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An accurate digital elevation model (DEM) of Piton de la Fournaise (Réunion Island) summit area for the year 1997.

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Abstract. Using three aerial photo acquired in 1997, we produced a digital elevation model of the summit part of Piton de la Fournaise volcano (Reunion island). The DEM accuracy was assessed using several kinematic GPS profiles. Due to the method that was used to produce it, this 1997 D.E.M. has the following characteristics: no steps (due to a regular grid of points), accurate merging of the two sub-D.E.M. obtained from the two couples of images, precise knowledge of the vertical accuracy by using kinematic differential G.P.S. data.

Introduction.

Piton de la Fournaise volcano is located on the Reunion Island (France), 700 km East from Madagascar (Figure 1). This basaltic shield volcano is one of the most active oceanic volcanoes in the world, with more than 14 eruptions since 1990 and more than 100 eruptions in the last 300 years.

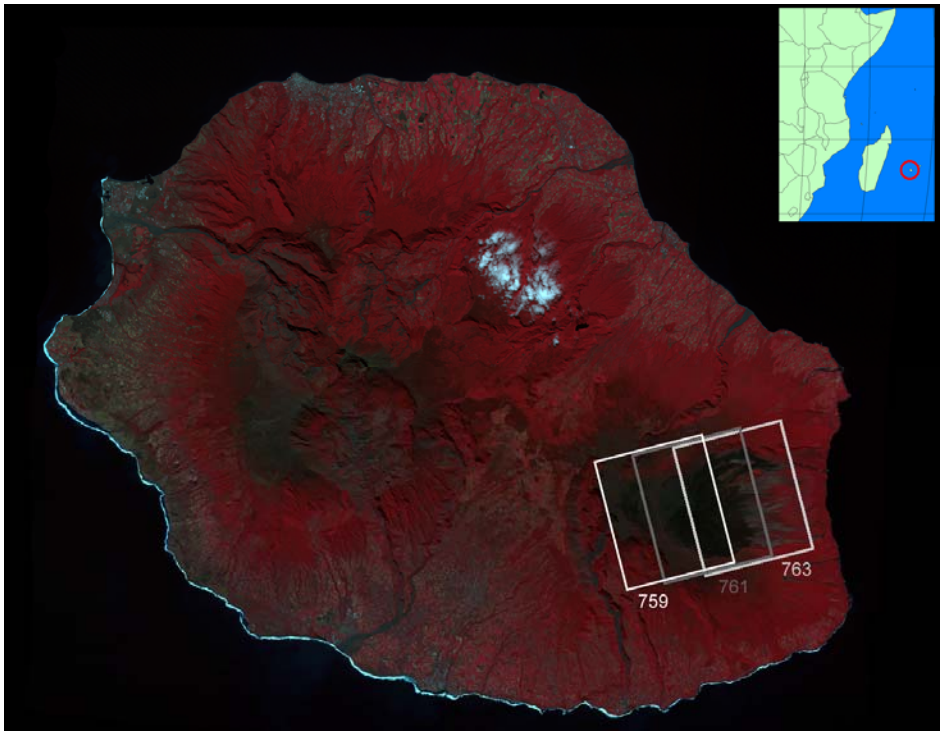

Figure 1: *Map of Piton de la Fournaise volcano with the location of the three images used in this study*

Several photogrammetric surveys were performed by the french Institut Géographique National (IGN) on the volcano between 1949 and 1997 (Table 1). Here, we present the Digital Elevation Model (D.E.M.) produced using three images acquired in july 1997 (campaign REU 119P). Our objective was to produce a DEM with enough accuracy to consider it as a reference for the year 1997 that corresponds to the end of a 6 years volcanic rest. In March 1998, the volcano resumed frequent eruptive activity.

Year	Mission name	Scale
1997	REU 119 C	1 : 30000
1997	REU 119 P	1 : 30000
1989	REU 112 C	1 : 20000
1989	REU 112 P	1 : 20000
1984	REU 111 C	1 : 25000
1984	REU 111 P	1 : 25000
1984	REU 112	1 : 25000
1978	REU 103 C	1 : 25000
1978	REU 103 P	1 : 25000
1966	REUNION 70	1 : 50000
1961	REUNION 6	1 : 25000
1950	REU 1	1 : 20000
1949	MAD 21	1 : 50000

Table 1: *List of photogrammetric surveys performed by the French Institut Géographique National (IGN) covering the Piton de la Fournaise volcano (La Réunion).*

Data.

The three aerial images at scale 1:30.000 (Figure 1) were scanned at a resolution of 1300 dpi. For the geo-coding we used six ground control points (red circles in Figure 2) measured in 1997 by differential GPS technique with an accuracy of ~2 centimetres (Table 2). We also used kinematic G.P.S. profiles to validate the DEM accuracy and increase it.

Name	X	Y	Z
BOR0	178621.641	36988.267	2578.640
1D40	179538.263	36881.158	2530.688
2D32	179948.622	37303.249	2493.885
1B20	176664.330	39589.855	2357.996
ENC0	175638.932	37341.804	2352.232
1B50	177640.351	33590.205	2280.343

Table 2: *Gauss-Laborde coordinates of six ground control points used for D.E.M. generation.*

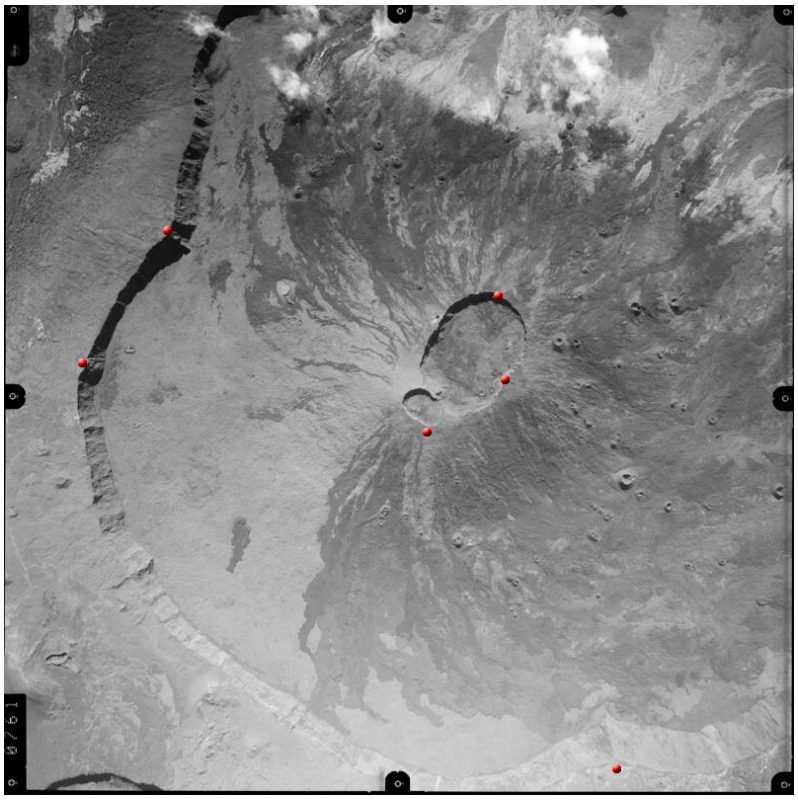

Figure 2: *1997 aerial image (reference 119 P761), with the location of the ground control points. Figure 1 shown a general location of this image.*

Data processing

The D.E.M. was produced using the stereo-photogrametric software Poivre (Poivilliers E, version 5-3.1) developed by the French Institut Géographique National (IGN) (Y. Egels, 2000). With the three available images, we created two pairs of stereo images.

The software Poivre was used, in manual mode, to obtain a series of x,y,z points belonging to the D.E.M on a regular 100 m grid. Additional points (~1000 points/km$^{2)}$ were added manually in particular areas like small cones and cliffs. We deduce a 10 m D.E.M. by gridding (using the krigging algorithm of Surfer 7, with a search ellipse radius of 200 m).

Using the 10m grid as reference search grid, a new automatic procedure of correlation with the stereo-photogrametric software is launched to obtain a regular 5 m grid.

To eliminate erroneous points, we use two selection criteria :

1. residual with the 10 m D.E.M. better than 5 m
2. correlation ratio : better than 60 %. Points with large errors in the automatic procedure were manually checked.

50 % of the points were deleted by this two criteria.

Using this method, two D.E.M. were obtained from the two different available stereo couples. To create a unique D.E.M. from the two available pieces, we performed a third order polynomial adjustment of the data belonging to the area common to both D.E.M.

The two corrected D.E.M. parts were transform in x,y,z points and introduced in Surfer 7 for krigging (ellipse radius 80 m). We obtain the final 10 m D.E.M. covering a 5 x 5 km area around the summit of Piton de la Fournaise volcano (Figure 3). The main characteristics of this 1997 D.E.M. are the following:
grid size 10m, 501 lines, 501 rows, Gauss-Laborde longitude range 176000-181000m, Gauss-Laborde latitude range 35000-40000m, elevation range 1744-2637m.

Accuracy assessment

During all steps of the D.E.M. generation, we estimated the horizontal and vertical accuracies and when possible tried to improve them. We calculated the elevation of 50 known differential GPS points (accuracy of the order of 2 centimetres). We found a vertical accuracy of ~3 meters of maximal error and ~1.6 meters of standard deviation.

Inside the 25 km² D.E.M. area, several kinematic G.P.S. profiles were measured between 1997 and 2001. The intrinsic vertical accuracy of kinematic G.P.S. has been shown to be of the order of 5 cm (Baldi et al., 2000) in the case of surveys performed carefully. Assuming that the available surveys for Piton de la Fournaise were performed with less care and that the rover antenna height is less well known, we estimate the accuracy of our G.P.S. profiles at 20 cm. Each file contain more than 10.000 points (Table 3).

File name	Day (1997)	First point E	First point N	Last point E	Last point N	Start hour	End hour
GCINEA97.325	325	176308.989	39318.248	176582.221	40092.982	06:54:46	11:50:18
GCINEA97.326	326	179301,886	37636,735	176311,835	39320,325	05:25:18	14:21:06
GCINEA97,330	330	179469,853	37677,624	176326,362	39329,455	05:09:18	14:59:24
GCINEA97.332	332	176317,723	39366,221	176317,351	39365,065	05:13:24	15:27:09
GCINEA97.334	334	179394,855	36750,295	176332,249	39328,229	04:53:09	14:10:12
GTOY1A97.332	332	175891,507	35600,402	177627,367	33618,133	08:42:42	10:24:00

Table 3 : *1997 Kinematic files, Piton de la Fournaise summit area.*

First, we reduced the global orientation of the D.E.M., to eliminate any possible rotation. For this, we calculated the 2D polynomial fit (third order) between the D.E.M. and two kinematic files covering a large part of it. We applied the correction to the D.E.M. on x and y axes and a vertical shift.

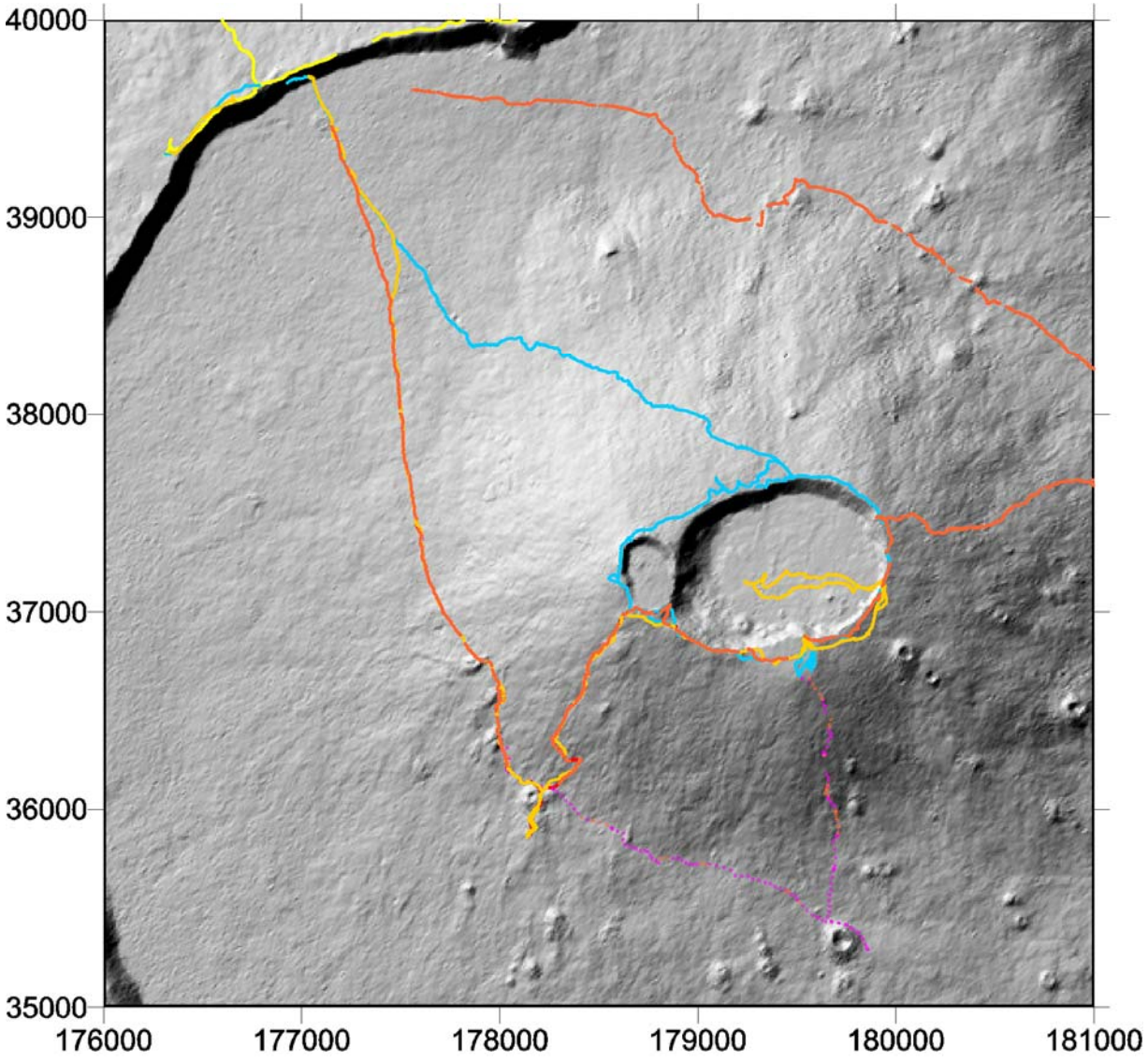

Figure 3: *Shaded DEM and kinematic GPS profiles on the volcano*

In a second time, we used four other kinematic files to calculate the vertical residual error. We find a standard deviation of ~1.5 m between the kinematic data and the D.E.M., with a maximal error of 3 m. The only area with an error larger to the maximum is in the cliff of Enclos Fouqué caldera (due to the horizontal accuracy of the D.E.M. an the most important error on G.P.S. measurement).

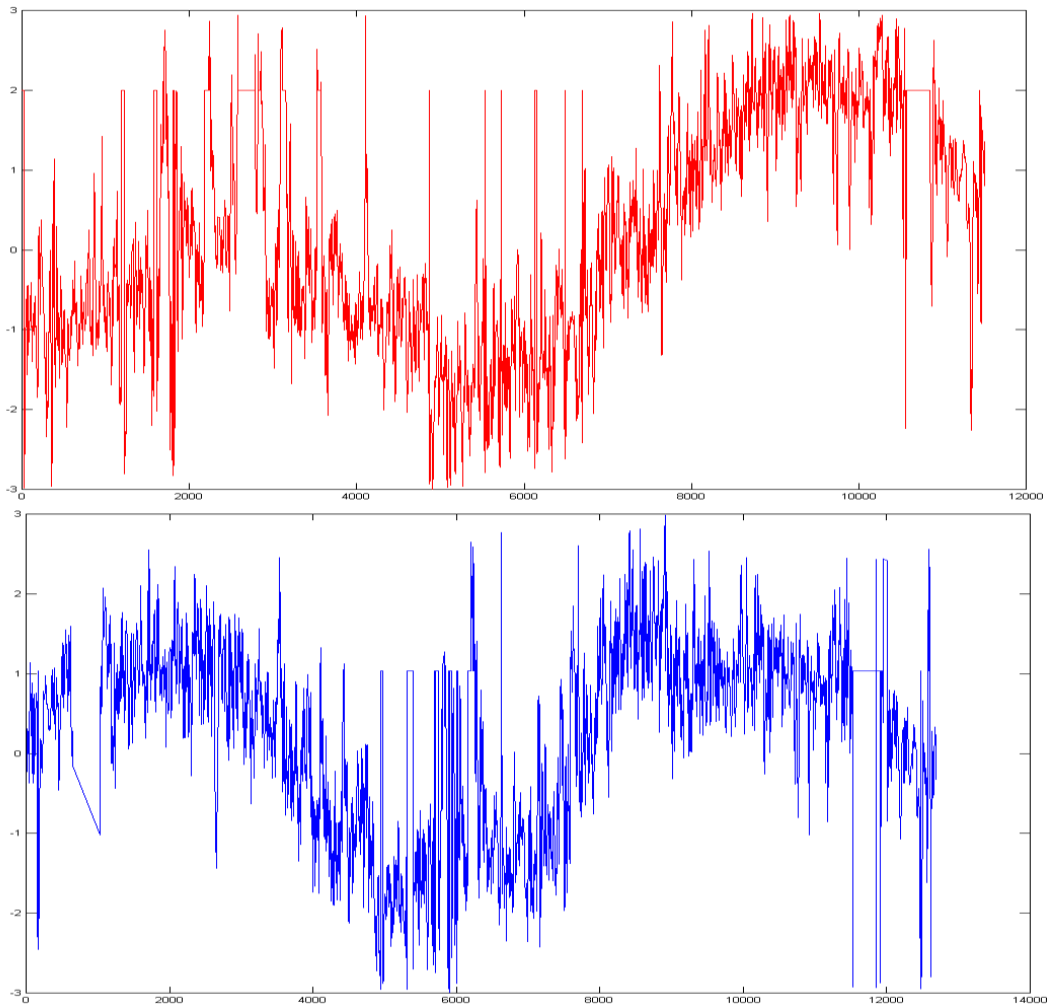

Figure 4: *Difference between D.E.M. and two kinematic G.P.S. profiles (without cliff areas).*

References.

Baldi P., S. Bonvalot, P. Briole and M. Marsella, Digital Photogrammetry and Kinematic GPS for Monitoring Volcanic Areas, Geophys. J. Int., 142, 801-811, 2000.

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