EVOSS Report Summary
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Final Report Summary - EVOSS (EUROPEAN VOLCANO OBSERVATORY SPACE SERVICES)

Executive Summary:

EVOSS “European Volcano Observatory Space services”, is centred on the development and the integration into a real-time browsable operational system, of a blend of advanced processing techniques for detecting and simultaneously analysing high-temperature features, syn-eruptive ground deformation, volcanic gases and volcanic ash at erupting, or severely unresting, volcanoes in Europe, Africa, the ocean islands and the Antilles. The Region of Interest includes more than 150 volcanoes that erupt, or have been erupting at least once in the last 12000 years (the Holocene geological epoch). EVOSS was designed to act in situations ranging from sustained unrest up to events of outstanding areal impact, that may even lead to withdraw personnel from the field or to evacuate the volcano observatory. This requires adaptive task scaling up to possible handing over the surveillance to space-borne observation during extreme events. The EVOSS concept was voluntarily restricted to EU, Africa and the Eastern Caribbean, but through R&D done during the project the system can readily be extended to global scale by exploiting the combined potential of geostationary and polar orbiting satellite platforms, hosting Infrared, ultraviolet and radar instruments.

Thanks to the faultless development of some crucial project elements (novel Remote-Sensing techniques in thermal analysis, inter-satellite SO2 data homogenization and high-precision Digital Elevation Model construction) and the successful porting of processing techniques from one payload to another, EVOSS has been able to monitor as many as 42 eruptions at 9 volcanoes in 7 countries in Europe, Africa, the Lesser Antilles, and the Indian Ocean, many of them simultaneously - as Nyiragongo, Etna and Nabro in July 2011.

EVOSS is founded on the synergetic fusion of three technological components:

1) High-temperature thermal anomalies service
dealt with by space-borne payloads operating in the InfraRed portion of the electromagnetic spectrum, which are able to capture temperatures of molten lavas as high as 1200°C (at Piton de la Fournaise, Reunion Isl., e.g.) and as low as about 600°C (at Ol Doinyo Lengai, Tanzania, e.g.). Key-instruments suiting the project’s requirements are the geostationary Meteosat Second Generation MSG-1, -2 and -3 satellites, whose radiometer SEVIRI provides for exceptionally frequent imaging (96 images daily of the whole of Europe, Africa and the ocean islands with active volcanism).

2) Volcanic Emissions service
Volcanic emissions dealt with are Sulphur Dioxide (SO2) and Ash.
SO2 is reliably retrieved from satellite measurements as it presents a few sharp absorption bands in the Ultraviolet and the infrared. EVOSS uses four polar orbiting payloads for SO2 detection and measurement: three operate in the UV (in daylight: OMI onboard NASA’s AURA, SCIAMACHY onboard ESA’s ENVISAT, GOME-2 on board EUMETSAT’s MetOP-A and -B) and one in Infra-Red (IASI on board EUMETSAT’s MetOP-A and -B).
In contrast to SO2, remote satellite detection of ash is hampered by the absence of narrow absorption bands in the spectral signature of ash., which displays broad shape absorption depending on the particle size distribution. Besides of the systematic acquisition and computing of all sort of Ash or Aerosol Absorption indexes, EVOSS has incorporated for post-processing and real-time geographic display the quantitative, MSG-SEVIRI borne ash data (height, ash loading and grain size distribution) by the European consortium EUMETSAT.
3) Ground deformation service

Based on Synthetic Aperture Radar satellites, this component is not real-time or near-real-time because of a combination of technical reasons (number and type of satellites, characteristics and cost of images, frequency of overpasses of polar orbiting). Since EVOSS acts at the scale of the one-third of emerged land worldwide, where the need for accurate Digital Elevation Models is acute, the blend of advanced interferometric techniques developed within the EVOSS consortium was used to reach top accuracy and hitherto unachieved vertical and horizontal resolutions in DEM building on four areas (Congo, Comoros, Montserrat, Reunion), and to develop intensity/coherency procedures for the detection of morphology changes associated to volcanic activity.

EVOSS was kept alive and operating beyond the close of the project, done on July 11, 2013.

Project Context and Objectives:

1.1 PROJECT PURPOSES

In ground-level volcano monitoring there are thresholds beyond which the capacity to observe, analyse, forecast events and advise concerned authorities can become overwhelmed. EVOSS built upon the prior experience of most of team members, that presently available and immediately future spaceborne observational methods can be effectively organised in a unique, multisatellite, multi-method system allowing - worldwide and with an acceptable level of error - simultaneous measurements of thermal volcanic features, ground deformation, volcanic ash and sulphur dioxide emissions in the mid-upper troposphere. This is an objective need often raised but never satisfied: with the exception of a few tens of volcano observatories equipped with ground-based monitoring systems ranging from satisfactory to excellent, indeed, the vast majority of dangerous volcanoes are very weakly monitored or not monitored at all on ground.

Worldwide, figures point to less than 50 volcanoes presenting at least two different monitoring arrays (usually seismic and tilt) at a sufficient level of completeness, against about 700 volcanoes having erupted in Holocene – the last 12'000 years. As it would not be financially realistic to imagine a major expansion of ground monitoring to achieve global coverage, a different strategy is required. Typically one does not know WHERE the next volcano to go active will be located. Furthermore, even where advanced observatories do exist, they can still be overwhelmed by unexpectedly powerful events. A great advantage of a satellite-based observing system is that it is invulnerable to damage due to the eruptive phenomena. One also has to allow for the fact that volcanic crises can be long lasting, from weeks to months (as it was the case of Nyamulagira 2011-2012, e.g.) or even years (as it was the case of Soufriere Hill’s, 1995-2010), and that in a large monitored area, more than one volcano may be active at the same time. This amounts to a strong case for implementing an automatic observing system which can operate continuously without relying on human operators, but which can be easily supervised.

These statement made the strong case for the development of the EVOSS’, spaceborne-only strategy.

The EVOSS concept arose from the synergetic merge of the operational needs of End Users having direct monitoring duties over an intercontinental theater (IPGP – Institut de Physique du Globe de Paris - in the Indian Ocean and the Antillas; BGS – British Geological Survey- in the Antillas, East Asia ,Atlantic and Indian Ocean; the Toulouse VAAC – Volcanic Ash Advisory Center- in Europe and Africa), and those who are not provided with sufficient monitoring means at local scale (Ethiopia, Djibouti, Congo, Tanzania, Comoros and Uganda) or dealing with sparse volcanic sites (the whole of West Indies). According to all End-Users, one key-driver for EVOSS’ achievements, was that the information should be delivered to the relevant trained users wherever they may be.

A final consideration is that the system be economically sustainable, ie. that the data are not too costly to acquire, especially as large areas must be covered and long time series may often be required.

The EVOSS system has been designed and created with the above considerations in mind. In EVOSS high-to-very high temporal resolution of data acquisition prevails over (but does not exclude) high-to-very high spatial resolution of images acquired seldom, as top refresh rates only can allow for effective information support to decision in case of crisis. With the exception of Radar (SAR) data used for measuring geometry and volume changes at strategic revisit rates – which deserve a totally different strategy for sustainability – EVOSS exploits data from weather satellites or from payloads on
research missions which (a) can be obtained free of charge, and (b) relate to missions programmed and funded for continuous use and operation of at least two satellites simultaneously.

As methods and algorithms for the unsupervised, robust management of large data streams were developed, tested and validated in EVOSS, we can conclude that – to date – the crucial part of EVOSS is sustainable and has the potential to undergo long-term operations, as it relies upon meteorological satellites.

The geographic stretch of EVOSS is 'global', as it simultaneously encompasses all >150 Holocene, potentially erupting volcanoes in Africa, the Lesser Antillas and Europe, exploiting all available Earth Observation satellite platforms - polar and geostationary, infrared and radar - from very-high spatial resolution (footprints as small as 1 meter) to very-high temporal resolution (revisit times as short as 15 minutes and, in perspective, 5 minutes).

EVOSS provides timely, quantitative information on very-high temperature thermal features (lava flows, lava domes, lava lakes), major ground deformations (centimeters to meters) and major aerosol emissions (Sulfur Dioxide and Volcanic Ash).

Upon completion of the design phase of the project, strong synergy was established with the EUMETSAT consortium, whose sensors and platforms are massively exploited in EVOSS. This cooperation implies the real-time exchange of volcano-oriented products. In particular, EVOSS carried out the validation of the volcanic ash products based on algorithms developed and run at EUMETSAT.

Finally, the feasibility of expansion – in the short term – of the EVOSS spaceborne field of view eastwards and westwards, exploiting the non-European geostationary platforms on East Asia and the Americas, was tested and demonstrated.

1.2 EVOSS OBJECTIVES

The main objectives of the EVOSS project were:

1) Scientific objectives, i.e the development and validation of innovative algorithms for exploitation of data from current space-borne Earth Observation instruments; in particular, the following three themes were dealt with:
   a. Detection and measurement of volcanic emissions (SO2 and volcanic ash)
   b. Detection and measurement of high temperature volcanic thermal features
   c. Analysis of volcanic ground deformation and topography changes by the new SAR platforms

2) Design and Implementation of the Information Service Infrastructure, able to provide the above information to the ‘champion’ end-Users, the VAACs of Toulouse and London, and the involved Volcano Observatories of Lesser Antilles, Reunion, Djibouti, Ethiopia, Comoros, Tanzania, Uganda and RD Congo (later joined by Iceland, Italy and Cabo Verde)

3) Real-scale demonstration of the EVOSS Information Service

4) Sustainability analysis of the overall EVOSS Information Service.

The EVOSS project activities were carried out in order to fit the following set of fundamental system requirements/restrictions, directly derived from the end-users’ needs and from the interpretation of the realistic contribution of any existing spaceborne Earth Observation system:

A) Focused on the higher end of volcano dynamics, from sustained unrest to eruption: EVOSS aims to provide information when it is needed (in distant crises), when the personnel is tied up by emergency operations (local crises, involving any Observatory), or when the intensity of unrest forces withdrawal of operators from the field or even displacement of the operation room (local).

This requirement is scaled on lessons learnt in the major crises experienced 1995-2006 at Soufriere Hills, 2002 at Nyiragongo, 2003 at Karthala, 2007 at Piton de la Fournaise.

B) Supra-regional operations theatre: EVOSS centralises multi-parametric EO information on surface thermal anomalies and aerosols from EU and African volcanoes showing unrest. This caters for the needs of the Users provided with multi-Observatory duties (IPGP, in the Caribbean and in Africa), wide area responsibility (VAAC of Toulouse, over Europe and Africa) or consulting for Institutions and Governments worldwide (BGS).

C) Very-high temporal resolution is given priority over high spatial resolution with low refreshment rates, as it is considered a methodological breakthrough in real-time surveillance

D) System(s) to be scaled on spatially scattered, long lasting crises (months to years);

E) Sustainability of data provision has priority: the cost of space-borne data is increasingly noncompatible with the real duration of major unrest cycles, spanning from months to years, or even decades at explosive volcanoes. Efficient space-borne
observation demonstrably suffers from temporal decorrelation (SAR interferometry) which can be inconsistent with the provision of high-spatial/high-temporal resolution datasets by constellations (e.g. Cosmo-SkyMED) with revisit times as short as 11 days. The development of customized business models were expected to assist in designing sustainability.

1.3 REAL-SIZE DEMONSTRATION OF EVOSS

An extensive technological demonstration of the EVOSS services has been carried out from 2011 until 2013; such operational demo has catalyzed the attention of twice the Users who had agreed at the time of the proposal.

New users/stakeholders include the Joint Research Center of Ispra, the Icelandic Meteorological Office, the United Nation UNOPS at the Volcanic Observatory of Goma, Congo, the London and the Washington VAACs, the Government of Djibouti, the Volcano Observatory of Karthala (Comoros), the Department of Geological Survey and Mines of Uganda, the Institute of Geophysics of Cabo Verde.

The total number of users and/or stakeholders involved in EVOSS is 18, twice the initial ones.

The EVOSS Earth Observation (EO) products are the only ones today able to offer accurate and multi-parameters information in a wide area (about 100 Km radius) around every volcanic source in the EVOSS field of view.

The EVOSS system is currently (15-09-2013) kept operational – for the part not involving costs to be incurred for data provision – beyond the contractual duration of the EC grant, that is, beyond June 30, 2013.

Project Results:

PRELIMINARY NOTE:

As a major complement to this concise written report, please

(1) accede - with the complimentary ID/pw in your possession or provided - separately from this report - upon request to the INFO desk evoss@cgspace.it - the on-line VVO (Virtual Volcano Observatory) at http://fornax.site4u.nl/Evoss/Account/Login.aspx and

(2) see the companion "EVOSS_Final_Report.pdf" with figures and results of the three major eruption cases.

Please note further that:

(3) ALL information from October 2011 to date, is stored and available on the said VVO; and

(4) upon request of a qualified subset of EVOSS’ stakeholder and institutional users, it was decided – on a voluntary basis – to keep the more sustainable part EVOSS’ VVO alive for a time of at least 6 months after the close of the project close on July 11, 2013. Time stretches to be renegotiated six-monthly.

EVOSS is a complete, distributed, automated, unsupervised, anywhere/anytime, real-time volcano monitoring system, designed to operate at supra-continental scales, up to worldwide.

The system is founded on the State-of-Art for thermal, SO2, ash and ground deformation remote-sensing; it was developed in about nine months (at the beginning of the project), and fine tuned-up in about nine supplementary months.

EVOSS is meant to assist in volcanic eruptive crises management by providing institutional End-users with immediately exploitable quantitative information, without subjective interpretation by specialized personnel – usually unavailable at most volcano observatories worldwide, and strictly unavailable where volcano observatories do not exist.

The structure of EVOSS is that of a “multi-pole, geographically distributed system”. In practice, spaceborne datasets from up 18 different satellites (up to 9 simultaneously), acquired at 5 downlink stations, are split and automatically processed in real-time at 6 locations in 4 EU nations.

Still in real-time, the outputs of the six processing chains are sent to a unique post-processing unit for real-time display in the geographic facility called the Virtual Volcano Observatory (VVO). This architecture was designed to allow knowledge and know-hows to remain with the inventors/developers, without concern for intellectual property.

The results conveyed to the VVO are arranged in four separate data streams: Thermal Anomalies, Ground Deformation and Volcanic Aerosols – the latter being split into Ash and SO2. The VVO simultaneously integrates, stores and visually post-
processes the information for all unresting/erupting volcanoes included in the Region of Interest, which covers at once: Europe, Africa and the Lesser Antilles. Each of the end-users involved can interact in real-time with, and/or download the full information from his specific area of interest.

According to the development lines in the original proposal, the EVOSS’ achievements were in five areas, four Science and Technology oriented, and one Economic:

1) Development of Real-Time (RT) and Near-Real-Time (NRT) products for (1.1) High-Temperature THERMAL ANOMALIES, (1.2) SO2 EMISSIONS, (1.3) ASH PLUMES and (1.4) GROUND DEFORMATIONS, exploiting all available payloads.
2) Build of the EVOSS INFORMATION SYSTEM for the RT availability of the four services (1.1) to (1.4) in the so-called Virtual Volcano Observatory (VVO)
3) 10-month, FULL-SCALE DEMONSTRATION of the RT/NRT provision of the four services by the VVO on Wide Area Network. Thanks to the earlier conclusion of activities in (1), the 10-month demonstration started earlier and finished later, thus becoming an effective 21-MONTH DEMONSTRATION.
4) Analysis of FUTURE PAYLOADS suitable for ensuring endurance of EVOSS operations, and TESTS OF PORTING of the High-Temperature Thermal Anomaly Service (1.1) on geostationary payloads operating at eastern longitudes.
5) Market, Business and SUSTAINABILITY ANALYSIS.

In this report on the S&T achievements in EVOSS, we shall report in detail on points 1 to 4. For point 5, the reader is addressed to the separate report on sustainability and market perspective, as well as to deliverables D-6.1.3 (Business model report) and D-6.2.3 (Business plan report).

1. THE EVOSS INFORMATION SYSTEM
The EVOSS Information System (EIS) provides a potentially unlimited number of distant End-Users with rapid web access to the whole of the geographic information created within EVOSS. EIS consists of the harmonic fusion of three main subsystems:

a) A “Cloud” of 7 data processing subsystems, run locally by 6 EVOSS Partners (scientific and industrial) plus EUMETSAT, to process in real-time crude satellite data and extract geographic parameters to push/pull write into the dynamic data repository of the EVOSS Data Processing System (DPS)
b) The Data Processing System (DPS), devoted to the real-time generation of geographic EVOSS products to feed the Virtual Volcano Observatory.
c) The Virtual Volcano Observatory (VVO), in charge of archiving and real-time distributing over WAN (Wide Area Network) the whole of the DPS-processed EVOSS products.

A CLOUD OF INFORMATION PROVIDERS
1. Thermal Anomalies located at CRPSM (Italy). Real-Time products (<1 hour behind real-time) delivered after automated, fully unsupervised post-processing by IESC with proprietary technology. Typical operational burden in EVOSS: 96 images daily (every 15 minutes).
2. SO2 and Ash Emission located at:
   a. KNMI (The Netherlands): SO2 and aerosol index from OMI data. Operated in NRT (Near-Real-Time) with fully unsupervised post-processing technology shared with NOAA. Typical operational burden in EVOSS: 1 image daily
   b. BIRA (Belgium): SO2 from SCIAMACHY data, aerosol index from GOME-2 data, ash and ice index from IASI data. Typical operational burden in EVOSS: 1 image daily until April 8, 2012.
   c. DLR (Germany) Aerosol index from SCIAMACHY data, SO2 from GOME-2 data. Operated in NRT with proprietary, fully unsupervised post-processing technology. Typical operational burden in EVOSS: 1 image daily.
   d. ULB (Belgium) SO2 index from IASI data. Operated in Delay-Time, with proprietary, fully unsupervised post-processing technology. Typical operational burden in EVOSS: 1 image daily.
   e. EUMETSAT: Real-Time ash products (<1 hour behind real-time) from proprietary MSG-1/-2/-3 data, with proprietary algorithm VOLE. Typical burden: unknown. Data broadcasted by EUMETCAST.
3. Ground Deformation located at TRE (Italy). It is operated in Delay-Time after delivery of crude satellite data, with automated, supervised post-processing technology by TRE. Typical operational burden in EVOSS: 220 images in 2 years. The advantage of the Cloud is th

DPS - THE EVOSS DATA PROCESSING SYSTEM
It is a scalable and modular system composed of standard data interfaces, able to post-process Thermal, Ground deformation, SO2 and Ash data pushed/pulled by/from the seven distant information providers (6 EVOSS Partners plus EUMETSAT) listed above. It has been designed according to established Software Engineering rules, and implemented exploiting geospatial Open Source software building blocks, and Open Geospatial Consortium (OGC) standards.

VVO - THE EVOSS VIRTUAL VOLCANO OBSERVATORY
The VVO is the thematic/geographic information provision infrastructure. It is located at CGS (Italy), and provides the users with customized, 24/7 web access to archived and catalogued EVOSS products for visualization or downloading. Its main functions are:
− Products publication and archiving.
− Product provision.
− Anomalous event notification.
The VVO provides secure access to available geospatial information to all registered Users. The development of the Virtual Volcano Observatory has taken into account geospatial data products harmonization policies, the INSPIRE directive and the current standardization initiatives. The Virtual Volcano Observatory was founded on a service-oriented architecture.

The main elements of the VVO are:
− Product Harvesting Facility,
− Product Management Facility,
− Metadata Catalogue Service,
− Product Access Services,
− Anomalous Events Management Facility,
− User Interface.
The Product Harvesting Facility and the Product Management Facility accomplish the first function, whereas Product Storage, Routing and Delivery functions are carried out through Catalogue Service, Product Access Services, and User Interface. The “Product Harvesting Facility” checks the availability in the Input Repository of a new EVOSS product with an assigned (but tunable) frequency, currently set at 5 minutes. When a new product is available, the “Product Management Facility” is activated in order to:

1. Convert the product format into a suitable format (e.g. from NetCDF to GEOTIFF).
2. Handle the product storage in the “Product Archive”.
3. Update the services (WMS / WCS /WFS)
4. Generate related metadata, and update the catalogue (CS-W)

The “User Interface” interacts with:
A) The “Metadata Catalogue Service” in order to discover available EVOSS products.
b) The Product Access Service” in order to (i) visualize, (ii) deliver or (iii) retrieve information from archived products according to specific and standard protocol (WMS / WCS /WFS / FTP).

A dedicated function – the Anomalous Event Management Facility – is in charge of the generation of the Anomalous event notification. When the product has been archived the “Anomalous Event Management Facility” is activated. This function checks the occurrence of a pre-defined “anomalous” event(s) and prepares a notification report. The notification report is delivered to the VVO in order to publish geographic warnings of detected events – as thermal anomalies, exceptional SO2 concentration, e.g.
The User Interface takes care of Anomalous Notification Report delivery.
2. S&T ACHIEVEMENTS

The scientific and technological achievements of EVOSS, are synthesized below split in the three main categories of data corresponding to active EVOSS’ services:

A) High-temperature thermal anomalies, B) Volcanic aerosols, and C) Ground deformations.

2.1 HIGH-TEMPERATURE THERMAL ANOMALIES

In ‘thermal’ passive remote sensing, four main physical parameters can be determined: Integrated temperature (Ti in K), Effective temperature (Te in K), Radiant flux (QRad in W), and – where appropriate – Effusion rate (Er in m^3/s).

The two latter, Radiant Flux (in Watts, broadly mirroring the instant thermal power output) and Effusion rate (in cubic meters per second, one of the two main parameters governing the spreading of lava flows – the other is topography) are the parameters of interest for volcano monitoring and prediction.

As in our case pixels are generally much larger than the size of the High-Temperature volcanic feature on ground, they can be obtained by applying “thermal sub-resolutions” methods which consist in solving a two-equation (“dual band”) and/or a three-equation (“three-component”) system to obtain the size of the portion of the pixel occupied by molten lavas. Accounting for the rheology of involved lavas – which is known by petrochemical literature for almost any volcano on Earth – it is then possible to convert the instant information obtained in Radiant Flux (for any eruption) or Effusion rate (for lava flows only).

In EVOSS, all such automated computing operations are based on the suite nicknamed MyMET, described in Hirn et al., 2009, over all volcanoes included in the SEVIRI “disk”.

Considering the past eruptive activity of volcanic edifices within the SEVIRI - MSG full disk, limits and performances of both algorithms, MYMET on SEVIRI data and MYMOD on MODIS data, in volcanic hot spot detection.

This analysis helped putting into evidence that the combined use of SEVIRI and MODIS data is needed to detect and monitor the intra-crater effusive activity or the emplacement of lava flow of low effusion rate at Piton de la Fournaise (Reunion Island) and Eyjafjallajökull (Iceland), to monitor the activity at Soufriere Hills (Montserrat Island) and Grimsvötn (Iceland), and to measure the activity of the small, permanent lava lake at Erta ‘Ale (Ethiopia).

As the Radiant Flux detection threshold for SEVIRI is in the order of 0.8 ÷1.0 GW, and that of MODIS is almost one order of magnitude lower, there are eruptive activities which are not detected by SEVIRI and are detected by MODIS – or its successor NPP – alone.

For this reason it was decided to run permanently two categories of “Hot Spot” products named according to the naming convention in the VVO facility: TAS-MSG (for SEVIRI) and TAS-MDS (for MODIS), regardless of the platform – MSG1, MSG2, MSG3, Terra or Aqua – they come from.

The Thermal Anomaly Service products are two:

«TAS-MSG - HIGH REFRESH RATE HOT SPOT»: Hot-spot detection, radiant flux and instant lava effusion rate by SEVIRI-MSG data analysis. Exploitable pixels present areas varying from 9 km^2 at nadir, to >38km^2 close to the border of the “disk”. The product is operational for EU and Africa volcanoes located within the whole SEVIRI disk, that underwent eruption between 2004 and the present day. They are:

- Stromboli and Mt. Etna (Italy),
- Hierro (Canary Islands, Spain),
- Jebel-al-Tair and Jebel Zub’air (Red Sea, Yemen),
- Manda Harraro, Dalafilla, Dabbahu, Erta Ale and Nabro (Ethiopia),
- Mt. Cameroon (Cameroon),
- Nyiragongo and Nyamulagira (Congo),
- Ol’Doinyo Lengai (Tanzania),
- Karthala (Grand Comore, Comoros),
- Piton de la Fournaise (Reunion, France),
- Soufriere Hills (Montserrat, B.W.I)
- Eyjafjallajökull and Grimsvötn (Iceland)
«TAS-MDS - DAILY HOT SPOT» : based on MODIS MIR and TIR (1 km² pixels). Delivery restricted to volcanic test sites characterized by A) a large pixel footprint on the SEVIRI image (over 20 km²) and/or B) a permanent, small-sized volcanic feature (if compared to the SEVIRI pixel area). Hot spots detection, radiant flux and instant lava effusion rate are provided by MODIS overpasses by Terra and Aqua, up to four times a day. Analysis of MODIS data was routinely carried out at:
- Piton de la Fournaise (Reunion Island), where the average SEVIRI footprint is about 27 km²
- Soufrière Hills (Montserrat Island), characterized by a SEVIRI footprint of 36.3 km²
- Eyjafjallajökull (Iceland), where the average SEVIRI footprint is 38.8 km²
- The 60-meter wide lava lake of Erta Ale (Ethiopia), where the SEVIRI pixel footprint is 15.3 km²
For reasons of manpower needs, the TAS-MDS service was discontinued in the post-grant, current running of the EVOSS system.

There are four relevant achievements of EVOSS in the field of the spaceborne EO of High-Temperature, magma-related, thermal anomalies on ground. They are:
1) EVOSS extended the exploitation of the thermal sub-resolution technique to geostationary payloads [see RD2 and RD3, among others]. This allowed raising the thermal and mass eruption information to rates of refresh high enough to integrate, parallel or even substitute the observation systems on ground (mass eruption rates are seldom measured during eruptions, mostly qualitatively and care of field operators);
2) EVOSS brought the inherent automation procedures to levels of sophistication and robustness high enough to permit keeping full 24h/24-7d/7 operation, thus making the EVOSS’ VVO the first global, unsupervised, information/decision support system for erupting volcanic spots non provided with a real-time monitoring system.
3) After a 6-month tune-up phase which started with the eruption of Nabro, Eritrea, the HT system proved almost faultless as it was running unattended during ~99% of the time, and detected and monitored all the 42 sub-aerial eruptions in the region of interest but one (Grímsvötn on 21/05/2011, because of the style, the short duration and the associated thick cloud of ash and steam).
4) The MyMET suite of algorithms used for the online post-processing of radiometers SEVIRI, was successfully ported on multispectral radiometers JAMI onboard the Japanese meteorological platforms MTSAT-1R and MTSAT-2

Combined analysis of SEVIRI and MODIS on relevant eruptions, helped putting into evidence that the combined use of SEVIRI and MODIS (or NPP) is needed to detect and monitor minor eruptive activity at Piton de la Fournaise (Reunion Island) and Eyjafjallajökull (Iceland), to monitor the activity at Soufrière Hills (Montserrat Island) and Grimsvötn (Iceland), and to measure the activity of the small, permanent lava lake at Erta ‘Ale (Ethiopia). As the Radiant Flux detection threshold for SEVIRI is in the order of 0.8 +1.0 GW, and that of MODIS is almost one order of magnitude lower, there are eruptive activities which are not detected by SEVIRI and are detected by MODIS – or its successor NPP – alone. For this reason it was decided to run permanently two categories of “Hot Spot” products named according to the naming convention in the VVO facility: TAS-MSG (for SEVIRI) and TAS-MDS (for MODIS), regardless of the platform – MSG1, MSG2, MSG3, Terra or Aqua – they come from. However, the temporal aliasing associated to the low overpass frequency of MODIS (up to four times daily at mid-low latitudes) may lead to missing short lasting eruptive events.

PERFORMANCE:
The High-Temperature Thermal Anomaly Service by SEVIRI (TAS) proved the most reliable and appropriate of all techniques used in EVOSS, in terms of effectiveness and of time-and-space resolution. Indeed, over 42 eruptions occurred in the Region of Interest, the HT-TAS based on SEVIRI has missed:
- 2 submarine eruptions (Jebel-Zubair, Yemen, and El Hierro, Canary Islands) – however, the system is not designed to deal with this type of events
- 1 short-lasting explosive eruptions in Iceland (Grimsvötn) – for reasons of threshold and of ground visibility hindered by the large ash-and steam mushrooms
- 1 minor eruption on Etna on March 4, 2013 – for reasons of visibility; the plume was properly detected by GOME-2

Not considering the submarine eruptions, for which a radiance-based technique is not appropriate (amplitude or spectral
reflectivity change techniques should apply, but they fall out of the current perimeter of EVOSS) we can conclude that the efficiency of the SEVIRI-TAS system bases on MyMET and measured as the number of missed events vs. the hits, is outstandingly high, in the order of 95%

2.2 NEW PAYLOADS ANALYSIS

From 2018 onwards, the Flexible Combined Imager (FCI) onboard all MTG-I satellites of the Meteosat Third Generation system – described above in 5.2.2 - will be the key-instrument for an enduring High-Temperature Thermal Anomaly service (HT-TAS). The MTG-I series will comprise four satellites, as it was the case for MSG. The first two MTG-I satellites will be presumably flown while MSG-4 and (probably) MSG-3, will be still operational.

Temporal resolution:
Leveraging on the three-axe stabilized platform advantage (meaning the instruments will be pointed at the Earth for 100% of their in-orbit time, repeat cycle and S/N ratios will be improved), geostationary real-time HT-TAS operations are expected to become potentially continuous. The scan rate will improve further passing from 15min to 10 minutes in full-disk scan (FDS), and from current 5 minutes on the northern half-disk to 2.5 minutes only (on the European quarter disk) in Rapid Scan (RSS) mode.

Spatial resolution:
Improved areal resolutions by a factor 3 in the SWIR (1 km2) and a factor ca. 2 in the MIR-TIR domain (2 km2), will allow better view, higher sensitivity to anomaly detection and easier solving of sub-resolution MyMET real-time algorithms exploiting the “Three-component” and the “Dual-band” methods. For example, the pixel footprint on Congo volcanoes will drop from ~10 km2 to ~4.4 km2 only; on southern Italy from current ~15 km2 to ~6.7 km2, on Réunion or Montserrat ~11 km2 (from current ~24 km2), and on southern Iceland ~17 km2 (from current ~38 km2).

The additional, higher resolution channels available in RSS mode in V-NIR (0.5 km pixel size) and TIR (1 km) are expected to bring additional clues to the thermal observation on ground. However, because of their different size, their exploitation deserves in-depth examination of the first series of real data, as soon as they will be available.

Because of its spectral resolution and spatial resolution, FCI onboard MTG-I is expected to be able to provide improved information on volcanic ash in the atmosphere, better than as currently done by the MSG family. The user community has already identified the crucial role of infrared instruments for future volcanic-ash monitoring. Improved capabilities (with respect to MSG) of the MTG imagery mission will provide further details on the extent of the ash plume, whereas the capabilities of the MTG sounding mission will be essential for the derivation of quantitative products with additional information on the composition and density of the ash cloud.

The Ultraviolet, Visible and Near-Infrared Sounding (UVN) instrument is a GMES’ Sentinel 4 instrument designed for geostationary chemistry applications, which will fly onboard the MTG-S satellites. UVN is a spectrometer taking measurements in the ultraviolet (UV: 305–400 nm), the visible (VIS: 400–500 nm) and the near infrared (NIR: 755–775 nm) with a spatial resolution better than 10 km. Its observations are restricted to Earth area coverage, from 30 to 65º N in latitude and 30º W to 45º E in longitude.

Its temporal resolution (observation repeat cycle) will be in the order of 60 minutes. UVN will be appropriate for detecting and measuring aerosol optical depths and volcanic SO2, with a temporal resolutions from 12 times (with respect to IASI) to 24 times better than the suite of polar orbiting UV payloads GOME-2 and OMI, currently in use for SO2 detection, measurement and tracking.

2.3 FEASIBILITY TESTS OF TAS PROVISION WITH MTSAT-JAMI

Tests of porting the MyMET methodology on data provided by the geostationary JAMI onboard platforms MTSAT-1R and MTSAT-2 operated by the Japan Meteorological Agency (JMA), were carried out in parallel with the tuning-up of the “HT Thermal Anomalies” branch of EVOSS. In view of future endeavors involving the expansion of the EVOSS concept to Asia or even worldwide, JAMI-MTSAT - orbiting at 145ºE – is theoretically suited to the quantitative monitoring of volcanoes located in Kamchatka, Japan, Philippines, Indonesia,
Vanuatu, New Zealand, at high revisit rates (30-minute repeat).

The JAMI (Japanese Advanced Meteorological Imager) instrument onboard the MTSAT (Multi-functional Transport Satellite) is a five channel sensor, with a pixel size of 1km (VIS) and 4km (IR) at Nadir. JAMI is characterized by data quality (8-bit) and temporal, spatial and spectral resolutions same as those of the GOES’ Imager, therefore, definitely worse than SEVIRI’s. As there is no other source of information allowing for high-to-very high revisit rates (as in all cases JAMI provides for 48 images daily) on East Asia, we decided to proceed in the experiment even though the lack of a SWIR channel forced choosing a configuration centred on the use of two TIR channels and one MIR only

Extensive research was carried out considering 12 volcanoes in the disk of JAMI, differing in location, eruptive style, duration and magnitude of eruptions:
- On Java Isl., Indonesia: KRAKATAU, MERAPI and SEMERU
- On Lesser Sunda Isl., Indonesia: RINJANI and BATU TARA
- On Sulawesi Isl., Indonesia : SOPUTAN
- On Sangihe Isl., Indonesia : KARANGETANG
- in Kamchatka, Russia : BEZYMANNY, KARYMSKY, KLIUCHEVSKOI, TOLBACHIK and SHIVELUCH

The petro-chemical/physical parameters of all volcanoes, needed for Radiant flux and Effusion rate calculation, were defined considering 1 km footprint data of MODIS (used as the calibration reference). For the two stratovolcanoes, Batu Tara (Komba Island, Indonesia) located at 7.792°S, 123.579°E and Tolbachik (Kamchatka Peninsula, Russia) located at 55.83°N, 160.33°E, a systematic, parallel calibration/validation study was carried out on higher spatial resolution data (1 km2) acquired by MODIS onboard Terra and Aqua platforms. Of particular interest was the conclusive study/monitoring activity carried on the 2012-2013 eruption of Tolbachik:
- the onset of the eruption was detected on JAMI-MTSAT data on November 28Th, 2012 at 14:30 UTC and at 15:35 UTC on a MODIS image. Lava effused from two fissures along the W side of Tolbachinsky Dol, a lava plateau on the SW side of the volcano.
- The largest radiant flux was observed at the onset of the eruption, with a measured value of 41.2 GW (± 30%) on JAMI data acquired on November 29, 2012 at 01:30 UTC. After December 26th, 2012, measured radiant flux values kept steadily below 10 GW.
- On June 14th, 2013, the effusive activity of Tolbachik volcano was ongoing and very fluid lava flows traveled to the W, S, and SE sides of Tolbachinsky Dol.
- On this September 15th the eruption is considered to be “possibly over” (KVERT source), even though the “orange code” alert status is kept for aviation. The eruption was monitored uninterruptedly until end-April 2013 behind real-time (daily refresh of the whole set of JAMI’s data of the day). It is worth noting that the MODIS’ and the JAMI’s radiant fluxes kept comparable all the time, after initial calibration.
After >5 months the tests were stopped: they were considered fully successful, as they proved the feasibility of automated thermal volcano monitoring also with JAMI.

According to the results of the thorough test outlined above, we may conclude that – although at spatial, spectral and temporal resolution half those of MSG/SEVIRI – the overall performance of JAMI-MTSAT fulfils the requirements for monitoring a broad variety of high-temperature volcanic features from high (active lava flows) to low intensity (strombolian summit activity), with tactical half-hour revisit frequency.
We can conclude that JAMI-MTSAT is the only reliable companion of SEVIRI on east Asia and west Pacific in the framework of global, tactical EO of volcanoes.
Visual details of the results of the validation study are in deliverable D-1.1.5 and in the attached file “Evoss-Final_report.pdf” (attached)

3. VOLCANIC AEROSOLS
3.1 SULFUR DIOXIDE EMISSIONS
The standard output of satellite SO2 retrievals is the vertical column (VC), which represents the amount of SO2 molecules in a column overhead per surface unit, at a given location. It is generally expressed in Dobson Unit, a unit in use for columnar density of trace gases in the Earth's atmosphere (1 DU equals 2.69 x 10¹⁶ molecules/cm²).

SO2 VCs are routinely retrieved from backscatter measurements of sunlight from UV spaceborne instruments, using the Differential Optical Absorption Spectroscopy (DOAS) technique (SCIAMACHY and GOME-2) or the Linear Fit algorithm (OMI). Although these techniques differ in the details, observation principles are founded on the application to atmosphere of the Beer-Lambert’s law of extinction.

In general, at an assigned wavelength λ, the signal I recorded at a sensor is proportional to its initial intensity I₀ attenuated by absorption and scattering in the atmosphere. The wavelength window for SO2 retrievals lies between 310 and 330 nm, where strong SO2 absorption occurs.

SO2 retrievals are obtained in a three-step process, based on the separation of the spectral fitting of absorption signals, and the determination of light path length.

The atmospheric absorbers (in particular SO2, but also interfering absorbing gases like O₃ and NO₂) are separated using the characteristic differential structures of their Rayleigh’s and Mie’s absorption cross-sections.

As a rule, the information on the height of SO2 plumes is not available at the time of observations although measurement sensitivity to SO2 is altitude-dependent. Consequently, the estimate of vertical columns implies parameterizing the plume height, which is usually done at three (sometimes four) different levels:

- The lowest level (typically <4-5 km as a function of the troposphere model in latitude and season) stands for SO2 originating from anthropogenic activities or low-to-mild volcano degassing at low altitudes.
- The middle tropospheric level is representative of conditions where SO2 is emitted from effusive volcanic eruptions or quiet top degassing top from high volcanic edifices.
- Finally, stratospheric levels are consistent with SO2 released from explosive volcanic eruptions.

In EVOSS, integration of vertical columns for instant mass estimate is done over the two upper levels, mid-tropospheric and stratospheric.

### 3.1.1 SULFUR DIOXIDE MONITORING

In EVOSS, daily SO2 measurements and the IR payloads (IASI), played a major role in detecting in NRT high levels of dynamics of the shallow plumbing systems of individual volcanoes in lack of high-temperature surface anomalies (magma not exposed at surface).

Processed information comes in Vertical Column (VC) concentrations (DU) with short delays – typically 2 to 3 hours – after the daily measurements by the three UV payloads GOME-2, OMI (and SCIAMACHY, until April 8, 2012). Partners providing SO2 product are:
- DLR, Germany, for GOME-2;
- KNMI, Netherlands, for OMI;
- BIRA, Belgium, for SCHIAMACHY (until it was operational)

Upon completion of the (automated) process, products are pushed into the repository run at CGS, Italy, where the post-processing chain is active to convert data to mass by column integration and frame them in the geographic VVO. In EVOSS, the mass integration is typically done on the two higher columns.

In the EVOSS’ VVO, VCs and mass estimates are shown for the highest column (15 km for GOME-2 and SCIAMACHY, 17 km for OMI). It is worth noting that for high SO2 column amounts (>25 DU), the eventual saturation of SO2 absorption may lead to underestimate VCs. It is therefore preferable to retrieve SO2 using an optimal estimation method based on full radiative transfer modeling. For these conditions, the height of the plume is also retrieved from spectral UV measurements, taking advantage of the different response of earthshine UV spectra at different plume altitudes.

From the start of the automated routine operations to date, and significant SO2 emissions available in the VVO repository were observed from the volcanoes below:

- El Hierro January 2013 (non validated)
- Etna Discontinuous, mostly syn-/post-eruptive
- Eyjafjallajökull April to May 2010
Grimsvötn May 2011
Jebel Zubair December 2011 (non validated)
Nabro June 2011
Nyamuragira * November 2011 to February 2012
Nyiragongo * Continuous
Soufriere Hills January 2013 (non validated)
* the pixel size does not allow discriminating but qualitatively the emissions from the two Congo volcanoes

3.2 VOLCANIC ASH

To date, several quantitative algorithms for detecting ash and estimating its principal parameters - plume height, grain size distribution (GSD) and ash loading - do exist. In contrast with SO2, however, remote sensing of ash is hampered by the absence of narrow absorption bands in the spectral signature of ash.

As the physical problem is severely under-determined, most algorithms rely upon the assumption of the plume altitude and/or the assumption of the microphysical properties of its components (GSD), which are mostly unknown for the actual plume. Another unknown is the actual tropospheric model at the place of the eruption and of the dispersing plume. The need for heavy parameterization for solving the physical problem, in general, results into poorly constrained quantitative information.

An additional difficulty is associated to the selection of detection methods exploiting radiance, reflectance or reflected radiance in the whole spectrum measurable from satellite, and the adaption to 24H unsupervised operations minimizing omitted detections and omission errors at once (including the effects of twilights).

As one of the main focus of EVOSS was on “maximizing the temporal resolution”, the principal target was that of making available and exploitable the information on volcanic ash derived from geostationary satellites. The latter, present the advantage to provide continuous information on the location of volcanic ash plumes, and thus are important for near-real time monitoring and potentially crucial for aviation industry.

Research into the possibilities to retrieve information on volcanic ash from geostationary satellites – in particular quantitative information - had been going for quite some time, and at the moment of the Eyjafjallajökull eruption it became clear that available algorithms were not sufficiently performing for affording real operations.

Due to the political and societal recognition of satellite measurements as an important information source, EVOSS and the EUropean METeorological SATellite (EUMETSAT) consortium quickly joined forces in order to make geostationary volcanic ash information available via the EVOSS service.

EUMETSAT had already initiated a pilot study into the capacity of a near-real-time service on volcanic ash, which led to releasing a report in April 2011 (Prata, 2011). The main findings of the report were that quantitative information on volcanic ash could be retrieved from SEVIRI measurements, in particular, ash (mass) loading and ash height.

In parallel to the assessment of the EUMETSAT product, it was agreed that KNMI would develop its own ash height product. Reason for doing so were:

a. at the time of the assessment it was unclear whether or not, and how/when EUMETSAT would make the information available, and
b. there was an alternative to the EUMETSAT’s methodology for calculating ash plume heights.

Even though EUMETSAT implemented the algorithm, dubbed “VOLE”, providing near-real time results, the quality of both mass loading and ash height had yet to be determined..

3.2.1 VOLCANIC ASH DETECTION BY SEVIRI

The prime reason that the SEVIRI measurements contain information about volcanic ash is that the extinction coefficients for silicates show clear wavelength dependence.

Therefore, brightness temperatures of the 10.8 micron and 12.0 micron channels slightly differ in presence of silicate aerosols as, in particular, volcanic ash. Furthermore, it turns out that this wavelength dependence differs between silicates on the one hand, and water vapor and ice on the other hand. As a result, volcanic ash can be detected, and volcanic ash clouds can in principle be distinguished from water vapor clouds (as a function of optical thickness and relative location of water vapor, ice and ash).

Further investigation of this effect has shown that quantitative information on the mass loading can be derived by complex radiative transfer calculations.
Although atmospheric volcanic ash loadings can vary by orders of magnitude, validation results show a good agreement between the mass loading derived from satellites and other instruments and measurements, indicating that the VOLE estimates of mass loads by SEVIRI are sufficiently accurate for practical use.

However, in the continuous 18-month use there were little possibilities offered of fully testing the algorithm as there were no major ash plumes erupted in the EVOSS’ (and SEVIRI’s) regions of interest. The only events – quite frequently occurring, 11 times in four months only in 2013 – were the mild eruptions (or strong lava fountaining episodes) at Etna: they offered the opportunity of observing that the algorithm’s criticalities in a complex, wet and relatively warm troposphere.

Identified criticalities are associated to:
(a) the detection - and the validation of detection - of ‘light’ ash plumes associated to steam;
(b) the frequent occurrence of false alerts associated to meteorological features.

Below, we give some examples taken from VVO, relating to the month of April 2013, during which there were 5 eruptions of Etna – the 3rd, the 11th, the 18th, the 20th and the 27th. The one on the 27th was also the last of the 2013 sequence. The examples refer to the three most significant ones, those of April 3rd, 20th and 27th, which gave rise to significant ash fallout. EUMETSAT’s “VOLE” reproduced properly the plume of the first eruption, but missed the two others, with significant commission error in the case of the 3rd eruption.

3.2.2 THE EUMETSAT’S PLUG-IN BY FOR THE EVOSS’ DPS
Upon establishment of an operational cooperation agreement established with the Remote Sensing and Products Division of EUMETSAT, the EVOSS’ Input Repository receives in real-time since April 2012 the outputs of the real-time algorithm VOLE, run 24/7 in Darmstadt on the stream of MSG data (full-disk, 15-minute, currently on MSG-3). VOLE is based on the original ash retrieval work by Dr F. Prata (NILU, Norway).

VOLE and its products represent the current State-of-Art for quantitative volcanic ash detection-and-tracking. They were included in EVOSS as an unforeseen complement to the suite of products originally proposed (Aerosol Ash Indexes by SCIAMACHY, GOME-2, OMI, IASI and SEVIRI, plus Ash-and-Ice indexes by IASI). The agreement included the carrying-out of a thorough, multi-temporal validation by EVOSS of VOLE’s Real-Time products (Ash mass loading, mean Ash particle size and Ash plume height), which are picked-up from the Input Repository, transformed in geographical vectors and included in the VVO for thematic display.

The results of the validation are reported in the «EVOSS Final report» with figures (attached) and the deliverable D-4.1-4 (Validation Report).

3.2.3 VOLCANIC ASH HEIGHT BY SEVIRI
Although the calculation of mass loading is thought not to be significantly sensitive to the actual ash height, the retrieval of ash mass loading requires a preliminary estimate of the ash height.

As the EUMETSAT’s VOLE algorithm shows sort of near-constant altitude ranges for individual days (and thus ash plumes), KNMI decided to determine first if a pixel may, or may not contain volcanic ash, by bringing in the computation the MIR band (8.7 micron) besides of the two TIR (12.0 and 10.8 micron) for TIR-TIR and TIR-MIR brightness temperature differentiation. Using ECMWF’s (Reading, UK) statistical troposphere profiles, altitude is determined from the 10.8 micron TIR brightness temperature in the local ECMWF temperature profile. Naturally, as the temperature profile is a climatological mean, the actual profile will be different from that and will remain unconstrained unless atmospheric soundings are carried out at the same time and the same place.

Overall, the two methods provide significantly different results, which leaves still unconstrained the height – with the inherent trade-off on the ash loading computation.

The most likely explanation is that the EUMETSAT method is unsuitable for a physically realistic detection of ash heights, as it uses the lowest brightness temperature as ash-height estimate for ash-pixels averaged over a very large area. The EUMETSAT ash heights will vary around the height of the lowest brightness temperature due to variations in surface (skin) temperature.

3.2.4 AEROSOL ASH INDEXES (AAI)
ULTRAVIOLET
The calculation of AAI is based on a residual that separates the spectral contrast at two ultraviolet wavelengths (340 and 380nm / 354 nm and 388 nm) caused by absorbing aerosols from that of other effects, including molecular Rayleigh scattering,
surface reflection, gaseous absorption and aerosol and cloud scattering.

For UV-visible sensors like GOME-2, OMI and SCIAMACHY (until it was operating <08-04-2012), the Absorbing Aerosol Index (AAI) is commonly in use also for volcanic ash, although ordinary UV-absorbing aerosols (desert dust, biomass burning, e.g.) are the prevailing trigger for AAI. A validating procedure commonly in use is that AAI is considered trustworthy only if it is simultaneously detected with an SO2 plume.

However, this procedure will fail as (a) there can be major SO2 emission without ash - which is the case of Nyiragongo, for instance - and (b) it is frequently observed that SO2 and ash undergo different fates, buoying at different altitudes thus spreading in different directions, at different speeds and with different dilution rates.

IN INFRARED

In Infrared, ash has a more marked and distinct spectral signature than in the UV wavelength range. In EVOSS, ash is measured with the geostationary SEVIRI and the polar IASI, onboard MetOp-A and -B (EVOSS has exploited only IASI-A). In terms of Index, the currently available ash algorithm for IASI is basically an Ash Index technique, which exploits the brightness temperature difference between channels of wavelength 8.6 and 8.1 micron. This difference is very sensitive for all types of ash: however, although the IASI Ash Index is more selective than the UV AAIs for volcanic ash, it may easily flag as ash other mineral dust.

In the eruption of Grímsvötn on May 29, 2011, IASI and the UV payloads allowed emphasizing the split of ash and SO2 we have recalled above as a major limit in the proper identification of Ash from Absorption Aerosol Indexes. In that eruption indeed, all sensors uniformly pointed to the SO2 plume being dispersed to the north and the ash to trend southwards.

There is no independent proof that SO2 had been transported to the north, excepting that 4 different payloads overpassing Iceland between ca. 8:00 UTC and 12:UTC measured the same pattern: which is a strong clue for the observation to be validated. Conversely, qualitative ground observations in Scotland confirmed that ash had well been transported southwards: the explanation is that ash and SO2 were not injected at the same altitude and did not follow the same path, as imagined.

3.2.5 CONCLUDING REMARKS ON THE REMOTE SENSING OF VOLCANIC ASH

Overall, from entry into operation of the VOLE processing line on ash (late April 2012) until the last observed event in the EVOSS timeframe (April 27, 2013), there were only 14 episodes of ascertained ash emission.

All such eruptions were at Etna, all moderate, short lasting and presenting the same eruptive style: lava fountaining with more or less relevant ash emission.

The observed behavior of the ASH Service in EVOSS was the following:
- The EUMETSAT’s VOLE-based service, scored 3 ash episodes detected and 11 missed, with an overall percentage of success as low as ~27% (by event detected: Yes/No), whereas NO conclusive validation of quantitative products «Ash Loading» and «Grain Size Distribution» could be done (see Validation Report, deliverable D-4.1-4).
- The AAI products with any UV payload (SCIAMACHY, OMI and GOME-2) scored even less, ~14=%,
- Significant “commission errors” were observed, in the order of 500% for SEVIRI’s VOLE and >700% for the various UV-based AAI (in number of events: 5 and >7 false alarms for each properly detected ash event, respectively).
- As for volcanic ash height, the apparently better performing algorithm by KNMI (see again Validation Report D-4.1-4 for eruptions falling out of the temporal and spatial perimeter of the EVOSS “Ash Service”) could not be tested on situations of major steam pollution of the ash signal as, for instance, these 14 eruptions of Etna and the large eruption of Nabro, June 12 - July 17, 2011.
- As Ash Indexes – UV or IR – are

We may conclude that – unfortunately – all figures shown above are large enough to spoil the trust in both the quantitative VOLE approach with SEVIRI, and the qualitative AAI approach with any UV or IR payload.

Overall, this calls for the urgent need of major improvements/advances in such sensitive field for the aviation.

4. GROUND DEFORMATIONS

4.1 DIFFERENTIAL SAR INTERFEROMETRY FOR DEM CORRECTION

The goal of RTD activities is the implementation of a service prototype focused on the need of rapid and precise DEM reconstructions for volume change assessment after major eruptions.
The base of this service was the computation of Differential interferograms on the area of interest computed on the basis of tandem pair images.

A Multi-interferogram approach is defined as a combination of more than one pair – when available – in order to reduce the noise component that is a strong source of errors.

In order to reduce the phase contributions and isolate changes induced by the event, a first, “baseline” DEM is computed using a long series of SAR data.

- The computation is done using the SqueeSARTM algorithm in ascending and descending geometry, to reduce areas that are not visible because of the chosen acquisition geometry.
- This pre-event interferometric DEM is kept as the master for future differentiation with a post-event DEM.
- The post-event DEM correction is done starting from the previous product, using whenever it is possible a multi-baseline approach (combination of several “tandem” pairs)

The current configuration of the COSMO-SkyMed (CSK) mission, allows acquiring “tandem” pairs, that is, images from two satellites overpassing the target area with a one-day interval only. This is the case of satellites SAR2 and SAR3 of the constellation CSK.

Short temporal baseline (a few days) can still be used (referring to TerraSAR-X 11 days, and PAZ-X travelling 4 days from TerraSAR-X, but also the forthcoming Sentinels, providing a revisit time of 12 days for each satellite. With longer intervals, a weak “no deformation” hypothesis should be adopted.

Both the setup and the provision of the service were jeopardized by the data availability. Indeed:

- The agreement was centred on 200 scenes (25 Ascending and 25 descending for each of the 4 test-and-demonstration areas).
- After clarification of the institutional responsibility share for data provision, the request was authorized in spring 2011 and placed via the “DAP” data order protocol.
- After the acquisition of some scenes, the new data distribution policy was introduced: from DAP to Data Ware House (DWH)

The application of SqueeSAR for baseline DEM computation to the 4 areas of interest was further limited by the availability of data: the planned amount of data (above) was the object of new cuts requested the DataWareHouse: each area could be covered just in one geometry, and time series had to be limited to a set of 15 scenes. This had a severe impact on the quality of the results for two reasons:

- Volcanic areas, characterized by eventually steep and generally rough topography, cannot be monitored from opposite point of view, causing the result to be incomplete in terms of coverage (foreshortening, shadowing and layover easily occur when relevant topography is present
- The limited number of images and the consequent shortage of the analysis window create a result with higher standard deviation: SqueeSARTM has a precision factor depending on the number of available acquisitions, their uniform distribution within the observation window, and the length of the observation window itself.

In conclusion, as offered in the proposal, the Ground Deformation Service worked on 4 areas: Grand Comore’s Karthala, Montserrat’s Soufriere Hill, Reunion’s Piton de la Fournaise, Nyiragongo-Nyiamuragira area in Congo, but each area was covered in one geometry only, with obvious biases because of the one-directional speckle and the amount of layover (minimum incidence angle was 27° for all images).

The summary of 126 Cosmo-SkyMED images received [Volcano, Area, Mode-Satellite, Orbit, Dates, Data] is below:

- Nyiragongo-Nyamuragira, Congo H4-01-02-03 Desc. 21/11/2012-14/04/2013 n. of images: 18
2) Piton de la Fournaise, Reunion H4-03 Asc. 14/04/2011-03/01/2012 n. of images: 19
3) Karthala, Grand Comore H4-03 Desc. 16/04/2011-22/07/2011 n. of images: 20
4) Soufriere Hills, Montserrat H4-01 Asc. 20/05/2011-30/12/2011 n. of images: 30

Strongly varying baselines between 0. And >1 km (the critical baseline for the 3-cm wavelength of SAR2000 is <0.2 km), only 3 pairs for the first series on Congo, and only 1 pair for the second series could be fully exploited for the planned full-SqueeSAR™ application.

4.2 PRECISE MULTITEMPORAL MONITORING OF GROUND DEFORMATIONS
In EVOSS, ground deformations are monitored by the SqueeSAR™ methodology, an evolution of the PS-InSAR™ ‘Permanent Scatters interferometry’ exploiting the EVOSS developed precise DEM computation by “tandem” measurements. No systematic ground deformation analysis was done, on account of the relatively small number of scenes, the restriction to one geometry only (Ascending or Descending) and the delivery delay, typically unsuited to the near-tactical information refresh which is the primary target of EVOSS.

However, differential multi-temporal ground deformation analysis was attempted with the second dataset on Congo, composed of 18 images acquired between November 2012 and April 2013. The analysis returned a framework of strong-to-moderate subsidence along the >22 km long 2011-2012 lava flow, and moderate-to-weak subsidence still acting on the Nyamuragira’s 2010 lava flow. The overall effect, well-known, is associated to cooling and crack failure-driven micro-collapses on newly emplaced lava flows. No precursory deformation was detected in the pre-eruptive phase in Autumn 2011, also because pre-eruption available images were limited to one month before onset, and did not contain evidence for active vertical dynamics.

See attached “EVOSS_Final_report” attached (with figures).

4.3 AMPLITUDE-COHERENCE DETECTION OF MORPHOLOGY CHANGES

Taking advantage of frequent SAR satellite overpasses and of sufficient data availability granted by the GMES Data WareHouse, ad-hoc amplitude and phase (separately) analyses of SAR data were carried out for “tactical”, semi-quantitative “change detection” assessment of newly opened eruptive features.

Indeed, the 06/11/2011 – 15/03/2012 lateral-to-excentric eruption indirectly associated to the Nyiamuragira volcano (eruptive vents opened 12-15 km east of the Nyamuragira summit craters, calling for a rift event rather than one strictly associated to that system, see the following figure) took place in presence of persistent cloud cover and bad weather on the whole eruptive theater, not allowing opto-electronic UV-VIS-NIR-SWIR-TIR vision of volcanic features on ground and in the lower atmosphere during the first two days of eruption.

The problem persisted for opto-electronic payloads acquiring at low temporal rates and any spatial resolution, even for MODIS, whereas the top-refresh rate of SEVIRI allowed see-through vision (and the related measurements), though scattered.

Large landscape changes associated to 2011-2012 eruption of Nyamuragira were mirrored by reflectivity and coherence changes between the first scene before the onset and the first scene after the end of the eruption. A sequence of six reflectivity SAR Cosmo-SkyMED-1 returned powerful evidence for appearance and build-up of the main eruptive of centre immediately after the onset of the eruption on 06/11/12.

Major changes in amplitude were observed during about one month, and showed the build-up and the evolution of the sequence of eruptive vents. Coherence drop and amplitude change, conversely, allowed the phase mapping of the lava flow by “Speckle Tracking”: the maximum flow length mapped is 22.5 km, about 20.5 km of which were done in the first five days of eruption.

The very-high resolution imaging capacity of the SAR constellation Cosmo-SkyMED- at the level of the 3-meter resolution offered by the satellite’s acquisition mode ‘Stripmap’ – was also exploited to observe morphology changes within the summit crater of Nyamuragira, during the eruption, its ending phases and the immediate post-eruption phase. Supervised change detection allowed observing and locating a major, over 300m long semicircular collapse which took place within the inner summit crater and triggered – or accompanied – the post-eruption resuming of degassing from Nyamuragira, in addition to the permanently degassing Nyiragongo’s lava lake.

5. DEMONSTRATION

The demonstration of the EVOSS information System was carried out over volcanoes covering a wide range of eruptive styles, from permanent lava lakes (Nyiragongo, Erta Ale) to strong strombolian (Etna, e.g.) effusive-to-phreatomagmatic (Karthala, e.g.) to explosive (Montserrat).

Following the negotiation, there was an agreement on 4 broad sites for demonstration and validation of the Ground Deformation Service – as it was subjected to some limitations in quantity and timeliness of data provision – while the demonstration of Thermal, SO2 and Ash was designed from the beginning with no areal limitation.
EVOSS TEST SITES CHOSEN (A-PRIORI) FOR GROUND DEFORMATION SERVICES
Piton de la Fournaise (Reunion Island) effusive
Soufriere Hills (Montserrat, B.W.I.) explosive
Karthala (Comoros) effusive, ephemeral lava lake, explosive
Nyamulagira (Congo) effusive
Nyiragongo (Congo) permanent lava lake

EVOSS TEST SITES FOR THERMAL AND VOLCANIC EMISSION SERVICES (ALL ERUPTIONS >2004)
Piton de la Fournaise (Reunion Island) effusive
Soufriere Hills (Montserrat, B.W.I.) explosive, SO2
Karthala (Comoros) effusive, ephemeral lava lake, ash, SO2
Nyamulagira (Congo) effusive, SO2
Nyiragongo (Congo) permanent lava lake effusive SO2
Etna (Italy) strombolian, effusive, ash, SO2
Stromboli (Italy) strombolian
Jebel-al-Tair (Yemen) effusive, SO2
Ol’Doinyo Lengai (Tanzania) explosive, low-temp. effusive
Manda Hararo (Ethiopia) effusive
Ert’a’Ale (Ethiopia) permanent lava lake
Dabbahu (Ethiopia) effusive, SO2
Dalaffilla (Ethiopia) effusive
Eyjafjallajökull (Iceland) effusive, explosive, ash, SO2
Grimsvotn (Iceland) explosive, ash, SO2
Nabro (Erithrea) explosive, effusive, ash, SO2
Jebel-Zub’Air (Yemen) submarine, SO2
El Hierro (Canary Islands) submarine, SO2

Full-size demonstrations were run without discontinuity in the periods:
• January 2010 – May 2011 for off-line products
• June 2011 – June 2013 for near-real-time products

In the above second phase, services entered operation progressively from June 2011 (Thermal) to October 2011 (SO2 and EVOSS-Ash) and April 2012 (EUMETSAT-EVOSS Ash)

Thanks to the continuous, quantitative, automated, real-time, integrated exploitation of satellite sensors SEVIRI, MODIS, OMI, GOME-2 and IASI, EVOSS has started offering in 2011 and is still offering to date the following services, over Europe, Africa and the Lesser Antilles:
– Real-time (15 minutes), detection, location and quantitative evaluation of Thermal Anomalies associated to Magma at surface at any volcano in the current area of operation (High-Temperature Anomaly Service)
– Real time (15 minutes) detection, location, mapping and quantitative monitoring of Volcanic Ash plumes, by State-of-Art technology (Volcanic Ash Service)
– Near-Realtime (<daily) detection, mapping and quantitative evaluation of Anomalous SO2 concentrations at any volcano in the current area of operation (SO2 Service)
– Delay-time Ground deformation and Volcanic pattern Change Detection by spaceborne Radars (Ground Deformation Service)

ERUPTIONS DEALT BY EVOSS IN OFF-LINE MODE
Nyamulagira (Congo) : Eruption January 2 to 29, 2010
Soufriere Hills (Montserrat) : Pyroclastic flow on February 11, 2010
Eyjafjallajökull (Iceland) : Eruption March 20, 2010
Manda Hararo (Ethiopia) : Eruption March 21, 2010
Piton de la Fournaise (Reunion) : Eruption October 14, 2010
Eruption on: December 9, 2010
Etna (Italy) : Eruptions on: January 12, 2011
April 9, 2011
May 11, 2011
Grimsvötn (Iceland) : Eruption May 24, 2011

ERUPTIONS DEALT BY EVOSS IN NEAR-REAL-TIME MODE
Nyiragongo (Congo) : Lava lake - permanent May 2012- June 2013 (SEVIRI)
Etna (Italy) : Eruptions July 9, 19, 25 and 30
Eruptions August 5, 12, 20 and 29, 2011
Eruptions September 8, 19 and 29, 2011
Eruptions October 8 and 23, 2011
Eruptions November 15, 2011
Eruptions January 3, 2012
Eruptions February 6, 2012
Eruptions March 4 and 18 , 2012
Eruptions April 1 -12 - 24, 2012
Eruptions February 2, 19-20, 21-22 and 28, 2013
Eruptions March 4 and 16, 2013
Eruptions April 3, 11, 18, 20 and 27, 2013
Nyamulagira (Congo) : Eruption November 6, 2011 to March 15, 2012
Stromboli (Italy): Eruption July 6, 2012 and January 19, 2013
Ol’Doinyo Lengai (Tanzania) Hot spots (wildfires) August 7 to October 18, 2012
Hot spots (wildfires) April 8, June 20, September 8, 2013
Soufriere Hills (Montserrat) : hot spots (unclarified) from August 6, 2012
El Hierro (Hierro, Canary Isl.): Submarine December 2011, May 2012, June 2013

The demonstration was based on the exploitation of the following 16 payloads (up to a maximum of 6 simultaneously) in the automated, quantitative post-processing and product provision in EVOSS:

n.3 SEVIRI InfraRed payloads on geostationary MSG-3 (0°), MSG-1 (3.5°E), MSG-2 (9.2°E),

n.2 MODIS InfraRed payloads onboard polar platforms Terra and Aqua

n.2 GOME-2 UltraViolet payloads onboard polar platforms MetOp-A and MetOp-B

n.2 IASI hyperspectral Infrared payloads onboard polar platforms MetOp-A and MetOp-B

n.1 OMI UltraViolet payload onboard polar platform AURA (Skytrain)

n.2 JAMI InfraRed payloads on geostationary MTSAT-1R, and MTSAT-2 (both at at 145°E)

n.4 SAR2000 Radar onboard platforms CSK-1, -2, -3, -4 of the Cosmo-SkyMED constellation.

Two further payloads (the synthetic aperture radar ASAR and UltraViolet payload SCIAMACHY) were run until 08/04/2012, then went lost with the ESA’s polar platform ENVISAT.

The following users have been using the EVOSS services and provided useful feedbacks to the team:
(Entities marked by asterisk * did not participate in the proposal but joined the project after the kick-off date)

VAAC AND AGENCIES
• Volcanic Ash Advisory Centre (VAAC), Toulouse, France
• Volcanic Ash Advisory Centre (VAAC), London, UK *
COLLECTIVE DEMONSTRATIONS OF EVOSS SERVICES, products and the underlying Science, and training of Users to the use of the Virtual Volcano Observatory, were held in:

- Keyworth, UK – 2012 for the UK and Toulouse VAACs, INGV (Italy), IMO (Iceland) and MVO (Montserrat)
- Addis Ababa, Ethiopia – 2013 for IGSSA (Ethiopia), INMG (Cape Verde), INGV (Italy), KVO (Comoros), UNOPS and OVG (DRC), DGSM (Uganda) and CERD (Djibouti)
- Dodoma, Tanzania – 2013 for GST (Tanzania)

Users from Africa have shown pragmatic operational interest in EVOSS.
In particular, Congo, Comoros, Djibouti and Tanzania asked for the TAS and SO2 services to be kept running beyond the project end.
This request is currently satisfied on a voluntary basis, as EVOSS is being run (though in slightly reduced configuration, to allow durability) for >6 months after the project close on July 11, 2013.
In eastern D.R. Congo indeed, during the long lasting (and on-going) crisis of the Nyamulagira-Nyiragongo volcanic area - close to the densely populated city of Goma - UNOPS and GVO still use EVOSS Thermal and SO2 near-real-time/delay-time products.
As the military unrest impels servicing of any instrument in the field since 2011, the EVOSS products are exploited for tracking the dynamics of both volcanoes but – principally and surprisingly - to contrast frequent spreading of uncontrolled false rumors about “major eruptions preparing or ongoing”.

An excerpt of main suggestions and constructive criticism from the Users community is reported below:

1) GOMA VOLCANO OBSERVATORY (Dr. K. Karume, Director):
“As you can understand, given the insecurity in the region, wars and loss of ground equipment, only remote sensing can help in such environment. This is exactly what EVOSS does. Whenever there is something wrong we refer ourselves to EVOSS and there is always in our monthly report a chapter dedicated to results with remote sensing by EVOSS. The current situation in Goma is a situation with no peace and no war, with many killings and guns in the town. We are working with less than 25% of our normal capacity”.

2) UNITED NATION UNOPS IN GOMA (Pr. D. Tedesco, expert in charge of managing UN support to GVO):
“It can become more appealing. The use of the portal (and of the data) from end-users will help add more information related to volcanic processes data through knowledge exchange”.

3) GEOLOGICAL SURVEY OF TANZANIA (Pr. A. Mruma, Head of GST – note that Ol’Doinyo last erupted in 2010):
“For the first time GST will be able to observe volcanoes and use this information to advise both the Tanzanian National Disaster Committee and local communities about the type, style and changes in eruptive activity of Ol’Doinyo Lengai, as well as any threat the activity poses to people, infrastructure, livestock and livelihoods”.

4) VOLCANO OBSERVATORY OF KARTHALA (Dr. H. Soulé, Director – note that Karthala kept quiescent since 2007):
“To monitor the Karthala activity, OVK relies on a network of seismic and inclinometric equipment, and a gas detection station. As equipment close to the volcano summit is the target of frequent vandalism and theft, however, the overall system is insufficient to allow warning people with short-to-very short notice. EV OSS’ satellite observations will be of great help for us as they will allow us:

- having a better view of Karthala in non-eruptive times;
- detecting more accurately and fast any Karthala’s eruption;
- having optimal monitoring of the Karthala’s eruptive activity during crisis times”

5) DJIBOUTI ‘S CERD (Mr. S. Abdi, research engineer at CERD – note, last eruption in Djibouti was in 1979):

“Djibouti’s rift, finishing underwater in the Khoubbet gulf, west of Djibouti, is the termination of the Ethiopian rift. Considering the small size of Djiboutian land, any eruptive or seismic activity in Ethiopia, Eritrea or Yemen has impact on Djibouti, both at the level of air traffic (as Nabro, in 2011) and at the level of uncontrolled rumors on eruptions preparing in the area of the 1979 Ardoukoba eruption. In 2012 and 2013, EVOSS was perfect in showing that no eruption was occurring nearby, and rumors were wrong. Although CERD runs a local geophysical observatory for seismology and deformations, in case of eruption EVOSS would still be needed for providing a real-time component and the thermal and SO2 information, which is not acquired by the observatory. SAR evidence of landscape changes would also be very much appreciated”.

5.1 CONCLUSIONS

6. CONCLUSIONS

EVOSS has been able to monitor - and distribute results in real-time to as many as 34 registered Users - 42 eruptions at 9 volcanoes even before completion of services available the Virtual Volcano Observatory.

The latter, entered the operation-demonstration phase in June 2011, was stepwise expanded until Spring 2012, and is continuously run since.

As of June 30, 2013, the volcanoes simultaneously monitored by EVOSS are: Stromboli and Etna (Italy), Hierro (Canary Isl., Spain), Jebel-al-Tair and Jebel Zubair (Red sea, Yemen), Manda Hararo, Dalafiilla, Dabbahu, Erta Ale (Ethiopia), Nabro (Eritrea), Mt.Cameroon (Cameroon), Nyiragongo and Nyamuragira (Congo), Ol Doinyo Lengai (Tanzania), Karthala (Comoros), Piton de la Fournaise (Reunion Isl., France), Soufriere Hills (Montserrat, B.W.I) Eyjafjallajökull and Grímsvötn (Iceland).

The thematic maps and data series we have widely shown in this report for Thermal, Sulphur Dioxide and Ash, can be browsed anytime and anywhere by any registered End-Users, knowing that the data stream is continuous and in real-time. Conversely, there is/was no true real-time for the Ground Deformation component, which may deserve another structure and an affordable data pipeline to become sustainable: this does not hold true at the moment, but a significant step-forward towards this target is expected to be done with the pair of Sentinel-1A/-1B Radar satellites, to be launched in 2014 and 2016 respectively.

Achievements were beyond our expectations for five objective reasons.

(1) The system design proved immediately effective, as assembly, homogenization and validation took shorter than scheduled;
(2) The suite of real-time algorithms originally chosen for all parameters - but ash - remained State-of-Art;
(3) State-of-Art products for ash were later introduced on-line, thanks to a test-against-service agreement with EUMETSAT;
(4) The demonstration was run in full configuration during more than twice the planned time, with less than 1% failure suffered by the overall EVOSS system, and less than 1% delays/adjustments due to space segments operations; and
(5) The expected effort for adapting algorithms to payloads’ lifecycles (swapping from MSG-2 to MSG-3, for instance, or using the four Cosmo-SkyMED-1, 2, 3 and 4) or porting onto new payloads for expanding the geographic horizons of EVOSS (as it has been the case for JAMI onboard MTSAT-1R and MTSAT-2) was – either in replacement of the already exploited ones when the become others as they become obsolete or whose real life cycle has gone too far beyond the design life cycle.

After the pre-operational experience done with moderate-to-high spatial resolution payloads, at moderate-to-low temporal resolution, on some volcanic spots worldwide within the demonstration project GLOBVOLCANO [RD28], EVOSS has disclosed one conclusive prospect, that is: the full integration of inhomogeneous data issuing at high-to-extra-high release rates from UltraViolet, Radar and InfraRed payloads, geostationary or LEO, is definitely at reach.

Keeping the temporal target of Near-Rea-Time to Real-Time processes and distribution of results in a format suitable for
immediate use by non-specialist personnel in charge of planning and crisis management, the next target is twofold: in real-time and worldwide. 

Achievement of such target requires a more complex setup in terms of running 7/24 operations, an important framework for telecommunication and data exchange, and establishment of effective co-operation agreements with major institutional stakeholders at the scale of volcanic hazards (almost worldwide).

It is anticipated that – on the one hand – the working scheme cannot be purely market-driven as there is a prevailing institutional components in the management of volcanic risks on national territories: on the other, it won’t be purely institutional as a large subset of End-Users (airlines and international hubs) is commercial.

Potential Impact:

EVOSS has impact on two areas: (1) the monitoring of a large number of individual volcanoes at the same time and (2) the direct monitoring or the forecast of ash plumes, and already had impact on the first one. Monitoring can be of interest for volcanoes monitored by observatories provided with acceptable completeness of the arrays, but is particularly important for that large majority of volcanoes without any valuable monitoring system. As for the plumes of volcanic ash - besides of using State-of-Art (EUMETSAT) products for ash loading and height - EVOSS presents the clear advantage of monitoring at once the thermal, ground deformation and gas outputs at all active volcanoes in the area of interest, which would offer the possibility of evaluating at all times the source term, the potential column and the height of the plume.

The following End-Users (about half of them joined the growing Users group after complimentary testing) have been extensively using the EVOSS services - and are still using them as the system is kept operating - though on a slightly reduced range of products - after the end of grant no. 242535, and provided useful feedbacks to our team of developers:

- Volcanic Ash Advisory Centre (VAAC), Toulouse, France
- Volcanic Ash Advisory Centre (VAAC), London, UK
- Volcanic Ash Advisory Centre (VAAC), Washington, USA (did not participate actively as no eruptive event occurred in its area of concern during the project time) *
- United Nation UNOPS at the Goma Volcano Observatory, Goma, Congo
- Icelandic Meteorological Office (IMO), Reykjavik, Iceland
- Department of Geological Survey and Mines of Uganda, Entebbe, Uganda
- Centre d'Etude et Recherche de Djibouti (CERD), Djibouti
- Geological Survey of Tanzania, Dodoma, Tanzania
- Goma Volcano Observatory (OVG/CRSN), Goma, Congo
- Karthala Volcano Observatory (OVK/CNDRS), Moroni, Comoros
- Addis Ababa Science Faculty (Geophysical Observatory), Ethiopia
- Seismic Research Centre, University of the West Indies, Trinidad
- Montserrat Volcano Observatory (MVO), Montserrat, BWI
- Instituto Nacional de Meteorologia e Geofisica (INMG), Cabo Verde

ALL Users have enthusiastically participated in the collective demonstrations and training session of EVOSS services (including the underlying science) held in Keyworth (Nottingham, UK) in October 2012, Addis Ababa (Ethiopia) in January 2013 and Dodoma (Tanzania) in June 2013.

The five main- main Users from Africa - whose governmental or institute's top representatives asked for the thermal and the SO2 services to be run beyond the project duration - have particularly appreciated the EVOSS service for pragmatic reasons, indicating the main path to follow for future exploitation of the parts of EVOSS pertaining to institutional bodies.

In eastern D.R. Congo, during the long lasting (and on-going) anthropic crisis hitting Virunga (the Nyamulagira-Nyiragongo volcanic area), close to the densely populated city of Goma - UNOPS and GVO still use EVOSS Thermal and SO2 near-real-time/delay-time products. As the military unrest impels servicing of any instrument in the field since 2011, the EVOSS products are exploited both for tracking the dynamics of both volcanoes, and contrasting the frequent spreading of uncontrolled false rumors about “major eruptions preparing or ongoing”.

In extreme synthesis (please view in the attachment "EVOSS_Final_report" and cfr. related deliverables.)
The main suggestions and constructive criticism received from the Users community concerned with the ground-based monitoring of volcanoes:

a) ‘As you can understand, given the insecurity in the region, wars and loss of ground equipment, only remote sensing can help in such environment. This is exactly what EVOSS does. Whenever there is something wrong we refer ourselves to EVOSS and there is always in our monthly report a chapter dedicated to results with remote sensing by EVOSS. The current situation in Goma is a situation with no peace and no war, with many killings and guns in the town. We are working with less than 25% of our normal capacity’ – by the Director of the Goma Volcano Observatory.

b) ‘It can become more appealing. The use of the portal (and of the data) from end-users will help add more information related to volcanic processes data through knowledge exchange’ – by the senior expert of United Nations' UNOPS in charge of the monitoring programme to the benefit of GVO.

c) ‘For the first time GST will be able to observe volcanoes and use this information to advise both the Tanzanian National Disaster Committee and local communities about the type, style and changes in eruptive activity (of Ol’Doinyo Lengai) as well as any threat the activity poses to people, infrastructure, livestock and livelihoods’ – by the Head of the Geological Survey of Tanzania.

Concerning the volcanic aerosols (and in particular volcanic ash), conclusive statements by the VAACs of Toulouse and London were the following:

d) Make joint interpretation of different data sets easier. Such as SO2 releases and Heat anomalies. As InSAR processing is already a part of the portal, introducing the interferograms as a product would be very useful addition. The portal has the potential of being a good monitoring tool as well as a response tool, especially with regard to Deformation - by the VAAC of London;

e) Currently, there is no aviation users (generally represented by IATA - International Air Transport Association) requirement for depicting the current or predicted extent of SO2 areas. This implies that precursory activity of interest for VAAC would be in priority pre-eruptive activity with clues that the eruption would be explosive. Information about general pre-activity can be anyway of interest for awareness of forecaster (early warning) - by the VAAC of Toulouse.

In conclusion, based on 2 full years of operations of the Virtual Volcano Observatory, 1.5 of which with full ash functionality (but with variable score, to be seriously improved in the years to come) it is possible to assess that:

(1) the "institutional market" is at reach for countries which cannot have or cannot run an observatory, but finalization of any consolidation effort cannot happen without strong institutional support - at the level of governments or national agencies. This will provide a strong trade-off with the anywhere/anytime quantitative early warning of volcanic activity, although a convincing business model could not be drawn.

(2) the commercial market, mainly composed of airlines and international hubs, will be at reach once the ash component will be robust and fine tuned-up - which does not seem to be the case today.

List of Websites:

is the website of the project

is the Virtual Volcano Observatory, which can be acceded with ID/pw in your possess or to be requested tevoss@cgspacet