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The height of mountains

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ABSTRACT. In May 2004 a new measurement was performed of the depth of the snow on the summit of Mt. Everest with a new instrument coupling a Ground Penetrating Radar and a Global Positioning System (GPS). The instrument was carried to the top and was made to slide up and down along 8 profiles crossing the summit. This way it was possible to outline the surface of the snow covering the summit and of the rocky surface under it. From this it was discovered that the two summits do not coincide and a new value for the elevation of the snow summit and for the rocky top under it was obtained. Reference was made to the IGS (International GPS Service) permanent station in Lhasa and to the permanent GPS station at the Ev-K^2-CNR Pyramid Laboratory along the Khumbu Valley in Nepal.

1. Introduction

During the last decade much mention has been made of the re-measurement of some of the most famous mountains of the Alps and Himalayas presenting values that, despite the millimetre accuracy of the instruments employed showed differences that ranged even up to a couple of metres (Poretti, 1995, 1998, 2000; Pretti *et al.,* 2000).

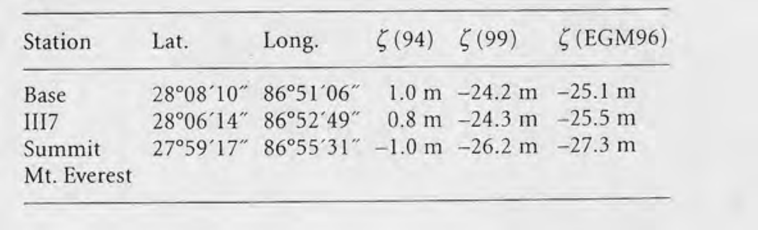
Which are the variables that play such an important role in these measurements, and how are they evaluated when calculating the height of a mountain?

The height of a mountain is determined by three main factors. The first is the geoid or the sea level calculated under the summit. The second depends on the accuracy of the elevations of the points in the valley from which the measurements are performed, and on the mareograph taken as a reference (height datum). The third factor depends on the amount of snow on the summit. This changes from season to season and from year to year with a variation that exceeds a metre between spring and autumn.

The Italian measurements in the Alps are, for example, referred to the mareograph in Genoa, the Austrian ones to the mareograph of Trieste, while those of the Swiss State Office for Geodesy and Topography refer to an average between the mareograph of Genoa and that of Bordeaux. For this reason, the Italian and Swiss measurements present a constant difference of about 20 centimetres.

Therefore, it is easy to imagine how much greater the difference will be between the Chinese and the Nepalese measurements of Mt. Everest that refer respectively to the mareograph of Quingtao on the Yellow Sea and to Karachi on the Indian Ocean at a distance of more than 6000 km. This distance has been reduced during the past decades thanks to ever more dense and precise

Table 1 - Geoidal heights under the summit of Mt. Everest (from Zeitschrift für Vermessungwesen 11/1999).



Station	Lat.	Long.	ζ(94)	ζ(99)	ζ(EGM96)
Base	28°08′10″	86°51′06″	1.0 m	–24.2 m	–25.1 m
III7	28°06′14″	86°52′49″	0.8 m	–24.3 m	–25.5 m
Summit Mt. Everest	27°59′17″	86°55′31″	–1.0 m	–26.2 m	–27.3 m

geometric levelling networks, and can be shown by the height differences of the border points between Tibet and Nepal.

Topographic measurements performed by satellite technology with DORIS, Glonass or Global Positioning System (GPS) systems have reached a very high degree of accuracy and reliability. The instruments are now compact and light enough to be carried to the summit of the mountains and determine the ellipsoidal heights. It is very important to calculate the difference between the ellipsoid and the local or global geoid because from that depends the height of the mountain above sea level.

2. The new determinations of the geoid under the summit of Mt. Everest

Satellite measurements obtained by GPS or DORIS beacons provide the coordinates of a point of the Earth with reference to its geometric surface, an ellipsoid defined with internationally recognised parameters.

The measurements of elevation are referred instead to the "mean sea level" that is approximated by another surface, the geoid, that represents an equipotential surface on which the oceans would lie if they were homogeneous, at constant temperature and not perturbedted by atmospheric elements. This surface is determined from time to time by means of measurements of gravity and deflection of the vertical, by national (local geoid) or international institutions (global geoid). The geoid is very well defined on the oceans, or in areas where gravity measurements are very dense, while it is less precise in mountain or remote areas where gravity measurements are sparse.

In 1992, when the researchers of the Ev-K2-CNR Committee, in collaboration with the National Bureau of Surveying and Mapping of Beijing carried out the measurement of the mountain (Table 1 and Fig. 1), the difference between the Geodetic Reference System (GRS80) ellipsoid and the geoid was calculated, from the Chinese side, as 25.14 m. Later on, in 1996, the new geoid EGM96 showed the value of 27.3 m while in 1999 a new calculation from the Chinese researchers rose to 26.2 m. The 1999 National Geographic measurement referred to the most recent value of 28.74 m. Adding this value to that of 8821.09 m of the ellipsoidal height one obtains the value of 8849.82 that is rounded to 8850 m. The value obtained from the Chinese-Italian measurement of 1992 would have been of 8852.25 m and therefore sensibly larger (see Table 2). This difference has been explained by the fact that the snow covering on the summit had been eroded by the strong winter winds.

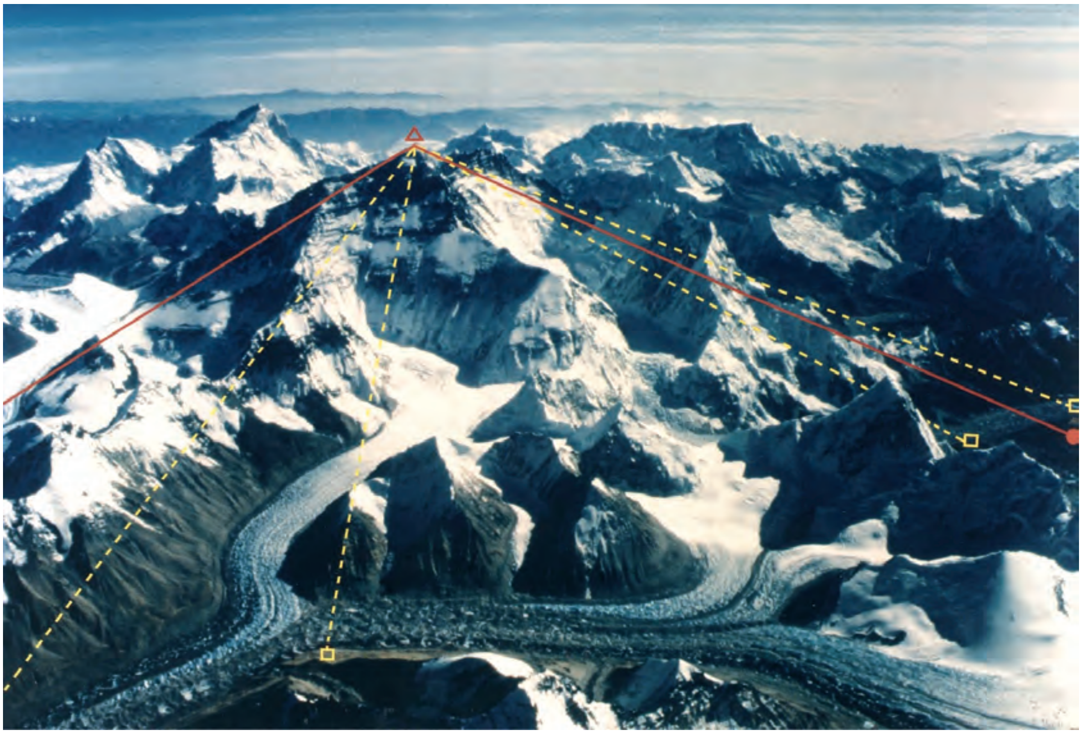


Fig. 1 - The scheme of the 1992 Mt. Everest measurement.

We can now compare the values of the height of Mt. Everest with reference to the snow surface and to the geoid-ellipsoid separation (Table 2). Thus we can say that the variations of the height of Mt Everest are mainly due to the variation in the snow layer and to different values of the geoidal undulation N.

Table 2 - The elevation of Mt. Everest with the geoid - ellipsoid separation N.
(*) Local geoids. The negative values indicate that the geoid lies under the ellipsoid.

	N	Geoidal El.	Ellips. El.
Survey of India 1852		8840	
Sidney Burrard 1904 (Burrard and Hayden, 1908)		8882	
De Graaf Hunter 1930	-30.18(*)	8854±5	8823.82
B. L. Gulatee 1954	-35.05(*)	8848	8812.95
Desio and Caporali 1987	-39.00	8872	8833.00
Ev-K2-CNR/NBSM 1992	-25.14(*)	8848.65±0.35	8823.51
J. Y. Chen 1999	-26.20(*)	8849.71	8823.51
EGM96	-27.30	8849.82	8822.52
Washburn and Chen 1999	-28.74	8850.±2	8821.26

Fig. 2 - September 29, 1992: Benoit Chamoux on the summit of Mt. Everest with the surveying instruments and the first Leica 200 GPS.

It is therefore, necessary that eventual comparisons between the elevations of the mountains be carried out using a reference system, internationally recognised, and not affected by an occasional snowfall.

To obtain a definitive measurement one should agree that the elevation must be taken with respect to the rock surface by performing a reliable determination of the depth of the snow layer.

If reference were made to the rock surface and to the ITRF datum using the GRS80 ellipsoid all ambiguities would drop and one could carry out comparisons even up to an accuracy of a centimetre.

The EV-K^2-CNR Committee (established in 1987 by Professor Ardito Desio) has been involved in these activities through the TOWER (Top of the World Elevations Remeasurement) project, that carried out measurements of Mt. Everest in 1992 (Fig. 2) and 2004, K2 in 1996, Matterhorn in 1999, Mt. Dufour in 2000, Cerro Aconcagua in January 2001, and Mont Blanc in September 2004 (using GPS only) with classical and GPS technology.

In order to determine the depth of the snow on the summit of a mountain a new instrument was designed using the most advanced technology. It is a portable Ground Penetrating Radar (GPR) coupled with a GPS. This instrument was used for the first time within the framework

Fig. 3 - April 2004: the first prototype of an IDS georadar coupled with a Leica GPS.

of the "K^2 – 2004 Fifty Years Later" expedition on Everest in May 2004 and in September 2004 on Mont Blanc.

3. The measurement of the depth of the snow

The instrument, the idea of which was conceived by the Centre of Telegeomatics of the University of Trieste in collaboration with the company SOGEST Geophysics, was realised by IDS-Ingegneria dei Sistemi S.p.A., a dynamic company located in Pisa and with remarkable experience in this field, being the only Italian producer of GPR systems.

After several trials on alpine glaciers (Canin, Stelvio, Moelltal, Marmolada) with some climbers who were possible candidates for carrying out the measurements on the summit of Mt. Everest, two prototypes with IDS antennas coupled with Leica MX421L single frequency GPS receivers (Fig. 3) were built.

Antennas with nominal frequency of 900 Mhz were chosen for these prototypes due to their ability to penetrate ice and snow. The data were saved on an industrial-type C*ompact Flash Card* at a rate of 10 samples per second and with 2048 samples at a 16 bits/sample. The power supply was provided by a special rechargeable lithium battery that could be used continuously for more than 7 hours.

In building the prototypes, most of the components were devised for their reliability and lightness. The "body" was made in light fiberglass of aeronautic type "S". Externally two skates were provided for stabilising the instrument in case of wind or soft snow. The weight was kept to 4 kg, battery and remote control included.

4. Work programme on the summit

The measurement of the thickness of the snow layer on the summit of a mountain like Everest depends on the capacity of the mountaineers involved to carry out the necessary operations in accordance with a previously agreed work-plan, keeping in permanent radio contact with Base Camp for eventual suggestions or changes.

The carefully planned surveying programme proposed a series of georadar profiles near or through the snow summit that might show the outline of the rock under the snow cap, in order to be able to find the rock summit when the surface profiles were calculated.

Once on the summit, the climbers had to reach the first outcrop of rock (at a distance of about 20 metres), start the double frequency Leica 1200 GPS master station (which was then left fixed on the outcrop), assemble and start the GPR, paying attention to the pre-heating phase and the linking up with the satellites from the built-in Leica MX420L GPS.

The next phase involved pulling the GPR up to the apparent summit. Two of the climbers were involved in this, one in front and one behind the instrument, to keep it stable and to avoid it turning over in strong winds. A few metres from the outcropping rock a check of the snow depth was to be made using a snow probe in order to calibrate the instrument.

At the summit, the GPR continued recording for several minutes, in order to link up with the fixed stations and to improve the accuracy of the calculation of the elevation.

The GPR had to be then gently released from the summit crest along the slope following 3 to 5 m long profiles in order to cover all the summit area in the best possible way.

The last step involved mounting the sight target and the reflecting prisms for the classical trigonometric levelling measurements taken for comparison with the satellite ones.

5. The arrangements at the foothills of Mt. Everest

During the hours immediately before the measurements at the summit of Mt. Everest, some observation points in the Base Camp area were arranged. One point was located at the confluence of the two glaciers that come down from the north face of Mt. Everest (Rongbuck and Fast Rongbuck) for the classical measurement with theodolite and distance meter. In the vicinity a Leica GPS 530 with 1 Hz recording rate was installed.

Another Leica 300 GPS double frequency receiver was located on the trigonometric and levelling bench mark of the Chinese GPS network in the Base Camp area.

A third reference point was the permanent GPS station at the Pyramid Laboratory of the Ev-

Table 3 - The base stations for the calculation of the coordinates.

GPS Station	Latitude	Longitude	Ellips. height
Lhasa	29° 39' 26.426''N	91° 06' 14.364''E	3624.658
Base Camp	28° 08' 09.812''N	86° 51' 06.203''E	5125.190
Interm. Camp	28° 06' 17.471''N	86° 52' 16.734''E	5285.856
Summit Master	27° 59' 16.500''N	86° 55' 30.587''E	8811.281
Pyramid Lab	27° 57' 33.271''N	86° 48' 47.125''E	4993.422

Fig. 4 - The climber Claudio Bastrentaz operates the GPR on the summit.

K^2-CNR Committee located in Nepal along the Khumbu glacier.

These points will be taken into consideration in the global processing in order to link those observed on the summit geographically providing a reference to benchmarks of known coordinates.

6. The observed profiles

The morning of the May 24, 2004 four climbers carried out the exceptional task of taking the measurements on the summit of Mt. Everest, operating without oxygen for more than 2 hours. These were Alex Busca who coordinated the operations by keeping contact with Base Camp, Karl Urterkircher who operated the instrument and reported every phase of the survey, Mario Merelli who also assembled and erected the pole with the target and the prisms for the classical measurements and Claudio Bastrentaz who carefully recorded the whole process on film (Fig. 4).

At base camp, Roberto Mandler and Giorgio Poretti followed the operations of the climbers by radio trying to imagine their movements, interpret the pauses and anticipate their requests for clarifications while the researchers Marco Lipizer, Andrea Zille and Gino De Min were involved with the classical surveying of the summit.

The presence of an exposed narrow ledge on the east side, very close both to the summit and to several obstacles on the crest (such as lots of votive flags, a framed picture of the Dalai Lama, abandoned ropes and used oxygen bottles), meant that it was not possible to perform profiles along a regular network. Instead they were taken converging towards the summit along the south/SW and NW slopes as illustrated in Fig. 5.

Tarcisio Bellò and Marco Confortola also reached the summit the following day, while the rest of the second team, who was waiting at Camp 3, decided to give up because of the strong winds.

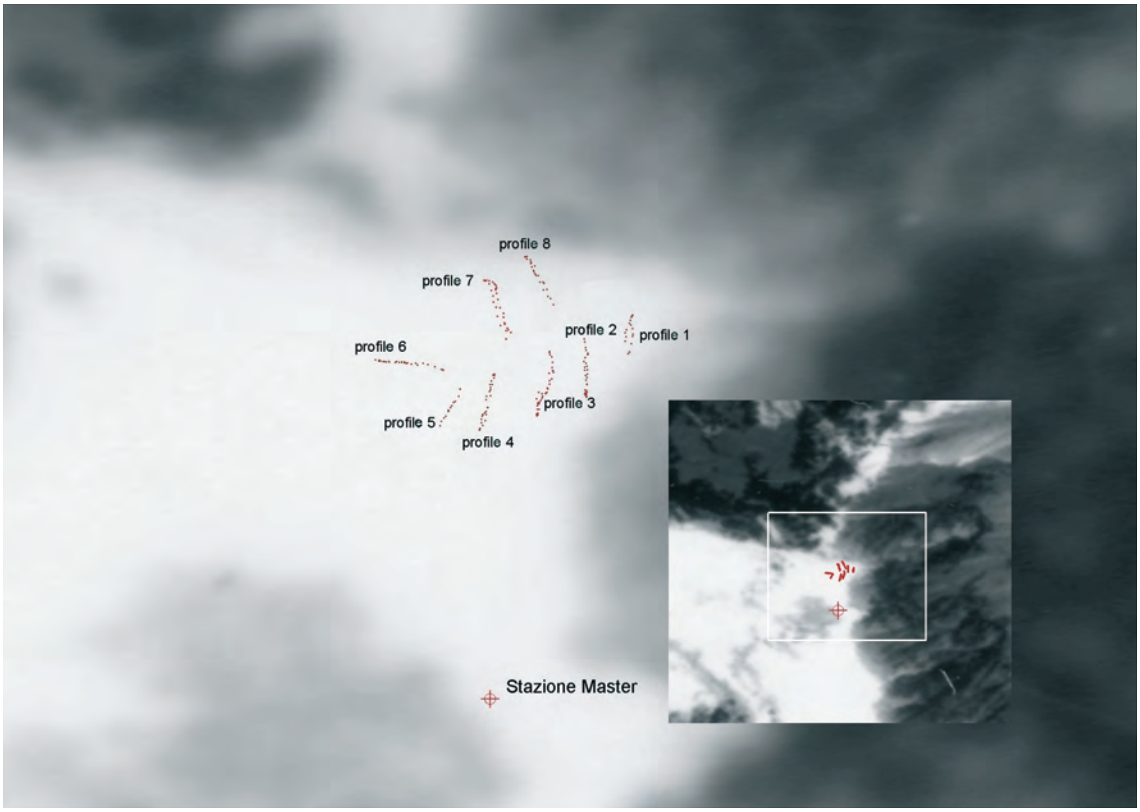


Fig. 5 - Radar profiles on the summit (air photo enlarged).

7. The classical measurement

After the GPR surveys were carried out, a pole with a red sight target and three reflecting prisms was erected on the snow summit. Its position was then surveyed by the Leica T2002K theodolite with DI3000S distance meter installed in the foothills of the mountain at the confluence between the Rongbuk and the Fast Rongbuck glaciers at a distance of 14 km from the summit.

The climbers involved in surveying the summit left after two hours while the angular measurements were still in progress. During the following days efforts were made to retrieve the target and the prisms but unfortunately in vain.

The values obtained refer to the reflecting prisms and the optical target:

distance: 14,428.160,
zenit angle: 84.27887,
height diff.: 3540.742.

In order to carry out the necessary corrections to the height values the refraction coefficient, that depends on the difference of pressure and temperature between Base Camp and the summit,

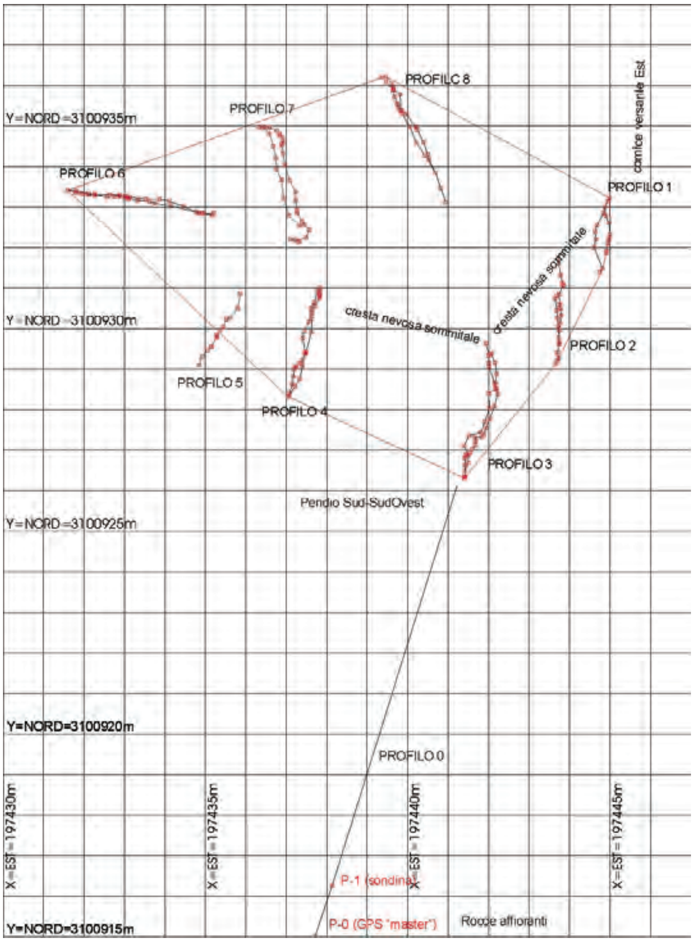


Fig. 6 - Radar profiles on the summit (squares sides = 1 m).

has been taken into account. During the night of May 26, the deflection of the vertical was calculated with the Astra system (Lipizer *et al.*, 2001) with 128 astronomic observations. The results are:

$$\xi = 4.69'' \pm 0.54'' \qquad \eta = -7.59'' \pm 0.44''$$

for the point of ellipsoidal coordinates:

$$\varphi = 28° \ 08' \ 13.63'' \qquad \lambda = 86° \ 51' \ 19.5'' \qquad h = 5179 \text{ m}$$

These values turn out to be very small if compared to the ones observed in 1992 on the southern side of the mountain (Caporali, 1996; Gulatee, 1954), but they are in good agreement with those presented by Chen (1994) for some points of the Tibetan Base Camp area. This suggests a flattening of the gravity anomalies under the Tibetan plateau.

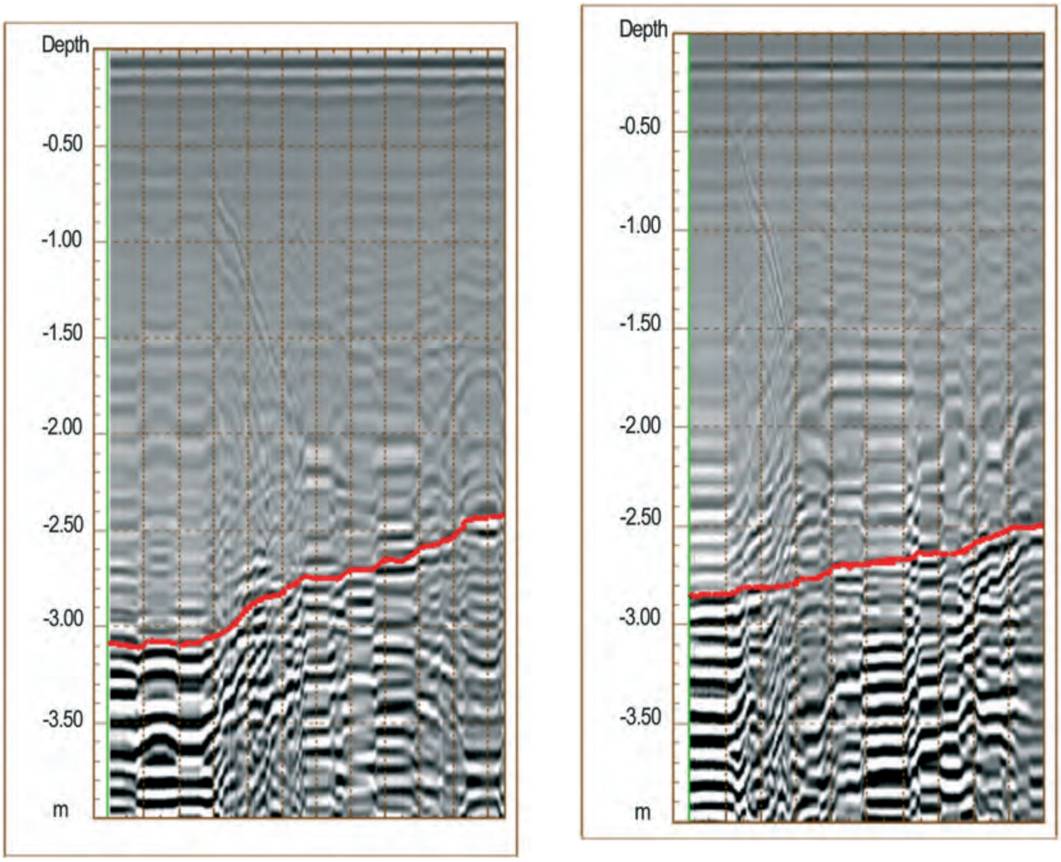


Fig. 7 - Examples of radar sections with the contours of the rock under the snow outlined; both profiles refer to paths from the summit crest along the south and SW slopes; the thickness of the snow is “apparent” because it was surveyed on slopes with differing inclinations.

7. Radar profiles, computation of the depth of the snow, and of the elevations

The data processing related to the elevations took into consideration all the information obtained along the profiles and in different GPS recording stations established in the neighbouring area, including the permanent station at the Pyramid Laboratory of the Ev-K2-CNR Committee in Nepal.

This point, located along the Khumbu glacier, not far from the South Base Camp of Mt. Everest, coincides with a beacon of the French positioning system DORIS (Tavernier *et al.* 2005) operating there for more than 12 years (Poretti *et al.,* 1994). Together with the data of the IGS (International GPS System) station in Lhasa it will create a suitable framework for the coordinates of the summit of the mountain in the ITRS reference system.

The measurements performed on the summit on May 24, 2004 followed 9 radar/GPS profiles (Table 4). The first, named Profile 0 was performed on the SSW slope from the outcropping rocks at 20 m south of the summit, up to the snowy top of the crest. At the start of the recording session, the radar remained side by side with the GPS Master for several minutes where the depth of the

Fig. 8 - The start of the master GPS (static) station and of the GPR/GPS (mobile) in correspondence to the rock outcrop on the southern slope under the summit of Mt. Everest (photo K. Unterkircher).

snow was 20 cm and during the progress to the summit it passed near a point where the depth of the snow should have been verified (~50 cm). Unfortunately it was not possible to retrieve the data file due to recording problems, probably caused by the very low temperature occurring during the night.

Once the summit was reached the radar computer started to record correctly while the 8 profiles were performed (see Fig. 6). During the analysis of the recorded data, profiles 5 and 7 showed some problems in the GPS position values due to temporary loss of signal. However, both profiles were performed at rather lower elevations, in particular with respect to the snowy top of the summit covered mainly by profiles 1, 2 and 3. A plane sketch of the profiles is presented in Fig. 6.

Table 4 - Description of the radar profiles.
(*) damaged recording and (°) profiles with loss of GPS signal.

Profile	**Location on the summit**	**Time/r**
0 (*)	on the SSW side, from the rock outcrop to the summit	-
1	on the eastern edge of the summit crest with North-South direction and back.	23”0
2	East of the snow top of the summit in the North-South direction	50”8
3	West of the summit with North-South direction and return.	41”5
4	West of the previous profile, with North-South direction and return.	33”2
5 (°)	at a lower elevation with NE-SW direction.	29”2
6	West of the previous profiles and at lower elevation, with East-West direction.	33”1
7 (°)	on the NW side, starting from the summit with South-North direction and back	34”0
8	on the NW side, starts from the crest with SE-NW direction	30”7

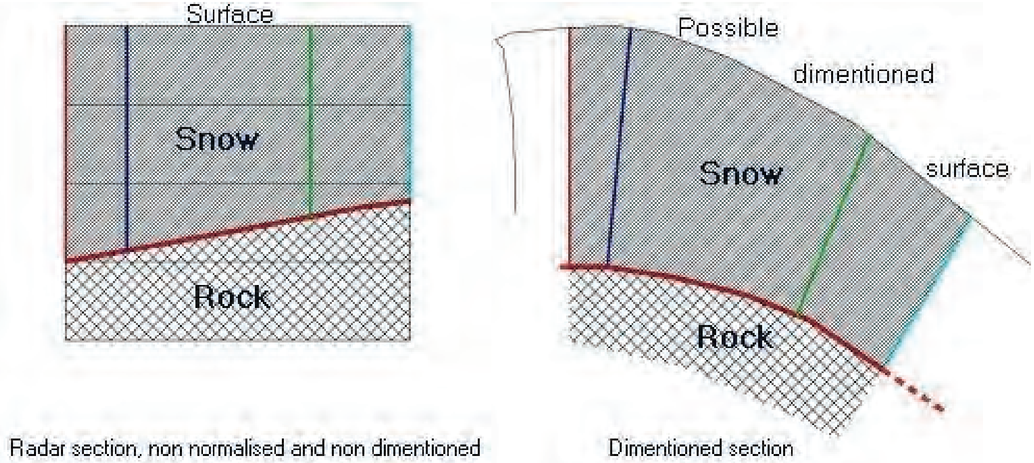


Fig. 9 - Example of "normalisation" of a radar section with altimetry deformation.

During the phase of release and recovery of the instrument there was a possibility of loss of a certain number of satellites, as the antenna was in a very inclined position.

For every profile, once the plano-altimetric behaviour was determined, a graphic section was constructed in order to proceed to the processing of the radar data. The processing of the radar data was based on the GPS position of the profiles that allowed to "normalise" the progress, often irregular in the manual dragging of the instrument on the snow and to dimension the progress on the slope (Fig. 9).

In the radar recordings, the reflecting surface between snow layer and the underlying rock is usually rather evident (Fig. 7). The application of low-pass filters enhanced the behaviour of the rock surface with respect to the discontinuities caused by the overlapping snow layers.

A very big problem instead was the determination of the propagation velocity of the radar waves within the snow layer in order to pass from the "reflection times of the signals" (recorded in nanoseconds) to the "depths of the reflectors" (calculated in metres). For this purpose a direct measurement of the thickness of the snow was tried also on the summit, but the snow layer turned out to be deeper than the available probe (2.4 m). In view of this eventuality a profile was planned, that started from where the snow layer was very thin (outcropping rock in Fig. 8) and passed near a point of known snow thickness before proceeding towards the summit. The loss of this first profile made a software calibration necessary with a process known as "migration" of signals. This is applied to some standard forms (known as "reflection hyperbolas"), recognised in the recordings and determined by the presence of possible objects hidden in the snow at a low depth (oxygen bottles, pipes, etc.). In this way, the sections were obtained correlating the shift of the antenna and the depth of the rock.

During the data processing, the position of the phase centre of the GPS antenna was taken into account with respect to the radar sensor in contact with the snow and of the vertical angle of the profiles along the slope. For every profile, starting from the GPS points, new shifted points were obtained on the snow surface and the point on the rock was determined by the depth measured on the normal to the radar antenna plane. The perpendicular to this point produces another point

Fig. 10 - Climber Mario Merelli operating the GPR on the steep slope along the SW ridge (foto K. Unterchircher).

on the snow surface and a new value for the depth of the snow that depends on the inclination of the slope (Fig. 10). The new sets of points on the snow surface and those on the rock underneath were gathered in a database.

On the reduced data, an interpolation programme was applied that allowed the reconstruction of the surface of the snow cap and of the underlying rock with an error slightly over 2 cm as an average on all the points of the survey. From the sampling of the polynomial functions on a regular grid of 10 cm side, it was then possible to draw the contour lines showing the maximum elevation points of the two surfaces (Figs. 11, 12, and 13). Along one of the lines crossing the points of maximum elevation a section was drawn that enhances the two summits and the distance between them.

The processing of the kinematic survey took into consideration the data recorded along the profiles, those of the Master station at the outcropping rock and those recorded in several GPS stations, including also the permanent GPS station of the Pyramid Laboratory of the Ev-K2-CNR Committee in the Kingdom of Nepal. This point, located on the side of the Khumbu glacier, not far from South Base Camp, coincides with a point where elevations and coordinates were already determined during previous surveys and has bean linked to a beacon of the French orbitography system DORIS for more than 12 years.

Together with the data of the IGS in Lhasa, it also allowed the correct framing of the coordinates of the summit in the ITRF system.

8. Computer models of the snow and rock surfaces

Analysis of the results of the processing of the radar profiles shows a general thickening of the snow layer in correspondence to the summit crest, with maximum thickness between 285 and

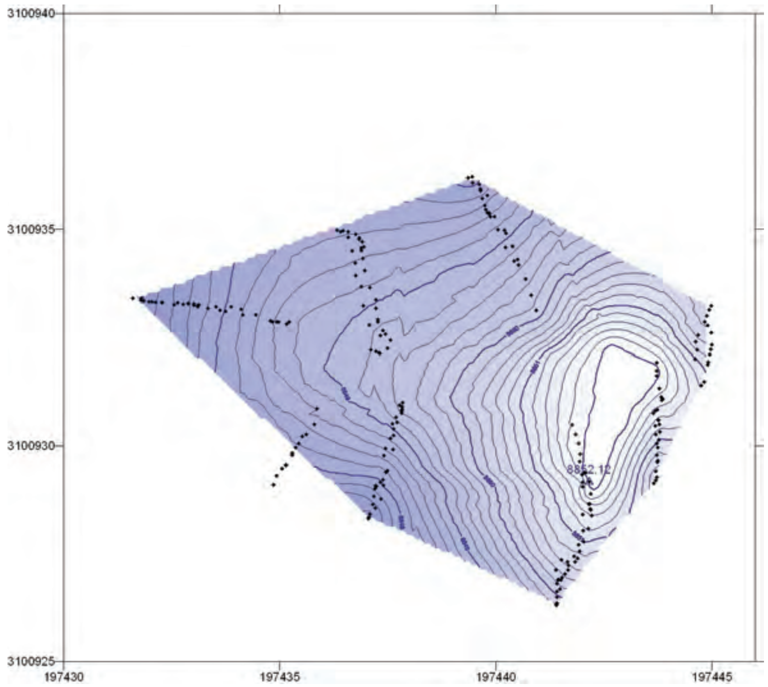


Fig. 11- Contour lines of the snow surface.

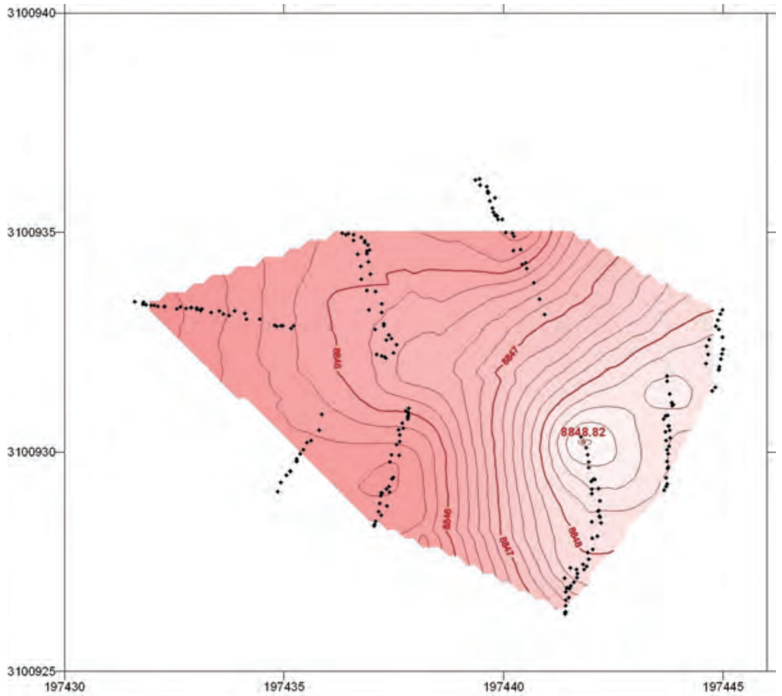


Fig. 12 - Contour lines of the rocky surface.

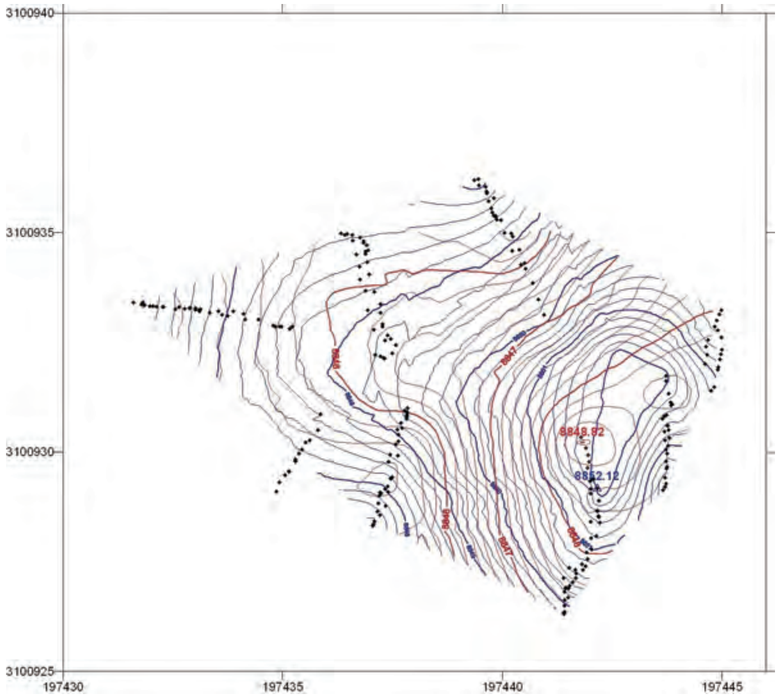


Fig. 13 - Superimposed contour profiles.

370 cm, in particular along the profiles 1, 2 and 3 which can involve the snow top of the summit more directly.

The data recorded by the GPS Leica MX421L locate points on a surface parallel to the snow surface at a distance of 15.8 cm that represents the height of the phase centre of the GPS receiver with respect to the centre of the source of the radar signals on a cone having an amplitude of 45° in the direction of progress and 30° in the transverse. The axis of the cone always remains orthogonal to the emitting antenna. The reflections received by the antenna are in any case perpendicular to the rock surface according to a spherical sector with radius equal to the measured depth of the snow.

To model the rock surface, one must consider a pencil of spheres whose centres are located on the snow surface and whose radius change with the depth of the snow measured every tenth of a second. The envelope surface fitting this pencil of spheres represents the rocky profile for the points of which the coordinates are consequently recalculated (Figs. 7 and 9). Two sets of points are obtained representing the profiles of the snow and of the corresponding rock surfaces.

Unfortunately, it was not possible to recover Profile 0 (damaged while recording), which started on the outcrop of rock and was performed on the south-SW slope from the master GPS to the summit. The fact that it was initiated on the rock surface could have helped calibrate the radar better.

As mentioned earlier, the profiles were mostly surveyed starting from the summit and by letting the radar slide down along the slope and then pulling it back up towards the summit. In the two examples given (that include only the downward tracks) the rock under the snow can be outlined. The snow layer presents at the beginning a maximum thickness corresponding to the summit and decreases to its minimum in the south (on the right side of the scheme in Fig. 7) approaching the outcropping rock. Some horizontal reflection bands, typical for GPR prospecting and for the ground that was penetrated, are evident inside the snow mass.

There are also several point-like anomalies caused mostly by interruptions and irregularities while the instrument was being pulled over the surface, but also due to the presence of heterogeneities inside the snow.

9. The depth of the snow in correspondence to the summit

From the analysis of the surfaces resulting from the processing of the radar and GPS data one can easily deduce that the two maxima do not coincide. One must therefore distinguish a maximum elevation "on the snow" and a maximum elevation "on the rock". The two summits are at a distance of about one metre in the direction of the prevalent wind (Fig. 14).

For the snow surface the maximum elevation corresponds to a point on the profile P3, that is obviously shifted with respect to the original GPS point and shows an elevation of 8852.12 m. Here the rock is detected at 8848.44 m a.s.l. and therefore the snow cap has a thickness of 3.68 m.

For the rock surface, the point of maximum elevation corresponds to three points surveyed always along the P3 profile and also shifted to the north of the relative GPS points. They show an elevation of 8848.82 m a.s.l. These points of highest elevation are located at a plane distance of 1.15 m to the north of the snow summit.

On the point of maximum elevation of the rock, the surface of the snow shows an elevation of 8851.82 m a.s.l. and consequently a thickness of 3.04 m.

Summarising, these data and the previous considerations in Table 5 one can conclude that the elevation of the snow has been calculated at 8852.12 m while the one with respect to the bedrock turns out to be 8848.82 m.

It is interesting to compare this data with that recorded in 1992 when the depth of the snow, measured with an avalanche probe on the highest point, turned out to be 2.55 m (Poretti *et al.,* 1994). As an average of the classical and satellite measurements a value for the ellipsoidal height

Table 5 - Comparison between the 1992 and 2004 surveys.
Introducing different geoid-ellipsoid separations.

	Snow 2004	Rock 2004	Snow '92 with Chinese geoid	Rock '04 with Chinese geoid
Ellipsoidal Height	8823.38	8820.08	8823.51	8820.08
Geoidal Undul. N	-28.74	-28.74	-25.14	-25.14
Geoidal Height	8852.12	8848.82	8848.65	8845.22
Depth of Snow	3.68	3.04	2.55	3.04
Rock Elevation	8848.44		8846.10	
Snow Elevation		8851.86		

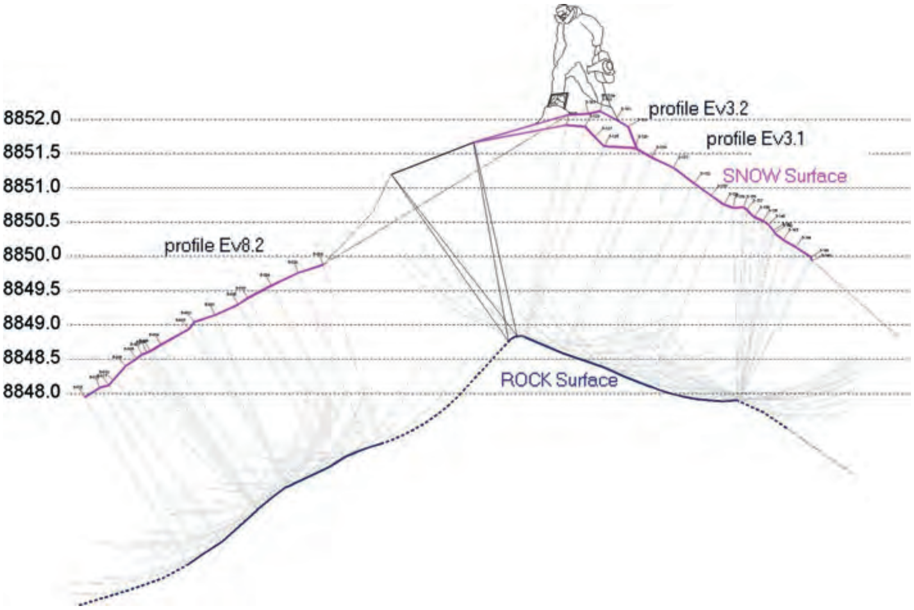


Fig. 14 - Section along two profiles crossing the summit.

was obtained very close to the one provided by the present survey (a difference of 13 cm). The largest divergence therefore was in the geoidal undulation that differed by 3.60 m from the one adopted in 1999.

The coordinates of the snow summit were determined from the GPS recordings while those of the rock summit were estimated on the digitised interpolation surface (Table 6 and Fig. 15).

10. Local and total error in the measurement

A very important component in the calculation of the height of the mountain is the estimate of the probable error of the coordinates and the elevation. Errors in the GPS measurements on the base triangle, between Base Camp and the Master station, from the Master station to the radar and in the radar measurement must be taken into account. One must also add the error of interpolation with polynomial best-fit.

Starting from the permanent IGS station in Lhasa and from Point G of the Pyramid Laboratory

Table 6 - Coordinates of the snow and rock summits.

	Latitude	Longitude	Height
Snow Summit	27°59'16.963''	85°55'31.736''	8852.12
Rock Summit	27°59'16.998''	85°55'31.723''	8848.82

Fig. 15 - The pole with target and prisms on the summit of Mt. Everest after the GPR survey.

one can determine the following errors declared by the outputs of GPS processing performed with precise effemerids and a standard atmosphere:

a) Triangle Lhasa, Base Camp North: 0.019 m.
b) Triangle Base Camp, Intermediate Camp, Master Station: 0.094 m.
c) Master Station to georadar kinematic single frequency GPS: 0.049 m.
d) In the estimate of the velocity of propagation of the radar signals in the snow, without direct calibration one can assume an error of 20 cm. This is larger than the one obtained in 1992 with the use of an avalanche probe, but reduces the uncertainty of the single measurement.
e) There is, finally, the indeterminacy of the method of approximation of the 4th degree polynomial surfaces that was calculated at 1.5 cm for each surface.

The total error can be estimated at 0.23 m neglecting the intrinsic error of the IGS station in Lhasa and that of the EG96 Geoid.

One can state the elevation of the snow summit of Mt. Everest as 8852.12 ± 0.12 m a.s.l. while that of the rock summit is 8848.82 ± 0.23 m a.s.l. with reference to the IGS station in Lhasa. With the Chinese geoidal height one obtains the values of 8848.52 and 8845.22 m, respectively.

11. Concluding remarks

Classical and satellite instruments employed in the measurement of the height of a mountain have become ever more sophisticated and accurate, allowing the measurement of the depth of the snow in correspondence to the snow summit and the surrounding areas. The instrument employed, a ground penetrating radar coupled with a GPS provided the coordinates and the depth of the snow along 8 profiles on the summit of Mt. Everest. This permitted the reconstruction of a mathematical model of the snow and of the rock summits and to differentiate between height of a mountain “on the snow” or “on the rock”.

The results obtained can be improved with a direct calibration of the radar and surveying more profiles intersecting laterally and on the crest with those already obtained. The calculation of the geoid can also be improved with more measurements of gravity and of the deflection of the vertical.

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