Precise Determination of the Orthometric Height of Mt. Kilimanjaro

Team KILI2008, Portugal, Tanzania, Kenya, The Netherlands, U.S.A., Egypt

Key words: GPS, Positioning, Vertical Datum

SUMMARY

Mount Kilimanjaro, located in Tanzania, is the highest mountain in Africa. Furthermore, this dormant volcano is the highest “stand-alone” (it has an almost perfectly shaped volcano form) and “walkable” (it is not necessary to use special climbing equipment) mountain in the world. Located on the plate boundary between Somalia and Victoria tectonic blocks, Mount Kilimanjaro started to be formed about 750000 years ago being currently constituted by three major volcanic cones, Kibo, Mawenzi, and Shira. The first reaches approximately 5900m.

In the past, several attempts were carried out to observe the precise height of this mountain. In 1952, the British Ordnance Survey did the first determination of the height of Uhuru peak (the top of Kibo volcano) by triangulation points over distances of more than 55Km. The computed value was 5895m. In 1999, a first attempt to apply spatial techniques (GPS) has been done and a new value of approximately 5892m was obtained. However, the observations were obtained using single-frequency receivers and the EGM96 global model was used to convert from ellipsoid height to orthometric height. This was a major issue since the uncertainties associated with this model for this region were of several meters.

In order to reduce the uncertainties in the determination of the height of Mount Kilimanjaro, a new mission was carried out in October 2008. This project, called KILI2008, involved 19 researchers from institutions of six different countries: Tanzania, Portugal, Kenya, The Netherlands, USA, and Egypt. To achieve such goal, GPS (Global Positioning System) data was combined with gravimetric observations. The gravimetric observations were necessary in order to construct a local geoid with sufficient accuracy. Three teams carried out observations during 10 days, with two teams carrying gravimetric around and in the mountain, whereas a third team was doing GPS observations on the top of the mountain.

This presentation will focus on the description of the adopted methodologies that were used to accurately observe the ellipsoidal heights and to compute the local geoid. In order to validate the results, different groups processed the GPS observations using different software packages and different strategies. Similar procedures were applied to the geoid computation. The computed surface is also compared with the one obtained using global models, in particular the recently released EGM2008 model.

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1. INTRODUCTION

Mount Kilimanjaro is the highest point of Africa and the highest isolated mountain which summit can be reached without the use of special climbing equipment. Furthermore, its location close to equator associated with the existence of permanent glaciers and its almost perfect volcano shape clearly discernible in the middle of African the savanna have contributed to make this mountain one of the most important natural landmarks in the world.
In begin of 2008, the Survey and Mapping Department (SMD), Tanzania and the Instituto Geofísico Infante D. Luíz (IDL), Portugal started to prepare a project, called KILI2008, with the goal to reduce the ambiguity in the value of the orthometric metric of Mt. Kilimanjaro since the previous measurements had diverged of several meters.

1.1 Previous Measurements

The first measurement of the orthometric height of Mt. Kilimanjaro was done in 1952 by the British Ordnance Survey using trigonometric leveling. The estimated value was 5895m with respect to the national vertical datum of Tanzania. This figure was in the past the value commonly accepted for the orthometric height of Mt. Kilimanjaro. However, the uncertainty associated with this computation had several meters since it was based on triangulations with sides having lengths of about 55Km and height differences of about 4000m (Pugh, 1954; Dickson, 1954).
In 1999, a first attempt to determine the orthometric height of Mt. Kilimanjaro using GPS (Global Positioning System) was done by an international team formed by Tanzanian and German researchers (John *et al.*, 2000). The final value obtained was 5892.55m. Since GPS provides the height (h) with respect to a reference ellipsoid (WGS84), it was necessary to know the local geoid undulation (N) in order to estimate the orthometric height (H):

$$H \cong h - N \qquad (1)$$

In order to compute the local geoid undulation (N), John *et al* (2000) used the EGM96 global model (Lemoine *et al.*, 1998). This model was computed using an heterogeneous gravimetric dataset (terrestrial and satellite) and it contains coefficients of the Earth's gravitational potential expressed in terms of spherical harmonics up to degree 360, which corresponds to a resolution of 30' (approximately 56Km at equator). The claimed uncertainty was of ±50cm. However, this value was clearly optimist for the Kilimanjaro region as the comparisons between different global geoid models proved.

1.2 Uncertainties of Global Geoid Models

In order to properly evaluate the uncertainty of 1999 estimation, we compared the EGM96 model with GPM98B (Wenzel, 1998), another global model later produced with a higher degree, 1800, which corresponds to a resolution of 6'(approximately 12Km at equator). Figure 1 compares the modeled differences for the Kilimanjaro region as given by the two models:

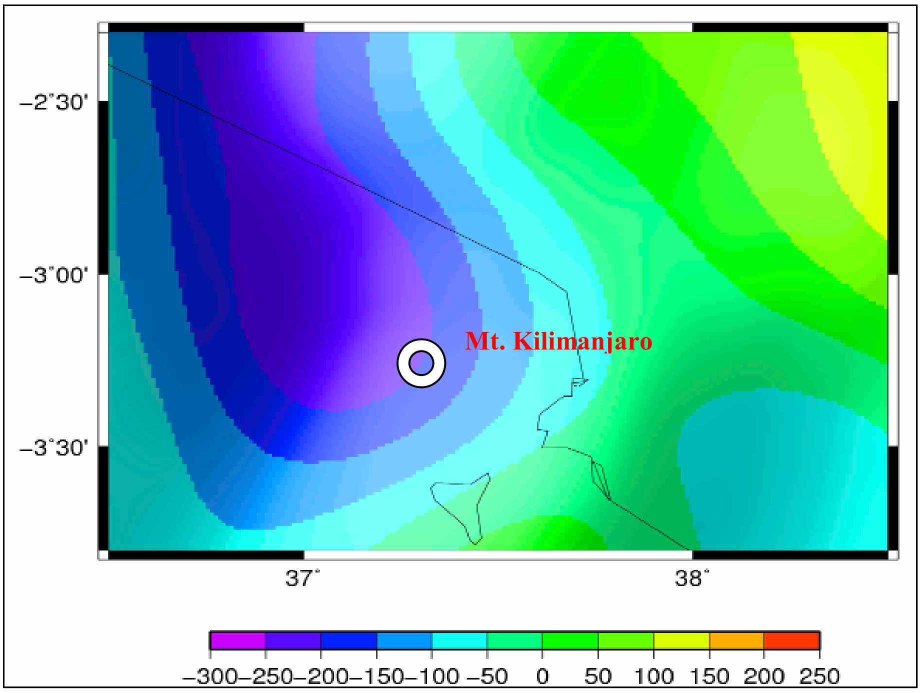

Figure 1 – Difference (cm) between the predicted geoid undulation as given by GPM98B and EGM96.

Around the summit of Mt. Kilimanjaro, we could observe differences that reached almost 3m. The conclusion is obvious: depending of the model that we were using in Equation 1, we could have differences on the final orthometric height for Mt. Kilimanjaro of about 3m. This was a good measure of the real uncertainty of the value computed in 1999. Furthermore, the estimated ellipsoidal height was also derived using a short period of time (Angelakis, 1999), which was also contributing for the larger uncertainty associated with the estimated value.

The potential errors associated with the uncertainty of the geoid model were later confirmed by comparing EGM96 with EGM2008 (Pavlis *et al.*, 2008), another global geoid model released already after the start of the KILI2008 project. This model is clearly an improvement with respect to the previous models. The coefficients of the Earth's gravitational potential are expressed in terms of spherical harmonics up to degree 2190, which corresponds to a resolution of 5' (approximately 9Km at equator).

Figure 2 shows the 3D surfaces of EGM96 and EGM2008 for the Kilimanjaro region. The better resolution of the EGM2008 model is clearly perceptible, namely the influence of the large mass of the Kilimanjaro mountain. The EGM96 surface is too smooth due to the large wave length of the model. Differences between these two models vary between -1.86m in the base and +1.76m on the mountain top.

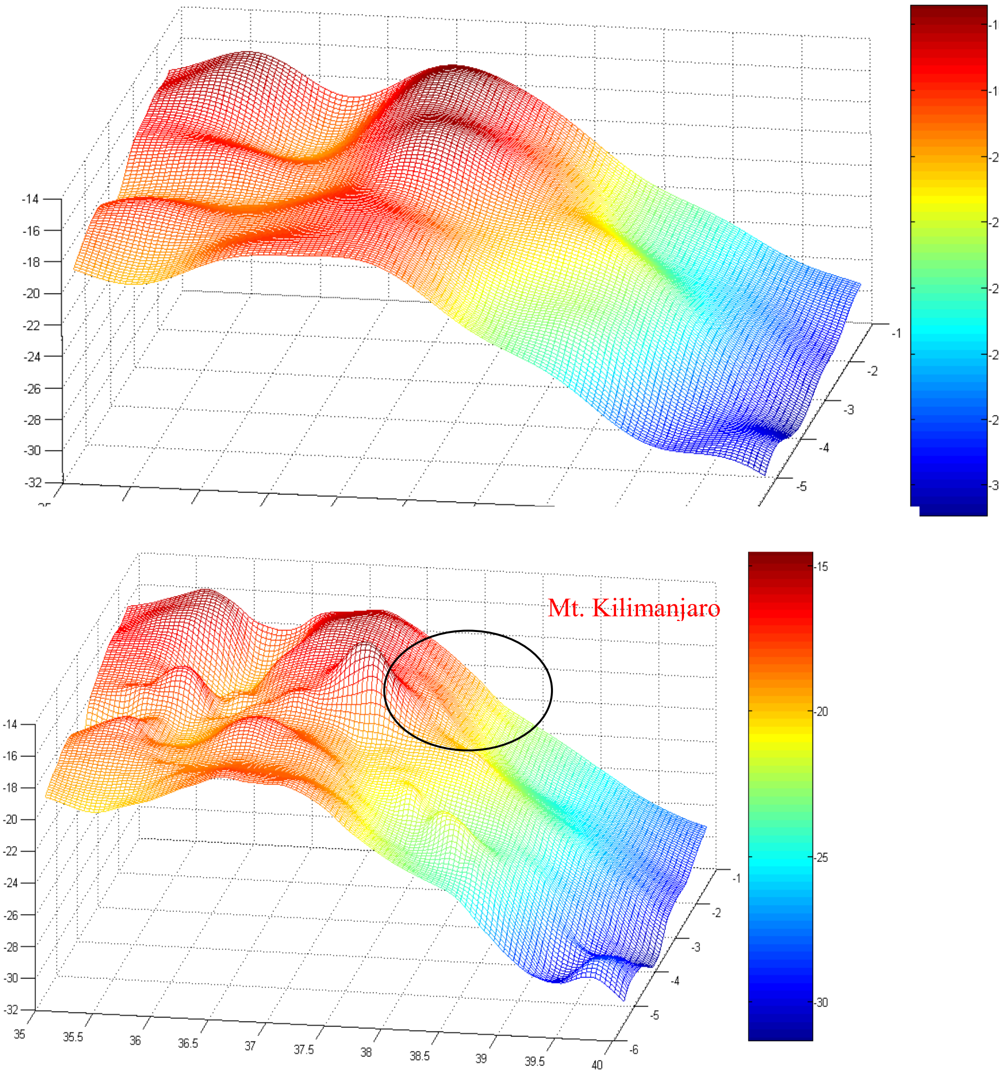

Figure 2 – EGM96 (above) and EGM2008 (below) geoid undulations (with respect to WGS84) for the Kilimanjaro region.

2. DATA ACQUISITION

2.1 Methodology

Leveling is still the alternative to GPS for the measurement of orthometric heights. If it can be more accurate (in particular the geometric leveling), it also requires much more time. This is particularly true for Mt. Kilimanjaro. To measure the orthometric height using geometric leveling would require several months of field work, which was not feasible due to time, logistic and financial constraints. Therefore, combining GPS observations with the use of a model for the geoid undulations was the unique alternative to measure the orthometric height of Mt. Kilimanjaro. And, it was clear to us that the only option to reduce the uncertainty in the determination was by computing a dedicated local geoid model and by guaranteeing a reliable estimation of the ellipsoidal height.

The estimation of a local geoid demanded the acquisition of gravimetric data in a grid centered around the mountain that needed to be as dense as possible. This posed major logistic issues because the access to the mountain was only possible through the few existing routes. To carry out gravimetric observations close to the summit using any of the routes would take several days with high risk of failure of the data acquisition since the gravimeters demand a constant power supply using batteries, and there was no possibility of recharge them. Furthermore, the acquisition of the gravimetric data on the top of the mountain, although important, was not essential to compute the local geoid. Therefore, in order to optimize the existing resources, we decided to not acquire gravimetric observations on the summit. Since we had two gravimeters available, one team did observations around the mountain (including some points in Kenya) and the second team acquired observations by approaching the center of the mountain as much as possible different available routes. This was done on a daily basis except when this gravimetric team joined the GPS team for the first two days of hiking heading to the summit.

The GPS team used the longest route (Marangu route, southeast) to climb the mountain. During the ascension, GPS points were acquired with an approximate 200m vertical difference. The major reason for this acquisition (except when this was done in parallel with the gravimetric observations) was to obtain data points for other studies (e.g., validation of Digital Terrain Models).

Two reference stations were installed in the framework of the KILI2008 expedition. The first one (donated by Trimble) was installed in Moshi and it is now a CORS (Continuous Operating Reference Station) to be part of the AFREF project. The second was installed in Himo, close to the departure gate during the duration of the field works in order to ensure redundancy of the reference stations (see Figure 3).

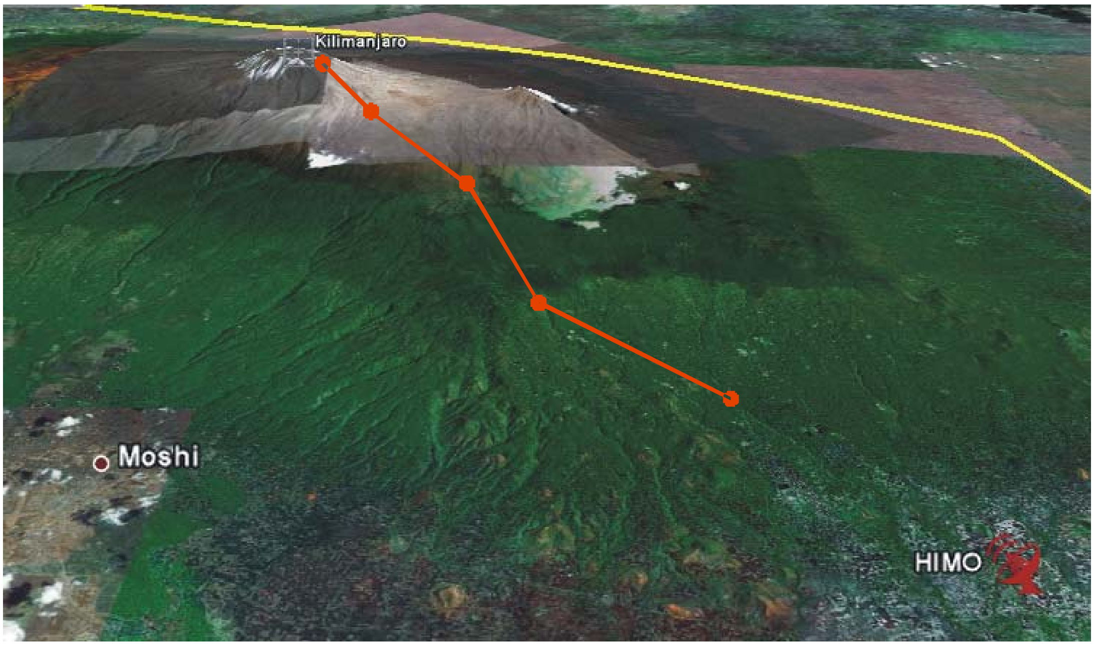

Figure 3 – 3D image with location of the GPS reference stations (Moshi and Himo) with respect to the Marangu route (approximated by the red line) used by the GPS team (extracted from Google Earth).

2.2 Data set

Figure 4 indicates the locations of all data points (GPS and gravimetric). At every point, GPS and gravimetric data were simultaneously collected with the exception of the points above 3200m in Marangu route where only GPS observations were done.
In total, there were 106 points with GPS observations and 99 gravimetric points at the end of the campaign.

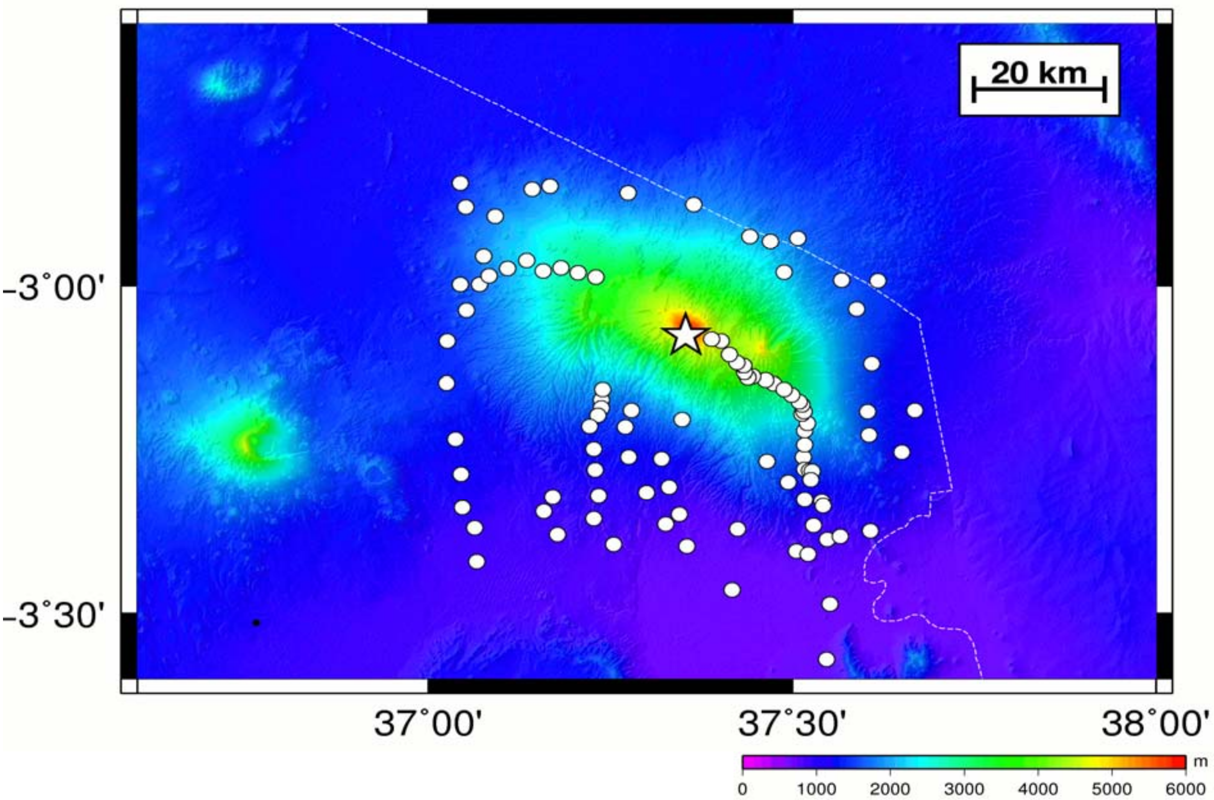

Figure 4 – Distribution of the acquired Gravimetric and GPS data points. Star indicates the summit (Uhuru peak).

3. RESULTS AND DISCUSSION

3.1 Processing

3.1.1 Geoid Computation

In order to estimate the local KILI2008 geoid, we used the standard Residual Terrain Modelling strategy of Forsberg and Tscherning (1981).
First, we used degree 0-360 of EGM2008 to compute the long wavelengths of the geoid. We used also a spherical harmonics decomposition of the topography of the Earth to compute the topography of the Earth to degree 360. Using this smooth, long wavelength topography it was possible to correct the geoid to account for this topography. Thus, we applied to the so-called

height anomaly corrections. Note that by using EGM2008, we implicitly used the reference level of EGM2008. The degreees 0-360 of EGM2008 were also used to compute the long wavelengths gravity field which were subtracted from the gravity observations.

Secondly, we used the SRTM topography. The changes in geoid due to the mass between this high resolution digital terrain model and the smooth topography (degree 0-360) were computed (residual terrain correction). It was also computed the effect of the attraction of the mass on the gravity observations which were then also subtracted.

Finally, Least Squares Collocation (LSC) were applied to the remaining gravity observations,after subtracting degree 0-360 of EGM2008 and subtracting the attraction of the mountain,in order to convert these gravity disturbances into geoid undulations.

The total KILI2008 geoid (Figure 5) is the sum of degree 0-360 of EGM2008, the geoid due to the mass of the mountain and the geoid contribution computed with LSC.

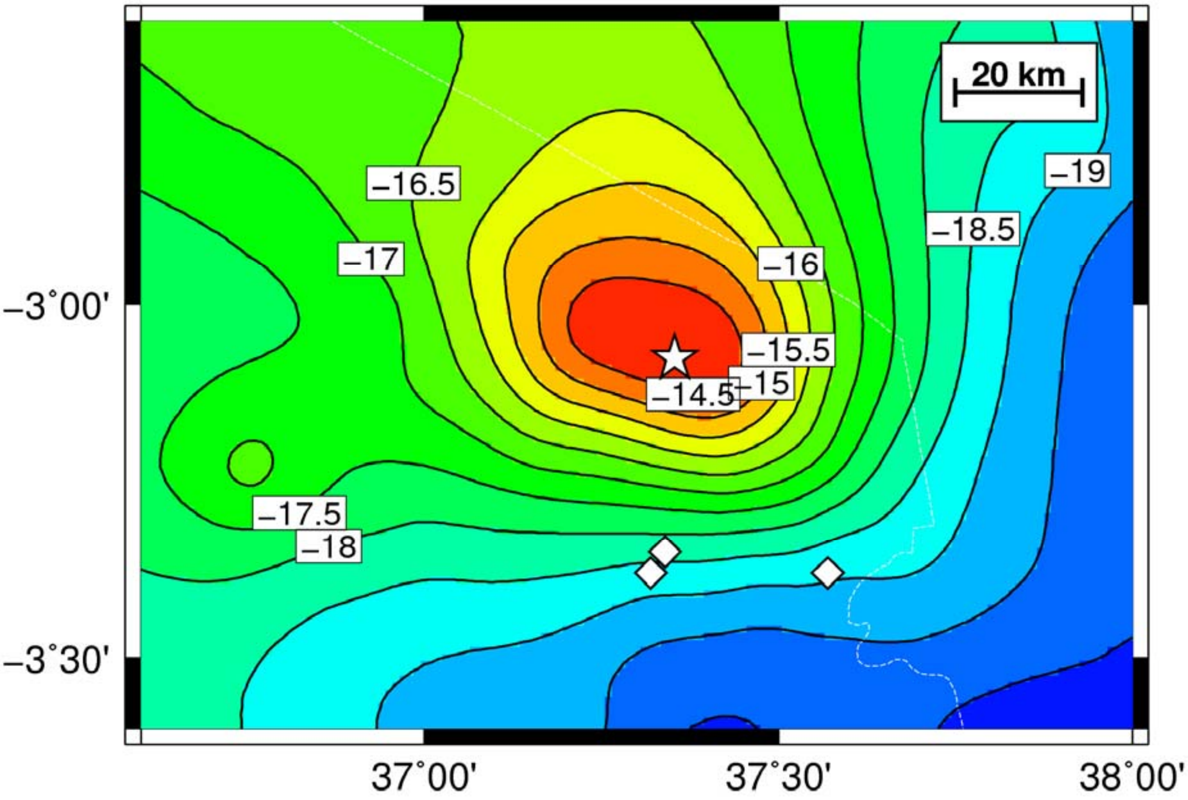

Figure 5 – The KILI2008 geoid model: geoid undulations with respect to WGS84

3.1.2 GPS solutions

The GPS solutions were obtained using different GPS data processing applications. First, the computation of the precise ellipsoidal heights with respect to the latest realization of the global reference frame, ITRF2005 (Altamimi *et al.*, 2007), for the two reference stations (Moshi and Himo) was done using the GIPSY academic software package (Webb and Zumberge, 1995). Details how this is done using a global network of reference stations can be found in Fernandes *et al.* (2008).

The positions of these two stations were fixed in order to compute the ellipsoidal heights for the other points. This was done using TBC (Trimble, 2008) since this application is fine-tuned to process short baselines efficiently. Due to the relatively short time of observations (30-45m for most of the points), the baseline approach is preferable than the use of the PPP strategy with ambiguity fixing (Blewitt, 2008) used in GIPSY. The only exception was the solution for the Uhuru peak since we were able to collect 5h of data (much more than initially planned). We have computed solutions using GIPSY, BERNESE (Hugentobler *et al.*, 2005), TBC, and for external check, we also used some online processing services: AUSPOS (AUSPOS, 2008) and SCOUT (SOPAC, 2008).

3.2 Ellipsoidal Height

Table 1 lists the obtained values using the different processing software packages. We can observe that the differences between the processing software packages reached 0.5m when we compare the results obtained with the academic applications and with TBC. The probable major cause for these differences is the modeling of atmospheric perturbations. Although the baseline between the reference stations and the Uhuru Peak was relatively short (30Km to Moshi, 40Km to Himo), there is a tremendous vertical gradient between the references and the rover (4000m). The academic software packages are able to estimate simultaneously with the 3D-positions the zenith tropospheric delay caused by the presence of water vapor in the atmosphere, whereas the TBC only introduces standard corrections which do not take into account the large difference in pressure and temperature between the top and the bottom of Mt. Kilimanjaro.

Table 1 – Computed value of the ellipsoidal height for Uhuru Peak (summit of Mt. Kilimanjaro) using several GPS processing software applications.

Solution	Value (m)
GIPSY	5875.43
BERNESE	5875.59
AUSPOS	5875.48
SCOUT	5875.56
TBC	5875.07

The differences between the solutions obtained with the academic applications reach 16cm. There are several explanations for these differences. Different procedures where used to align the solution with the global reference frame and different models for the antenna phase center variations were applied. For instance, the BERNESE solution is based on a regional alignment with ITRF2005 and the AUSPOS is aligned with ITRF2000 (a previous realization of the global reference frame). These solutions also used relative phase centers whereas the GIPSY solution was based on absolute phase centers variations. This is the reason why we have selected GIPSY as the final solution for the ellipsoidal height instead of averaging the different solutions. Nevertheless, the comparison between the different solutions provides us an estimative of the real uncertainty in our computations.

3.3 Orthometric Height

In order to compute the orthometric height, we applied Equation (1) using the ellipsoidal height computed with GIPSY and the geoid undulation predicted by the KILI2008 model. This is consistent since the ellipsoidal height and the KILI2008 geoid undulations are both referred to the WGS84 ellipsoid. Therefore, we compute the orthometric height with respect to the global datum used at EGM2008 that intends to minimize the differences between the Mean Sea Surface and the geoid at a global scale. Consequently, we can state that the current value for the orthometric height of Mount Kilimanjaro is the value given in the first row of Table 2: 5889.91m.

However, the official value must be given with respect to the national vertical datum of Tanzania. In order to achieve such goal, it is necessary to compute the offset between the global and the Tanzanian vertical data. This is possible if we know both values at some points (ideally, as close as possible to the top of the mountain). In the Kilimanjaro region, only one existing benchmark with known orthometric height referred to the official Tanzanian vertical datum was found close to Moshi. This point was observed with GPS and the orthometric height with respect to the KILI2008 Datum was computed. The difference between the two orthometric heights in the Moshi benchmark was 1.28m. This offset was applied to the value computed for the Uhuru Peak with respect to the KILI2008 datum and a final value of 5890.79m was determined for the orthometric height of the highest point in Africa considering the Tanzanian vertical datum.

Table 2 – Orthometric heights of Mount Kilimanjaro computed with respect to different reference data (see text for details)

Reference Datum	Value (m)
KILI2008 (Global) Datum	5889.51
Tanzanian Vertical Datum	5890.79

3.4 Concluding Remarks

The final value obtained for the orthometric height of Mt. Kilimanjaro is about 4m lower than the initial established by trigonometric leveling when we consider the Tanzanian vertical datum (and about 5.5m if we consider the global vertical datum). And it is also lower about 1.3m than the previous estimative with GPS done in 1999. Clearly, this difference is larger than the associated uncertainty of our computation. The error in the computation of the ellipsoidal height is at decimeter-level as it can be concluded by comparing the different computed solutions using different processing software packages and different methodologies. The error on the geoid computation is also at decimeter-level (±15cm), which give us a final total uncertainty of about 25cm in the computation of the orthometric height of Mt. Kilimanjaro. This does not include the possible error on the conversion from the KILI2008 vertical datum into the Tanzanian vertical datum. Since we had only one point available, there was no possibility to verify the measured offset.

The improvement on the computation of the final value for the orthometric height of Mt. Kilimanjaro is now more dependent of the improvement in the models used to compute the ellipsoidal height and the geoid undulation than in the acquisition of more observations.

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