GPS and Digital Photogrammetry: an Integrated Approach for Monitoring Ground Deformations on a Volcanic Area

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Abstract

This paper describes an airborne GPS project conducted in 1996 over the island of Vulcano. The objective of the study was to experiment a fast and accurate procedure for an aerial photography mapping application with a scale adequate for ground deformation monitoring. A short description of the geological and geophysical features of the area of interest is presented. A summary of results from the airborne and ground GPS observation processing is provided. Softcopy workstations were used to process the images and preliminary results evaluated.

Introduction

In the Aeolian Island Arc (Southern Tyrrhenian Sea) two volcanoes, Stromboli and Vulcano, are still active and continuously monitored by geophysical, geochemical and geodetic surveys. The Vulcano island is located along a very active fault system and was involved in last eruptive process in 1888-1890; its activity is characterized by eruptions separated by long intervals of quietness during which fumarolic activity persists and the central conduit is filled by solined lava. Since 1987 a certain unrest has been observed in the form of temperature increasing, variation of chemical composition of fumarole gases, opening of new fractures and relatively low seismicity.

In the last 20 years within a broader geophysical program for monitoring the activity of the island, the area has been systematically investigated by means of repeated geodetic (both horizontal and vertical) surveys, microgravimetric measurements and tilt stations.

After the Patti earthquake (1978, M=5.5), the northern part of the island was found to have subsided relative to its southern part; this deformation process was followed by a prolonged sinking of about 4 cm up to 1981. The subsequent surveys did not shows any further significant deformations until 1990, when a small subsidence of the NW sector of the rim of La Fossa crater was observed (Obrizzo et al., 1994).

The terrestrial geodetic methods, though characterized by high accuracy, require to design the measurements on a polygonal basis; this led to the fact that the deformation pattern can be derived on the basis of a limited number of points thus often precluding the detailed knowledge of the deformations related to eruptive dynamics, such as subsurface dike propagation, eruptive vent, lava flow, etc. For this reason it was decided to experiment the use of the aerial photogrammetry technique as a mean to obtain a full coverage of the island with images at a large-medium scale (1:5000 and 1:10000); the accuracy achievable on mapping products at such scales can allow by comparison with earlier products to detect larger deformation patterns (Fritsch, 1986, Zlotnicki et al, 1990, Achilli et al, 1994). Furthermore, the use of GPS observations for establishing aerial control points and, as a consequence, reducing the number of required ground control points allowed for a fast and accurate surveying of the control network. On the side of the processing of the images in digital form, the use of softcopy workstations allows for some time reduction when automatic procedures can be successfully applied.

The first experiment was carried out on the "Fossa di Vulcano" area with the acquisition of photos at a relative scale of 1:10000 taken during different flights performed in 1971, 1983 and 1993. The images were scanned at a resolution of 1000 dpi (pixel size = 25 micron) and processed on the Helava Digital Photogrammetric Workstation (DPW710); using the Helava module for automatic correlation, a Digital Terrain Model of the area under investigation was produced with a five meter square grid and 250000 correlated points for any model. The comparison between the different surveys showed a mean standard deviation of the residuals of about 0.5 m, evidencing a narrow zone with greater residuals in the fumarole area and allowing the estimation of the terrain volume involved in a major landslide which affected the North-Eastern side of the volcanic cone in 1988 (Achilli et al, 1997).

The 96 GPS Photogrammetry Project

In September 1996 an airborne GPS-photogrammetric project was performed over the Vulcano Island. The images were taken at two different flight heights in order to accomplish 1:5000 and 1:10000 photo scales. Two flight missions (day 272 and 273) was necessary to obtain full coverage of the island with no clouds. The aircraft was equipped with a WILD RC20 camera communicating with a GPS configuration designed for the use of two receivers (Ashtech ZXII and Trimble SSI) connected to the same antenna; since it was decided to mount the antenna on the fusolage in correspondence of the camera, the spatial offset between the GPS antenna and the camera resulted of about 1.5 meters in the vertical and few centimeter in horizontal component.

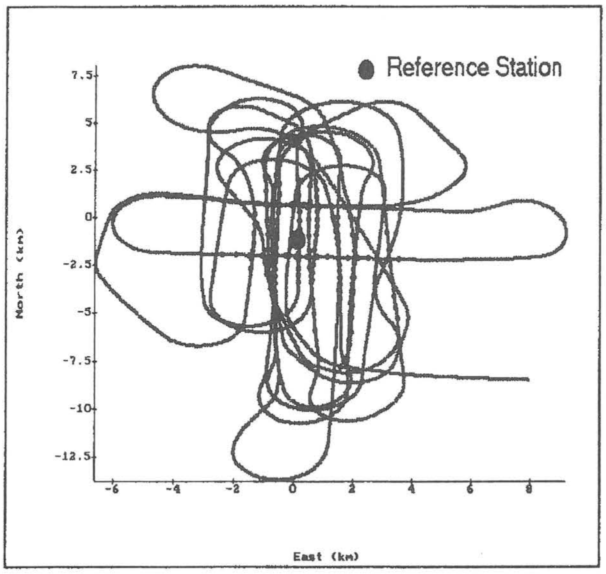

Figure 1 Horizontal trajectory of aircraft (Day 273)

GPS data collected on the aircraft and at the reference stations on the ground (three on the island and one at the airport) were processed using OTF kinematic algorithms. Figure 1 shows the horizontal trajectory of the aircraft on day 273 and the approximate location of the reference stations on the ground.

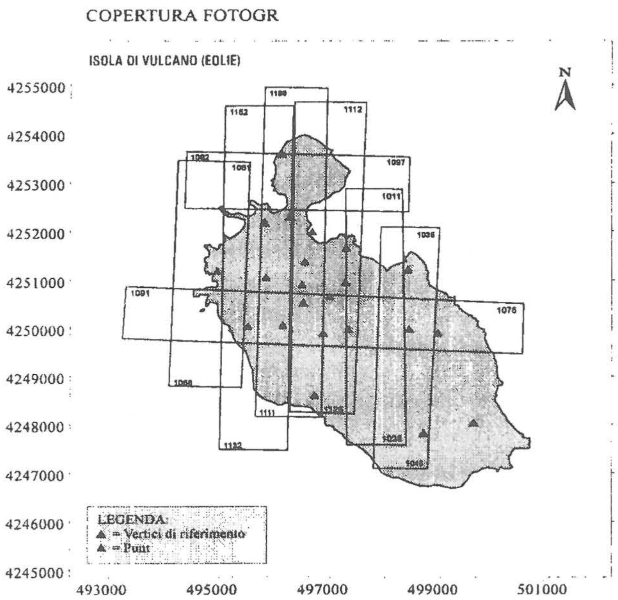

Figure 2: GPS control network on Vulcano Island

An accurate GPS control network was established in the project area placing on the ground specially designed aerial targets painted in black and white. GPS receivers were continuosly operating on three master control points while the rest of the points were measured with session of about 30 minutes.

GPS observations were reduced using the Bernese program and the network was tied to ITRF through the station of Matera. Results from the network adjustment showed standard deviation of few millimeters on the horizontal components and 1-5 centimeter on heights. Figure 2 shows the location of the ground control points and the coverage of the photos at 1:5000 scale flight.

Integration of GPS and raw photo measurements

The performance of a GPS-photogrammetric project implies the simultaneous collection of aerial imagery and of GPS observations. The GPS antenna and the camera system are spatially and temporarly connected, thus allowing for the determination of the positions of the photo centers at the instant of each exposures.

The procedure of meansurations allow to determine raw photo measurements that are to be combined with the raw GPS measurements. The combination of the two types of measurements occurs during the performance of a bundle adjustments where, after the interior orientation, the reduced photo measurements are combined with the GPS exposure station coordinates. The latter are derived by interpolating the kinematic solutions for GPS antenna positions at time of exposure; the interpolated positions should be reduced at the camera perspective center by applying the measured spatial offset. The incorporation of control points into the Bundle Adjustment permits to obtain final object 3D coordinates; when GPS is used to measure Ground Control Point and camera stations the final coordinates can be directly the 3D geocentric X,Y,Z (WGS84) (Colomina, 1993).

Since most of the AT programs are developed to work in Local Space Rectangular (LSR) Coordinates, transformation of the GPS coordinates are required to obtain map projection coordinates like, for example, UTM. The transformation from ellipsoidal to gaussian coordinates induce deformations which can be computed using the linear deformation coefficient and which grows with the distance from the central meridian. In order to reduce deformations the gaussian coordinates are usually scaled by a factor k=0.9996.

Owing to the limited size of the area under investigation (4' x 4') and of the vicinity to the central meridian of UTM fuse (mean longitude $\lambda \cong 15°$), the expected deformations can be considered neglectable for the purposes of the project if the reduction factor is not applied. Thus the parameters adopted in this study to transform the WGS84 geodetic coordinates (lat/lon) into gaussian grid coordinates are: $k = 1$; $N_0 = 0$; $E_0 = 500.000$ m; $\lambda = 15° 00' 00''$. This transformation was applied to the control network coordinates resulting in linear deformation lower than 1,000000248. As a consequence it is clear that the results from the AT cannot be affected by deformation larger than the required accuracy at the decimeter level.

Kinematic GPS Data Processing

The GPS observables collected at 1 seconds from the aircraft and at the 4 reference stations were processed using two different programs, GEOTRACER (TerraSat) and PNAV (Ashtech,1994) which perform On-The Fly ambiguity solution. The results obtained from two softwares provided trajectories of the aircraft with showed differences at few centimeters level (8.1 +/- 4.7) By comparing solutions from different reference station it was accessed that the overall repeatability of the kinematic solutions was at 5-10 cm level. The performance of the two model receivers (SSI and Z12) was similar, showing, in absence of drastic changes in the satellite configuration, difference in the position at 1-2 centimeter level (rmsΔE = $\pm$ 1.2; rmsΔN = $\pm$ 1.2; rmsΔh =$\pm$ 1.4).

The GPS trajectories were interpolated at the instant of exposure and a number of camera centers selected and the corresponding images were processed as described in the following.

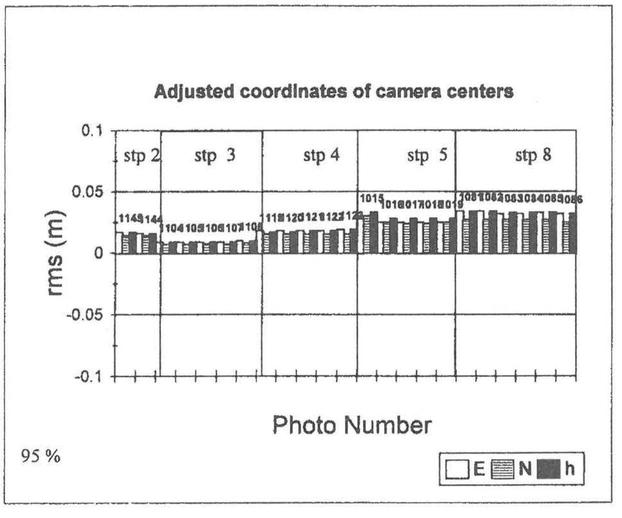

Figure 3 Standard deviations of the adjusted coordinates for camera centers

In order to correctly use the redundant information on the position of the camera centers from the three solutions (one for each reference station on the island) they were combined into a rigorous adjustment with computation of relevant statistics and associated errors. Figure 3 show the results of the adjustment.

Digital Photogrammetry

In the last decade Digital Photogrammetry Workstations (DPW), first developed within research laboratories, have reached the status of commercial products as alternative to the analytical plotters (Heipke,1995). A complete digital station can fulfill all the processing steps from image scanning to the DTM and ortophoto generation, frequently using automatic or semiautomatic procedures. It usually runs on high-cost platform and requires specialized operators. Recently low-cost systems for digital image analysis have been developed to run on Personal Computers. Among the former type of system, the Helava system (Miller, 1992), one of most up-to-date and complete DPW on the market, was adopted in this work. A photogrammetric block formed by 23 images covering the top of the Vulcan was processed for the production of a Digital Terrain model and relative ortophoto. At the same time, the low cost StereoView (Menci, 1996) system was experimented to process a pair of stereo images and the automatic extraction of DTM. In the following preliminary results obtained using Helava and StereoView are reported.

Data processing with HELAVA

The Helava workstation allows for acquisition of digital images with an high resolution scanner and for their interpretation using automatic or semi-automatic procedure. An image correlation algorithm is able to automatically measure a DTM from the oriented digital photographs; the operator can make necessary corrections to the model using editing functions. The phase of model edition is function of the relief characteristics and can be laborious in presence of discontinuities and disturbances which cannot be easily filtered.

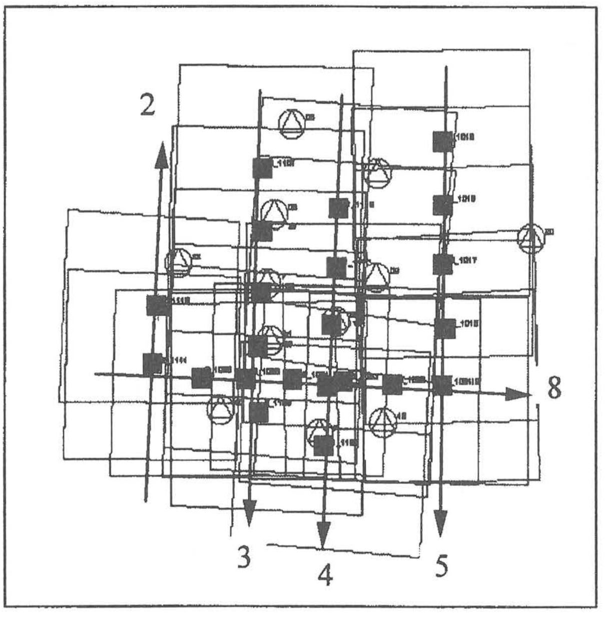

Figure 4 Photogrammetric block processed with Helava

A photogrammetric block formed by 5 strips including 23 photos was analyzed using the Helava system. The images were digitized using the scanner coupled with the Helava DPW at a resolution of 1000 dpi (dot per inches) which results in a pixel size of 25 micron. At the 1:5000 scale the corresponding ground pixel resolution is of about 12.5 centimeters. Since the correlation algorithm can work at subpixel level, even for a 1/3 pixel the resulting ground resolution is about 5 cm, enough to obtain a DEM accuracy at the decimeter level.

The workstation was used to observe the image coordinates using an automatic procedure. The internal bundle adjustment program (HATS) was used for the airborne triangulation of the entire block. Standard deviation on residuals of control and pass points resulted of about 5 cm. The x and y image coordinates of all control and pass points were transferred to a PC and reformatted for a different bundle adjustment program (ASW) which provided similar results as the Helava AT program. In Figure 4 the ASW triangulated positions for the camera centers are compared with the directly measured coordinate obtained with the GPS processing.

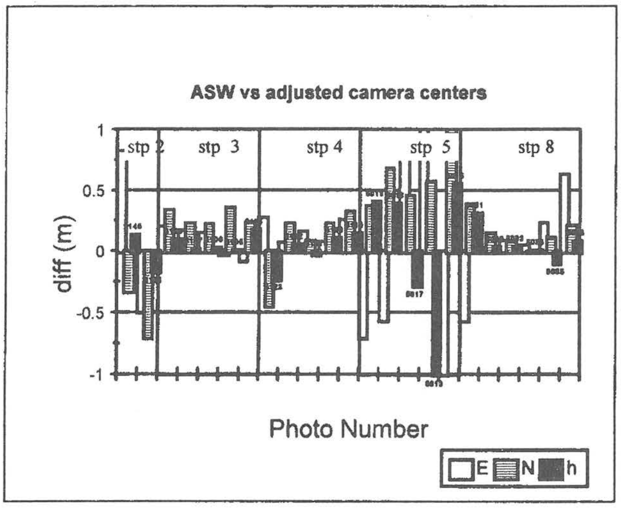

Figure 5 Difference between triangulated and GPS camera centers

At a first comparison (Figure 5), the difference observed between the East, North and height components resulted to be of the order of 50 centimeters or more for strip 2 and 5 and of less than 20 centimeters for strip 3,4 and 8.

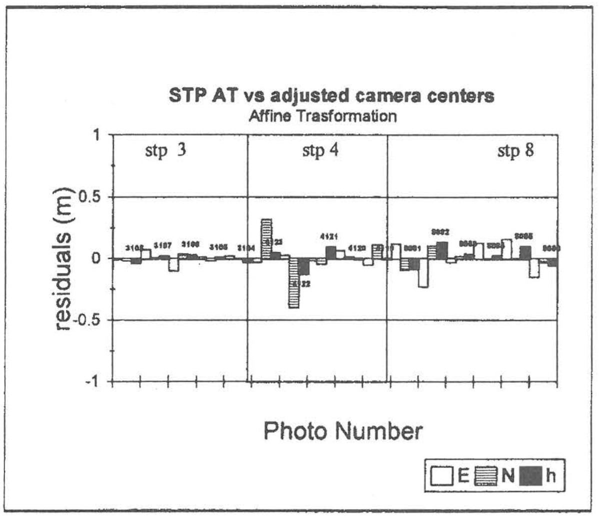

Figure 6 Residuals between GPS and AT camera centers (affine transformation)

This discrepancy is due to weakness of the adjusted solution for strip 5 and 2 which are poorly constrained. The ASW program was adopted for the adjustment of a reduced block of images which included the 2 central strips (3 and 4) and the cross strip (8). The two set of coordinates for the camera centers, that is GPS and those obtained for the selected images, were compared using an affine transformation which results are shown in Figure 6.

Further analysis is necessary in order to incorporate the GPS camera centers as actual aerial controls and thus improving the results from AT adjustments.Using the image automatic correlation module, a DTM of the central part of the Vulcano was generated with a spacing of 5 meters. In Figure 7 preliminary results are displayed as spatial contour lines. Once the DTM will be completed and quality assessment performed to ensure 10-20 centimeters accuracy, an accurate geo-related data set will be available for comparisons with previously derived model. The DTM will be also used for the production with the Helava station of an ortoimage at a convenient scale.

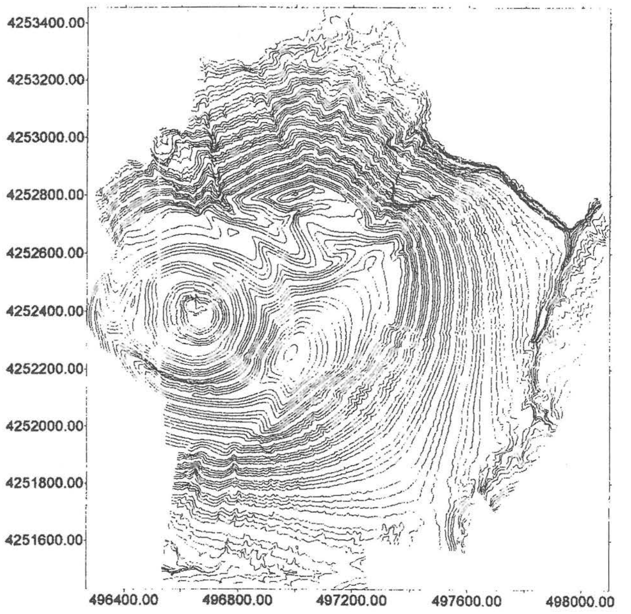

Figure 7 Contour lines from Helava DTM

Data processing with STEREOVIEW

Data processing and DTM generation were also carried out using the StereoView300 system (Menci,1996), a PC-based photogrammetry
workstation which uses standard hardware and Win95/NT operating system. The algorithms implemented in StereoView allow to manage greyscale or true-color images without using dedicated hardware. StereoView integrates a stereo viewing system that uses an infrared emitter and liquid crystal glasses.

StereoView adopts an area based digital matching algorithm; the user can select the correlation level between 0 and 1, depending on the accuracy the homologue points identification requested.

The systems was tested using a pair of images covering the central area of the volcan (0.238 km^2). Photographs were scanned at 1000 dpi by the scanner Nikon AX 210 with transparency unit corresponding to medium ground pixel dimension of 0.127 m. Images orientation was performed using GPS Ground Control by a Bundle Block Adjustment module; the results showed residuals of less than 10 cm on control points. The image matching procedure was performed using an area based algorithm with correlation level of 0.7 and a matching area of 26 x 26 pixels. The number of matched points resulted to be

9524. The required processing time from scanning to the DTM generation was of about 3 hours. Further analysis will be performed in order to evaluate the results.

Conclusions

Provided the accuracy of aerial photogrammetry is generally lower than geodetic surveys, the possibility of defining with high spatial resolution the strain field, make this technique very useful for monitoring strong deformation process of volcanic areas.

The data collected during the experiment conducted over the Vulcan Island, that is images at 1:5000 and 1:10000 scale and GPS kinematic camera positions, will allow to define the geometry of the calderic structure with an expected accuracy at the decimeter level.

Two different systems were experimented for processing digitized images and rapidly obtaining DTM of the area.

Acknowledgment

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