System 500 on Kilimanjaro
Or, how high is a mountain?

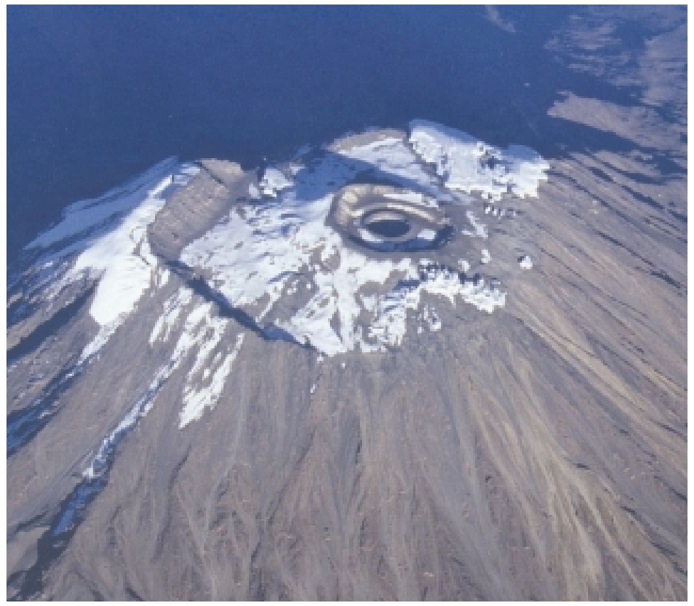


Photo: Eberhard Messmer

Kilimanjaro lies in the north of Tanzania, about 3° south of the equator. This extinct volcano towers about 5000m above the surrounding plains (themselves about 800m to 1000m above sea level), has a base of approximately 60km x 40km, and is the world's largest free-standing mountain. With fascinating climatic zones ranging from tropical forests to glaciated summit regions, and wonderful views over the vast plains of East Africa, Kilimanjaro attracts many tourists from all over the world particularly as the standard ascent requires no special mountaineering skills.

A triangulation survey carried out in 1952 using Wild T2 theodolites gave a height of 19340ft or 5895m. This is the height currently quoted by the Tanzania National Parks Authority and that appears on most maps.

Discussions in 1998 and 1999 between the Ministry of Lands and the University College of Lands and Architectural Studies (UCLAS), Tanzania, and the University of Karlsruhe, the Karlsruhe University of Applied Science and the E. Messmer Survey Company, Germany, led to the idea of re-measuring the mountain. It was obvious that GPS should be used as the survey would be easier, faster, more accurate, independent of weather, and unequivocal results would be obtained in the International Reference Frame (ITRF).

After months of organization and searching for suitable sponsors, the survey started in mid September 1999. The Tanzania National Parks Authority was extremely helpful and guides, porters and accomodation were organized by a tour operator. The majority of participants were from the organizations mentioned above, about half being from Tanzania and half from Europe. One of the delights of the entire campaign was the spirit of cooperation and friendship amongst this international group of surveyors, most of whom had never met each other before.

Leica receivers were used, SR530 from Karlsruhe University and Leica Geosystems AG, Heerbrugg, and SR299 from the Ministry of Lands and UCLAS. As all equipment has to be back-packed on Kilimanjaro, the small, light SR530 were employed on the mountain whilst the older SR299 measured at triangulation points and bench marks on the plains below.
The base for the survey was the Philip Hotel in Moshi, the small, pleasant town at the foot of Kilimanjaro. An SR530 set up on a pillar on the hotel roof ran more or less continuously for seven days in order that accurate ITRF coordinates could be computed and the entire network tied to this point.

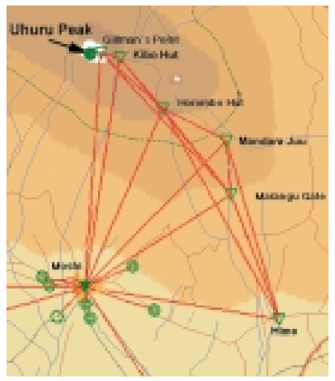
The team was split into two groups. The first group manned the base station and took GPS measurements at new points and existing control points at the foot of the mountain. The second group climbed the mountain, established new points during the climb, and measured a network of GPS baselines.

Because of its height, proximity to the equator and to the sea, Kilimanjaro has a range of unique ecological zones. The lower slopes, the homeland of the Chagga people, are fertile and intensively cultivated, a paradise of bananas plants, avocado trees, coffee bushes and other tropical crops. After entering the park, the climber passes through a rain-forest belt, a heath and moorland region, and an alpine-desert zone, before reaching the final steep slopes to the snow and ice covered summit area.

Permanent markers were placed at points at the foot of the mountain, at the park entrance, at the various huts along the route, on the crater rim and at the peak. Using four SR530 receivers, a network of short and medium-length baselines was measured between all points and the permanent station at Moshi.

***Below*: Very long baselines from IGS stations.**

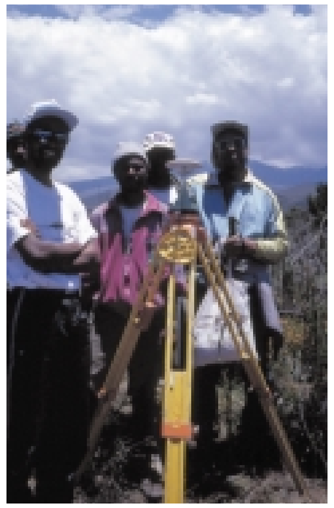
Kilimanjaro GPS network



The receivers were all pre-programmed so that anybody could use them. As the expedition leaders were not sure who would finally reach the summit, even the guides were trained to use the receivers. They found the SR530 fascinating and easy to use, but struggled to set up and centre a tripod. Who says that modern technology is complicated?

From the park gate at Marangu to the top of Kilimanjaro, the distance to be trecked is about 40km with a climb from 1900m to almost 5900m. The key to success is to go slowly and steadily in order to acclimatize well. As the ascent took 4½ and the descent 1½ days, there was plenty of time for GPS measurements. Although anybody who is fit and acclimatized should reach Kibo Hut at 4700m, the final 1200m to the summit is a serious undertaking: the mountain is steep, the air thin and cold, the rough path winds over scree and rocks, the attrition rate is high and many climbers turn back.

Leica SR530 near Horombo Hut (3700m), with Kibo and Uhuru Peak in the background.



GPS survey team with Leica SR530 at Mandara Juu (2845m).

26 September 1999 was the big day! Receivers were already running at Moshi, Marangu Gate, Horombo Hut and Kibo Hut as the summit party reached the crater rim at Gillman's Point. By 06.30 a point was marked and an SR530 measuring and recording at 5708m above sea level.

As the 1½ hours needed to cover the last 200m climb and 2km distance around the crater rim from Gillman's Point to the summit at Uhuru Peak are extremely tiring, the equipment was reduced to a minimum. The decision to take a light, carbon-fibre pole instead of a tripod to Uhuru Peak proved to be correct. The pole was held against the board marking the summit and several on-the-fly initializations were made. The receiver at Gillman's Point served as the reference.

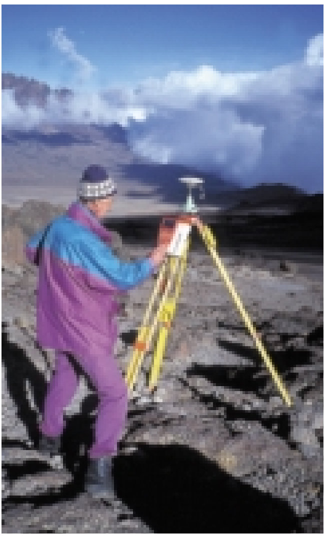
Everyone who made it to the top was exhilarated but exhausted. The final celebration was the ultimate experience, a Leica SR530 kinematic survey on the roof of Africa to the strains of Ebi's guitar. Bryan, our chief guide, had not only taken us to the summit, he had also carried the guitar!

Back at Moshi two days later, all data were downloaded to a PC and backed up. A quick preliminary computation showed that the results would be good and the campaign successful. The major processing task then fell on Nikolaos. Using Bernese Software and all available data, he computed very long baselines from five IGS stations to determine the ITRF coordinates of the pillar at Moshi to centimetre accuracy.

The entire GPS network was then computed with both Bernese and SKI-Pro. The results agree remarkably well. The ITRF ellipsoidal height of Uhuru Peak was calculated as 5875.50m and is certainly correct to 5cm. An orthometric height of 5891.77m is obtained after applying the EGM96 world geoidal model, but one has

Leica SR530 reference station at Gillman's Point (5708m).

On-the-fly initialization at Uhuru Peak.



GPS measurements at Kibo Hut (4700m), looking towards Mawenzi (5149m).

to be aware that the uncertainty in this model for this part of Africa could well be in the order of 1m.

As all existing triangulation points and bench marks are to the south of the mountain and not of uniform quality, it is impossible to compute a rigorous transformation into the Tanzanian datum and only a height shift was calculated. Applying this shift gives an orthometric height of 5892.55m in the Tanzanian (mean sea level) datum.

Now what does all of this mean? For the geodesist the height of Uhuru Peak is now known exactly, 5875.50m ITRF ellipsoidal height. For the non-surveyor, Uhuru Peak is 5893m above sea level.

Celebration at Uhuru Peak

As the result of the 1952 survey was 5895m, the reader may wonder if Kilimanjaro is now two metres lower than before. Unfortunately, it is impossible to tell. The 1952 survey was based on vertical-angle measurements over distances of more than 55km and height differences of over 4000m. Any surveyor who did triangulation in the middle of Africa in the middle of the last century knows that it was almost impossible to achieve height accuracies of a metre or so over such distances and height differences. Rather than pondering over the difference, perhaps one should be amazed at the agreement between the 1952 and 1999 surveys and admire the work carried out 50 years ago.

The seven days of GPS survey in September 1999 produced a network of permanently marked points with centimetre-accuracy ITRF coordinates. This net will form the basis for further surveys on Kilimanjaro and possibly in the neighbouring Rift Valley region. A solid foundation for future high-accuracy monitoring of the mountain has now been laid.

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