GLOBVOLCANO: EARTH OBSERVATION SERVICES FOR GLOBAL MONITORING OF ACTIVE VOLCANOES

S. Borgström(1), M. Bianchi(2), W. Bronson(3), M.L. Tampellini(4), R. Ratti(4), F.M. Seifert(5), J. C. Komorowski(6), E. Kaminski(6), A. Peltier(6), P. Van der Voet(7)

(1) Istituto Nazionale di Geofisica e Vulcanologia - Osservatorio Vesuviano - Via Diocleziano, 328 - 80124 Napoli, Italy, Email: sven@ov.ingv.it
(2) Tele-Rilevamento Europa - T.R.E. srl - Via Vittoria Colonna, 7 - 20149 Milano – Italy - Email: marco.bianchi@treuropa.com
(3) MDA Geospatial Services - 57 Auriga Drive, Suite 201 Ottawa, Ontario K2E 8B2 Canada - Email: wbranson@mdacorporation.com
(4) Carlo Gavazzi Space S.p.A. - Via Gallarate 150 – 20151 Milano, Italy - Email: ltampellini@cgspace.it, rratti@cgspace.it
(5) European Space Agency – ESRIN - Via Galileo Galilei, 64 – 00044 Frascati (Roma), Italy – Email: frank.martin.seifert@esa.int
(6) Institut de Physique du Globe de Paris - 4, Place Jussieu, B89, 75252 Cedex 05, Paris France - Email: komorow@ipgp.jussieu.fr, kaminski@ipgp.jussieu.fr, peltier@ipgp.jussieu.fr
(7) TerraSphere Imaging & GIS B.V - Keizersgracht 114 1015 CV Amsterdam The Netherlands - Email: paul@terrasphere.nl

ABSTRACT

The GlobVolcano project (2007-2010) is part of the Data User Element (DUE) programme of the European Space Agency (ESA).

The objective of the project is to demonstrate EO-based (Earth Observation) services able to support the Volcano Observatories and other mandate users (Civil Protection, volcano scientific community) in their monitoring activities.

The set of offered EO based information products is the following:
- Deformation Mapping
- Surface Thermal Anomalies
- Volcanic Gas Emission
- Volcanic Ash Tracking

The Deformation Mapping service is performed exploiting either PSInSAR™ or Conventional DInSAR (EarthView® InSAR). The processing approach is selected according to the availability of SAR data and users’ requests.

The information services are assessed in close cooperation with the user organizations for different types of volcano, from various geographical areas in various climatic zones. Users are directly and actively involved in the validation of the Earth Observation products, by comparing them with ground data available at each site.

In a first phase, the GlobVolcano Information System was designed, implemented and validated, involving a limited number of test areas and respective user organizations (Colima in Mexico, Merapi in Indonesia, Soufrière Hills in Montserrat Island, Piton de la Fournaise in La Réunion Island, Karthala in Comore Islands, Stromboli and Volcano in Italy). In particular Deformation Mapping results obtained for Piton de la Fournaise were compared with deformation rates measured by the volcano observatory using GPS stations and tiltmeters. IPGP (Institut de Physique du Globe de Paris) is responsible for the validation activities.

The second phase of the project (currently on-going) concerns the service provision on pre-operational basis. Fifteen volcanic sites located in four continents are monitored and as many user organizations are involved and cooperating with the project team.

In addition to the proprietary tools mentioned before, in phase two also the ROI_PAC software will be tested for PALSAR processing on the Arenal volcano (Costa Rica).

The GlobVolcano Information System includes two main elements:
- The GlobVolcano Data Processing System, which consists of EO data processing subsystems located at each respective service centre.
- The GlobVolcano Information Service, which is the provision infrastructure, including three elements: GlobVolcano Products Archives, GlobVolcano Metadata Catalogue, GlobVolcano User Interface (GVUI).

The GlobVolcano Information System represents a significant step ahead towards the implementation of an operational, global observatory of volcanoes by a synergetic use of data from currently available Earth Observation satellites.
1. **GLOBVOLCANO DATA PROCESSING SYSTEM**

The GlobVolcano Data Processing System is devoted to EO (Earth Observation) data processing and GlobVolcano products generation. It consists of seven data processing sub-systems based on existing and mature processing techniques.

### 1.1. Deformation Mapping Service

The Deformation Mapping Service is useful in order to analyze and understand the geophysical mechanisms governing the volcanic system and its dynamic characteristics.

Two different processing approaches are adopted in order to provide both global and detailed monitoring of the area of interest: Conventional DInSAR (Differential Synthetic Aperture Radar Interferometry) and PSInSAR™ (Permanent Scatterers Synthetic Aperture Radar Interferometry). Both processing approaches exploit Envisat ASAR data in order to generate GlobVolcano products.

The use of Conventional DInSAR approach allows increasing temporal resolution of deformation mapping products when the alert level increase by exploiting capability of ASAR sensor to image an area with different geometry. Furthermore, DInSAR analysis is advantageous for the detection of fast deformation, since it can supply users with interferograms providing useful information at least for a first qualitative analysis.

On the other hand, PSInSAR™ exploits a point-wise approach and provides high accurate deformation estimation (Atmospheric Phase Screen estimation and removal) for a set radar targets exhibiting a coherence level constant in time, called Permanent Scatterers.

- Conventional DInSAR provides accurate deformation estimates of wide areas. This service is useful when an high temporal resolution is required (e.g. in case of alert level escalation). The software tool EarthView® InSAR (MDA Inc.) is adopted in order to implement this service. The convetional DInSAR Service is located at MDA Inc. (Canada).

- PSInSAR™ allows the monitoring of the temporal evolution of the deformation over long time period. The measurements points identified over the area of interest can be considered a sort of “natural geodetic network”. The deformation of each point is measured with a millimetre accuracy. PSInSAR™ Service is located at T.R.E. (Italy).

In addition to the tools mentioned above:

- The processing of ALOS PALSAR data available on Arenal volcano (Costa Rica) is currently on-going exploiting the ROI_PAC software. A preliminary DInSAR analysis has been carried out exploiting ASAR data. This study has shown the limits of C-band data due to the vegetation coverage over the area of interest. Thus the choice to carried out a further analysis using L-band PALSAR data, less affected by vegetation.

- The Coherent Target Monitoring (CTM) processing approach has been applied over Cumbre Viejea (La Palma).

### 1.2. Surface Thermal Anomalies Service

The Surface thermal Anomalies Service is based on the synergetic use of:

- High spatial resolution satellite data acquired over long revisit intervals by ASTER (onboard TERRA), and HRVIR or HRGT (onboard SPOT-4 and -5).
- Low spatial resolution satellite data acquired with daily frequency by MODIS (onboard TERRA and AQUA).

The combined use of the above instruments allows to increase the frequency of observation and the level of detail. Suitable EO data and processing methodology depend also on heat intensity and the size of the thermal volcanic anomaly. In fact the choice of the EO-data and the processing methodology is a function of the eruptive style, the volcano dynamics and the expected/observed thermal anomaly associated.

- TERRA ASTER data acquired before April 2008 allows dealing with both high (i.e. summit crater activity, active lava flows, lava lakes, lava fountains, lava domes) and low temperature (i.e. pyroclastic flows and lava flow cooling, crater lakes, low-temperature fumarolic fields) surface anomalies, whereas data acquired after April 2008 allows dealing with low temperature anomalies only.
- SPOT-4/5 (HRVIR / HRGT) data allows dealing with high temperature surface anomalies (i.e. active lava flows and lava lakes).
- TERRA/AQUA MODIS data allows dealing with high temperature surface anomalies (i.e. summit crater activity, active lava flows, lava lake, lava fountains, lava dome).

Two software tools are adopted for the implementation of the service:

- MyVOL (IESConsulting): high spatial resolution surface thermal anomalies.
- MyMOD (IESConsulting): low-spatial resolution/high-temporal resolution surface thermal anomalies.

### 1.3. Volcanic Gas Emission (SO₂) Service

The Volcanic Gas Emission (SO₂) Service is provided to the users by a link to GSE-PROMOTE – Support to Aviation Control Service (SACS). The aim of the service is to deliver in near-real-time data derived from satellite measurements regarding SO₂ emissions possibly related to volcanic eruptions. Global observations of SO₂ derived from satellite measurements in near-real-time may provide useful
complementary information to assess possible impacts of volcanic eruptions on public safety. Furthermore, the monitoring of ∑O² volcanic emission is useful in the frame of early warning, as eruption precursor. The service is focused on the timely delivery of ∑O² data derived from different satellite instruments, such as SCIAMACHY, OMI and GOME-2. The exploitation of these instruments allows the generation of three different kinds of products:
- ∑O² Notification: exceptional ∑O² concentration is automatically notified via e-mail to subscribed users.
- Near Real Time: ∑O² vertical column density (Dobson Unit - DU) available within 3-6 hours after measurements.
- Archive: global maps are usually available about 2 weeks after the end of the months and generated by reprocessing monthly acquisitions.

The Volcanic Gas Emission (∑O²) is located at: BIRA IASB Belgium (SCIAMACHY data), KNMI The Netherlands (OMI data) and DLR IMF German (GOME 2 data).

1.4.1.4. Volcanic Ash Tracking Service

The Volcanic Ash Tracking Service is provided to the users by a link to GSE-PROMOTE – Support to Aviation Control Service (SACS). The aim of the service is to track the ash injected into the atmosphere during a volcanic eruption. The tracking of volcanic ash is accomplished by using SEVIRI-MSG data and in particular the following channels VIS 0.6 and IR 3.9, and along with IR8.7, IR 10.8 and IR 12.0. This service takes advantage of the MSG SEVIRI Scan cycle (15 minutes). Thus the provided product is an animated temporal sequence (i.e. animated GIF). The temporal resolution of the sequence is, at best, 15 minutes. The Volcanic Ash Tracking Service is located at CGS, Italy.

2. GLOBVOLCANO INFORMATION SERVICE AND USER INTERFACE

The GlobVolcano Information Service is the product provision infrastructure of the GlobVolcano Information System and includes the following elements:
- GlobVolcano Products Archives,
- GlobVolcano Metadata Catalogue and
- GlobVolcano User Interface (GVUI).

GlobVolcano Products Archives store GlobVolcano products generated over the areas of interest during the project. Each GlobVolcano products archive offers two main functionalities: WMS (Web Map Service) for products visualization through the GVUI and products delivery / downloading.

The GlobVolcano Metadata Catalogue stores metadata related to each GlobVolcano product available in the product archives. The GlobVolcano Metadata Catalogue offers CS-W (Catalogue Service for Web) functionality to store and query metadata of geographic datasets in a catalogue.

The GlobVolcano User Interface is the front end for the user and it uses the Virtual Earth platform as its base. Microsoft Virtual Earth is a map viewer application running in any browser.

The GVUI offers the following functionalities:
- Geographic area selection and visualization
- Metadata search and visualization
- User Login
- Products search
- Products selection and visualization
- Products selection and delivery (download)

Two different access points are distinguished:
- Private User Interface for registered users, and
- Public user Interface for not registered users.

All the above functionalities are available for registered users, whereas only a subset of functionalities is available for not registered users (i.e. geographic area selection and visualization, Metadata search and visualization).

Besides these functionalities, the GVUI offers the basic Virtual Erath functionalities, such as zooming, panning, base layer selection (satellite aerial image, road map or both), 2D and 3D view.

Fig. 1 shows an example of products visualization exploiting the GlobVolcano User Interface and the 3D view. The pictures reports a deformation mapping product generated over Piton the la Fournaise (La Reunion).

![Figure 1. GVUI - Example of deformation mapping product visualisation exploiting the 3D view. Area of interest: Piton de la Fournaise, La Reunion.](image-url)
By exploiting the GVUI each GlobVolcano user is able to: explore the GlobVolcano metadata catalogue, identify GlobVolcano products available over his volcano(es) of interest, visualize metadata, visualize GlobVolcano products, and download GlobVolcano products.

3. DEFORMATION MAPPING RESULTS

Tab. 1 summarises volcanoes analysed during the project and specifies for each volcano the processing approach adopted and the EO-data used for the study.

Table 1. Deformation mapping processing approach adopted for each volcano site.

<table>
<thead>
<tr>
<th>Site</th>
<th>Data Processing</th>
<th>SAR Data</th>
</tr>
</thead>
<tbody>
<tr>
<td>Areanal (Costa Rica)</td>
<td>DInSAR</td>
<td>ALOS - PALSAR</td>
</tr>
<tr>
<td>Colima (Mexico)</td>
<td>DInSAR</td>
<td>Envisat ASAR</td>
</tr>
<tr>
<td>Cumbre Vieja (La Palma)</td>
<td>CTM</td>
<td>Envisat ASAR</td>
</tr>
<tr>
<td>Hilo (Hawaii)</td>
<td>PSInSAR®</td>
<td>Radarsat 1</td>
</tr>
<tr>
<td>Mt. St. Helens (US)</td>
<td>PSInSAR®</td>
<td>Radarsat 1</td>
</tr>
<tr>
<td>Nyiragongo (Congo)</td>
<td>DInSAR</td>
<td>Envisat ASAR</td>
</tr>
<tr>
<td>Pico (Azores)</td>
<td>DInSAR</td>
<td>ALOS - PALSAR</td>
</tr>
<tr>
<td>Piton de la Fourmaise (La Reunion)</td>
<td>PSInSAR®</td>
<td>Envisat ASAR</td>
</tr>
<tr>
<td>Stomboli (Aeolie Islands)</td>
<td>PSInSAR®</td>
<td>Envisat ASAR</td>
</tr>
<tr>
<td>Vulcano (Aeolie Islands)</td>
<td>PSInSAR®</td>
<td>Envisat ASAR</td>
</tr>
</tbody>
</table>

Some example of results obtained are reported in the following sections.

3.1. DInSAR: Nyiragongo (Congo)

A dataset of 29 ASAR descending acquisition (from June 2005 until March 2009) has been analysed and the six interferometric pairs (Tab. 2) have been selected, based on temporal decorrelation, atmospheric conditions at time of acquisition and the perpendicular baseline.

Table 2. Interferometric pairs selected for the final analysis.

<table>
<thead>
<tr>
<th>Date</th>
<th>perpendicular baseline [m]</th>
<th>95% confidence interval [cm]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Jan-5-06 to Feb-9-06</td>
<td>-47</td>
<td>0.96</td>
</tr>
<tr>
<td>Dec-21-06 to Jan-25-07</td>
<td>-68</td>
<td>0.88</td>
</tr>
<tr>
<td>Jun-14-07 to Jul-19-07</td>
<td>-92</td>
<td>0.63</td>
</tr>
<tr>
<td>Nov-1-07 to Dec-6-07</td>
<td>-86</td>
<td>1.66</td>
</tr>
<tr>
<td>Apr-24-08 to May-29-08</td>
<td>-73</td>
<td>0.93</td>
</tr>
<tr>
<td>Dec-25-08 to Jan-26-09</td>
<td>-13</td>
<td>0.93</td>
</tr>
</tbody>
</table>

The results are restricted to areas with high coherence which are effectively the lava regions around the volcano (Fig. 2 Red circle).

Factors affecting the quality of results include:
- the perpendicular baseline which, if unequal to zero, stationary topography induces a phase in the interferograms that cannot be perfectly removed. Thus, the number of used images has been reduced.
- the deformation signal is mixed in with atmospheric phase signals, that can be correlated with height.

Fig. 3 shows colour representation of the vertical change results for the period: Dec-21-2006 to Jan-25-2007. In order to extract reliable information from the generated deformation products, a low coherence mask is generated and applied to the deformation map.
3.2. CTM: Cumbre Vieja (La Palma)
A dataset of 23 ASAR descending acquisition (from October 2003 until March 2009) has been analysed, two scenes (October 2003 and July 2004) have been removed because the time span is too large, and one data (May 2006) has been eliminated due to strong atmospheric effect. Thus the CTM analysis have been performed using 20 ASAR images (from March 2006 to March 2009).

The first step in the CTM procedure is the statistical analysis of the phase in all input images. The purpose of this step is to find a subset of all pixels that contain useful phase information that can be used for deformation measurements. The output of this procedure is a map with the phase quality (i.e., estimated coherence) of each pixel. Coherence value of 0.9 has been used as a threshold to identify hard targets.

The coherence along volcano is not sufficient due to vegetative cover. Thus deformation profiles generated are restricted to area identified in Fig. 4 by a red box. The density of points outside of the box is not enough to establish relationships and makes it difficult to connect between target clusters on the island. Profiles of detailed measurements are generated representing point measurements of deformation (Fig 5).

3.3. PSInSAR™ Piton de la Fournaise (La Reunion)
Two ASAR datasets have been used for the analysis of Piton de la Fournaise volcano:
- ASAR Ascending S2 dataset: 42 scenes from May 2003 to March 2009;
- ASAR Ascending S4 dataset: 42 scenes from May 2003 to March 2009.

The crater area is characterized by very fast motion and abrupt changes. Differential interferograms present very fast fringes, Fig. 6 and Fig. 7. Thus an ad-hoc permanent scatterers analysis has been performed over Piton de la Fournaise.

Figure 4. Cumbre Vieja (La Palma): CTM Analysis was restricted to the area identified in the red box due to the density of detected targets.

Figure 5. Cumbre Vieja (La Palma): deformation profiles. In this example, point ID #12205, deformation rate is -2.4 mm.yr.

Figure 6. Piton de la Fournaise (La Reunion): S4 Ascending T127 differential interferogram: Mar-22-2006, Dec-07-2005, Bt=105 days, Bn=175 m.
The application of the conventional PSInSAR™ approach would cause the loss of a great part of the pixels in the area. In fact many pixels don’t obey to the model for the whole period of observation, because of eruptions or seismic events, that yields to strong changes and subsequently to the loss of coherence. Two cases are therefore possible:
- A unique coherent temporal cluster of images is found: in this case a unique time series is given for the analyzed pixel. The displacement rate is computed as the linear trend of the time series.
- It is not possible to find an entire coherent time interval, the whole time span is divided in two or more independent subsets. Each temporal cluster has its own master (instant of reference with displacement equal to zero). The displacement rate is computed as the linear trend of the longest temporal cluster.

3.4. PSInSARTM Vulcano (Aeolie Islands)

The PSInSAR™ has been performed using two ASAR datasets:
- Forty-five Envisat ascending scenes from January 2003 until March 2009
- Thirty-seven Envisat descending scenes from July 2003 until April 2009.

The LOS (line of sight) velocity fields estimated for ascending and descending datasets are depicted in Fig. 10 and Fig. 11.
Wherever ascending and descending results are simultaneously available and it is possible to identify the same PS in both dataset, a decomposition to easting and vertical displacement components is possible (Fig 12 and Fig 13).

4. VALIDATION (PITON DE LA FOURNAISE)

The validation activities have been carried out by IPGP over the reference test sites: Piton de la Fournaise (La Reunion) and Karthala (Comoros Island).

The first stage of the validation is the identification of the time periods for which ground data was available to validate the product. Because instruments may suffer much environmental stress in volcano area, not all the GPS stations provide a continuous record. Over Piton de la Fournaise five permanent GPS stations (BORg, DSRg, SNEg, GITg and ENCg) provide such a record between April 2004 and March 2007. ENCg and GITg are reference GPS stations that do not show significant deformation during the period.

Thus PSInSAR™ measurements were compared with GPS measurements of three stations (BORg, DSRgm, SNEg Fig. 14).

GPS measurements of deformation rates are classically used to characterize the deformation that occurred during non eruptive unrest before an eruption and recovery phase after an eruption. The GPS stations do not provide accurate information for the huge deformation rates associated with eruptive phases. InSAR products are not relevant either during an eruptive phase, because both the high deformation rates and the large total deformation are too big to allow a good enough coherency between images used to compute the interferograms. Thus the second step of the validation is the identification of the longest time period without ongoing eruption perturbing both the record of GPS and SAR measurements. The selected period ranges between March and October 2005. Two different deformation phases can be distinguished inside the above period: the first from March to July and the second from July to October.
The third step of the validation was to transform the vertical and horizontal displacement recorded during the reference validation period by each GPS stations into an equivalent displacement along the line of sight of the satellite (LOS), as a function of the incidence angle with respect to off-nadir direction and the angle of the observation (orthogonal to the azimuth direction with respect to West).

This step is graphically explained in Fig 15, where:

- \( \delta \): incidence angle w.r.t. off-nadir direction (ASAR S2: 23°; ASAR S4: 33°)
- \( \theta \): angle of observation (orthogonal to the azimuth direction w.r.t. West)

The following table presents the estimates of displacement rates in the Line of Sight of the satellite as inferred from the PSInSAR™ time series and from the GPS ground record for the reference validation period. PSInSAR™ estimates were obtain using the time series of the closest pixels. Due to some variability in the deformation recorded in the different pixels, the precision of that method is about 0.05 mm/day. The GPS deformation rate is obtained by a linear regression through the data.

**Table 3. GPS measurements and PSInSAR™ measurements comparison.**

<table>
<thead>
<tr>
<th>GPS station / time period</th>
<th>GPS value / S2 PSInSar value</th>
<th>GPS value / S4 PSInSar value</th>
</tr>
</thead>
<tbody>
<tr>
<td>BORg 03-2005 - 07-2005</td>
<td>-0.11 mm/day / -0.10 mm/day</td>
<td>no record</td>
</tr>
<tr>
<td>BORg 07-2005 - 10-2005</td>
<td>+0.15 mm/day / +0.05 mm/day</td>
<td>no record</td>
</tr>
<tr>
<td>DSRg 03-2005 - 07-2005</td>
<td>+0.14 mm/day / +0.10 mm/day</td>
<td>+0.16 mm/day / +0.12 mm/day</td>
</tr>
<tr>
<td>DSRg 09-2005 - 10-2005</td>
<td>+0.30 mm/day / +0.20 mm/day</td>
<td>+0.29 mm/day / +0.34 mm/day</td>
</tr>
<tr>
<td>SNEg 03-2005 - 07-2005</td>
<td>-0.25 mm/day / -0.19 mm/day</td>
<td>-0.24 mm/day / -0.17 mm/day</td>
</tr>
<tr>
<td>SNEg 07-2005 - 10-2005</td>
<td>-0.29 mm/day / -0.33 mm/day</td>
<td>-0.24 mm/day / -0.24 mm/day</td>
</tr>
</tbody>
</table>

The comparison between the two data sets shows a good agreement between the two methods, within their associated error bars.

5. ACKNOWLEDGEMENTS

The team would like to thank all the volcano observatories that cooperate with the project.

The team would like to thank Falk Amelung who provides Radarsat data for Hilo (Hawaii).