MemoVolc program

ESF - Short Visit Grant n°4851

Analysis of Doppler radar signals of Etna eruptions

Estelle Bonny

Laboratoire Magmas et Volcans, Université Blaise Pascal, Clermont-Ferrand, France

Hosted by the INGV Catania

15 days (22/04/2012-06/05/2012)

Supervisor: Franck Donnadieu

1. Purpose of the visit

A Doppler radar (VOLDORAD 2B: http://wwwobs.univ-bpclermont.fr/SO/televolc/voldorad/) was set up on Etna by the Observatoire de Physique du Globe in Clermont-Ferrand (OPGC) in 2009 and is used by INGV Catania to monitor eruptive activity at Etna's summit craters. The high activity of Etna, generating many ash plumes gives us a good opportunity to improve our understanding of the dynamics of ash plumes and quantify kinetic parameters and mass loading, in the context of a well instrumented volcano laboratory. In this context, we visited for 15 days our colleagues in Catania to carry out an analysis of the series of radar signals recorded in 2011-2012. In the mid-term, these investigations are expected to directly benefit both institutes, the INGV Catania for improving its monitoring of Etna, and the Laboratoire Magmas et Volcans – OPGC for improving the interpretation and quantification of radar signals.

2. Description of the work carried out during the visit

A. INGV plan during an eruption

During the first day, the tremor was going up and around 7pm, we went on Etna to see the activity which started with lava flows and followed by Strombolian activity with lava fountains (paroxysm at about 2am the 24). Thus, the next day, sampling of the deposits from the eruption of the NSEC was made, that is what the INGV do after every eruption. In the field, 13 samples were taken to estimate the spreading of the eruptive products (Fig. 1). We were able to confirm that the ash cloud spread out in

Figure 1: Sampling map of 24 April 2012 paroxysm.

the NE direction. It was meanly scoriae called sideromelano (yellow glass in thin section and no microcrystal visible in the groundmass). Associated with mapping, the INGV can later carry out measurements on the deposits to extract more information on the dynamics of the plume such as mass flux and ash dispersal.

B) Geophysical methods

Doppler radar principles and retrieved parameters

The radar installed on Mount Etna is a Volcanological Doppler Radar (Voldorad 2B) located at La Montagnola ≈3km South-East of the NSEC. This ground-based pulse radar records continuously using L-Band wave (23.5 cm) and is able to monitor all types of explosive activity (Donnadieu et al., 2009). The radar has an elevation angle of 15.5° and a beam angle of 9° (Fig. 2). Each pulse lasts 1 µs and the pulse is emitted every 100 µs which makes the radar gate 150m deep (c.dpulse/2 = 150m). Voldorad 2B is able to detect particles crossing the antenna beam in up to 11 gates ranging from 3135 m to 4635 m (these being slant distances from the radar) with G1 and G2 (at 3135 and 3285 m) being closer to the NSEC, as shown by the highest power recorded in these gates during all eruptions of NSEC.

Caracteristics	Symbole	Voldorad 2B
Transmitted frequency (MHz)	ft	1274
Peak power (W)	Pt	60
Wavelength (cm)	λ	23,5
Antenna beam elevation (deg)	θ	15,5
Antenna beam width (deg)	α	9
Antenna beam azimut (deg)		350
Pulse repetition period (µs)	tr	100
Pulse duration (µs)	τ	1
gate width (m)	L	150
thermal camera elevation angle (deg)	15	
thermal camera fov (deg)	18,8° (v) - 25° (h)	

Figure 2: Characteristics of radar Voldorad 2B created by OPGC and recording continuously Mount Etna activity since 2009.

INGV-Catania receives the radar signal in their operations room which is permanently occupied (by continuous 8 hours shifts). A real time monitoring alert message is automatically sent by email at the beginning and the end of the eruptive signal (Fig. 3).

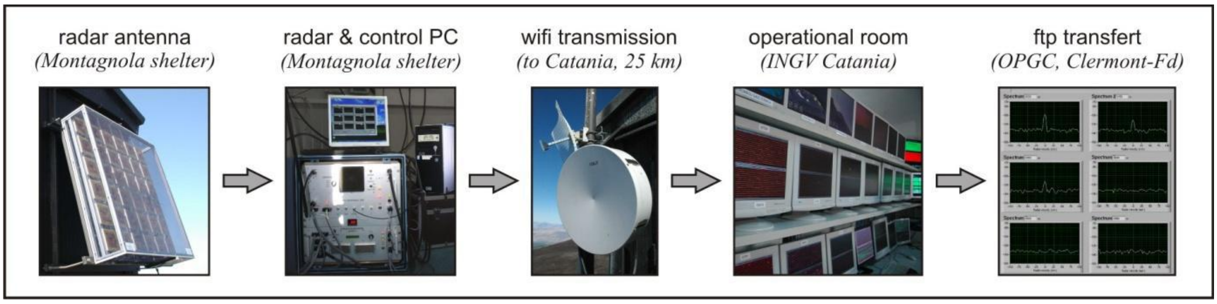

Figure 3: Operational diagram illustrating the successive steps the radar data goes through. The radar antenna (without its radome here), located on Etna's southern flank (La Montagnola), transmits an electromagnetic wave and receives the echoes backscattered by the particles in the beam. The radar then amplifies, filters, and digitizes the received signal, which appears in real-time as Doppler spectra on the control PC in the shelter. Data are stored on a server in the shelter. From there the data is transmitted by WIFI to INGV's operational room in Catania (Sicily). At last, they are transferred to the OPGC (Clermont-Ferrand, France) by FTP, and displayed every 2 min on its website (http://wwwobs.univbpclermont.fr/SO/televolc/voldorad/TRetna.php). Modified from Valade 2012.

Thermal videos

One visible (EMOV) and one thermal (EMOT) camera are located in the same shelter as the radar at La Montagnola. The camera network on Mount Etna uses both thermal and visible cameras and allows continuous, real-time ground-based imaging of the volcano activity every 1-2 sec [e.g., Andò and Pecora, 2006; Behncke et al., 2006, 2009]. The elevation angle of the thermal camera is 15° and it has a field of view (FOV) of 25° horizontally whereas the horizontal FOV of the visible camera can change between 3° and 47.5° depending on the optical zoom applied (Calvari et al., 2011).

Volcanic tremor and infrasound

Volcanic tremor can be defined as a persistent seismic signal that is observed only near active volcanoes, lasting from several minutes to several days, preceding and/or accompanying most volcanic eruptions (Fehler, 1983; Julian, 1994; Ripepe, 1996; Metaxian et al., 1997). At Mount Etna, the EBEL station (about 1 km East of NSEC) records the volcanic tremor which is shown every minute and was used to compare with radar signals. After Konstantinou and Schlindwein (2002), the driving mechanism for tremor seems to involve complex interactions of magmatic fluids with the surrounding bedrock. The study of the volcanic tremor can deduce the location of the source of activity. In the case of Etna, it is common in the scientific literature to use a tremor filtered between 0.5 and 5 Hz because this is where the power of the spectrum is concentrated for this volcano. The volcanic tremor given by INGV-Catania was processed by Root Mean Square (RMS).

C) Case study of the 12/01/11 eruption

Radar geometry and precise radar beam location

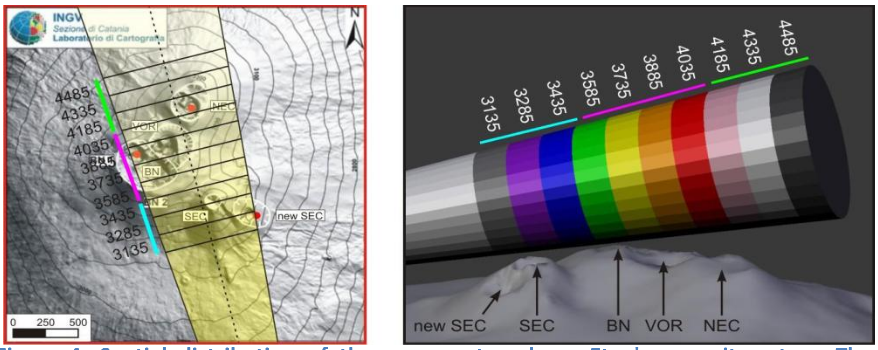

Figure 4: Spatial distribution of the range gates above Etna's summit craters. The colored segments highlight the possible gate groups which could be defined to monitor specific eruptive vents: cyan for the new Southeast Crater (SEC), magenta for the Bocca Nova (BN) and Voragine (VOR) craters, and green for the Northeast crater (NEC). Valade S. thesis 2012.

The radar is located at an altitude of 2610m, 602m below the summit of the NSEC, and the antenna beam points in between the BN and SEC craters (Fig. 4). To better constrain the real position of the radar beam bottom above the craters, we used thermal videos from short-lived eruption of Bocca Nuova on 25 August 2010 because the plume front ascent and penetration in the beam could be clearly observed. We determined the lower limit of the beam from the position of the plume front on the thermal images at the onset of the radar echoes in the main range gate at 3735 m at 13:09:12 UTC. Thermal videos of the first paroxysms on the 12 January 2011 were also available and allowed us to constrain the oriental limit of the radar beam. We used the scale given by Calvari et al. (2011) on images from the 12/01/11 eruption to locate the conical beam for the first gate at 3135m and the 5th gate at 3735m

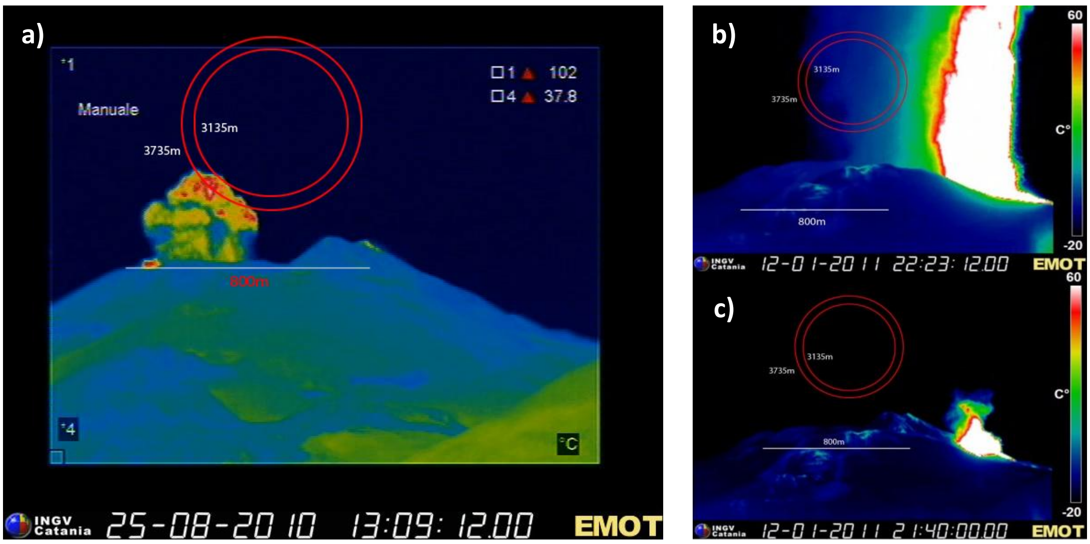

Figure 5: Thermal images at La Montagnola with the location of the radar beam in red circles (588m in diameter for G1 and 500m for G2). a) 25/08/10 Bocca Nuova eruption; b and c) 12/01/11 eruption of the NSEC. Courtesy of INGV-Catania

with a diameter of 500m and 590m respectively. One image at 21:40:00, where the radar began to detect the paroxysm with the SE crater still visible for scale, and one image at 22:23:12 UTC, during the climax of eruption with fountains entering the radar beam, were used to do that (Fig. 5b and c).

Description of the 1st paroxysm

The 11-13 January 2011 eruption initiated a long series of paroxysms (25 as of May 2012) of the NSEC. It is thus important to look at it first to understand the main dynamics of this type of eruption and the associated radar signature. The eruptive episode started on 11 January with weak Strombolian activity inside the pit crater. This intensified on 12 January, and culminated during the night of 12-13 January with lava fountains 300-800 m high and an ash plume 4 km in height (Calvari et al., 2011). The ash plume was blown towards the south and rose at least 4000 m above the summit of Etna, which caused disruption of air traffic and closure of Catania's international airport during several hours. After 21:15 explosions became almost continuous, suggesting, according to Calvari et al. (2011), a shift from Strombolian to a transitional eruptive style [e.g., Parfitt, 2004; Spampinato et al., 2008]. At about 21:50, spattering from the pit crater became steady and the emission style evolved to fountaining. Around midnight, the eruptive activity returned to Strombolian style. The end of the eruptive episode took place around 13:00 UTC (all times are UTC) on 13 January [see Calvari et al. (2011) for more details on the chronology of the eruption].

Voldorad 2B started recording a signal related to the eruption at 21:40 on 12 January. This ended at 23:40 (Fig. 6). It was able to detect the ash plume mainly in the gates at 3135 m and 3285 m, and up to 5 range gates (between 3135 m and 3735 m) during the peak of power between 22:20 and 22:30 (F.Donnadieu- OPGC report). This paroxysm can be divided into three parts: the waxing phase, the paroxysm and the waning phase. i) The waxing phase where the signal increases strongly from 21:40 to 21:50; ii) The paroxysmal phase, associated with lava fountain activity (Andronico et al., 2012 in review), was recorded at about 21:50 and lasted about an hour and a half. Plateau-like average values started at 21:56 lasted until 23:08 when P3135 and P3285 had constant average values (-107 and -114 dBm, respectively) despite large (10 dB) oscillations. The signal declined slowly between 23:13 and 23:21 which marked the end of the paroxysm; iii) The waning phase when the signal dropped dramatically and abruptly at 23:21 by nearly 10 dB. Only a single, narrow jet of fluid lava raised no more than 100 high with weak echoes only at 3135 m continuing until 23:40.
During the paroxysm, a maximum peak is seen at 22:22 (only one is distinguished), where the

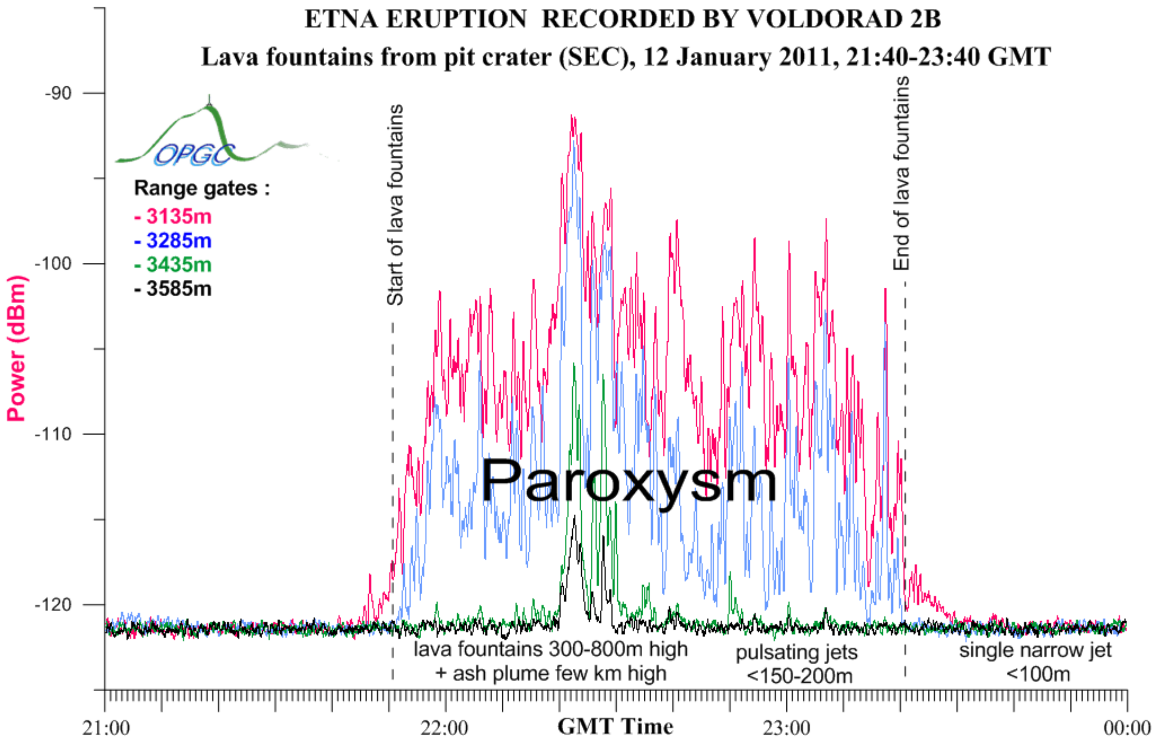

Figure 6: Radar power time series of the 1st eruptive episode of a new pit crater at Mt Etna on the 12th January 2011.

velocity increased suddenly to 70m/s and the power from -107 dBm in average to -90 dBm (log units) which means an increase of +15 dBm (i.e. +30 dBm above noise level).

3. Description of the main results obtained

A) Qualitative interpretation of January 12 2011

The backscattered power is a complex function of the number and size of particles crossing the radar beam through their absorption and diffusion properties (e.g. Gouhier and Donnadieu, 2010). However, the echo power is a good proxy of the amount of material in the beam. Maximum radial velocities give the highest along-beam velocity recorded in the interior of the plume. The discrimination between positive (P+, V+max) and negative (P-, V-max) parameters also gives information about the axial (1D) component of the tephra trajectories (away or towards the antenna respectively). Thus, comparing P+/P-, V+max/V-max and their evolution through the different range gates give insight into the ash plume dynamics, kinetics, and extension. To interpret these radar

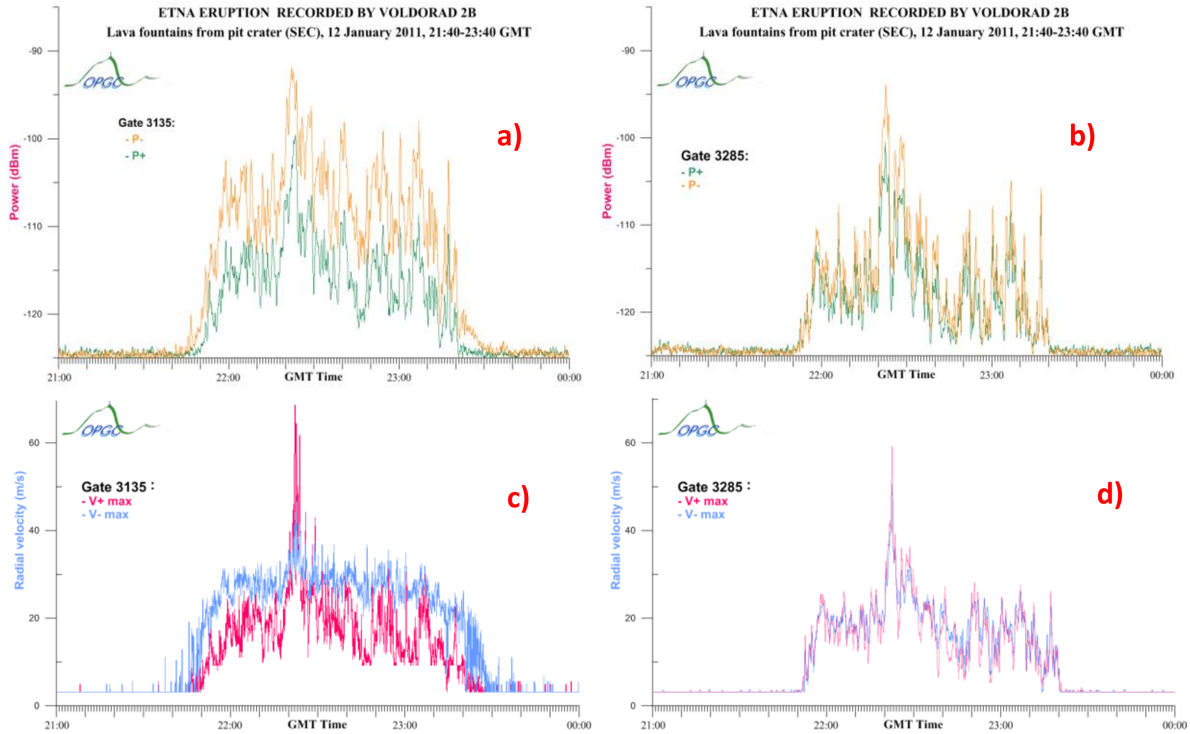

Figure 7: Radar time series of power and velocity of January 12 2011 eruption of the NSEC. a) Power at 3135m b) power at 3285m c) radial velocity at 3135m d) radial velocity at 3285m

power and velocity time series, we distinguished: 1) the maximum peak (high power and velocities in 4 range gates); from 2) the rest of the signal with notably lower value of power and velocities (in only 2 gates, the extension of the plume is less important at the beam elevation). These two behaviors are different and thus required two different interpretations.

1) Looking at all the gates together, we can see that the maximum for P+ (-100dBm) and P- (-90dBm) is for G1 which leads us to say that the pit crater is located at the distance of the first gate. For G2 (3285m) and G3 (3435m), P- and P+ have similar values but some peaks are higher for P- because we have more particles going towards the radar. In G4 (3585m), P- begins to be higher than P+. Beyond those 4 gates very little to no power is detected, hence a maximal extension of the emissions through the beam (N-S) of 600m during the peak (Fig. 11). During the paroxysm, P3135 dominated by P- by an order of magnitude (i.e. P- = 10× P+) and V-max3135 was surprisingly constant at 30 m/s (Fig. 7a and c). This is an argument for fallout from the plume, confirmed by videos because no blocks falling from the fountain can

be seen in the east side, only on the west side (Fig. 8). Those particles from plume fallout are relatively cold and buoyant (no incandescent bombs). The oscillations might be due to change of direction of the jet axis or intermittent bubbles bursting. In the first gate, V-max is always higher than V+max. The average velocity is quite stable around 20 m/s for V+max and 30 m/s for V-max. The wind did not have a high influence on the fountaining direction because it was blowing south at about 8 m/s (from soundings at Trapani on 13/01/11 at midnight). Furthermore, in G2 (3285m) and G3 (3435m) V+max and V-max are really well correlated. Finally, at G4 (3585m) V-max is higher than V+max where the wind could have affect the direction of the lapilli falling from the plume towards the South where the radar is.

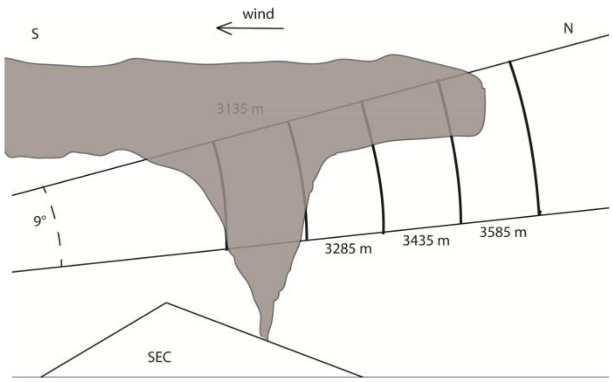

Figure 8: Schematic view of the spatial relationship between the ash plume and the radar beam.

2) Detailed analysis of the thermal videos between 22:20 and 22:30 allowed us to see some interesting features. For instance, a translation of the lava fountain towards the west is visible on the thermal videos at about 22:20:30. The highest peaks of power are found at about 22:22:20 and 22:22:45 in the radar data but it is not clear in the thermal videos why it occurred at those times. However, it is mainly true that we have high radar power when the fountain is strong and thick (22:23) and low when the fountain is small and thin (22:25:10). Furthermore, some peaks in the radar time series can be distinguished with the thermal videos. It corresponds to bubbles rising and bursting that we can see in the videos with a characteristic mushroom shape for example at 22:16:45. We can hypothesize that some peaks in the radar are related to bubble bursting and produced these cycles. During this peak, V+max undergoes a sharp increase from about 20 m/s to reach 70 m/s in a few minutes and only an increase of 10 m/s for V-max. However, the maximum radial velocity occurs at the same time of the power peak and it shows that particles erupted by the lava fountain were more directed away from the radar because of the soundings geometry (particles ejected by the fountain have vertical trajectories, at about 70° from horizontal, but we have to correct for the 15° of elevation). Thus, the highest amount of ballistic emission from the fountains is detected with positive value.

B) Tremor-radar correlation

A plot of the tremor, infrasound and radar data was made to see if we could find a relationship between surface and seismic measurements (Fig. 9). Because of the different temporal resolution between the data sets (only 1 min for the tremor and a temporal resolution of 0.1 sec for the radar) it is hard to quantify a relation but in general, we can see a good correlation between them. The radar data were smoothed (51-point running average) to better see the relation. At the beginning of the episode, a peak in the volcanic tremor can be seen about 5 minutes before that witnessed in the radar data. After 22:05, the two graphs follow the same trend with large

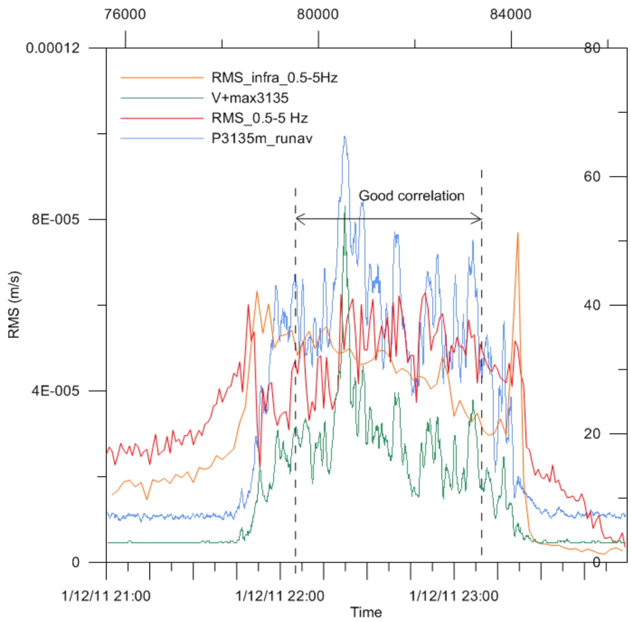

Figure 9: Plot of the volcanic tremor, the power and V+max of the first gate. See caption in top right.

peaks at the same time. Thus, tremor and radar signals are almost synchronized. This time interval where we have a good relationship starts 15 minutes after the beginning of the paroxysm and ends 11 minutes after its end. After 23:10, the two signals are out of phase again, with the radar being about 2 minutes behind the volcanic tremor. However, we can notice that the volcanic tremor began to slowly increase during the night of 11-12 January (INGV-report) or about 20 hours before the radar detection but was back to background level at 00:30 on 13 January (50 min after the end of the radar detection).

C) Compilation of eruptions data of Etna's New SE Crater since 12/01/2011

Twenty-five eruptions were recorded by VOLDORAD 2B since the beginning of the new eruptive phase of the NSEC. I try to compile the following eruption parameters: the paroxysm duration, the maximum power and radial velocity, and the wind direction (Fig. 10). With this table, and looking at all the time series, we can say that four lava fountain episodes were detected by VOLDORAD2B (those of 12/01/11, 28/09/11, 15/11/11 and 05/01/12).They had the highest power detected and a sharp increase in the radial velocity of the first or second gate. To classify all these eruptions, a graph

Date	Repos	Start c	End det	Paroxism pha	Paroxy	Tini d	wanin	Max ra	Max po	deltaP	time o	gates	Lava fount	wind d	wind st	V+max/V-max
24/04/2012	11,5	01:05	02:25	01:35-02:15	40	30	10	60	-105	16	01:55	11		NE/ E	9	60/30
12/04/2012	10,5	13:46	15:20	14:32-15:10	38	62	10	60	-100	21	14:30	6		E	20	60(3285m)/40(3135m)
01/04/2012	14	01:55	03:40	02:41-03:35	54	46	5	34	-102	19	02:45	4		E	13	34(3285m)/30(3135m)
18/03/2012	14	07:30	10:05	08:25-09:40	75	55	25	30	-108	13	08:45	4		E	2	35(3285m)/28(3135m)
04/03/2012	23	07:20	09:32	07:30-09:30	120	10	2	40	-105	16	08:52	4		NE	26	40(3285m)/30(3135m)
09/02/2012	35	00:50	06:30	01:00-06:00	300	10	30	30	-108	13	02:35	2		W/SW	16	30(3285m)/20(3135m)
05/01/2012	50	05:00	06:55	05:45-06:45	60	45	10	53	-90	31	06:10	6	100-150m	SE	17	53(3285m)/42(3285m)
15/11/2011	23	11:00	12:45	11:20-12:25	65	20	20	55	-95	26	11:55	4	800m	SE	2	55(3285m)/38(3285m)
23/10/2011	15	18:30	21:10	18:45-20:15	90	15	55	36	-105	16	19:25	3	300m	SE	19	36(3285m)/25(3135m)
08/10/2011	10	14:10	15:20	14:45-15:10	25	35	10	40	-103	18	14:58	4		E	23	40(3285m)/35(3135m)
28/09/2011	9,5	18:50	20:05	19:33-19:55	22	43	10	65	-90	31	19:35	5	600-800m	SW	15	65/50(3135m)
19/09/2011	11	11:50	13:30	12:30-12:50	20	40	40	35	-104,5	17	12:36	3		E	49	35(3285m)/25(3135m)
08/09/2011	10	06:50	08:30	07:31-08:17	46	41	13	36	-98	23	09:05	3		S	18	35(3285m)/36(3135m)
29/08/2011	9	03:50	05:10	04:10-04:45	35	20	25	27	-103	18	04:42	6		SE	10	42(3285m)/25(3135m)
20/08/2011	8	06:55	07:50	07:10-07:35	25	15	15	43	-94	27	07:28	4	sev m	S	5	43(3135m)/37(3285m)
12/08/2011	7	08:25	10:17	08:50-10:05	117	25	12	26	-105	16	08:30	4		SE	7	22/26(3135m)
05/08/2011	6	21:30	23:20	21:55-23:10	75	25	10	35	-97,5	24	22:08	4		SE	10	28/35(3135m)
30/07/2011	5	18:50	21:30	19:35-21:15	100	45	15	32	-105	16	19:38	3	450-500m	E	28	26/32(3135m)
25/07/2011	6	03:00	06:20	04:00-05:30	90	60	50	25	-110	11	04:10	3		E	50	29(3285m)/26(3135m)
19/07/2011	9,5			00:00-02:30	150								200-250m	E	35	no data
09/07/2011	58	13:49	15:20	14:03-15:14	71	14	6	40	-98	23	14:35	4		SE	16	38/40(3135m)
12/05/2011	30	00:00	04:00	01:50-03:20	90	110	40	38	-95	26	02:35	4		S	32	38(3135m)/30(3285m)
10/04/2011	51	09:10	13:20	10:48-12:37	109	98	47	35	-100	21	10:50	3		NW	5	35(3285m)/28(3135m)
18/02/2011	36	06:40	13:30	07:20-10:50	210	40	160	31	-102	19	08:30	4		S	28	31(3285m)/25(3135m)
12/01/2011		21:40	23:40	21:50-23:21	91	10	19	70	-90	31	22:22	5	300-800	S	16	70(3135m)/65(3285m)

Figure 10: General parameters extracted for all the eruption from the radar data, wind information and reports of OPGC and INGV.

of the power or velocity (using the gate with maximum values) against a common time scale where made. The first gate at 3135 m was used for almost all eruptions except from the 24/04/12 and 29/08/11 episodes where we had more power in the 3285 m gate. We could differentiate them into three different durations: long duration (above 2 hours), short duration (less than 1 hour), and in between; and two characteristics shapes: triangular or top-hat shaped. Moreover, all eruptions were detected between 2 and 6 gates apart from the last paroxysm of the 24/04/12. This can be explained by a strong wind (although the Trapani sounding gave only 18 m/s) blowing to the North-East for the lower portion of the plume. The wind direction is therefore really important to better interpret the radar data. More precise data could help to quantify the real effect of the wind on radar detection an especially on the particle velocity.

Using field data on fallout properties (grain size distribution, density etc) acquired in the frame of the ongoing TERMEX program of CNRS, we will then be able to quantify kinetic and mass loading parameters of the series of ash plumes (Donnadieu et al., 2005, 2012; Gouhier & Donnadieu 2008, 2011).

4. Future collaboration with host institution

My work at INGV-CT strengthens the ongoing collaboration with INGV Catania (research agreement INGV-CT - OPGC - CNRS) on the use of the OPGC Doppler radar at Etna (VOLDORAD 2B) for both monitoring and scientific investigations. It resulted in a description and interpretation of the radar signals from the first event of the series of lava fountain episodes occurred in 2011-2012 at the new SE Crater and opens the way to better understand the dynamics and quantify the emitted products of all events. This visit was very useful and undoubtedly enhanced the work capacity and communication of our group at OPGC-INGV and should lead quickly to publications.

5. Projected publications / articles resulting or to result from the grant

One publication is in preparation of the Etna's activity in 2010. At least one radar-focused publication is expected from the analysis of the series of events in 2011-2012. Co-authored publications are also expected from collaborative multi-method studies led by INGV-CT and integrating radar data. ESF will be duly acknowledged in all publications and communications.

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References

Donnadieu et al., 2009 ; Valade.S thesis, 2012; Andò and Pecora, 2006; Behncke et al., 2006, 2009; Calvari et al., 2011; Fehler, 1983; Julian, 1994; Ripepe, 1996; Metaxian et al., 1997; Konstantinou and Schlindwein, 2002; Parfitt, 2004; Spampinato et al., 2008; F.Donnadieu- OPGC report, http://wwwobs.univ-bpclermont.fr/SO/televolc/voldorad/; Andronico et al., 2012 in review; Gouhier and Donnadieu, 2010; INGV-report, http://www.ct.ingv.it/; Donnadieu et al., 2005, 2012; Gouhier & Donnadieu 2008, 2011.