Topographic Mapping of The Volcano Nevado Ojos Del Salado Using Optical and Microwave Image Data

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Abstract

The area of interest is located at the border between Chile and Argentina at 27°10' S. latitude and 68°30' W. longitude in the High Cordillera of the Andes and includes the second-highest mountain of America, the Nevado Ojos del Salado. Although the official Chilean altitude is given as 6,880 m, other figures can be found in the literature and various other maps. Situated in a picturesque volcanic terrain rising above the Puna de Atacama, Nevado Ojos del Salado is not only interesting from a geomorphological point of view, it is, e.g., the world's highest volcano, but also has recently become a much-favored destination of the mountaineering world.

Unfortunately, this area is not covered by reliable and publicly available maps at scales larger than 1:250,000. Therefore, this paper describes the methods employed in and results obtained from topographic mapping of this remote area using spaceborne as well as airborne remotely sensed data. Exploiting Space Shuttle Earth-viewing photographs, ERS-1 Synthetic Aperture Radar images, and aerial photographs, it was intended to derive orthophotos, digital elevation models, topographic/geomorphological base maps, including various derivatives, such as anaglyphs, stereograms, and axonometric views, respectively, at a minimum of costs.

In order to get a general overview, i.e. to generate a base map of the area, stereoscopic hand-held photographs from NASA's SSEOP database were used. Parallax-free stereo vision was achieved by means of an analytical plotter. Ground control points were taken from the existing Chilean maps at scales 1:250,000 and 1:500,000 in order to georeference the image content. A digital orthophoto and a topographic base map at 1:400,000 are presented.

Furthermore, two overlapping same-side ERS-1 SAR images from adjacent descending orbits were acquired and provided in digital format by the European Space Agency. In a first step, the image data was radiometrically enhanced, and proper radar stereograms were generated for image interpretation purposes. This is followed by a brief discussion of recently developed mapping methods for radar images.

In order to facilitate large-scale mapping a strip of panchromatic aerial photographs at 1:30,000 scale, provided by the Instituto Geografico Militar de Chile, was photogrammetrically oriented using ground control points measured in one of the Shuttle stereopairs at 1:840,000 scale. As a result, a topographic map at 1:15,000 scale and a high-resolution digital elevation model of the central part of the Nevado Ojos del Salado were generated. The photographs, given as analog paper prints, were scanned and thereafter digitally rectified and mosaicked to form an orthophoto of the volcano Ojos del Salado. A stereomate of this orthophoto was produced as well. The scope of this work also includes various combined image-line maps.

The presented cartographic products, available either in analog or in digital format, for the first time allow detailed geomorphological mapping of the Nevado Ojos del Saldo and its surroundings and provide a far better means of orientation for mountaineers in this very remote and deserted area in the Andes.

Introduction

The area is located at the Chilean-Argentine border at 27°10'S. latitude and 68°30' W. longitude in the Andean High Cordillera of South America (Figures 1 and 2). The landscape is of volcanic origin (Zeil, 1964 and 1979, and Sulzer, 1994) and comprises a series of spectacular volcanoes. One of them, Nevado Ojos del Salado, is well known as the world's highest volcano and America's second-highest mountain. For several decades this volcano has not been active any more, but fumaroles still give off sulphurous smoke, and hot springs can be found. W. Penck, one of the first explorers of the Andean High Cordillera, travelled through this area during two geological field campaigns in 1912/13 and 1913/14. His interesting diary (Penck, 1933) gives a detailed description of the unique landscape and the

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harsh environment he had experienced. Actually, he never mentioned the Nevado Ojos del Salado and, of course, he was not aware that this area contained the highest volcano of the world. At the turn of the century the Chilean-Argentine boundary commission placed Ojos del Salado on their map giving its altitude as 6,100 m. H.A. Carter (1957) also reports on the early days of mountaineering in the Ojos del Salado region. In 1955 the Argentine press announced Ojos del Salado to be 7,100 m high, higher than Mt. Aconcagua, whose altitude at that time was given as 7,021 m. One year later Chilean climbers measured the peak at 7,084 m by means of an aneroid barometer. H.A. Carter was the first one to determine the altitude of Ojos del Salado by means of rigorous geodetic measurements. According to his survey the altitude of the Ojos del Salado is 6,885 m (Carter, 1957). In the official maps of Chile the altitude is given as 6,880 m. Figures found elsewhere differ from this value.

Depending on the information needed for a specific geoscientific investigation of an area, various remotely sensed data and collateral information, e.g., topographic maps and in-situ observations, have to be used. For a geomorphological interpretation at various scales of the area around Ojos del Salado, topographic maps are the source of basic information. Whereas it was not possible to order maps from the Argentine mapping authorities, the Instituto Geografico Militar de Chile provided several maps at scales 1:500,000 and 1:250,000. Unfortunately, Ojos del Salado is not covered by the newly (1985) published 1:250,000-scale maps. Instead, the provisional map (carte preliminar) dating from 1954 had to be used for the major part of the study area as a main cartographic reference. The idea was to update this map by means of reasonably-priced satellite image data. The obtained satellite image map was then used in the photogrammetric evaluation process of a small strip of aerial photographs for large-scale mapping.

NASA Space Shuttle Hand-held Photographs

Since 1981, Space Shuttle astronauts have taken tens of thousands of Earth-looking photographs with hand-held cameras, such as Hasselblad and Linhof systems. Details on the Space Shuttle Earth Observations Project (SSEOP) can be found in Lulla *et al.* (1993). Most of the applications of Shuttle images are related to geological, oceanographic, environmental and meteorological studies, whereas this paper focusses on topographic mapping as one of the key issues. The appropriate Space Shuttle photographs covering the area of interest were selected from an electronic database provided by NASA. Only photographs with stereoscopic coverage were selected. Altogether 4 stereopairs were found in the catalogue. All selected photographs were obtained with a NASA-modified Hasselblad 500 EL/M 70-mm camera

South America

Figure 1 Location of the study area

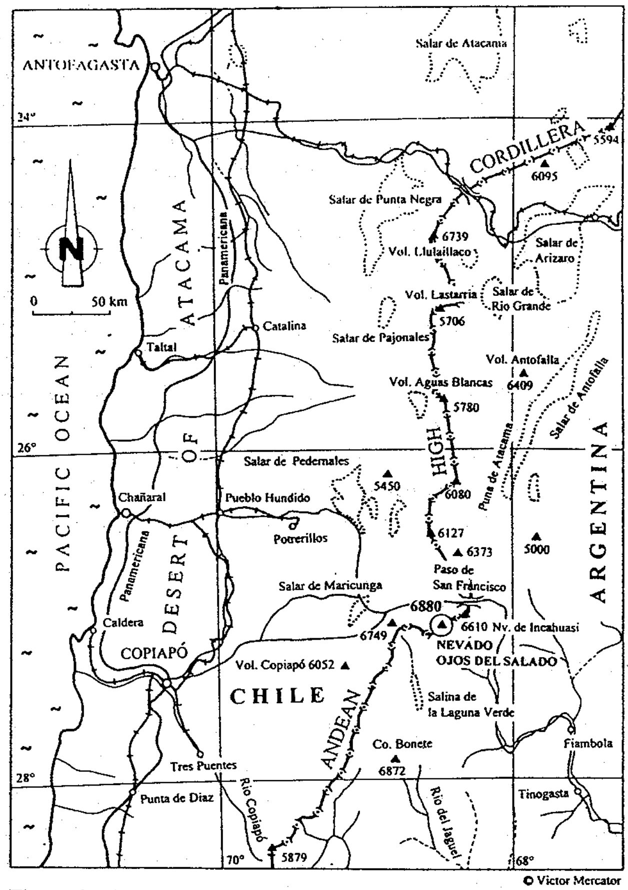


Figure 2 Sketch map

equipped with interchangeable Zeiss 100-mm CF Planar f3.5 or 250-mm CF f5.6 lenses. Kodak Ektachrome Professional 5017 (ASA 64) film was used. Additional parameters of the Shuttle photographs are listed in Table 1.

4x4-inch colour transparencies, enlargements of the original 2.5x2.5-inch film material, were provided by the Earth Data Analysis Center, The University of New Mexico, in good quality. Due to the very low sun elevation at the time of acquisition long shadows are present in the photos. However, the volcanic land forms are strongly emphasized by the illumination of the sun. Finally, the stereopair from the Shuttle mission STS61C was selected for the mapping task. The scale of these photographs, taken at oblique views, is approximately 1:840,000. Its spatial resolution can be compared with that of Landsat Thematic Mapper. The successful application of Shuttle images to topographic and thematic mapping has been shown, e.g. by Kostka (1987). Parallax-free stereo vision was achieved by means of rigorous photogrammetric methods implemented on an analytical plotter DSR-1 of Kern. The rms-error of the parallax measurements is given with ±13 µm. Nevertheless, there are some limited areas with larger parallaxes. This can be explained by the facts that the lens distortion was not considered, the film was not completely flat at the time of exposure and, what is more, the picture was taken through one of the windows of the Space Shuttle, which may cause inhomogenities in the image geometry.

The most troublesome task was the subsequent absolute orientation of the obtained stereo model in respect to the Chilean UTM-coordinate system. More than 30 ground control points (GCPs) were identified in the 1:250,000 and 1:500,000-scale maps. Since most of the GCPs had to be taken from the preliminary map "Ojos del Salado", rather large residuals were encountered, especially in planimetry up to 3,000 m. Numerically, the accuracy is ±90 m in height and better than ±800 m in planimetry. A topographic base map including drainage lines, lakes, spot heights, break lines, prominent ridges and other distinct geomorphological features has been plotted at a scale of 1:250,000 (Figure 3). Because of the small base-to-height ratio of 0.1 a DEM of the study area was not derived by means of contour lines. Instead, vertical profiles were digitized at an interval of 500 m. The profiles were triangulated using IDL-software, and contour lines with a contour interval of 250 m and a DEM with a grid spacing of 125 m were interpolated, respectively. The contour lines were added to the base map (see also Figure 3).

Subsequently, the transparencies were scanned using the VX3000 Image Scanning System with a pixel size of 25 µm (≅21 m ground resolution) in the panchromatic mode. In a first step the digital data was rectified using a projective image-to-object transformation. The rectified data set has more or less epi-polar geometry, so that stereograms can be viewed three-dimensionally without any problems. Examples of two selected stereograms are shown in Figures 5 and 6. Due to the large off-nadir looking angle of up to 39° to the north a projective transformation does not meet the requirements for high-precision rectification with an accuracy in the order of the given ground resolution. Existing relief displacements have to be compensated by means of a DEM. Finally, the digital data set has been geometrically rectified using the orientation parameters derived from the analytical plotter and the DEM obtained in the photogrammetric evaluation process. For the orthophoto a pixel spacing of 25 m was selected. Figure 4 shows the orthophoto at 1:400,000 scale, derived from the STS61C-45-20 hand-held photograph.

ERS-1 Synthetic Aperture Radar Images

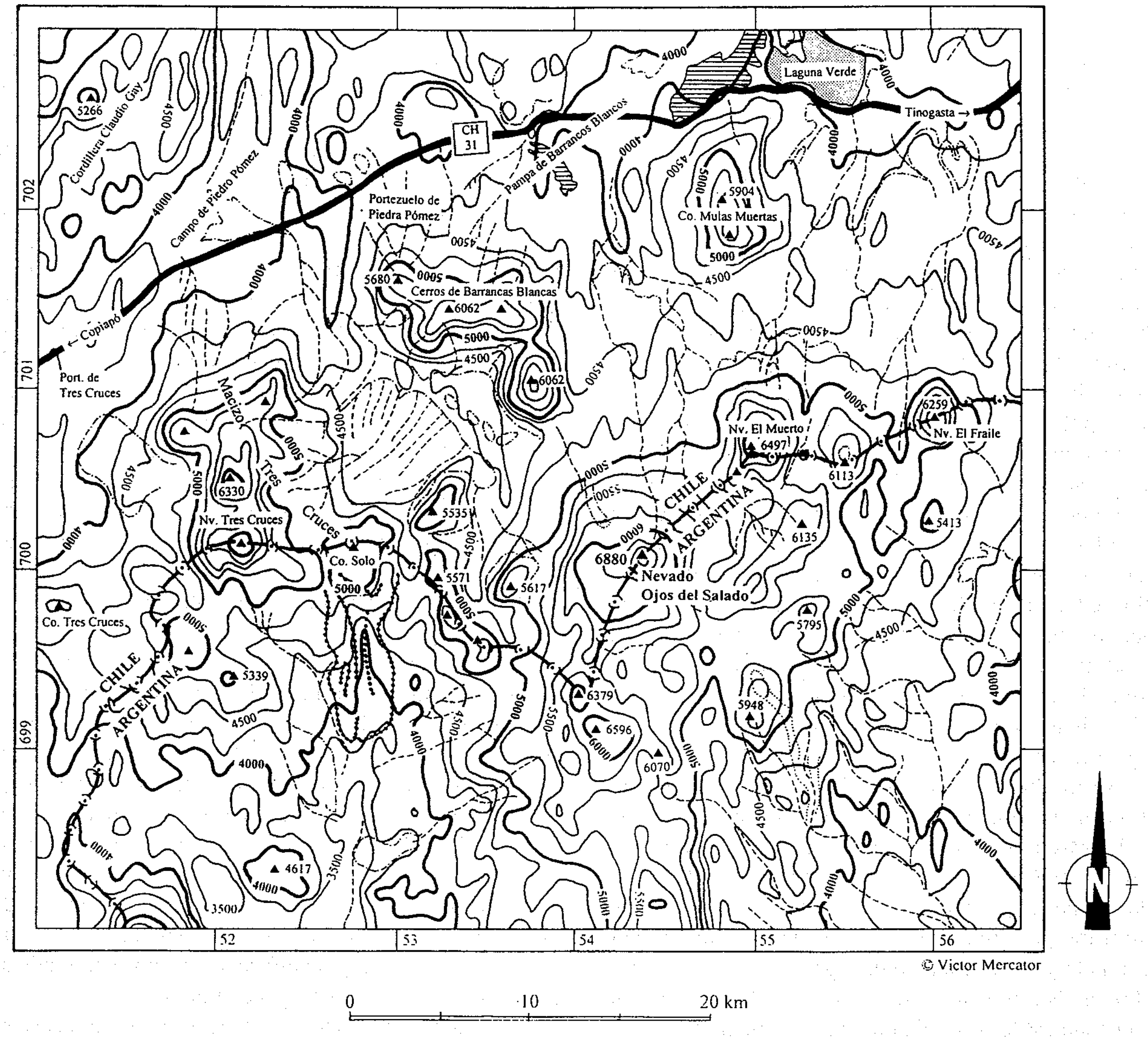
Since the acquisition of optical image data highly depends on good weather conditions with a minimum of cloud cover, radar images, which do not depend on weather conditions or daytime, were also analysed. Kaufmann *et al.* (1994 and 1995) describe two methods of unconventional mapping using overlapping ERS-1 SAR Precision Images. The first method is a hybrid approach using classical ways of photogrammetric mapping based on analog images which have been derived from radiometrically enhanced digital SAR data. The second method is designed to derive three-dimensional topographic information semi-automatically by means of image correlation techniques.

Two same-side ERS-1 SAR stereopairs from descending orbits were acquired over the study area in April and May, 1992, transmitted to the data receiving station located at Cuiabá, Brazil (see Figure 1), processed at the German Processing and Archiving Facility (D-PAF), and provided in digital format as ESA specified ERS-1 SAR Precision Images with a pixel spacing of 12.5 m. The ground coverage of the 4 SAR scenes is shown in Figure 7. All images were acquired during a 35-day repeat cycle (multi-disciplinary phase). Fielding *et al.* (1986) and Chorowicz *et al.* (1994) demonstrate how radar images can contribute to volcanologic studies.

Table 1 Parameters of the selected SSEOP photographs covering the Nevado Ojos del Salado. The frame numbers refer to the stereopair (left and right stereo partner).

Mission Code	Roll - Frames	Lens (mm)	Date	Time (GMT)	Sun Azimuth	Sun Elevation
STS61 C	45- 19/20	250	13-Jan-1986	22h06m	254°	17°
STS511	40-83/84	250	1-Sep-1985	21h52m	281°	5°
STS511	45-65/66	100	2-Sep-1985	20h53m	287°	16°
STS511	46-80/81	100	2-Sep-1985	20h52m	289°	18°

NEVADO OJOS DEL SALADO

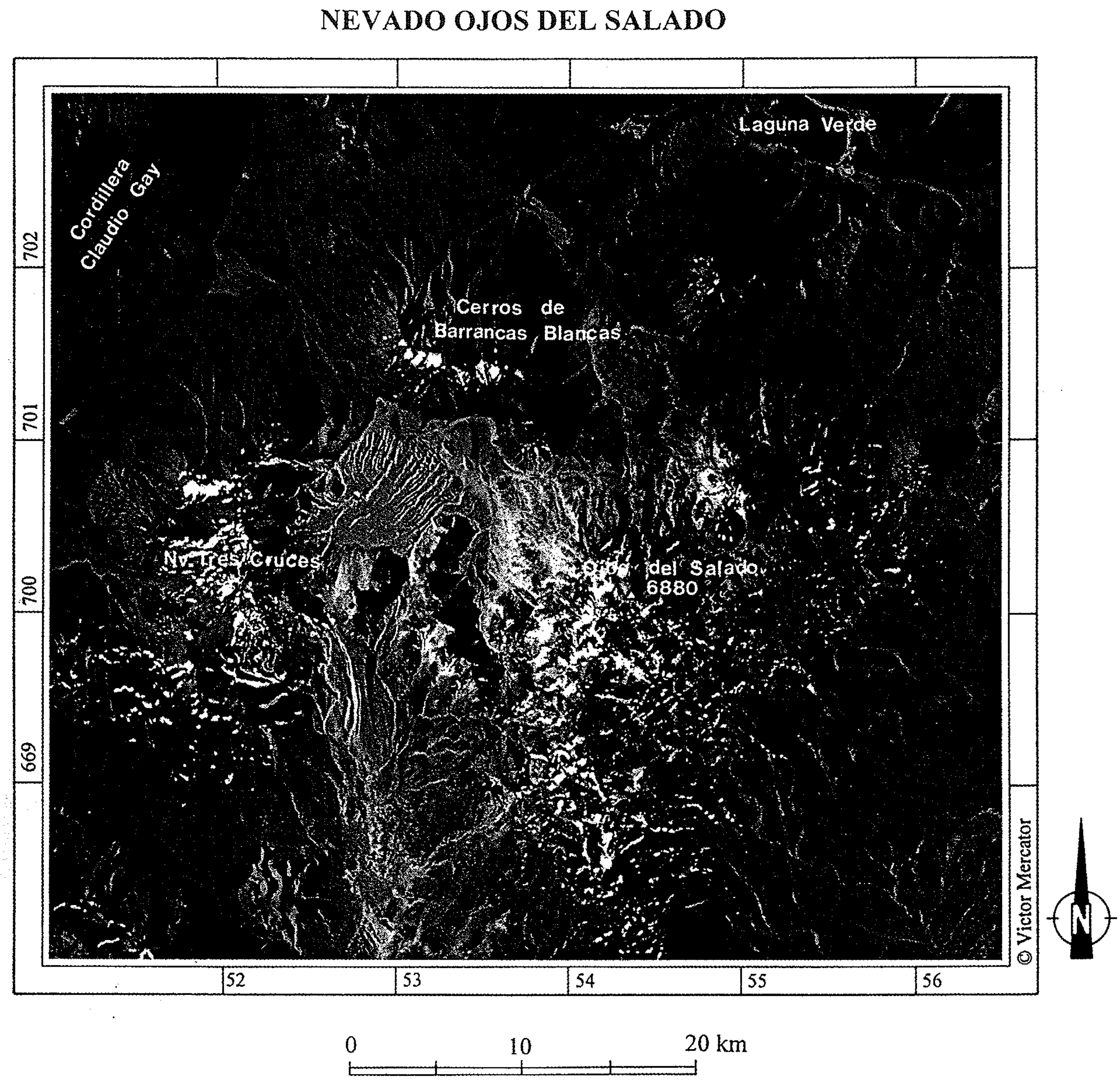


Coordinate system: Universe Transverse Mercator (zone 19).
Geodetic reference: GCPs from Chilean maps 1:250,000.
Photogrammetric evaluation by V. Kaufmann, 1994: Contour interval 250 m, heights above m.s.l.

Figure 3 Topographic map of the region around the Nevado Ojos del Salado (reproduced at 1:400,000 scale).

Since the radar echo heavily depends on surface roughness and slope, various objects, such as volcanoes, craters, ashfans, lava flows, erosional surfaces, river beds and other structural objects can be identified and delineated very nicely (figure 8).

As far as this study is concerned, none of the previously mentioned methods have been actually applied to the available data. Instead, the SAR inherent speckle noise has been reduced by means of block averaging in order to improve the visual perception of the image content. Figure 9 shows a radar stereogram extracted from the mosaicked radar images (see also Figure 6 for comparison). Unfortunately, the Nevado Ojos del Salado is only partially located within the small strip of stereoscopic coverage. Due to the high-relief terrain and the steep looking angle of ERS-1 the image geometry is considerably distorted. As indicated in Kaufmann *et al.* (1994) there is a demand for stereo-radargrammetric mapping in order to georeference, e.g., drainage lines, lineaments, faults, etc., especially in high-mountain regions where image distortions are quite large.



Coordinate system: Universe Transverse Mercator (zone 19).
Geodetic reference: GCPs from Chilean maps 1:250,000 (Laguna Verde 2600-6730, 1985 and Ojos del Salado 2769, 1954).
Image source: SSEOP STS61C-45-20 colour photograph at 1:840,000 scale.

Figure 4 Orthophoto at 1:400,000 scale derived from Space Shuttle STS61C-45-20 photograph.Same area as shown in Figure 3.

Aerial Panchromatic Photographs

Although high-resolution spaceborne images, e.g. from SPOT or Russian MK-4, are available, aerial photographs still remain the ideal source for medium- to large-scale mapping. 5 panchromatic aerial photographs, given as black-and-white paper prints, were used in order to carry out large-scale mapping of the volcanic complex of the Nevado Ojos del Salado. These photographs date from May 1, 1961, and were provided by the Instituto Geografico Militar de Chile. The image scale varies between 1:45,000 and 1:27,000 due to the great height differences of the terrain. Since no transparencies of the photographs were available, the rigorous photogrammetric evaluation was carried out using a Zeiss-Jena TOPOCART stereoplotter, which had been upgraded from analog to analytical. This stereoplotter offers the exceptional opportunity to work with opaque photographic prints as well. The photogrammetric mapping procedure is summarized in the following:

- Relative orientation of the aerial photographs showed

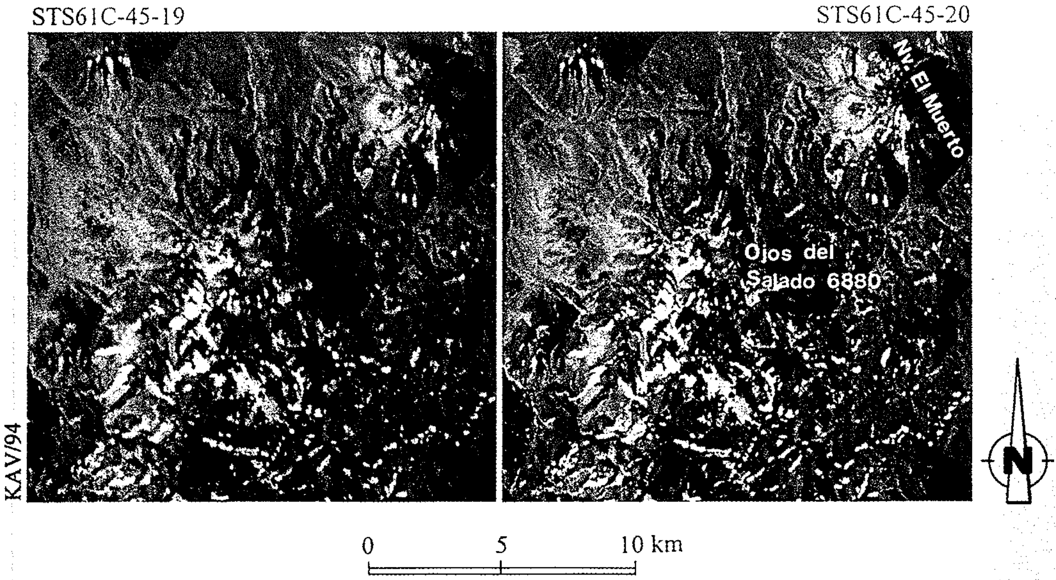


Figure 5 Stereogram of the Nevado Ojos del Salado derived from Shuttle STS61C-45-19/20, January 13, 1986

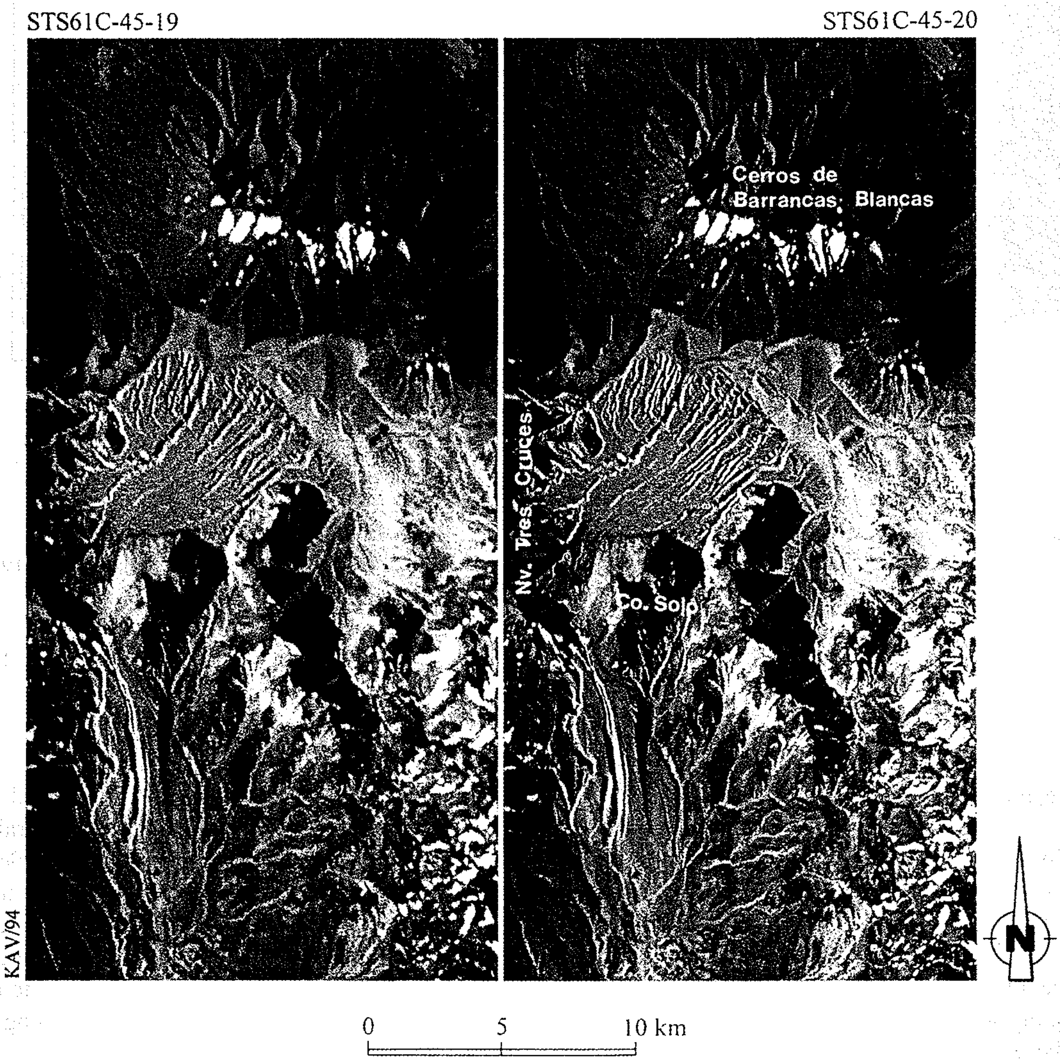
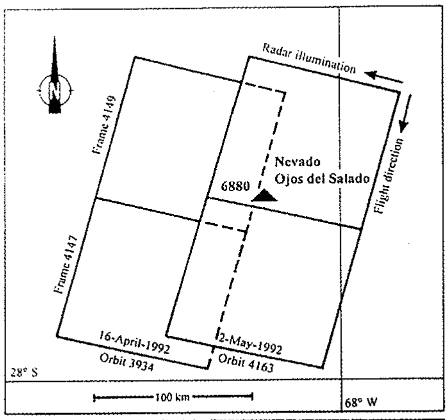


Figure 6 Stereogram of an area in the western part of the Nevado Ojos del Salado

Figure 7 Coverage of ERS-1 SAR images



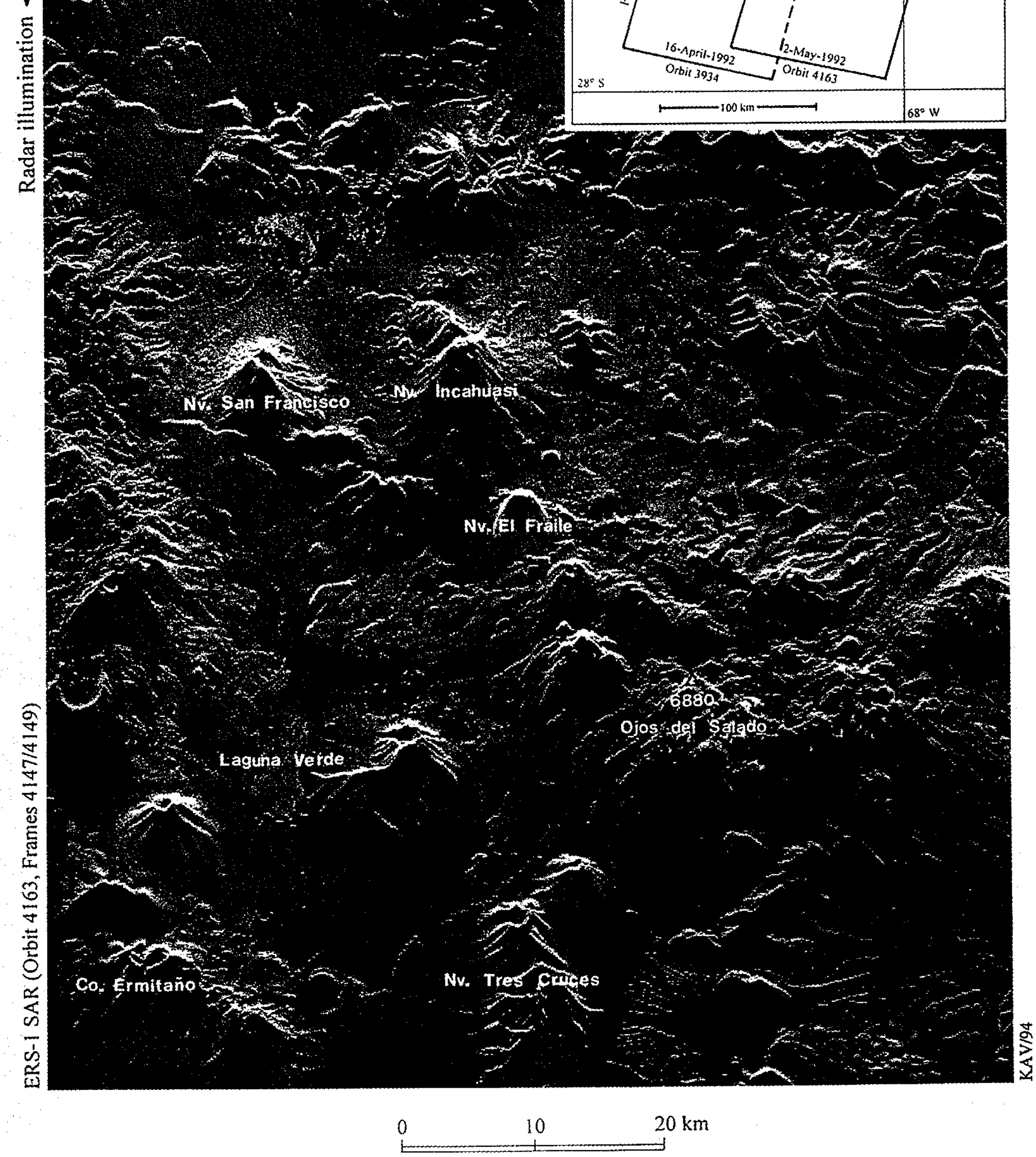


Figure 8 Part of the ERS-1 SAR image dating from May 2, 1992 acquired over the area of interest

±15 µm of remaining parallaxes. As a result, the overlapping photographs can be viewed three-dimensionally without any problems.

- In order to solve the absolute orientation of the strip an unconventional method was considered. Due to the small scale of the 1:250,000 topographic map "Ojos del Salado", no GCPs could be found. So it was obvious to refer to the Shuttle image stereopair dealt with in Paragraph 2 of this paper. 17 GCPs which could also be discerned in the 4 aerial stereo models of the strip were identified in the Shuttle stereopair . Subsequently, the aerial strip could be transformed into the Chilean UTM-coordinate system by means of an aerotriangulation using a block adjustment. The accuracy obtained is ±180 m in planimetry and ±50 m in height according to the coordinate system defined by the Shuttle stereopair. The accuracy of the absolute height

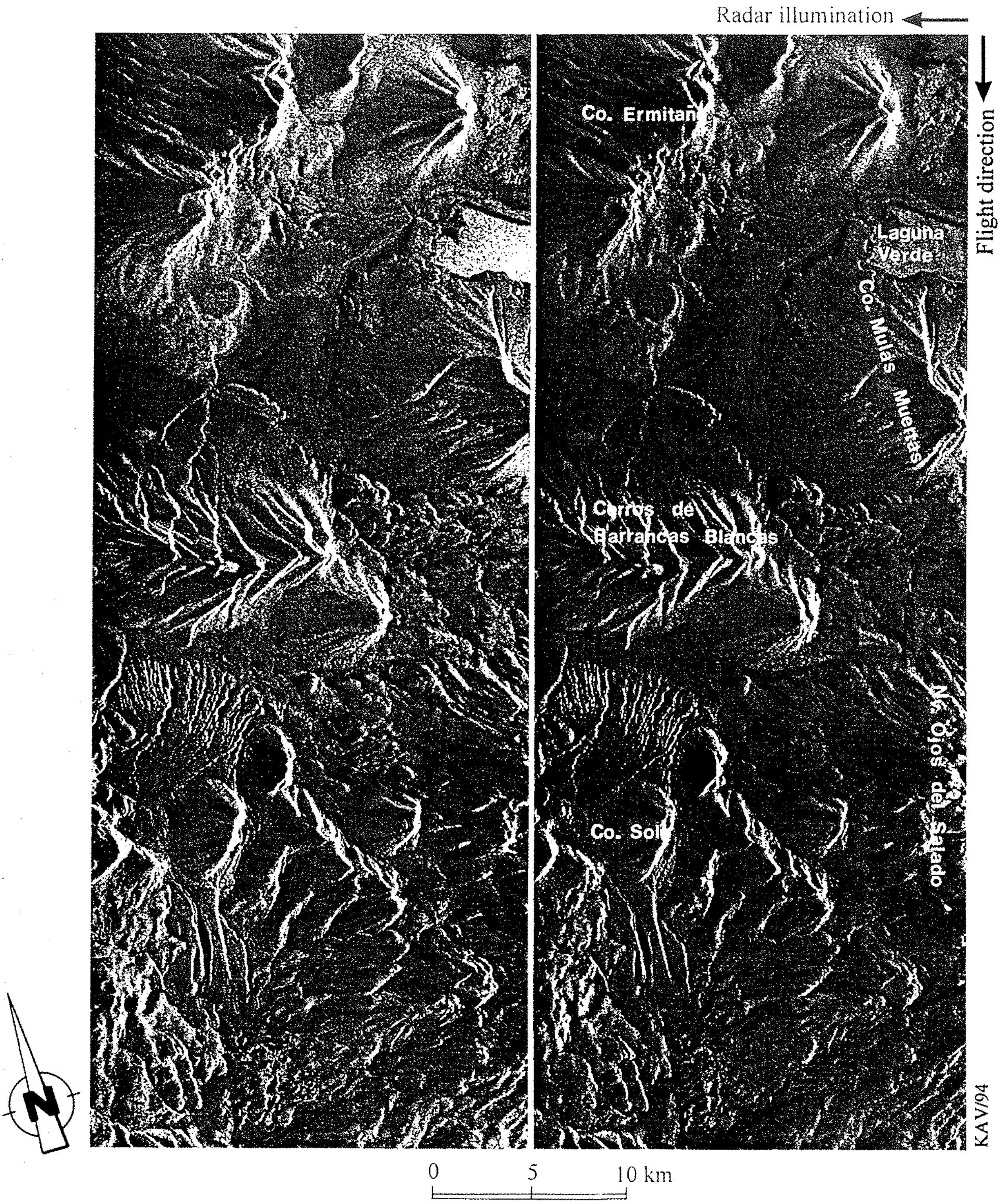
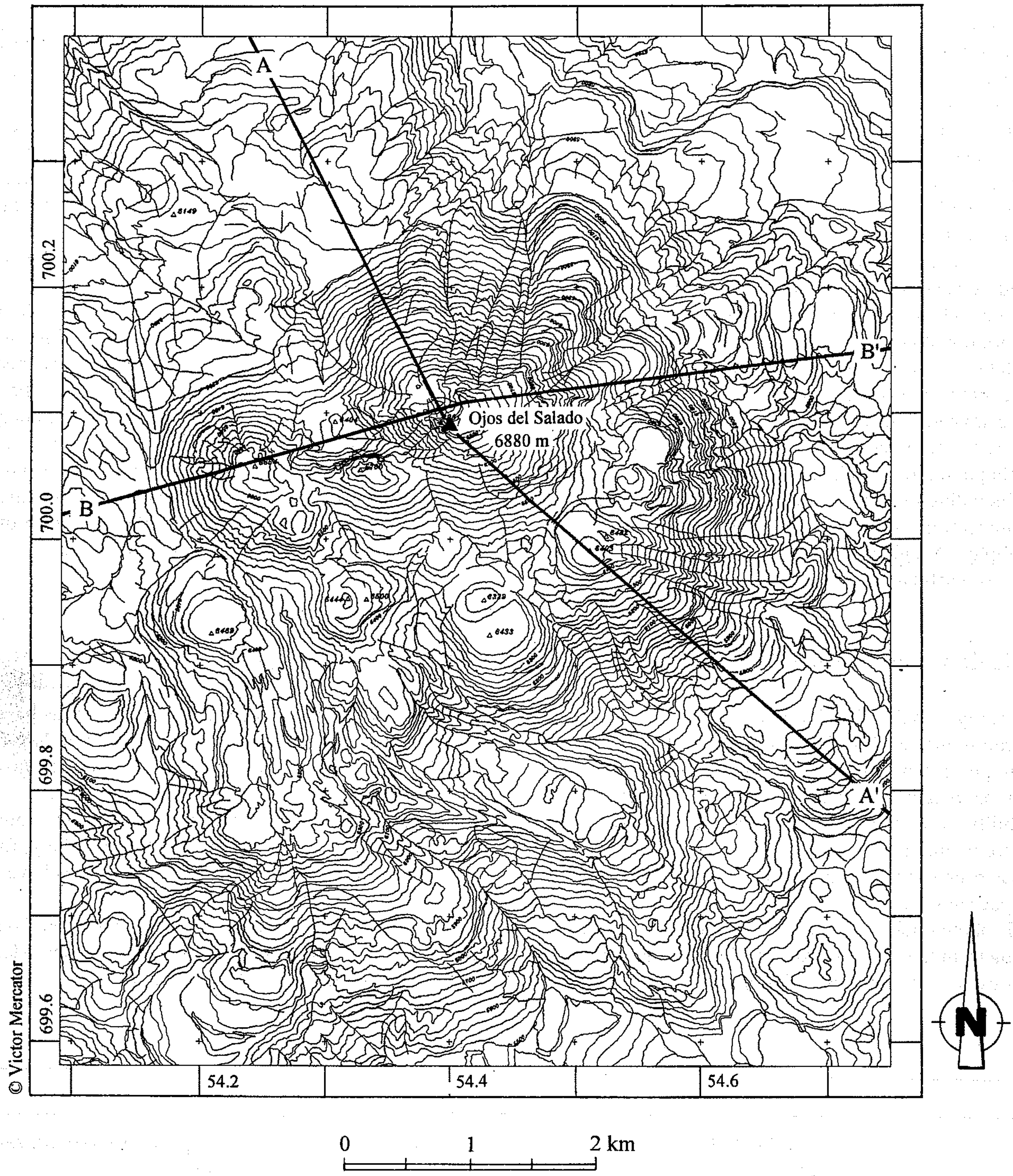


Figure 9 ERS-1 SAR stereogram (April and May, 1992) of the same area as shown in Figure 6.

measurements in the aerial strip in respect to the map coordinate system is therefore ±100 m. The planimetric accuracy is far worse. However, this does not matter too much because geomorphological studies rely on scale, horizontal control and north pointing of the stereo models rather than on absolute datum in planimetry.

- For three stereo models contour lines at an interval of 25 m, as well as drainage lines, ridge lines, other geomorphologically prominent ridges, and spot heights were digitized using a mapping environment which has been developed using AUTOCAD. Finally, a topographic study map at 1:15,000 scale was prepared (Figure 10).

NEVADO OJOS DEL SALADO



Coordinate system: Universe Transverse Mercator (zone 19).
Geodetic reference: SSEOP STS61C-45-19/20 stereopair, GCPs from Chilean maps 1:250,000.
Image source: Aerial photographs, 1961.
Photogrammetric evaluation by R. Benzinger, 1994: Contour interval 25 m, heights above m.s.l.

Vertical profiles (A-Á) and (B-B́) see Figure 11.

Figure 10 Topographic map of the Nevado Ojos del Salado (reproduced at 1:50,000 scale)

- Additionally, selected vertical profiles were plotted in order to assist the geoscientist in his analysis (Figure 11).

The three-dimensional data set derived from the photogrammetric mapping process was thereafter used to interpolate a high-resolution DEM with a pixel-spacing of 10 m. Axonometric views of the DEM are shown in Figure 12. In a next step the analog prints were scanned by means of an A3-scanner (HP ScanJet IIc) with a resolution of 300 dpi (≅85 mm pixel spacing). This data was digitally rectified using the DEM, afterwards radiometrically adjusted and mosaicked to form an orthophoto covering the area of interest (Figure 13). For the orthophoto a pixel spacing of 2.5 m was selected, which was found to be optimal in respect to resolution and the reasonable amount of data. A stereomate of this orthophoto was produced as well (see also Figure 13). This data set allows a comfortable geomorphological interpretation of this high-relief terrain by a geoscientist, with the advantage that the derived line map, which may be drawn by hand, directly relates to the selected geometry of the orthophoto. A combined image-line map at 1:15,000 scale, including the orthophoto, contour lines, spot heights and annotation, was composed by means of digital cartography. Anaglyphs of the area of interest were also found to be useful in the visualization process of the volcanic terrain.

Conclusions and Outlook

Currently, a multitude of earth observation systems each year acquire thousands of images of the earth's surface. As to what type of remotely sensed data has to be selected for a certain mapping project depends on many parameters, e.g., availability, resolution, cost and time factor, software and hardware requirements, etc.

It has been shown that small-scale topographic mapping from space at scales 1:250,000 to 1:500,000, using NASA's SSEOP photography, can be an alternative to operational mapping from space, always keeping in mind the limitations caused by poor ground resolution and sometimes unstable imaging geometry. SSEOP data is available at a very low price. It can be used for preliminary or special studies of remote areas for which no updated or reliable topographic maps exist. The potential areas are of course limited to the ground coverage of the Space Shuttle missions. Geometric rectification of oblique-viewing Shuttle photographs has been demonstrated applying hybrid methods. In a further study high-resolution image data acquired from spaceborne remote sensing systems, e.g. SPOT, MOMS-02 or Russian MK-4, will be considered. This implies that GCPs have to be measured using GPS-techniques in a field survey. The desirable scale of the final topographic map should be 1:50,000 or 1:100,000.

Digital orthophotos at 1:15,000 scale proved to be very useful in large-scale geomorphological mapping of the Nevado Ojos del Salado, especially the DEM was needed not only in the rectification process but also for visualization of the terrain and in quantitative geomorphometric analysis, e.g., aspect and slope maps, and relief energy maps. The absolute orientation can be improved by previously mentioned spaceborne data, or, if possible, by means of GPS-controlled aerotriangulation, the latter being unlikely because of the difficulties induced by the high-mountain terrain.

Acknowledgements

The study presented in this paper has been originally triggered by R. Kostka, Graz University of Technology, and H. Badura, Schladming, Austria. H. Badura let us have the aerial photographs for scientific work, after he had come back from an expedition to the region around Ojos del Salado. His contribution is appreciated very much.

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The author is pleased to thank Mrs. L. Gleasner from the Earth Data Analysis Center, the University of New Mexico, for her help in ordering the SSEOP data.

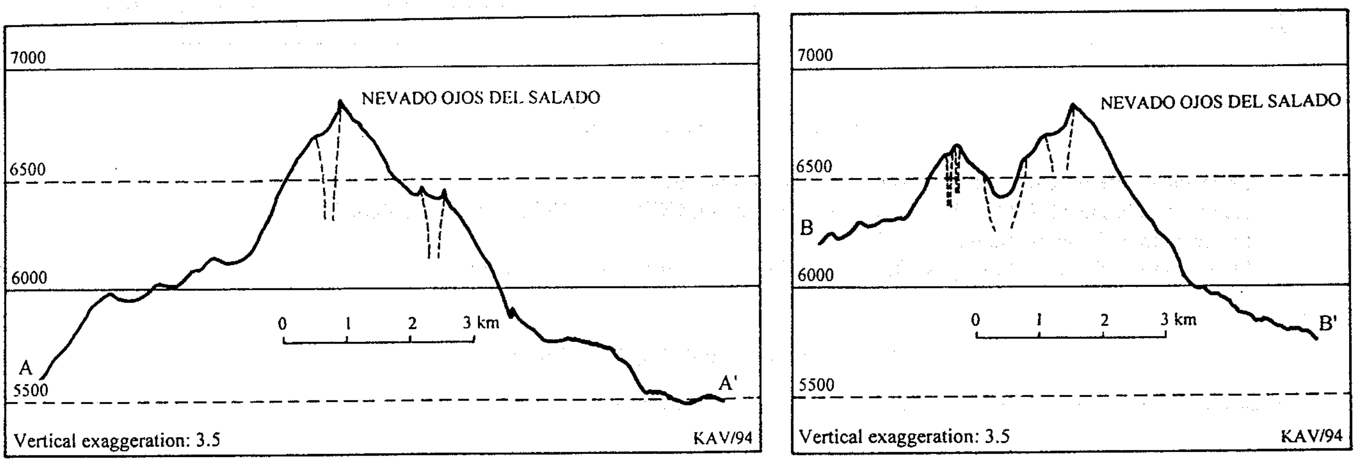

Figure 11 Vertical profiles (see also Figure 10 for location)

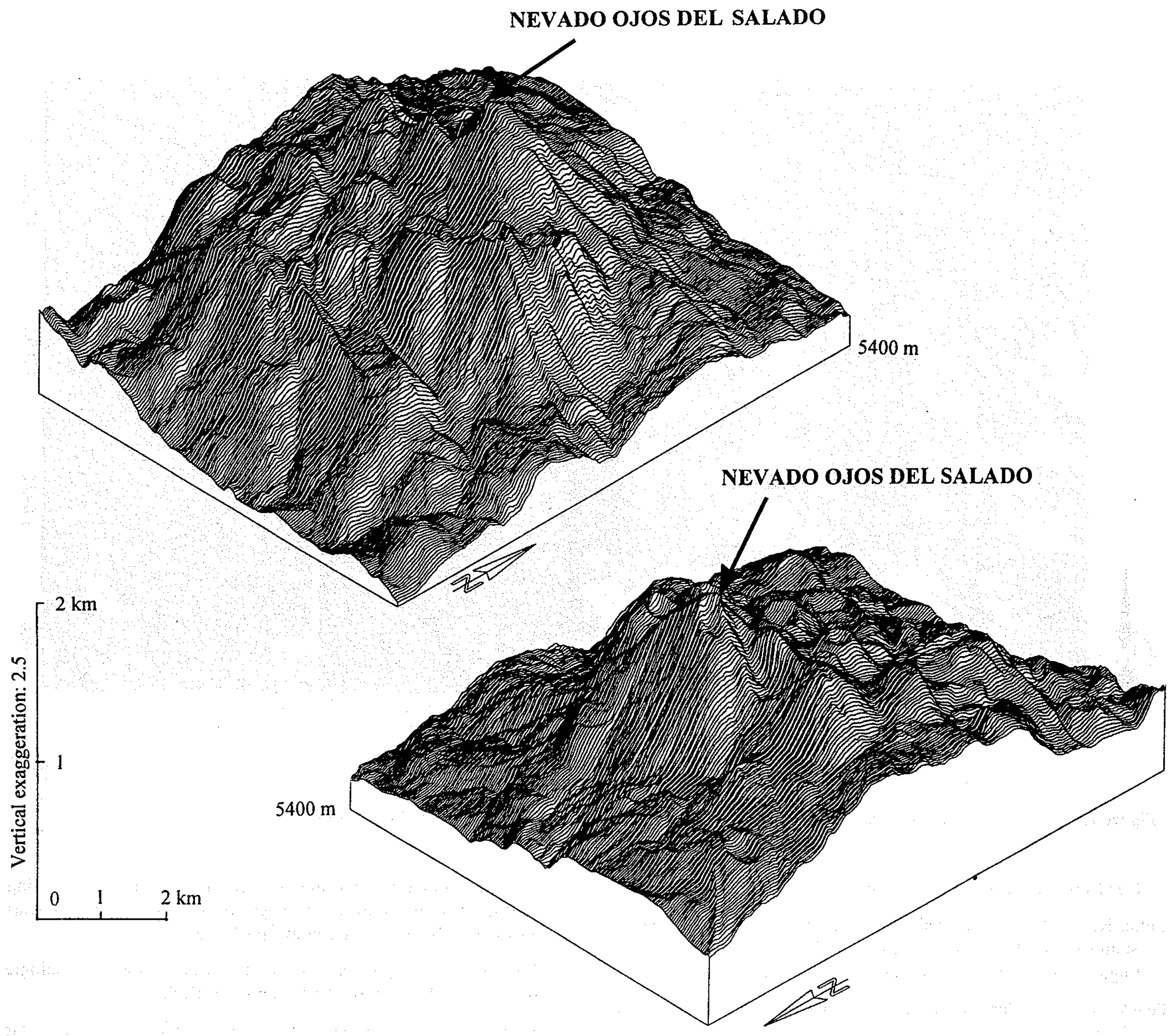

Figure 12 Axonometric views of the Nevado Ojos del Salado

The Shuttle images were scanned at the Institute for Computergraphics (Head Prof. Dr. F.W. Leberl) of the Graz University of Technology with the help of M. Gruber.

The high-resolution DEM was computed at the Institute for Image Processing of Joanneum Research Graz.

Furthermore, the support of F. Widder, University of Graz, is thankfully acknowledged. He gave us valuable background information concerning mountaineering activities at the Nevado Ojos del Salado.

References

Carter, H.A., 1957, The American Alpine Club Expedition to the Ojos del Salado. The Geographical Rev., Vo. 27, pp. 240-250.

Chorowicz, J., *et al.*, 1994, Geometric objects detected by ERS-1 SAR images in different geodynamic contexts. Proceedings of the 2nd ERS-1 Symposium, Hamburg, 1993, ESA SP-361, Vol. 2, pp. 923-929.

Fielding, E.J., *et al.*, 1986, SIR-B radar imagery of volcanic deposits in the Andes. IEEE Transactions on Geoscience and Remote Sensing, Vol. GE-24, No. 4, pp. 582-589.

Kaufmann, V., *et al.*, 1994, Stereo-radargrammetric evaluation of ERS-1 SAR images: A case study in Southern Italy. Proceedings of the 2nd ERS-1 Symposium, Hamburg, 1993, ESA SP-361, Vol. 2, pp. 1211-1216.

Kaufmann, V., *et al.*, 1995, Some experiments on relief mapping from space using microwave and optical data: Looking at the badlands in Southern Italy. EARSeL Advances in Remote Sensing Vol. 4, No. 2, pp. 130-138.

Kostka, R. (ed.), 1987, Die erderkundende Weltraumphotographie und ihre Anwendung in der Gebirgskartographie. Mitteilungen der

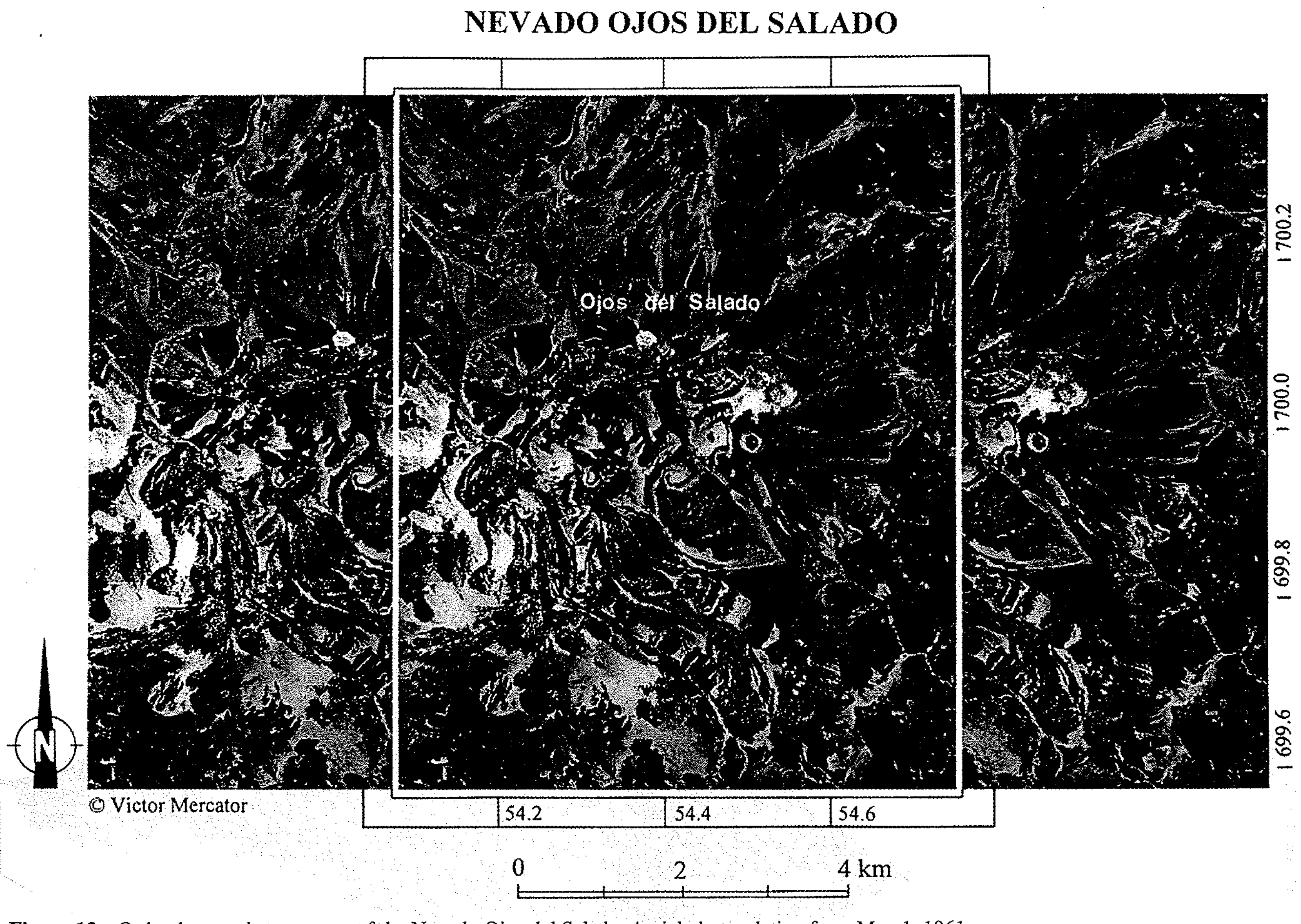

Figure 13 Orthophoto and stereogram of the Nevado Ojos del Salado. Aerial photos dating from May 1, 1961.

Geodaetischen Institute der TU Graz, Vol. 57, 217 p.

Lulla, K., *et al.*, 1993, Global geological applications of the Space Shuttle Earth Observations Photography database. Photogrammetric Engineering and Remote Sensing, Vol. 49, No. 8, pp. 1225- 1231.

Penck, W., 1933, Puna de Atacama. J. Engelhorns Nachf: Stuttgart, 232 p.

Sulzer, W., 1994, Geomorphological mapping of the Nevado Ojos del Salado using optical and microwave image data. Proceedings of the 3rd International Symposium on High-Mountain Remote Sensing Cartography. Instituto de Investigaciones Aplicadas de Ciencias Espaciales, Mendoza, Argentina, pp.38-46.

Zeil, W., 1964, Geologie von Chile. Beitraege zur regionalen Geologie der Erde, Vol. 3, Gebrueder Borntraeger, Berlin, 233 p.

Zeil, W., 1979, The Andes, A geological review. Beitraege zur regionalen Geologie der Erde, Vol. 13, Gebrueder Borntraeger, Berlin, 260 p.