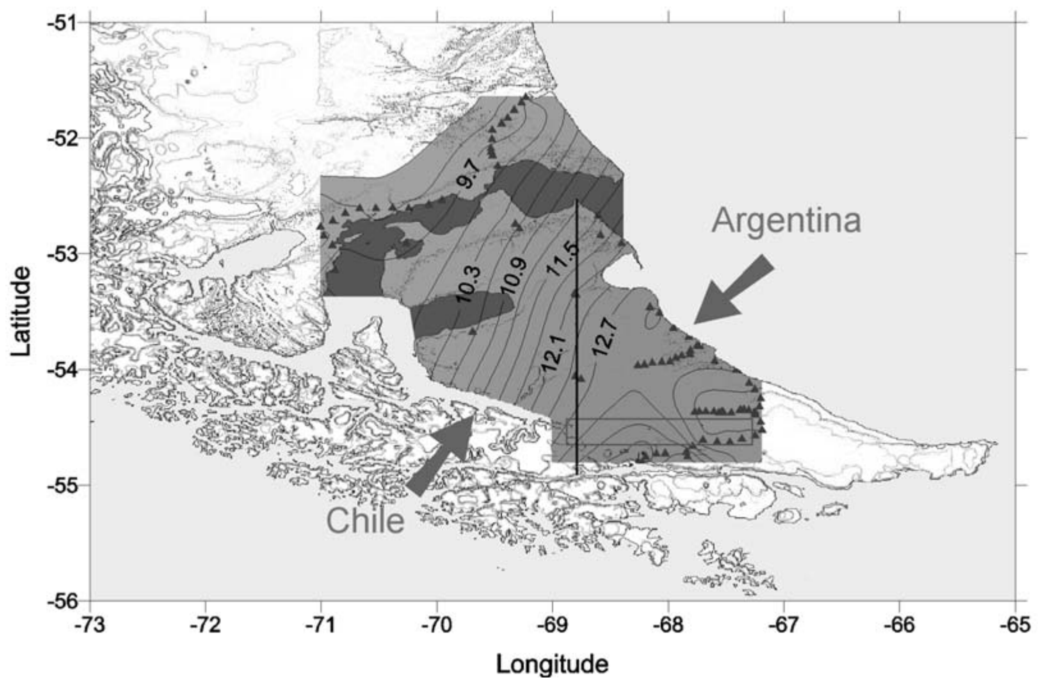

FIGURE 1 | **Previous regional geoid model, obtained from GPS and levelling (triangles). Isolines represent geoid height with equidistance of 0.3 m. The grey area indicates the region where the model may be considered valid.**

be transformed into natural heights if there exists an adequate geoid model for the considered region. Therefore, further improvement of the presented geoid model is of high practical relevance, especially in the identified key region in the south-west of the island, and information of the geoid shape obtained from alternative methods is of great value.

In the southern part of the Isla Grande de Tierra del Fuego, the Fagnano Lake extents over 100 km East-Westward. In the present work, the geometry of the lake surface has been determined with respect to the ellipsoid. The aim of the experiment was to investigate whether the mean lake level (MLL) could be considered as a good representation of an equipotential surface, and if the information of water level can be used as a complement for the existing geoid model.

The geometrical relationship between the surfaces involved in this context is illustrated in Fig. 2.

METHODOLOGY AND OBSERVATIONS

The determination of the lake level was based on kinematic measurements of a GPS antenna mounted on a buoy (Fig. 3). This GPS buoy was operated from a zodiac with sampling rate of 1 sec and with deployment intervals of more than 5 min. It was deployed at measurement points widely distributed all over the lake and forming profiles along and across the lake axis (Fig. 4).

In order to obtain the required accuracy, the GPS measurements were carried out in differential mode. For this purpose, a set of fixed control stations around the lake shore (Fig.5) were occupied simultaneously on special GPS markers with known coordinates (International Terrestrial Reference Frame [ITRF] 2000, epoch 2003.18). The subsequent processing of the GPS buoy measurements (GPSurvey 2.35 software) in kinematic mode resulted in time series of ellipsoidal coordinates during the observation time. In this study, we focussed on the height component. Thus for each GPS buoy measurement, the instantaneous height of the lake's water surface at the position and the time of the buoy deployment has been obtained with respect to the ellipsoid.

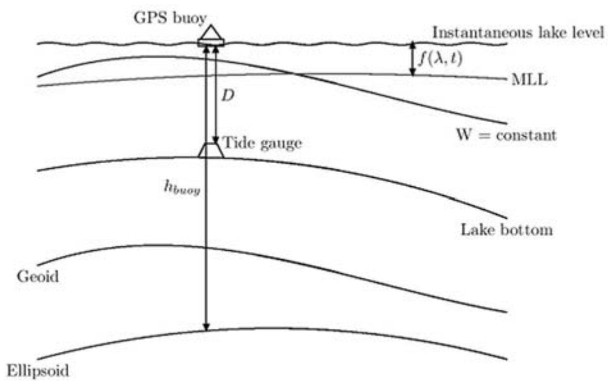

FIGURE 2 **Geometry of the problem. MLL: mean lake level (a priori it is not an equipotential surface). W: equipotential surface close to MLL; f(Ï,t): hydrodynamic correction (numeric function); D: height of the water column above the pressure sensor (tide gauge); hbuoy: ellipsoidal height of the GPS buoy.**

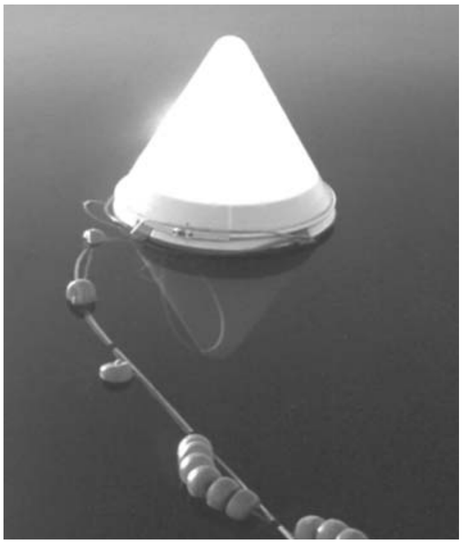

FIGURE 3 **GPS Buoy.**

The lake level observed by the GPS buoy, however, is subject to variations driven (due to) by external forces (e.g. winds). The long observation periods at the GPS buoy deployment allowed to account for the very high-frequency lake level oscillations, induced by waves by filtering techniques.

In order to correct the GPS buoy measurement results for the instantaneous deviations from the mean lake level, pressure tide gauges were operated during the buoy observations at three locations in the lake (Fig. 5).

Based on the obtained tide gauge records, the main period lengths, the respective amplitudes, the spatial behaviour (wave length) and the driving forces of the lake level variations have been determined (Richter et al., 2004). An interesting feature hereby is the seiches, periodical water level oscillations on a specific frequency. The fundamental seiche mode of Lago Fagnano shows a period length of two hours, and although the seiche amplitudes are generally small (during the GPS buoy operations their contribution did not exceed some cm) their effect on the water level may differ considerably among different parts of the lake. Further contributions to the lake level variations occur on longer time scales and may

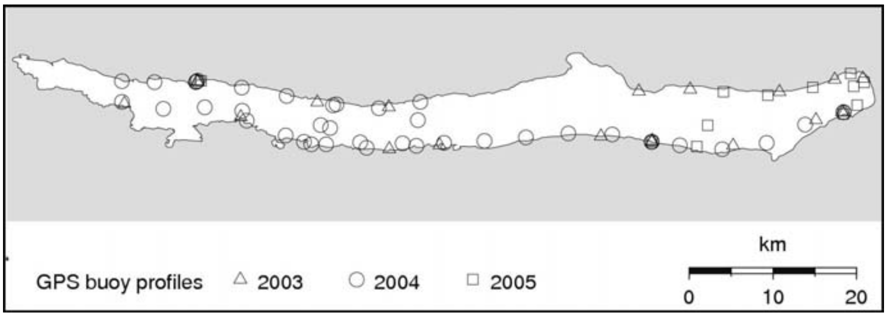

FIGURE 4 **Distribution of GPS buoy observations in the Lago Fagnano. The location of the lake corresponds to the marked area (rectangle) in Figure 1.**

reach a magnitude of a few decimeters. However, in contrast to the seiches, they act uniformly over large parts of the lake. Due to the elongated shape of the lake, the lake level variations occur mainly in East-West direction. As a result of the tide gauge analysis, the momentary deviation of the water surface from the mean lake level can be modelled for any position along the lake axis at any time during the tide gauge operation. The lake level anomaly, $f(\lambda, t)$ at longitude λ and time t is composed of a long-term deviation depending mainly on t and the contribution of periodical seiches, varying with time and along the lake axis.

The ellipsoidal heights of the GPS buoy, $h_{buoy}(\varphi, \lambda, t)$, at the deployment locations all over the lake surface were then reduced to MLL as:

$$\hat{h}(\varphi, \lambda) = h_{buoy}(\varphi, \lambda, t) - f(\lambda, t)$$

To infer the absolute ellipsoidal height of the lake surface from the buoy measurements, the vertical offset between the water surface and the antenna reference point has been determined (with an accuracy better than 1 cm) and checked during all measurement campaigns.

Observation data:

GPS buoy measurements / Period	*Tide gauges records*
23 / February 2003	1 (16 days)
49 / February 2004	3 (12 days)
14 / February 2005	3 (1 year)

RESULTS

The described analysis results in a picture of the spatial variations in the ellipsoidal height (ITRF 2000, epoch 2003.18) of the MLL as shown in Figs. 6 and 7. Along the East-West profile (Fig. 6), a steep increase of the mean lake level of the western part with respect to the eastern part of the lake has been detected. On a distance of about 20 km, the mean lake level height rises more than 40 cm.

According to North-South directed transversal profiles depicted in Fig. 7, the mean lake level at the southern shore is systematically higher than at the northern shore (Figs. 6 and 7). Furthermore, all obtained transversal profiles indicate a mean lake level depression in the lake center. In the South, the gradients of the ellipsoidal lake level heights reach 15 cm on 2 km.

The accuracy of the determined MLL heights has been estimated to be ± 5 cm for one single buoy position, and between ± 2 and ± 3 cm for the entire profile. The error budget of the lake level height determinations is composed of GPS measurement errors, deficiencies in the hydrodynamic correction, $f(\lambda, t)$, uncertainties in the reference station coordinates, and the vertical GPS buoy offset.

According to Fig. 6 the main qualitative results have been observed in the three campaigns 2003, 2004 and 2005. In the western part of the investigated area, the topography of the mean lake level is determined very well. For the lake centre, the available data are insufficient to represent the N-S behaviour of the mean lake surface. In the eastern end of the lake, abundant measurements have been obtained, but exhibit a larger scatter than in the West. This might be partly explained by a more

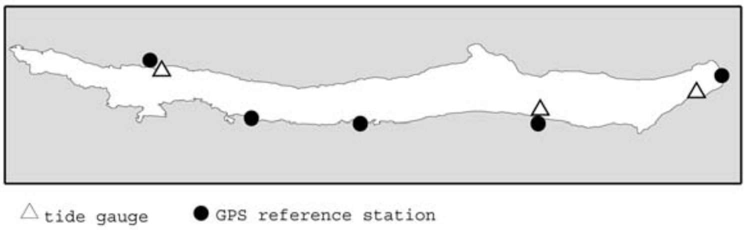

FIGURE 5 **Distribution of tide gauge sites and GPS reference stations in the Lago Fagnano.**

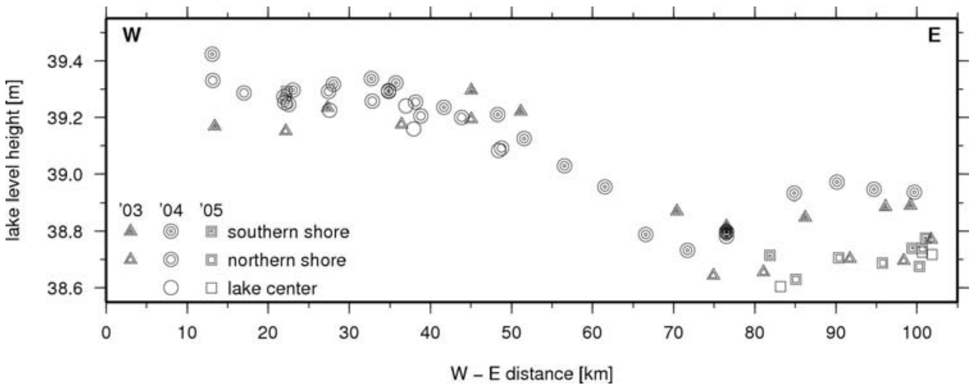

FIGURE 6 **The variation of the MLL along the lake's E-W axis as determined from the GPS buoy observations. Symbols indicate the location in North-South direction; the results of the measurements in 2003, 2004 and 2005 are included, corrected for an absolute lake level shift. They have been corrected for an absolute lake level shift. Note the jump in ellipsoidal lake level height from east to west.**

intense and complex hydrodynamic activity in the eastern Lago Fagnano, that is affected by fast changing wind conditions concentrated near the confluence of the Lago Fagnano and the Rio Claro valleys (approximately at km 75; Fig. 6).

In general, the obtained results are regarded as plausible. The overall lake surface shape in North-South direction shows a high correlation with the local topography. The MLL increase to the South agrees with the existence of high mountains near the southern shore (higher than in the North), which result in a larger mass concentration. Moreover, the lake level depression in the centre of the lake may be interpreted as the gravitational impact of the negative-density anomaly caused by the lake's water body (Fig. 7).

Two points located on the lake shore have been related to the levelling network of the island. The

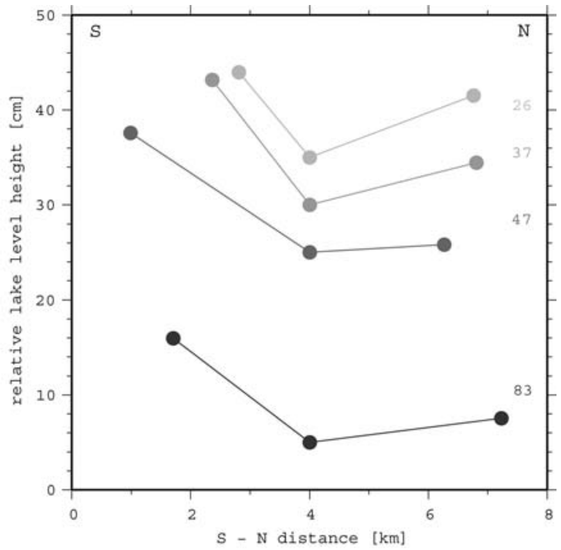

FIGURE 7 **Relative changes in lake level heights in N-S direction as determined by transversal GPS buoy profiles. Numbers to the right indicate the distance (km) of the profile from the western end of the lake according to Figure 6. Note the depression in the centre of the lake, interpreted as an effect of mass deficiency.**

height difference from these points, being 25 km apart, compared with the GPS levelling difference corrected by the lake level variation between them, agrees within less than 2 cm. This is a satisfactory proof that in that portion of the lake, MLL is close to an equipotential surface. Further comparisons are being planned, on despite of the difficulties imposed by the topography, and realising that the complete validation of this supposition is very important.

These results allow the conclusion that the determined shape of the lake surface can be attributed to a large extent to the local geoid, resulting in:

Mean Lake (MLL) $\cong$ *Equipotential surface*

Based on this finding, the relation of the MLL to the geoid has been established for a GPS levelling reference point with known geoid undulation close (300 m) to one of the tide gauges:

$$\Delta N = N(W) - N(W_0) = 26.44\ m$$

where N(W) is the undulation of the equipotential surface W of the MLL, and N(Wo) is the geoid undulation at the reference station.

Applying this level difference to the ellipsoidal heights of all GPS buoy points, $\hat{h}(\varphi, \lambda)$, a surface that approximates the geoid beneath the lake is formed, and hence it can be incorporated into the geoid model analysis, as:

$$N(\varphi, \lambda) = \hat{h}(\varphi, \lambda,) - \Delta N$$

The resulting improved regional geoid model is shown in Fig. 8 and a comparison between the global geopotential model EGM96 (Lemoine et al., 1998) and the recent one EIGEN-CG01c (Reigber et al., 2004) is depicted in Figs. 9 and 10. A similar analysis over the lake is presented in Fig. 11. The tide gauge of Ushuaia, on the southern shore of the island, is the

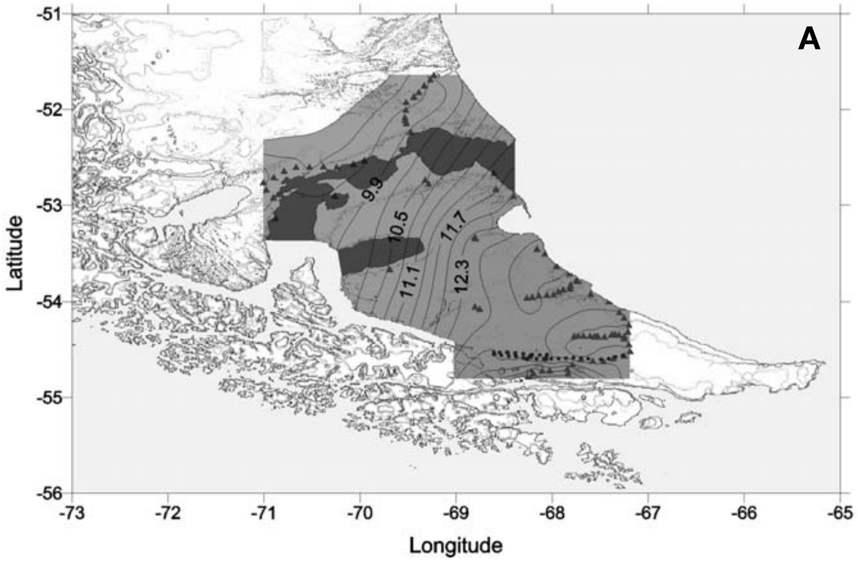

FIGURE 8 | **Regional model of the geoid based on the observed geoid undulations, including the determined MLL heights. Isolines represent geoid height with equidistance of 0.3 m. The integration of the MLL modifies substantially the shape of the geoid in the west of the island (Fig.1), poorly covered by the GPS levellings before. Here, a strong positive gradient towards south becomes evident. The results for the eastern part of the lake confirm the previously existing model.**

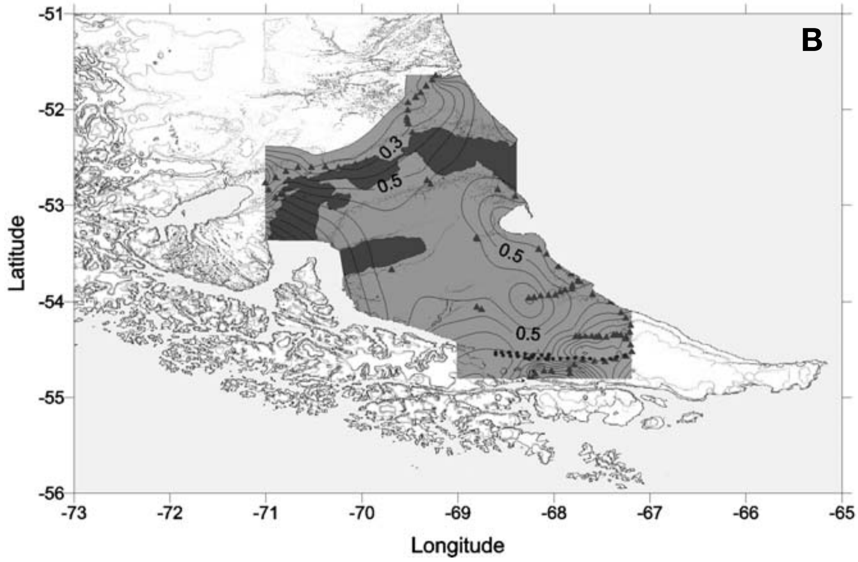

FIGURE 9 | **Differences between the improved regional geoid model and the global geopotential model EGM96 (Lemoine et al., 1998). The global model EGM96 does not represent sufficiently the local geoid of the investigated area, in particular around and south of the lake. The differences show a southward gradient of 60 cm in 30 km. Isolines every 0.1 m.**

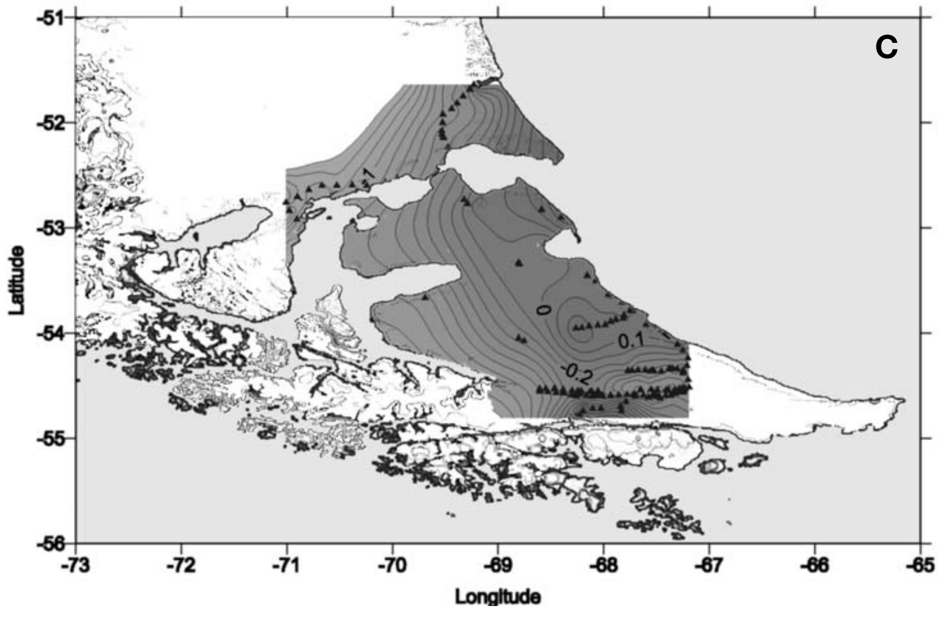

FIGURE 10 | **Differences between the improved regional geoid model and the global geopotential model EIGEN-CG01c (Reigber et al., 2004). In an absolute sense this model shows a better agreement with the observed results over the central part of the Island. Isolines every 0.1 m.**

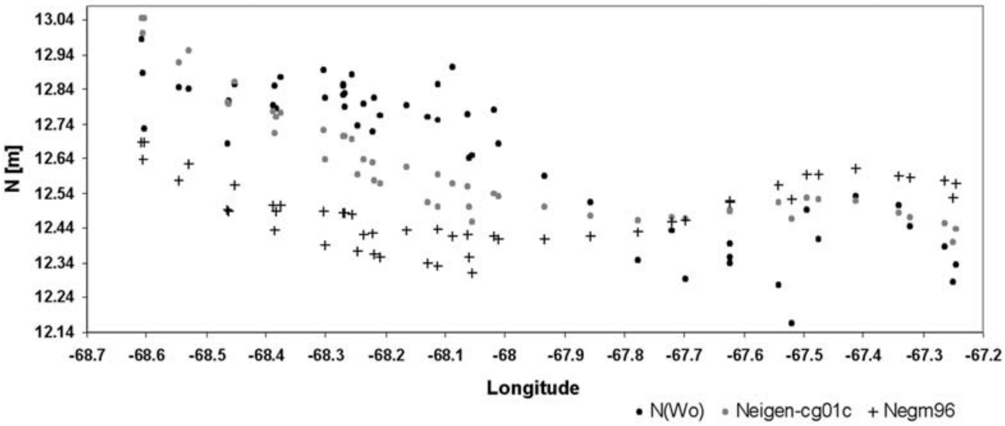

FIGURE 11 **East-West profile along the lake showing the geoid undulations N(Wo) from the GPS buoy measurements and two geopotential models (EGM96 and EIGEN-CGO1c). The EGM96 undulations were shifted by a constant to agree with N(Wo) on the eastern part of the lake. It is quite clear that the EIGEN-CGO1c shows a better agreement with the observations toward the west of the lake, which is close to the Andes Mountains.**

height reference of the local geoid. At this location the geoid undulation difference with EGM96 is about 0.5 m, while whit EIGEN-CG01c is close to cero.

CONCLUSIONS

A regional geoid model has been established for the Argentine portion of Isla Grande de Tierra del Fuego that is based on classical GPS levelling and gravimetric data. This method, however, is restricted to areas accessible by roads, and yields an incomplete data coverage in the remote parts of the island.

In the present work, an experiment has been successfully carried out to determine the equilibrium water surface topography of Lago Fagnano, and to use this information as a complement for the existing geoid model. A suitable method has been developed to measure the ellipsoidal mean surface heights of a water body using a GPS buoy and tide gauges. In our study, an accuracy between ± 2 and ± 3 cm has been achieved.

The use of a natural water surface for the determination of an equipotential surface is an appropriate alternative in remote areas of difficult access for gravimetric observations, as in the present case.

The obtained accuracy is comparable with that of the existing GPS levelling results, and the good agreement found between both methods allows to incorporate the lake level information in the regional geoid model.

The integration of the MLL information contributes notably to the representation of the local geoid.

The derived geoid undulations show a strong correlation with the local mountains and the lake floor topography (Lodolo et al., 2002).

Existing gravimetric information for this area will be used to optimize the present results in the near future.

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