Mount Kilimanjaro Orthometric Height by TZG08 Geoid Model and GPS Ellipsoidal Heights from 1999 and 2008 GPS Campaigns

Prosper E. Ulotu
Ardhi University, Dar es Salaam, Tanzania. e-mail: ulotu@aru.ac.tz, pepulotu@gmail.com

***Abstract*—**
Mountain Kilimanjaro is the highest mountain in Africa; it is located in Tanzania on the northern border of Tanzania and Kenya. Its highest peak Uhuru is located at latitude $3^\circ 04' 35''$ South of equator and longitude $37^\circ 21' 14''$ East of the Greenwich Meridian.

Several attempts to obtain the exact height of Mount Kilimanjaro using different survey techniques have been deployed since 1889. Documented results show height range between 6010m in 1889 and 5891m in 1991; differing by 119 metres. The 1952 result of 5,895m above mean sea level (msl) has remained the official height of the mountain to date. After 1952, two attempts were made to obtain the orthometric height of the mountain using modern approach of GPS levelling; a technique that requires accurate ellipsoidal and geoidal heights. During the two last attempts in 1999 and 2008, ellipsoidal heights were obtained by geodetic GPS positioning at Uhuru peak, the highest point on Kibo cap. Due to non-availability of precise and accurate geoid model for Tanzania, the 1999 and 2008 heights were obtained as 5892 and 5891 metres respectively. The major cause of the significant vertical difference of up to 4m from the official height is attributed mainly to absence of precise geoid model, since the ellipsoidal heights from the two GPS campaigns are quite close. Tanzania has now a dedicated precise gravimetric geoid model, TZG08, which was carefully computed to take care of rough mountainous topography. Furthermore it is compatible with Global Navigational Satellite Systems (GNSS) which includes GPS. Evaluation of the four most recent global and regional geoid models for Tanzania using different approaches have all passed TZG08 to be the best gravimetric geoid model for Tanzania for the time being.

The aim of this paper is to compute a more accurate orthometric height of Mount Kilimanjaro by utilizing the current most precise geoid model for Tanzania, TZG08, together with the 1999 and 2008 GPS campaigns ellipsoidal heights using GPS levelling method.

The result of the GPS levelling using TZG08 gravimetric geoid model and the Kil_1999 and KILI2008 GPS ellipsoidal heights is that the orthometric height of Mount Kilimanjaro is 5,894.94m. Therefore the orthometric height of Mount Kilimanjaro is practically the same as the 1952 official height of 5,895m.

***Keywords*—** Mount Kilimanjaro Orthometric height, Tanzania TZG08 Gravimetric Geoid Model, Kil_1999 and KILI2008 Mount Kilimanjaro GPS Campaigns Ellipsoidal Heights

INTRODUCTION

Mountain Kilimanjaro is the highest mountain in Africa; it is located in Tanzania on the northern border of Tanzania and Kenya. Its highest peak Uhuru is located at latitude $3^\circ 04' 35''$ South of equator and longitude $37^\circ 21' 14''$ East of the Greenwich Meridian. The mountain is a young stratovolcano; in geological time scale it is less than 1.6Ma, found in the southern part of the East African Rift Valley System. It consists of three distinct volcanic peaks namely Shira, Mawenzi and Kibo, with Shira having the highest proportion of mafic rocks ((Hayes, 2004). Kilimanjaro is the world's highest free standing, snow-covered equatorial mountain. The highest point, the Uhuru peak is found on top of the Kibo cap. The massive dormant volcano which stands in splendid isolation above the surrounding plains, with its snowy peaks provides wonderful views over the vast savannah plains of East Africa, as a result it attracts many tourists from within and all over the world, partly because the standard ascent does not particularly require special mountaineering skills and equipment. But also for the richness of the Kilimanjaro National Park (KINAPA) which includes most of the forest lying above 2,700m above mean sea level (msl) around the mountain. In addition to the mountain snow caps and surrounding mountain forest, numerous mammals, reptiles, birds, and insects many of them endangered species are found within KINAPA. Climbing Mount Kilimanjaro is both exciting and challenging to almost every trekker and mountaineer in the world and the exact climbed height is of special interest not only to mountain climbers, but also to a wide variety of applications.

Although Kilimanjaro is conspicuous and close enough to the old trading caravan routes to be a key landmark for outsiders, there seem to be very few historical records. The only one reference to a great mountain west of Zanzibar was made by a Chinese traveller six or seven centuries ago. For the Western world, it was a publication in 1849 by Johann Rebmann, a German Christian missionary who brought the mountain to the attention of Europe. After several attempts by various outsiders to climb and height the summit, it was Hans Meyer who succeeded to height the mountain's highest peak, the Uhuru peak in 1889.

Attempts to Height Mount Kilimanjaro

Endeavours to height Mount Kilimanjaro date back to as early as 1889. Several attempts have been made to determine the exact height of the mountain using a variety of surveying and non-surveying methods. The outcomes of the methods led to variable results that ranged between 6010m in 1889 to 5891m in 2008 differing by 119 metres. A summary of the attempts made to height the mountain to date is given in Table-1 below.

Table-1: Documented initiatives to height Mount Kilimanjaro between 1889 and 2008

Year	Person/Organization	Method Used	Outcome/ Height (m)
1889	Hans Meyer	Uncontrolled aneroid barometry	6010
1904	Anglo Germany Boundary Commission	Trigonometric intersection	5892
1912	Klute	Leap Frog in controlled aneroid barometry	5930
1921	Gillman	Boiling point	5965
Unknown	East African Handbook	Unknown	6011
Unknown	Germany map – Kilimanjaro	Unknown	5963
Unknown	older German maps	Unknown	6010
1952	Director of Lands and Surveys, Tanzania	Reciprocal trigonometric heighting	5895
1999	Mount Kilimanjaro Expedition 1999	GPS levelling using EGM96 geoid model	5891.8
2008	KILI2008 Team	GPS levelling using EGM2008 global datum WGS84	5889.9

Sources: Hemed (2000), Angelakis (1999) and TeamKILI (2008)

The result from survey method of reciprocal trigonometric levelling obtained in 1952 as 5,895m above msl has remained the official height of the mountain to date; see (Pugh, 1954) and Hemed (2000) for more details. Since 1952, two more re-heighting of the mountain using modern method referred to as GPS levelling have been carried out to obtain orthometric heights of the mountain. Accuracy of heights obtained depend on the accuracy of its main constituents, the GPS ellipsoidal height, h and the gravimetric geoidal height, N. Both the 1999 and 2008 results differ substantially from the 1952 outcome as well as from one another as detailed in Table-2 below

Table-2: Outcomes of the 1999 and 2008 orthometric Height of Mount Kilimanjaro's highest peak by GPS levelling

Campaign	Latitude (deg)	Longitude (deg)	Ellipsoidal height h (m)	Geoidal Height N (m)	Geoid Model	Orthometric Height H(m)	GPS Processing Software	Processing Centre
1999	-3.0763586	37.3539608	5875.5134	-16.273	EGM96	5891.7864	BERNESE v4.0	University of Technology Karlsruhe
1999	-3.0763585	37.3539610	5875.4906	-16.273	EGM96	5891.7636	BERNESE v4.0	University of Karlsruhe
2008	Not Given	Not Given	5875.43	Not Given	Not Clear	5889.51	GIPSY	Bolama Portugal
2008	Not Given	Not Given	5875.59	Not Given	Not Clear	5889.51	BERNESE	Bolama Portugal
2008	Not Given	Not Given	5875.48	Not Given	Not Clear	5889.51	AUSPOS	Bolama Portugal
2008	Not Given	Not Given	5875.56	Not Given	Not Clear	5889.51	SCOUT	Bolama Portugal
2008	Not Given	Not Given	5875.07	Not Given	Not Clear	5889.51	TBC	Bolama Portugal

Source: Extracted from Angelakis (1999) and KILI2008 (2008).

Many important issues are given in Angelakis (1999) in respect of determination of orthometric height of Mount Kilimanjaro. They are such as coordinates of the Uhuru peak, GPS processing software and its version and the geoid model used. In addition, ellipsoidal height was independently processed at University of Technology Karlsruhe and at University of Karlsruhe. The outcomes from the independent processing are in very close agreement, see Table-2 above. Since the coordinates of Uhuru peak are nearly the same, the obtained geoidal heights are for the same point and are very close to each other.

In the case of KILI2008 (2008), there are a number of issues which are not explicitly given in the paper, or are explained but are ambiguous. For example, the coordinates of the observed point on Kibo cap where GPS positioning was conducted are not given, consequently anxiety for whether the comparison in the two campaigns is for the same point or how close is the point of 1999 to that of 2008 is not answered. Furthermore, it is stated in the paper that, by then EGM2008 had not been published, at the same time 99 gravity observations were collected around the mountain. In addition, initiative to determine a local geoid model of the mountain using what is referred to as 'standard Residual Terrain Modelling strategy of Forsberg and Tscherning (1981)' is advocated. When it comes to the determination of orthometric height of Mount Kilimanjaro, it is stated that 'orthometric height with respect to the global datum used at EGM2008' is used. If we recall that in the paper it is stated that EGM2008 global geoid model was released after the start of the KILI2008 project, it is not clear which geoid model has been used to provide the geoidal height of Uhuru peak in KILI2008. A more disturbing issue arises from the fact that in Table-2 five (5) different values of ellipsoidal heights were obtained from the GPS processing softwares, but the orthometric height based on what is referred to as global datum used at EGM2008 is the same, i.e. 5889.51m. This is not possible using the same geoidal height from the same geoid model and for the same Uhuru peak point, given that all the 5-ellipsoidal heights are different. In Table-2, TBC software is used and the outcome is significantly different from the rest, this is likely due to the fact that TBC software is for short GPS baseline processing.

In Angelakis (1999), it is stated that better results would be obtained if a more accurate geoid model was available. TZG08 which is a dedicated regional geoid model for Tanzania is now available, and has been proven to be more accurate than EGM96 (Ntambila, 2012). Although coordinates for the exact point where GPS positioning was conducted at the Uhuru peak are not given in KILI2008, the closeness of the ellipsoidal heights from the two campaigns suggests that observations were conducted at the same point used in the Kil_1999 GPS campaign. The average ellipsoidal height from the 1999 campaign is 5875.50m. If TBC results are discarded, the average ellipsoidal height from the 2008 is 5875.52m, i.e. they differ by 2cm. We conclude that, in both campaigns, the main problem is not the GPS ellipsoidal height but rather the geoidal height and thus a more suitable geoid model should be deployed in the GPS levelling for orthometric height of Mount Kilimanjaro. In the next section, summary of results obtained from validations of the existing four gravimetric geoid models for Tanzania is given below.

Best Gravimetric Geoid Model for Orthometric Height of Mount Kilimanjaro

Hitherto gravimetric geoid models covering Tanzania fully are five; this has been so since 1996. Of the five geoid models, only two are dedicated for Tanzania. The five gravimetric geoid models are: two global geoid models EGM96 (Lemoine F. G., 1998) and EGM2008 (Pavlis et al, 2008); recall EGM2008 is highly updated version of the previous EGM96. One African continent regional geoid model, AGP07 (Merry, 2007) and two dedicated regional gravimetric geoid models for Tanzania namely TZG07 by (Olliver, 2007) and TZG08 by (Ulotu, 2009).

In Ntambila (2012), assessment of the four geoid models was carried out. The main objective was to find out the one that performs better, so that a proposal could be made to the government for a National geoid model. The 4-geoid models are assessed for their performances on land and in the ocean part of Tanzania. The approaches followed in the assessment are:

1. Comparison of geoidal heights of the four geoid models at 23 GPS/leveling points in mainland Tanzania
2. Comparison of geoidal heights amongst the four geoid models at every $30' \times 30'$ grid intersection in the mainland
3. Comparison of the mean sea surface and geoidal heights of the four geoid models in the ocean area of Tanzania.

Summary of the results from the three approaches above is as follows:

1. From the GPS leveling, it is found that TZG08 performs better in mainland Tanzania.
2. In respect of inter-comparisons of the four geoid models amongst themselves, TZG08 and EGM08 fit each other better over Tanzania.
3. With regards to comparisons of the mean sea surface (mss) to gravimetric geoidal heights in the Indian Ocean portion of Tanzania, TZG08 geoid model performs better.

At the end it was concluded that TZG08 geoid model performs better in Tanzania compared to the other three gravimetric geoid models (Ntambila, 2012).

Further performance assessment of the same four geoid models was conducted in Tanzania mainland using 174 variable length geoid slopes by Willison (2013). The conclusion is that TZG08 has the smallest RMS and therefore has a better relative geometrical geoidal height fit. This finding cemented the earlier absolute geoidal fit to GPS and ocean levelling conducted by Ntambila (2012).

Based on the assessments of the four geoid models for Tanzania conducted in 2012 and 2013, it is concluded that TZG08 is the current best gravimetric geoid model for Tanzania. Therefore taking up from the conclusion reached at the end of Section-1 of this paper that the main problem of the two GPS campaigns of 1999 and 2008 in determining the orthometric height of Mount Kilimanjaro lies with non-availability of precise gravimetric geoid in the GPS levelling process. TZG08 will now be used to determine the orthometric height of Mount Kilimanjaro.

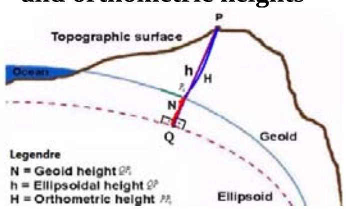
Methodology

Determination of Mount Kilimanjaro orthometric height is by GPS levelling technique using TZG08 gravimetric geoid model that was passed in the Ntambila (2012) and in the (Willison, 2013) validations as the best gravimetric geoid model for Tanzania in the meantime and ellipsoidal heights from the Kil_1999 and KILI2008 Mount Kilimanjaro GPS campaigns. GPS levelling method determines orthometric height from ellipsoidal height as illustrated in Figure 1 according to Equation (1),

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

where H is orthometric height, h is GPS ellipsoid height and N is gravimetric geoidal height all three heights are at the same point.

Figure 1: Relationship of ellipsoidal, geoidal and orthometric heights



Sources: Author's Construction

The GPS ellipsoidal height from the 1999 GPS campaign (Kil_1999) is 5875.50m and from the 2008 GPS campaign (KILI2008) is 5875.52m which are in good agreement and for the same Uhuru peak point. The coordinates for the Uhuru peak are solely picked from Angelakis (1999). Using surfer 8.1 from (Golden, 2002), geoidal height of Uhuru peak is extracted from TZG08 geoid model and this is presented in Table-3.

Table-3: Geoidal height of Mount Kilimanjaro highest point at Uhuru peak

Position		**TZG08 N**
Latitude d.ddd	Longitude d.ddd	(m)
-3.0763586	37.3539608	-19.43

Source: TZG08 Gravimetrci Geoid Model

Result

The orthometric height of Uhuru peak is computed from Equation (1) using the assessed and reduced ellipsoidal heights from Table-2 as well as geoidal height data from Table-3; the results are given in Table-4 below.

Table -4: Orthometric height of Mount Kilimanjaro highest point; the Uhuru Peak

Name	Position		TZG08 N (m)	Ellip-soidal height H(m)	Ortho-metric Height H(m)	Remark
	Lat. d.ddd South	Lon. d.ddd East				
Uhuru Peak	3.0763586	37.3539608	-19.43	5875.50	894.93	Kil_1999
				5875.52	894.95	KILI2008

***Source:** TZG08 Gravimetric Geoid Model and Ellipsoidal Heights from Kil_1999 and KILI2008 Mount Kilimanjaro GPS Campaigns.*

Conclusion

From the two orthometric height results in Table-4, we conclude that the Mount Kilimanjaro GPS campaigns of 1999 and 2008 came up with almost the same height of the mountain except a reliable precise geoid model was missing. Using TZG08 the best gravimetric geoid model for Tanzania, the orthometric height of Mount Kilimanjaro by GPS levelling is established as **5894.94m** which is practically the same as that of 1952 that used reciprocal trigonometric levelling that is 5895m above msl.

Acknowledgements

The author is grateful to the Millennium Kil_1999 and KILI2008 GPS campaigns for the precise GPS ellipsoidal height of Mount Kilimanjaro. The comments of an anonymous reviewer of this manuscript are highly appreciated.

REFERENCES

Angelakis, N., 1999. *Moutn Kilimanjaro Expedition 1999 GPS data processing and evaluation of the ITRF-position and height of Mount Kilimanjaro*, Dar es Salaam : UCLAS.

Golden, S., 2002. *Surfer 8 contouring and 3D surface mapping for scientist and engineers user's guide. Golden software.* Colarado, Patent No. Golden Software, Inc. 1993-2002.

Hayes, S. J., 2004. *Magmati Evolution of the Shira Volcanics, Moutn Kilimanjaro, Tanzania*, Brisbane: Queensland University of Technology.

Hayes, S. J., 2004. *Magmatic Evolution of the Shira Volcanics, Mount Kilimanjaro,* *Tanzania,* Brisbane: Queensland University of Technology.

Hemed, A. I., 2000. *A review of the previous methods used for the determination of the height of Moutn Kilimanjaro,* Dar es Salaam: UCLAS.

Lemoine F. G., Kenyon S. C., Factor J. K., Trimmer R. G., Pavlis N. K., Chinn D. S., Cox C. M., Klosko S. M., Luthcke S. B., Torrence M. H., Wang Y. M., Williamson R. G., Pavlis E. C., Rapp R. H. and Olsen T. R. 1998. *The Development of the Joint NASA GSFC and NIMA Geopotential Model EGM96,* New York: NASA Technical Publications.

Merry, C., 2007. *An updated geoid model for Africa.* Perujia, General Assembly of the IUGG.

Ntambila, T., 2012. *Validation of the recent geoid models for Tanzania,* Dar es Salaam: Ardhi University.

Olliver, J., 2007. The gravimetric geoid model of Tanzania. *Survey Review,* 39(305), pp. 212-225.

Pavlis, N. K. Holmes, S. A., Kenyon, S. C., Factor, J. K. 2008. *An Earth gravitational model to degree 2160: EGM2008.* Vienna, 2008 General Assembly of the European Geosciences Union.

Pugh, K., 1954. The Height Determination of Mount Kilimanjaro Tanganyika, East Africa. *Empire Survey Review*, XII(91), pp. 194-206.

TeamKILI, 2008. *Precise Determination of the Orthometric Height of Mt. Kilimanjaro,* Eilat: FIG Working Week 2009.

Ulotu, P. E., 2009. *Geoid Model of Tanzania from Sparse and Varying Gravity Data Density by the KTH Method,* Stockholm: Royal Institute of Technology.

Willison, D., 2013. *Geoid model validation using geoid slopes, study cases: AGP07, TZG07, TZG08 and EGM08 on 28 TPLN Benchmarks,* Dar es Salaam: Ardhi University.