A proposal in response to ESA AO for Earth Explorer Opportunity Missions

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Space Volcano Observatory

December 1, 1998

Institut de Physique du Globe de Paris

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Cover. Pyroclastic flow at Merapi volcano (November 22, 1994). Photo Mangin.

Executive Summary

Background. 1500 volcanoes on the Earth are potentially active. One third of them have been active during this century and about 70 are presently erupting. At the beginning of the third millennium, 10% of the world population will be living in areas directly threatened by volcanoes, without considering the effects of eruptions on climate or air–traffic for example. The understanding of volcanic eruptions, a major challenge in geoscience, demands continuous monitoring of active volcanoes. Presently, in spite of the efforts of many countries, only a few volcanoes are monitored by modern observatories. Even in the best equipped of them, real-time data acquisition on the very active parts of the edifices during crisis is still an extremely difficult and risky task. The only way to provide global, continuous, real–time and all–weather information on volcanoes is to set up a Space Volcano Observatory (SVO) closely connected to the ground ones. Spaceborne observations are mandatory and complement the ground ones as well as airborne ones (helicopters, drones, balloons,…) that can be implemented on a limited set of volcanoes. The project is designed to largely improve the understanding of the volcanic activity and to provide significant advances for the mitigation of volcanic hazards.

Scientific objectives. Our goal is to monitor both the deformations and the changes in thermal radiance at optical wavelengths from high temperature surfaces of the active volcanic zones, that is the areas where the magma reaches the surface: lava lakes, lava domes, lava flows, eruptive vent. For that, we propose to map at high resolution (1.5m pixel size) the topography and the thermal anomalies (pixel-integrated temperatures above ~ 450°C) of active volcanic areas. A size of 6 x 6km is large enough for monitoring most of the target features. A return time of one to three days will allow to get a monitoring useful for hazard mitigation. The active volcanic zones are unstable and often deform significantly prior to paroxysmal events, such as sudden collapses sometimes accompanied by flank pyroclastic flows (nuées ardentes). These zones are remote and dangerous. They cannot be easily equipped with ground equipment and are often masked from a ground based observer by clouds, but due to their elevation may be more easily visible from space. By monitoring the evolution of the topography it will be possible to precisely quantify the deformations with time. This will put constraints on the physical and dynamic processes of the system and contribute to hazard mitigation. Other applications like landslide monitoring, tectonic studies, will be possible. The mission will also provide a first global data base of high accuracy shape and deformations of volcanoes, that may contribute to the global study of terrestrial volcanism. The requirement of fast data processing and interpretation and the constraints on flux of descending data imply the set up of several ground based stations for data collection. The 12-15 major volcanological observatories of the world could host those receiving stations. The proposed space mission characteristics coupling high resolution and high return periodicity are not provided by any other satellite accessible to the scientific community and the possible exploitation of commercial high resolution imagery satellites in the future is not compatible with the operational requirements of a SVO mission.

C.1. Scientific Justification

C.1.1 - Background

1500 volcanoes on the Earth are potentially active, 500 of them have been active during this century and about 70 are presently erupting (*Table 1*). At the beginning of the third millennium, ten percent of the world population will be living in areas directly threatened by volcanoes, without considering the effects of eruptions on climate or air-traffic for example. About 30.000 people have died from volcanic eruptions in the past 50 years, and billions of ecus of damage has been incurred. Significant advances in eruption prediction and forecasting have been made in recent years, party as the result of studies of the major volcanic eruptions at Mount St Helens (USA) in 1980, Nevado del Ruiz (Colombia) in 1985, Pinatubo (Philippines) in 1991 and Unzen (Japan) in 1991. Over the same period significant progresses have been achieved in understanding of how volcanoes work, especially on a few volcanoes where a particular effort has been made (Decade volcano program) following the recommendations of the IAVCEI. This is the case for Etna, Vesuvius, Vulcano (Italy), Santorini (Greece), Teide (Spain), Furnas (Portugal), Sakurajima (Japan), Merapi (Indonesia), Popocatepetl (Mexico), but many other volcanoes are not sufficiently monitored and a catastrophe like that of Nevado del Ruiz could occur again, especially in the Andes. The understanding of volcanic eruptions, a major challenge for the geoscience community, demands continuous monitoring of active volcanoes. With the growth in world population - especially around volcanoes - and the increasing cost and sophistication of the engineering structures and technical installations, there is an increasing need to forecast catastrophic events and to mitigate their damaging effects. Presently, in spite of the efforts of many countries, only a few volcanoes are monitored by modern observatories. Even in the best equipped of them, real-time data acquisition on the very active parts of the edifices during crisis is still an very difficult and risky task. The only way to provide global, continuous, real-time and all-weather information on volcanoes is to set up a Space Volcano Observatory (SVO) closely connected to the ground ones. Spaceborne observations are mandatory and complement ground measurements as well as airborne measurements by airplanes, helicopters, drones, or balloons. While satellite observations can provide temporally continuous high-resolution imagery, airborne measurements (that have become very effective in the last years) provide very high spatial resolution at specific points in time, and ground-based methods typically provide high precision measurements at specific locations, limited by logistics and accessibility. The SVO project is designed to largely improve the understanding of the volcanic activity and to provide significant advances for the mitigation of volcanic hazards. Among the different geophysical parameters used for understanding and forecasting the evolution of an active, the deformations and the thermal changes are of primary interest. These parameters can be highly dynamic before and during paroxysms. As a first step in the set-up of a constellation of small satellites dedicated to volcanic hazard mitigation we propose the realisation of a satellite capable of measuring with a high resolution and a frequent sampling rate the topographic and thermal changes of the most central parts of the volcanoes.

Tectonic zone	Volcano	Altitude (m)	Country	Last strong event	Population within 20km around volcano (millions)
Europe	Etna	3350	Italy	since 1995	**0.5 (Catania)**
Europe	Stromboli	926	Italy	08/09/98	0.01
Europe	Grimsvotn	1725	Iceland	30/09/96	0.001
Africa	Nyamuragira	3058	Congo-K	27/10/98	**0.5 (Goma)**
North America	St. Helens	2549	USA	01/07/98	0.
North America	Yellowstone	2805	USA	09/01/98	0.05
Alaska	Chiginagak	2075	USA	07/11/97	<0.001
Alaska	Pavlof	2519	USA	03/06/97	0.
West Indies	Soufriere Hills	915	W Indies	12/11/98	0.1
Central America	Cerro Negro	675	Nicaragua	06/11/98	0.3 (Telica)
Central America	Popocatepetl	5465	Mexico	23/09/98	**>1 (Mexico City)**
Central America	Pacaya	2552	Guatemala	19/09/98	0.002
Central America	Arenal	1657	Costa Rica	05/05/98	0.05
Central America	Rincon De La Vieja	1916	Costa Rica	16/02/98	0.05
Central America	San Cristobal	1745	Nicaragua	20/05/97	0.002
Central America	La Madera	1394	Nicaragua	27/09/96	
South America	Fuego	3763	Guatemala	19/11/98	**0.5 (Antigua)**
South America	Guagua Pichincha	4784	Ecuador	07/10/98	**>1 (Quito)**
Japan - Aleutian	Iwate	2041	Japan	10/07/98	<0.001
Aleutian	Atka	1533	USA	30/06/98	<0.001
Japan - Aleutian	Sakura-Jima	1117	Japan	24/01/98	**0.5 (Kagoshima)**
Japan	Adatara	1718	Japan	15/09/97	
Japan	Hakkoda	1585	Japan	12/07/97	0.002
Aleutian	Shishaldin	2857	USA	03/06/97	<0.001
Aleutian	Okmok	1073	USA	02/05/97	<0.001
Aleutian	Amukta	1066	USA	17/09/96	<0.001
Kamchatka	Karymsky	1486	Russia	21/04/98	< 0.001
Kamchatka	Bezymianny	2882	Russia	05/12/97	<0.001
Kamchatka	Shiveluch	3283	Russia	31/07/97	<0.001
Kamchatka	Kliuchevskoi	4835	Russia	20/01/97	<0.001
South East Asia	Merapi	2911	Indonesia	since 1992	**>1 (Jogyakarta)**
South East Asia	Manam	1807	New Guinea	07/10/98	<0.001
South East Asia	Papandayan	2665	Indonesia	01/07/98	
South East Asia	Peuet Sague	2780	Indonesia	27/04/98	0.05
South East Asia	Karangetang	1784	Indonesia	19/04/97	
South East Asia	Rabaul	688	New Guinea	28/05/97	**0.1 (Rabaul)**
South East Asia	Krakatau	813	Indonesia	03/04/96	<0.001
Atlantic	Fogo	2829	Cape Verde	02/04/95	0.05
Indian Ocean	Fournaise (Piton)	2631	France	09/03/98	0.05
Pacific	Cerro Azul	1690	Ecuador	05/10/98	<0.001
Pacific	Kilauea	1222	USA	since 1983	0.002
New Zealand	White Island	321	New Zealand	02/11/98	0.
New Zealand	Ruapehu	2797	New Zealand	oct-97	0.02

Table 1: The most active volcanoes of the world during the period 1995-1998

C.1.2 - The SVO concept

An ideal space monitoring system for volcanoes would include sensors allowing in continuous and real-time:

1) High resolution monitoring of topographic changes (lava dome growth, determination of volume of eruptive products like lava flows, pyroclastic deposits, lahar deposits, volcanic landslides, plinian and strombolian deposits, …). A resolution of 1m (instead of 10m or more with most of the present systems) would be ideal for greatly increase the knowledge in this field.

2) High resolution monitoring of ground deformations due to the magma movement beneath the Earth surface in the plumbing systems of the volcanoes (e.g. due to the pressure and/or volume variations in magmatic chambers or reservoirs, dike emplacements, etc.) Vertical resolution in the order of 1 cm, relevant to a pixel in the order of 1 m^2, is enough for several applications and it would fruitfully integrate ground measurements nowadays carried out with geodetic techniques (e.g. GPS, levelling, EDM). However, sometimes very large deformations (in the order of several ten of centimetres) occur on volcanoes, for instance, close to the magma-injected fractures or near to very active faults. Those very large deformation also often correspond to the most violent events.

3) Thermal monitoring (1m resolution mapping and monitoring of the magmatic bodies, 5m resolution mapping and monitoring of the geothermal areas on volcanoes, 30m resolution mapping and monitoring of the low energy thermal anomalies, temperature profiles above the volcano and in the volcanic plumes, …).

4) Gas release analysis and monitoring ($H_2 0$, CO_2, SO_2, …).

5) Particle release analysis and monitoring.

Some of the above tasks are already partly covered with existing satellites, but others (the first task for example) are missing form the present space possibilities.

In the framework of this ESA AO, we propose to develop a new satellite dedicated the high resolution imagery of the most active areas of volcanoes (craters, lava flows and lava lakes, lava domes. The system will monitor the subtle changes of the volcano shape through a simple comparison of DEM realised at each passage. This new satellite is expected to greatly enhance the observations capabilities corresponding to the first three elements listed above. The high resolution topographic mapping (first task) will authorise a step forward both in volcano monitoring and in volcanological science, and it is our first priority. The second and third tasks (deformation monitoring, thermal monitoring) are already partly covered by other satellite techniques but not at very high resolution like we propose. Improvement in the mapping of anomalies is thus expected. The proposed system will monitor thermal changes of high temperature areas (in nigh time), by the use of high-resolution stereo images. The ground resolution will be 1.5m, the dynamic range 12 bits (11 useful bits), the minimum repeat time of observation 3 day, and the footprint for one single image 6 km x 6 km. A complete constellation of 3 or 6 satellite would allow monitoring any area every 24 hours or 12 hours. Although the system proposed here has a 3 days repeat time only (at equator, at higher latitudes the repeat time will be 2 or 1 day) its characteristics are unique and would already constitute a significant step forward in high resolution volcano monitoring from space.

None of the presently existing or planned satellite system meet those requirements that are mandatory for an effective monitoring of small, hot and highly dynamic sources of the volcanic phenomena. Satellites with visible and infrared system sensors allow either quasi-continuous global monitoring of non-polar areas of the Earth (including the volcanoes) with >1km pixels (geostationary meteorological satellites such as GOES8/10) or a non-continuous observation with repeat passes over a given area ranging between a few days (SPOT4) to a few weeks (ERS1/2, RADARSAT, LANDSAT TM, …) and intermediate pixel size (10-40m) or approximately 1 km pixels (NOOAA AVHRR and ERS-1/2 ATSR). Although the radar ERS and RADARSAT have enough and adequate dynamics of phase and amplitude signals, the SPOT and LANDSAT TM short-wavelength infrared sensors are not well adapted for the observation of very hot sources, because their dynamic ranges are only 8 bits and their gains were chosen to be sensitive across the range of radiance expected from reflected sunlight, with the result that pixels containing a high proportion of hot thermally radiant material become saturated. Despite their limitations, these systems have proved to be useful for the air-traffic alert during eruptions (in the case of meteorological satellites), for the detection and mapping of thermal anomalies (LANDSAT TM, ATSR, SPOT4), for the detection of ground deformation (ERS1/2, JERS, RADARSAT). However, due to the small extent of the most active part of the volcanoes and to the high dynamic character of volcanic activity, these systems can rarely be used as an operational contributor to effective volcano monitoring that requires a daily updating of the information.

Satellite	SPOT 4	LANDSAT TM	ERS	ECHO	SVO
Dynamic resolution [bit/pixel]	8	8	8-12		11
Coverage	Global	Global	Good	Global	Regional
Image size (km)	60 x 60		100 x 100	100 x 100	6 x 6
Repeat pass on a given area (days)	5-26	16	35	24	1-3
Pixel size (m)	10/20	10/30	8x20		1.5
IR capability	Y	Y	N	N	Y
Vertical DEM accuracy (m) versus DEM pixel size (m)	10/20m *vs* 20/40m	?	5/10m *vs* 40m		1.5m *vs* 1.5m 0.15m *vs* 20m

Table 2: Characteristics of some satellites used for Earth imagery

Although the launch of several commercial satellites for high resolution imagery of the Earth is expected in the next few years (for example the satellite IKONOS will have a pixel resolution of 1 m), the goals of SVO are not compatible with such commercial

satellite imagery for several reasons: repeatability largely depending on the other requests and probably larger than a few days, no real-time data download, cost. In addition, these satellite do not have the capability of single pass stereo imagery, and one stereo couple would imply data acquisitions separated by several days, thus less or no coherence on deforming areas. This would also greatly reduce the interest for volcano monitoring.
In the development of the SVO mission particular attention will be given to the ground segment that is a fundamental element when quick delivery of validated information is requested.

C.1.3 - Scientific Objectives

C.1.3.1 - Volcano monitoring

General goal

Our goal is to monitor both the morphological changes and changes in the pattern of thermal radiance of active volcanic zones, that is the areas where the magma reaches the surface: lava lakes, lava domes, eruptive vents… For that, we propose to map at high resolution (1.5m pixel size) the topography and the thermal anomalies (corresponding to pixels whose pixel-integrated temperature is above ~ 450°C) of active volcanic areas. A size of 6 x 6km is large enough for monitoring most of the target features. A return time of one day would provide sufficient monitoring for hazard mitigation, and a return time of three days is enough for improving greatly the temporal monitoring of remote volcanoes.
Active volcanic zones are unstable and often deform significantly prior to paroxysmal events, such as sudden collapses generally accompanied by flank pyroclastic flows (nuées ardentes). These zones are remote and dangerous. They cannot be easily equipped with ground instruments and are often masked from a ground based observer by low elevation clouds, but due to their elevation may be more easily visible from space (*see C.1.3.1.6 and annex for details*). By monitoring the evolution of the topography with differential DEM it will be possible to precisely quantify the deformations with time. This will put constraints on the physical and dynamic processes of the system and contribute to hazard mitigation. Other applications like landslide monitoring and post-earthquake studies will be also possible.
The requirement of fast data processing and interpretation and the constraints on flux of descending data imply the set up of several ground based stations for data collection. The 12-15 major volcanological observatories of the world could host those receiving stations (*see C.2.7*). The proposed space mission characteristics coupling high resolution visible and near IR imagery on selected targets with high return periodicity are not provided by any other satellite accessible to the scientific community and the possible exploitation of commercial high resolution imagery satellites in the future is not compatible with the operational requirements of the SVO mission.

We divide our discussion of the role of SVO in volcano monitoring into studies associated with lava domes and studies associated with lava flows:

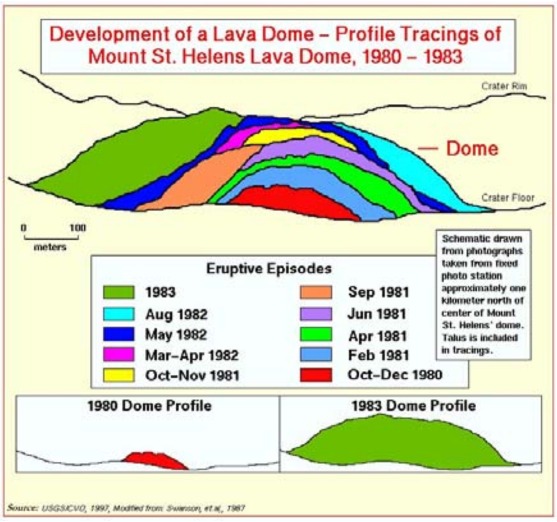
Studies associated with lava domes

Volcanic domes form on volcanoes when viscous lava is erupted slowly and piles up over the vent, rather than moving away as a lava flow does. The sides of most domes are very steep and typically are mantled with unstable rock debris formed during or shortly after dome emplacement. Most domes are composed of silica-rich lava which may contain enough pressurised gas to cause explosions during dome extrusion. Most domes are rather small, but some have volumes exceeding 25 cubic kilometers. The direct effects of dome eruption include burial or disruption of the previously existing ground surface by the dome itself and burial of adjacent areas by rock debris shed from the dome. Domes are extruded so slowly that they can be avoided by people, but they may endanger man-made structures that cannot be moved. The principal hazard associated with domes is from pyroclastic flows produced by explosions or collapses. Such pyroclastic flows can occur without warning during active dome growth and can move very rapidly, endangering life and property up to 20 kilometres from their sources. Such pyroclastic flows can also cause lahars if they are erupted onto snow and ice or incorporate water during movement or if they occur during rainy season in tropical areas.

Pyroclastic flows are avalanches (sometimes hot and glowing) that can move down slopes at speeds up to several hundred of km/h, devastating all living things in their paths. They are recorded from 237 volcanoes and 763 eruptions. For example, Java's Merapi had pyroclastic flows in 31 of its 66 historical eruptions since 1548 AD, and 11 of these 31 have been fatal. Montagne Pelée volcano (West Indies) has 51 dated pyroclastic flow eruptions. Only three occurred in historical time, but that of 1902 killed 28000 people in only a few minutes.

An example: the growth of the lava dome of Mount St Helens in 1980

A dacite lava dome began to form in the crater of Mount St. Helens on October 18, 1980, five months after the catastrophic events of May 18. The dome grew in a complex series of extrusions preceded, accompanied, and at times supplanted by periods of endogenous growth. The extrusions produced short (200-400 meters), thick (20-40 meters) flows, which we term lobes, that piled atop one another and generally did not reach the crater floor before crumbling into talus. The lobes were erupted in an overlapping, seemingly haphazard, manner that eventually built the composite dome. Most of the lobes were fed from the summit region of the dome, but a few issued from eccentric vents high on the flanks. Seventeen episodes of dome growth occurred between October 18, 1980, and October 22, 1986, inclusive. Fourteen episodes produced one lobe each, and three produced two lobes each (December 1980, March-April 1982, and February 1983-February 1984), when the dome ruptured at two different locations.



Endogenous growth (growing from within) began slowly 1-3 weeks before each extrusion. The rate of endogenous growth, determined by geodetic measurements of displacement of the surface of the dome, accelerated almost exponentially to the time of extrusion. The slow, pre-extrusive rise of magma up the conduit and into the dome caused radial cracking and thrust faulting of the crater floor and expansion of the dome itself; such deformation was useful in predicting the start of each extrusion. Endogenous growth generally affected only a relatively small sector of the dome, typically half or less. Commonly the oldest exposed part of the dome was the site of greatest endogenous growth, possibly because cooling and alteration had decreased the tensile strength of the crust, but many exceptions occurred. Some periods of endogenous growth caused sever fracturing, faulting, and distension of the dome. In May 1985 and May and October 1986, sector grabens tens of meters deep and hundreds of meters long resulted from endogenous growth, and outward-directed radial displacements of as much as 70 meters were measured. Endogenous growth was essentially continuous for one full year (February 1983 to February 1984) and became increasingly important during later episodes of growth as the volume of the dome and consequently its holding capacity enlarged. Overall, endogenous growth probably accounts for 30-40% of the volume of the dome.

Talus occurs as extensive aprons mantling the flanks of the dome and in irregular patches high on the dome. The talus accumulations comprise one of the most conspicuous features of the dome. Most of the talus formed from hot rockfalls during extrusion and rapid endogenous growth; only a minor amount was generated by cold rockfalls during periods of quiet. Hot talus blocks developed radial prismatic jointing during cooling. Renewed movement (slumping, rockfalls) broke the fragile, jointed blocks into several joint-bounded pieces and further contributed to the talus accumulation.

Volcano	Dome size (m)	Topographic changes during activity	Paroxysmal effect	Typical growth rate during activity	Frequency of events	Period of activity
Montserrat	300	Important. Up to 30% destroyed	Pyroclastic flows and plinian eruptions, dome collapse	950 000 m^3/day 4.2 m/day	Several/year	Since 1995
Mount St Helens	800 (height: 300)	Up to 100%	Plinian and blast	0.1-0.5 10^6 m3/day 0.5 m/day	Several/year at the beginning	1980-90
Unzen	200	Up to 30%	Pyroclastic flows	?	Several tens during activity	1991-94
Merapi	300	Up to 75%	Pyroclastic flows Avalanches, dome collapse	20 000 m^3/day 0.9 m/day	Several tens /year	Active

Table 3: Characteristics of four recently active lava domes

The dome slowly subsided and spread outward between episodes of growth, apparently as its hot, relatively ductile core yielded under gravitational stress. Typical maximum rates of spreading and subsidence during quiet periods were 2-5 millimetres per day.

When a lava dome is confined within a crater, collapse of the side of a dome cannot cause pyroclastic flows in the same manner as on the previous examples of unconfined lava domes. The example of the lava dome confined within the active crater of Lascar volcano (Chile) shows that when a dome is actively extruding there is little likelihood of a major eruption, but when the dome material is withdrawn back into the volcanic conduit the escape of gases is inhibited and a major explosive eruption will eventually result (Matthews *et al.* 1997). Such an eruption can result in widespread airfall ash deposits and also pyroclastic flows fed by collapse of the eruption column.

SVO applications

DEMs generated from SVO daytime images will provide unprecedented data for measuring and monitoring the growth of lava domes, and for mapping and determining the volume of any pyroclastic flows. By recording data at night, the SVO will document the distribution of hot pixels across the dome. As well as pinpointing the locus of lava extrusion, but will also reveal sites where the dome carapace has become sufficiently cracked to reveal enough of the hot interior to cause detectable thermal radiance in the near infrared. Any such sites near the edge of an unconfined edge of dome are likely to be mechanically unstable and their detection is expected to give warning of the occurrence and direction of collapse. For confined lava domes (such as Lascar) SVO night-time data will document the change in state of the dome from large and strongly radiant (eruption unlikely) to withdrawn and non-radiant (eruption likely), as demonstrated by Wooster and Rothery (1997).

Studies associated with lava flows

Lava flows present fewer hazards than lava domes. They are slow moving, so although they can destroy property and ruin agricultural land people can usually escape. However it is often difficult or impossible to monitor the development of a lava flow field during an eruption by ground-based techniques, particularly when a compound lava field is forming. Thus remote sensing is a valuable way to document events, for example by providing input to physical models of lava flow dynamics (see for a more complete discussion about the models in Kilburn, 1996), and by determining the rate and locus of post-emplacement subsidence of a new lava flow (e.g. Briole *et al*. 1997). The SVO will advance these studies by providing DEMs (day-time data) and locating the radiant vents, flow fronts, breakouts, and skylights above lava tubes (night-time data). During a volcanic eruption with lava flows, usual DEM with an accuracy of 10m in vertical and pixels of 20 or 40m are not accurate enough to correctly predict where the lava will flow in the following days, especially when relatively flat areas are interested by the eruption. The capability of SVO to provide very accurate DEM will greatly improve the capability of prediction of the future path of an active lava flow. In addition the possibility of refreshing the DEM every 1-3 days will allow to update the topography of the volcano in near real-time and thus to know the volume of erupted material. This will allow to evaluate the future trajectories of lava flows by using specific models already tested for real eruptions (e.g. the model proposed by Kilburn and Lopez, 1991 validated by Calvari et al. on 1991-1993 Mt. Etna eruption).

C.1.3.2 Landslide monitoring

Hundreds of active landslides exist around the world (*see for example http://geohazards.cr.usgs.gov/landslide.html*), several of them presenting a direct or indirect risk for inhabited areas and infrastructures (roads, railway lines, …). The monitoring of the most dangerous landslides of the world could be done using SVO in the same conditions as the monitoring of the most active volcanoes. In addition to the frequent calculation of DEMs, the images acquired on landslides could be analysed using coherence analysis methods. Landslides have several characteristics (spatial extension often less than one kilometre and possible large displacement rates) in common with active volcanic areas. Although landslides can be relatively easily instrumented during their initial phase of activity, in-situ instrumentation is more difficult and more risky in the active phase of a landslide. The capability of real-time DEM generation of the SVO could be very useful for improving the monitoring of some major landslides around the Earth. The other space techniques like SAR interferometry (ERS, ECHO) have the following limitations for this application:

- pixel size too large with respect to the small size of the area of interest
- repeat passes not enough frequent
- displacements too large and too inhomogeneous causing coherence loss between two acquisitions and preventing for fringe identification/unwrapping, even in case of coherent result.
- vegetation

Two application of SVO imagery could help for the monitoring of landslides:

1) Monitoring of the evolution of large active landslides with activity spanning several years or decades. This is the case, for example at St Etienne de Tinée (France), where the "La Clapière" landslide (surface: 0.5 km^2) has been active for several years with present displacement rates of 1 to 10 cm/day. Depending on the estimated level of risk, observations on those areas could be done every 1, 3, 6 or 12 months in order to estimate the deformation (deformation map of the whole area) and the volume displaced during the period. In Europe (especially in Italy and Switzerland), about 12 landslides are active with rates comparable with that of La Clapière. The main progress made possible by a system like SVO will be the possibility of periodically mapping at high resolution the unstable area and generating high precision DEM. This will provide new and important data to understand the mechanisms and evolution of the phenomena.
2) Monitoring of large landslides and mapping of the effects of mud flows (paroxysmal phenomena). There are several examples of landslides that accelerate during their activity and that can potentially generate mud flows during their final stage of activity. In the last few years, this has been the case in France at La Valette (Hautes Alpes) where the landslide evolved into a flow of several millions of m3 during several months and at Boulc en Diois (Drome) also. At Gourette (Haute-Pyrénées) a landslide of 6

millions of m^3 has reached velocities of motion of 1m/day during its paroxysmal phase. For such landslides, the SVO should be used in maximum acquisition mode for duration of one to several months (typical duration of such events) and the data (DEM and images) would be necessary in near real-time for the risk mitigation purpose. In France one such event occurs every two years in average. A few ten of such landslides are reported world wide every year.

Recent landslides in the Azores archipelago

Landslides are one of the most common natural hazards at the Azores, being associated with heavy rain falls, earthquakes and volcanic eruptions. On the 31st October 1997 several landslides occurred at S.Miguel island killing 29 people that were living in Ribeira Quente village. Several countries were particularly affected during this major event. Several houses and bridges were partially or totally destroyed, the communications and the energy supply system were disrupted and areas of fertile land became covered by mud. Almost all the main roads were greatly affected or even cut and Ribeira Quente village stayed isolated for more than 12 hours. The main cause of this large-scale phenomenon was a local and catastrophic rainstorm. The strong SE winds that accompanied the heavy rain and the vulnerability of the volcanic soils, already saturated in water after long periods of continuous precipitation, certainly contributed to the magnitude of the event. For the bigger slides, it may be that failure conditions had already been initiated days, weeks or even months before, and that backwall cracking had already started. The occurrence of the 1997 landslides emphasised the importance of landslide monitoring. This phenomenon clearly showed that warning and alert systems are needed in order to minimise the impact of future and probably larger events, including volcanic eruptions and earthquakes. During the past several landslides occurred associated with volcanic eruptions due to flank instability. Earthquakes also triggered large-scale landslides being the most recent ones related with the 1998 Faial seismic crisis.

C.1.3.3 Mudflows

In volcanic areas, the risk of landslides of mud flows in higher that in many other areas, because the terrain made by recent volcanic deposits is generally not consolidated. Recently (April 1998) a large mud-flow destroyed several villages in the Naples area (Italy) and killed several hundred of people. The villages were built downhill of unstable pyroclastic deposits of Vesuvius volcano. Several landslides of unconsolidated materials occur every year in the Acores (Portugal) in the steep walls of the caldera rims of the active volcanoes of the archipelago. During the recent hurricane "Mitch" several landslides and mud flows of unconsolidated material of Cerro Negro volcano (Nicaragua) have devastated, killing several tens of people. In 1995, the melting of the glacier of the Nevado del Ruiz volcano (Columbia) associated with the unrest of that volcano caused the death of more than 20.000 people in the city of Armero. Although the landslides often occur during heavy rains, and could not be monitored with SVO (for visibility reason and also because of the very short notice time), a mapping of the stability of these areas could be done using images acquired every 6-12 months and could help in the identification of the most hazardous places not necessarily identified previously. In the case of Armero (Columbia) deformations of the glacier were observed by scientists visiting the volcano prior to the mud-flow. If more and highly accuracy satellite data had been available at that time, they might have proved very important to increase the confidence in the field observations and convict the authorities of the level of danger. Similar situations may occur in the future in monitored or non monitored strato-volcano covered by snow and ice (Andean volcanoes, volcanoes of Kamchatka, Japan, Alaska, Iceland). The SVO data could be used not only to monitor topographic changes in areas subject to mud- flows, but also to predict the trajectories of future potential mudflows. Indeed the capability of very accurate DEM generation of the system would allow to realise this task. Accurate maps of mud flow hazard could be realised and could help the authorities to prevent people to build houses in exposed areas. The risk of future mud flow is higher on volcanoes having been active recently and where the pyroclastic deposits are extremely unstable. This is the case for example around Pinatubo volcano that erupted in 1991, with large amounts of sulfur dioxide injected in the upper atmosphere, and very thick deposits around the volcano. Although the eruption ceased, the volcano continues to be a major hazard to the people who have returned to the area around the volcano. Dangerous mudflows (*lahars*) could be generated by heavy rains, and could still sweep down river valleys and wash out roads and villages, or bury low lying areas in several meters of mud and volcanic debris. These mudflows are considered to remain a severe hazard around Pinatubo for the next 10 to 15 years at least.

C.1.3.4 Faults mapping and earthquakes study

The high resolution capability of the SVO is compatible with the use of the system for three main objectives related to earthquakes and faulting:
firstly, to obtain detailed images of fault traces for studying their holocene cumulative displacement, and for mapping the largest earthquakes through the identification of the last ruptures;
secondly, to obtain these images of the area struck by a large earthquake in order to better model its rupture mechanism and its induced effects, including the damage to man-made structures;
thirdly, for guiding emergency and rescue operations as well as post-seismic scientific studies.

Tectonic deformation

The measure of coseismic or cumulative displacements is an essential element of seismotectonic analysis. The use of SPOT images has allowed remarkable progress for the measure of horizontal cumulative slip for periods of time ranging from 10 to 100 thousand years. However, for improving our understanding of the earthquake cycle on active faults, one needs a refined description of the topography in the fault vicinity. Typically, the requested map scale is 1/5000, which is rarely available, and can not be obtained with DEM generated by SPOT. Furthermore, large paleohistorical earthquakes with several meters of coseismic horizontal slip may have shifted small streams enough for being detectable on a 1.5 m pixel image, as has been shown on the Hayuan fault in China (Gaudemer et al., 1995). The present SVO project would thus greatly improve our knowledge of the recent seismicity on some of the major fault systems of the earth.

Earthquake faulting

For a 6 km x 6 km image, and a 1.5 m pixel, only shallow earthquakes with magnitude 6 or more are expected to provide a detectable signal, in the form of surface rupture (dislocation of 1 m or more) and deformation. A complete coverage of the epicentral area for a magnitude 6 event (typically with a 20 km long source dimension) would require a 30 km x 30 km image, hence about 25 images 6 km x 6 km. A magnitude 7 would require more than 100 of such images. The scientific targets which can be aimed with such data are numerous: fault trace mapping and coseismic slip quantification; studies of specific steps, bends, jogs on the fault; fault branching; fault termination. The latter is particularly important for identifying the location of possible strong aftershocks.

Induced natural phenomena

Landslides and rock or cliff collapse are the most common induced effect of earthquakes; rapid detection of these can help to guide rescue operations, and identify areas of increased risk.

Induced flooding

Fault scarps and landslides can generate dams several meters high on rivers, which results in the flooding of large areas; details on the dam structure and location can help to take appropriate safety measures for the population and the traffic.

Damage to buildings and man-made structures

Images with 1.5 m pixel would provide very valuable data for having a first rapid estimate of areas with large damage. Grade 3 damage and over (moderate to heavy structural damage) in the MSK classification would indeed be detectable, at least by comparison of preseismic and postseismic images, if not directly on the postseismic image. Hence, areas of MSK intensity VIII and larger would be detectable, corresponding to many buildings of class B (brick building) and a few of class C (reinforced concrete) suffering damage of grade 3, and to many buildings of class A (adobe house) and a few of class B suffer damage of grade 4. MSK intensity IX corresponds to many buildings of class C with grade 3 damage, and many buildings of class B and a few of class C with grade 4 damage. In the MSK scale, "a few" is 10%, up to 20%; "many" is 20% to 50%, up to 60 %. This can lead to a rapid mapping of the intensity areas of VIII and above, as well as to the identification of damage to specific structures: bridges, highways, railways, factories with high induced hazard, etc....

It can also give an accurate extent of fires. The latter can help to assess the damaged zone even if the earthquake occurred during the night. This information can be particularly valuable for the assessment of destruction in a large city and will be of great help for the planning of the rescue operations, considering the lesson from the Kobe disaster.

In the case of a large earthquake, two cases can arise:

- if the area of the earthquake was a predefined target, a set of images are retrieved in the first phase of the experiment, defining the pre-earthquake state (for natural as well as for man-made structures, such as active faults and large

urban areas). After the earthquake, the acquisition of the images will have to follow a priority order (25 images may need one month
or more to be recovered). This priority order can be programmed in advance, or defined according to preliminary informations from the coseismic effects, for guiding field work and/or emergency operations.
- if the area was not a predefined target, priorities in the imaged areas have to be given very rapidly, for guiding field work and emergency operations, or for generating a new preseismic data base in case of a large aftershock.

It is clear that from the point of view of risk mitigation and rescue planning, a repeatability of one day or less in the delivered images can be of vital importance, and a repeatability of 1-3 days is still very useful.

C.1.3.5 Comparative Planetology

Volcanism is one of the endogenic key processes during the crustal evolution of many Solar System bodies. In the absence of any extraterrestrial volcanic samples from known parent bodies which can be analysed on Earth (with the exception of lunar probe material and martian SNC meteorites), the physical and chemical properties of volcanic products on planets and moons have to be determined by remote sensing techniques. These include orbital a-, g-, X-ray, Radar, and neutron spectroscopy, visible and near-infrared reflectance spectroscopy, multispectral mapping, and in-situ analyses carried out by landers (Basaltic Volcanism Study Project 1981, Pieters and Englert 1993).
While after the discovery of a wide and exotic range of planetary surfaces by spacecraft missions theoretical studies and experimental work have become essential for understanding extraterrestrial volcanic processes (e.g. Wilson and Head 1994), comparative planetology using a photogeologic or geomorphologic approach will still be a key technique in resolving the role of volcanism and related volatiles (Mouginis-Mark and Holloway 1990).

For example, a variety of landforms has been identified on the Martian surface which resemble terrestrial volcanic features and are described by the same terminology. Evidence for both explosive and effusive volcanism has been found on both hemispheres of Mars, e.g. lava flows with lengths that exceed the length of their terrestrial counterparts by far. Many studies tried to relate morphologic parameters of the flows (length, width, area, thickness etc.) to lava rheologies and effusion rates (Hulme 1976, Moore et al. 1978, Baloga 1987). However, the relationships between lava composition, temperature, shear rate, and viscosity are still poorly understood even for the Earth. The goal of a completely general model of lava-flow motion which can be applied to all terrestrial planets (Wilson and Head 1983) will certainly benefit from an extensive dataset of high-resolution topographic information obtained by one sensor and, therefore, being comparable. The High Resolution Stereo Camera (HRSC) was recently tested on terrestrial volcanoes (Gwinner et al. 1998) and will be flown on the ESA mission Mars Express to be launched in 2003. DEMs derived by this instrument will be used to improve the models describing lava flow properties (Hauber et al. 1998). Since the SVO project will provide stereo images covering active volcanoes with a wide compositional range which are accessible to field measurements and laboratory studies, it will considerably support these studies.

High resolution orthoimages provided by Mars Express HRSC will also be essential to the study of Martian surfaces thought to consist of pyroclastic rock deposits. Recent results of the Mars Pathfinder Mission (Rieder et al., 1997) indicate the presence of silicic material on Mars implying a higher degree of crustal differentiation than previously thought. Due to lower gravity and atmospheric pressure, explosive volcanism could be of larger extent compared to the Earth assuming similar composition and volatile contents. The recognition of explosive deposits by photogeologic and geomorphologic techniques requires the analysis of small erosional features and their comparison to similar terrestrial surfaces of known explosive volcanic origin.

Furthermore, basic textural surface properties such as porosity, macroscopic surface roughness, and mean particle albedo will be determined by photometric modelling based on the multi-angle observations provided by Mars Express HRSC. Photometric analysis of surfaces is a specific application of radiative transfer modelling and requires DEM information together with multi-angle observations of the reflected radiant energy. Through knowledge on the specific photometric characteristics of different surface types, photometric modelling can be applied as a classification technique (Regner 1990). While the *modelling techniques* can be improved using a smaller number of test data sets (Gwinner et al. 1998), the specific photometric characteristics of terrestrial explosive deposits needed for comparative classification of the Martian surfaces can only be determined by analysing a great number of observations at many volcanoes.

The high resolution DEM and multi-angle image data acquired by SVO will provide a unique database for this purpose. Therefore, the recognition and characterisation of explosive deposits on Mars will profit significantly from SVO, concerning both morphological and photometric analysis.

C.1.3.6 Other applications

Forest fires can be observed with SVO. Any topographic changes in specific areas due to any flow or avalanche disasters or landslides could be observed as well. Additional observations are options for high-priority demands, but no competitive mission goals.

The capability of the SVO mission to provide highly accurate DEM will be of great interest for several studies related to the internal structure and dynamics of the volcanoes (for example gravity studies), for studies of volcano morphology and for studies related to the erosion on volcanoes.

In addition, we propose to open also the mission to other partners. For that, 20kg of payload mass could be made available in the spacecraft for additional instruments, provided that there is no conflict with the main SVO instrument (CCD camera). This payload might be selected by a dedicated AO or added during the phase A of the project. Priority would be given to light instruments that could complete the main scientific objectives of the mission, for example:
1) Light, low spatial resolution multispectral camera for the thermal monitoring (1.1 to 14µm). A possibility to reduce weight is to mount different matrix sensors (three) in an unique camera body with a single lens. The sensors could cover three different spectral bands in 1.1-14 mm

IR range arranged in a classical optic geometry (an opportune prisms combination) widely used in professional 3-CCD camera. The multispectral IR camera should have the same field of view of the high-resolution panchromatic camera for along track stereometry but a lower spatial resolution (6 m instead of 1.5 m would be enough in most cases for the purpose of thermal monitoring). The three matrix sensors would be selected among sensor type that operate at high temperature. Two kind of sensor are presently available: PtSi CCD image sensors and microbolometers arranged in a focal plane array. PtSi CCD's operate on the short-medium wave IR band between 1.1 and 5 mm at 80-120° K and need of a Sterling microcooler or a Peltier cell cooler. They have a high spatial resolution (presently 811x508 pixels) and in the next future the CCD matrix will be increased up to 1k x 1k pixel giving performance up to 1/4 of the resolution of the panchromatic camera thus meeting the 6 m x 6 m resolution mentioned above. Uncooler microbolometers operate on the medium-long wave IR band between 7 and 14 mm and do not need of any cooling system. In the next future they will have up to 0.5k x 0.5k pixels (presently 320x240 pixels) and will perform a 1/8 of the resolution of the panchromatic camera.

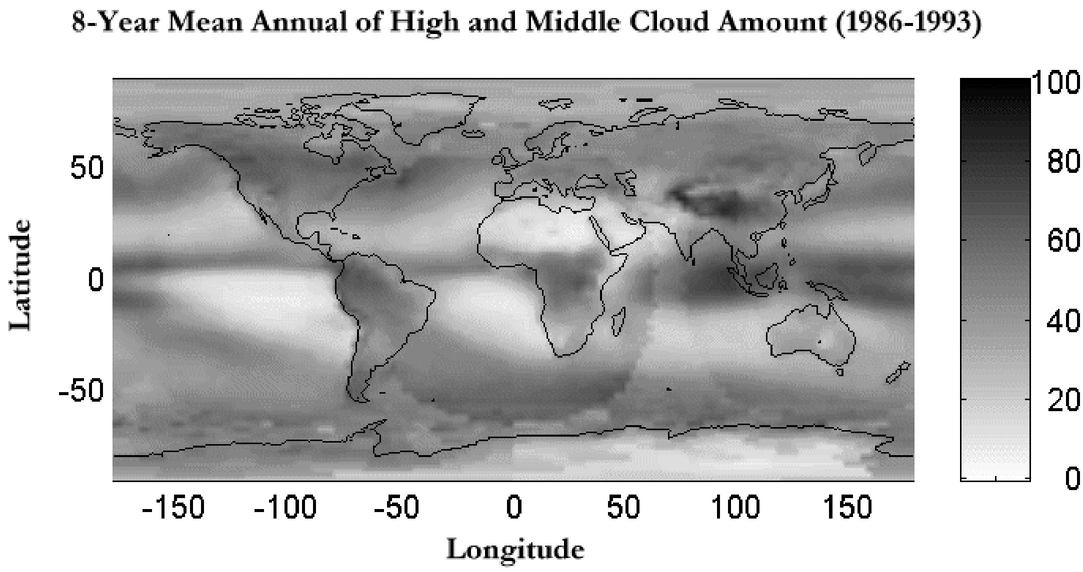
2) Light, low spatial multispectral camera for the chemical characterisation of volcano plumes (should include UV channels for the stratospheric SO_2).

3) Pressure gauge for recording of the gravity atmospheric waves excited by the volcanic eruptions.

4) Radio-science experiment for the determination of the 2D structure of the ionosphere (TEC: total electronic content) over some specific volcanoes equipped with ground stations.

C.1.4 - Statistics on the cloud cover on the volcanoes

The limited factor for Earth remote-sensing in visible wavelength is the cloud cover. We used the database of the International Satellite Climatology Project (ISCCP) to determine the percentage of visibility on the volcanoes listed in Table 1. We analyzed a time series of 8 years of daily data (1986 to 1993) (Mourot, 1998). The percentage of visibility depends on the location of the volcano on the Earth and on its elevation. The highest volcanoes are visible more often in average. The long term percentage varies from 33% to 70% of visibility. This value is expected to be significant on all volcanoes located in continental areas or with high elevation, whereas it may be somewhat overestimated for volcanoes of low elevation with oceanic climate conditions. This because the grid size of the ISCCP catalog (0.5°) may include data over sea generally less cloudy. Volcanic plumes make sometimes the observation more difficult, but largely depends on the type of activity of each particular volcano and can also be considered as a useful parameter for the SVO mission. The global average of visibility for the panel of 47 volcanoes in Table 1 is 55%. On some volcanoes, additional data confirm the validity of our result. For example, on Piton de la Fournaise, five years of continuous range measurements over the summit crater using an automated Electronic Distance Meter (EDM) with distances ranging between 1600 m and 3200 m indicate 55% of visibility (65% from the ISCCP data). The analysis of more local and more frequent data available for a 4 months period (1/12/92-28/2/93) on three Philippine volcanoes located in a relatively cloudy area with respect to the global average (Mayon, Pinatubo, Taal) indicate that the clouds are less frequent in the morning than in the afternoon (Mourot, 1998). Our analysis need to be refined, but it seems that the more favourable time window for day-time observations will be between 10:00 and 12:00 local time. This constraint will be used for the definition of satellite phasing. In consequence, the night-time passes would occur between 22:00 and 24:00 local time. Although the band of the planned CCD camera is limited to 0.4 µm - 1 µm (*see C.2.4*), and thus covers the near IR only, it has to be noted that the cloud cover are significantly more transparent in the range 0.8 µm - 1 µm than in the pure visible band. This will enhance the capability of night observation in case of thin could cover or thin volcano plume.



Volcano	Altitude (m)	Percentage of year without clouds	Country	Receiving station
Etna	3350	69	Italy	OVE
Stromboli	926	67	Italy	OVE
Grimsvotn	1725	53	Iceland	
Nyamuragira	3058	33	Africa-C	
St. Helens	2549	40	USA	LVO
Yellowstone	2805	40	USA	LVO
Chiginagak	2075	52	Alaska	AVO
Pavlof	2519	55	Alaska	AVO
Soufriere Hills	915	70	W Indies	ANT
Cerro Negro	675	57	Nicaragua	POP
Popocatepetl	5465	56	Mexico	POP
Pacaya	2552	61	Guatemala	POP
Arenal	1657	48	Costa Rica	POP
Rincon De La Vieja	1916	51	Costa Rica	POP
San Cristobal	1745	58	Nicaragua	POP
La Madera	1394	52	Nicaragua	POP
Fuego	3763	61	Guatemala	POP
Guagua Pichincha	4784	39	Ecuador	COL
Iwate	2041	49	Japan	USU
Atka	1533	56	Aleutian Is	AVO
Sakura-Jima	1117	50	Japan	SAK
Adatara	1718	46	Japan	USU
Hakkoda	1585	52	Japan	USU
Shishaldin	2857	56	Aleutian Is	AVO
Okmok	1073	56	Aleutian Is	AVO
Amukta	1066	57	Aleutian Is	AVO
Karymsky	1486	51	Russia	
Bezymianny	2882	48	Russia	
Shiveluch	3283	48	Russia	
Kliuchevskoi	4835	48	Russia	
Merapi	2911	47	Indonesia	VSI
Manam	1807	40	New Guinea	
Papandayan	2665	43	Indonesia	VSI
Peuet Sague	2780	27	Indonesia	VSI
Karangetang	1784	47	Indonesia	VSI
Rabaul	688	35	New Guinea	
Krakatau	813	38	Indonesia	VSI
Fogo	2829	70	Cape Verde	UAC
Fournaise (Piton)	2631	65	France	OPF
Cerro Azul	1690	85	Ecuador	COL
Kilauea	1222	74	USA	HVO
White Island	321	64	New Zealand	AUK
Ruapehu	2797	59	New Zealand	AUK

Table 4: Visibility of several volcanoes (data source: ISCCP)

C.1.5 - Relevance to the objectives of the Earth Explorer programme (ESA SP-1227)

The observation of the solid Earth as well as the contribution to the mitigation of volcanic hazards are relevant to the objectives of the Earth Explorer programme.

C.1.6 - Relevance to other programmes, to global interests and to regional needs

Our project is relevant to the objectives of the United Nations (UN) that declared the 1990’s decade as the International Decade for Natural Disaster Reduction (IDNDR) and corresponds to the field of research encouraged by the IUGG (International Union of Geodesy and Geophysics). The project is also relevant to research areas supported by EU in the framework of the fourth and fifth Research and Development programs (especially in the field of environment/volcanic risk and in the field of space related activities). Our project is also relevant to the help of less developed countries often under-equipped with ground based monitoring system, although the volcano risk is often higher that in developed countries.

In the context of volcano monitoring, the SVO project shares several objectives with the goals of the EOS mission. The higher resolution of the SVO mission and its highly focused application to volcano monitoring (frequent repeat passes, real time data download, …) make SVO complementary to the achievements that can be expected from the EOS mission. The project to which SVO applies most in the context of planetary geoscience is the ESA Mars Express mission to be launched in 2003. However, other planetary missions like the Mars Sample Return Mission or the Mars Netlander Mission (both 2005) would also benefit from better models of volcanic activities derived from accurate 3D information. Studies on other terrestrial bodies (Mercury, Venus, Moon) will also be supported by the interpretation of data obtained by SVO.

Complementarity between the SVO and the EOS missions

The Earth Observing System (EOS) is the key element of NASA´s Mission to Planet Earth, the main contribution of NASA to the U.S. Global Change Research Program set up to coordinate research on global change in the US. The major goal of EOS is an integrative, large-scale initiative to explore the functioning of the planet as a whole (Asrar and Dozier, 1993). Beginning in 1998, consistent and well-calibrated spacecraft-based observations from a variety of orbits will be made for at least 15 years.

The mechanisms of how volcanic eruptions contribute to climatic change by releasing volatiles in the atmosphere are addressed by various sensors of the EOS program (*Mouginis-Mark et al.*, 1991). While surface imagery of volcanoes (provided by ASTER, MISR, and MODIS) will not be the prime objective of EOS, volcanic plumes and aerosol injection in the atmosphere and their subsequent global dispersion will be monitored by ASTER, EOSP, MISR, MLS, and SAGE III (see Table 4 for EOS sensors used in volcano monitoring; *Asrar and Dozier*, 1994). Due to its multi-purpose character, however, this mission will not provide continuous observation of more than 2-3 active volcanoes per day. No dedicated instruments for volcano monitoring will be implemented. In case of eruptions, delays of data provision of several weeks will be possible and are due to the orbit parameters, the need for targeting high resolution instruments, interference with other experiments depending on the same instruments, and the centralised data transmission and processing concept of the mission. Moreover, none of the EOS sensors provides high resolution stereo images necessary to monitor the topographic changes indicative of possible eruptions, nor do they provide the accuracy of DEM details required to model and predict volcanic hazards. The surface-oriented SVO project is, therefore, complementary to the more atmosphere-oriented EOS Volcanology program and will yield additional information to the interdisciplinary science approach of EOS. Accurate and fast localisation of the centres of increased volcanic activity by SVO will support the operation of EOS instruments for atmospheric, plume topography, thermal, and laser ranging measurements as well as the planning of very high resolution airborne campaigns and field measurements. In turn, atmospheric observations by EOS sensors will support the detection of volcanic activity, adding to the scientific value of SVO data.

Sensor	Main Target	Maximal Ground Resolution (m)
ASTER	Surface, Atmosphere	15
GLAS	Surface, Atmosphere	70
MISR	Surface, Atmosphere	275
MODIS	Surface, Atmosphere	250
MLS	Atmosphere	3 x 300,000 horizontal
AIRS	Atmosphere	13,500
EOSP	Atmosphere	10,000
TES	Atmosphere	500

Table 5: Ground resolution of EOS sensors used for observations of volcanic eruptions (after Mouginis-Mark et al., 1991; Kramer, 1996)

C.1.7 - Public outreach and educational program

As observed by an ESA report (ESA/SPC(98)30, 21/9/98), the prediction of catastrophes on Earth is expected by the European public to be one of the main benefits of the ESA missions. The SVO project team is therefore ready to be associated to the Communications and Public Relations activities of ESA for the Earth Explorer missions. The SVO team considers as part of its future duties in the framework of the SVO mission the following activities:

1) Dissemination of preliminary scientific results of the mission with specific public relation interest (images of volcanoes and landslides, 2D/3D animations showing the topographic changes, …). Products will be made available to the general public through appropriate dissemination media (DVD-ROM), electronic distribution (WWW), paper (booklets, stickers), …

2) Set-up and update of a data base usable by schools, libraries, museums, individuals. The data base will include the history of the SVO scientific objectives, elements on physics of the volcanoes, information about human and economic risk associated with volcanic and landslide hazards.

C.2 - GENERAL MISSION CHARACTERISTICS

C.2.1 - Mission overview

The SVO (Space Volcano Observatory) mission is intended primarily for near continuous monitoring of deformation and the thermal changes in the most active areas on volcanoes (lava domes, lava lakes, active craters, eruptive vents, lava flows). These areas are generally not accessible to ground based techniques. To avoid competing science, only the instruments necessary for the volcano monitoring purpose will be implemented on the satellite. The satellite has to be on a helio-synchronous circular orbit of a specific altitude which has to be determined with precision in respect of an optimal access criterion to targeted areas. We have provisionally chosen an altitude close to 685 km (*see C.2.5.1*). There is no dependence to other missions, but the SVO mission will be complementary to the future SAR interferometry missions (like the mission ECHO, to the future EOS mission and to the ongoing SPOT and LANDSAT programs. It will have links with several programs of meteorological observation on the Earth that are already used for the large scale observation of volcanoes (NOAA AVHRR, GOES 8/10). The SVO mission will also have some links with the Volcano Ash Advisory Program (VAAP) that is a structure supported by the International Civil Aviation Organisation (ICAO) for the monitoring of volcanic ash plumes and aircraft safety. Nine Volcano Ash Advisory Centres (VAAC) are already operational: Toulouse (France, Buenos Aires (Argentina), Darwin (Australia), London (UK), Montreal (Canada), Tokyo (Japan), Anchorage (USA), Washington (USA) , Wellington (NZ).

The originality of the SVO is the coupling of a high resolution capability on pre-defined targets and a 3 day repeat time (24/48 hours for a constellation of 2 satellites and 12 hours for an ideal constellation of 6 satellites. In response to the ESA AO, we propose the realisation of a first SVO satellite. Only one satellite is not optimal for hazard mitigation, but will be enough in many cases. For scientific purpose, one satellite observing two/three years will bring a unique set of data at high spatial resolution, high temporal sampling rate on the volcanoes. One very valuable aspect will be the global character of the mission that will provide topographic data on many volcanoes, a very important data set for the subsequent missions. The proposed width of the area to be observed is 6 km x 6 km. Such an area corresponds in general to the active and most dangerous part of the volcanoes has often an extension of a few hundred of metres to a few kilometres. Even if the effects of the eruptions create a risk at much larger distances, this is the area where most of the precursory phenomena occur and this is the area more difficult and risky to monitor with ground based methods. The proposed pixel size is 1.5m. Image capture will be done without long storage on board and will be based on the direct reception of images by ground stations located where the need is real (a list of 15 volcanological observatories that may hosts data receiving stations is given in section C.2.7). This strategy permits to minimise the delay for accessing the data, that is fundamental for a system dedicated to risk mitigation. It will also allow to lower the weight and cost of the satellite. Finally, it will also enhance the scientific collaboration between European and non EC researchers. The cost of some direct reception stations may be supported by bilateral or multilateral scientific agreements. This mission will contribute to the advancement of European Earth Observation capabilities.

C.2.2 - Mission tasks

The scientific objectives implicate the following tasks :

1) to be able to capture, in the day-time part of the satellite track, a maximum stereo set of 3 images of volcano summits, to build accurate, reliable and very frequent DEMs of volcanoes in activity (aim : daily or a maximum of two to three day coverage).

2) to be able to capture, in the night-time part of the satellite track, a monocular view of an active volcano to map (essentially in close infrared wavelengths) hot surfaces whose pixel-integrated black body temperature exceeds about 450°C, and thus lava flows and active terminal domes on volcanoes, this with an analysis sharpness of about 1.5 meters at nadir. No temperature measurement will be possible because the targets are expected to be thermally heterogeneous even within a single pixel, and with only a single, panchromatic, band it will not be possible to determine the size of sub-pixel radiant surface. The aim is only to detect and to map hot areas and their evolution.

3) to be able to carry out relative localisation of night and day images, with an accuracy of about 5 meters (by use of projectors installed in the field, or by he use of natural lights that could be geo-referenced in urban or inhabited areas).

4) to be able to ensure the following observational task
- Daily coverage of 30 targets (volcanoes with the highest level of risk).
- Weekly coverage of 40 other targets (other volcanoes with on-going eruption or in a presumed unrest phase).
- Annual coverage of the 500 volcanoes known as active in recent history.

C.2.3 - Mission duration, timetable requirements

The mission has a self-exploratory objective, it must show the contribution of a simple optical imaging system for geological risk analysis (essentially volcanic). The proposed mission duration is of two/three years. There are no timetable constraints, but earlier is better. The mission has no direct correlation with any other.

C.2.4 - On board instruments

The SVO will include only a CCD matrix 4k x 4k camera with one panchromatic channel (0.4 - 1 µm) and a GPS receiver for the orbit calculation.
A secondary payload with a total mass of 20kg may be added during the phase A by a specific AO for payload (*see in C.1.3.6 suggestions for possible additional payloads*).

C.2.5 - Observation requirements

C.2.5.1 - Satellite orbit

The first orbitographic requirement is a world wide Earth coverage with the best possible repeatability compatible with the basic limitations of lateral aiming of the satellite. This maximum angle should not go beyond 40°. This angle limits the access to any arbitrary interesting zone to not more than once every 3 days, and a more frequent access requires more than one satellite. The orbits that allow access in 3 days have altitudes between 660 and

730 km, but also between 740 and 830 km. The first orbit interval will be preferred to the second for photometric reasons.

While we consider this first requirement, we may look for a second interesting feature that would be to revisit the more often possible all the possible sites with the line of sight as vertical as possible so as to see the inner part of volcanic craters in the best possible observation conditions. The request to go over a given site every N days is equivalent to choosing an orbital period equal to the day duration multiplied by a given fraction. The table below gives the characteristics of various orbits selected.

Angle in °	Minimal number of passes for a world wide coverage	N if orbital phasing is correct	Orbital Altitudes allowing for a correct phasing	Inclination of orbital planes in °
<5	369	27 days	solution 1: **670,5 km** solution 2: **694 km** solution 3: **706 km** solution 4: **718 km**	solution 1: **98,072** solution 2: **98,168** solution 3: **98,217** solution 4: **98,266**
<10	185	15 days	solution 1: **661 km** solution 2: **703,5 km**	solution 1: **98,034** solution 2: **98,206**
<12,5	145	12 days	solution 1: **709 km**	solution 1: **98,229**
<15	121	9 days	solution 2: **717 km**	solution 1: **98,262**

Table 6: Possible satellite orbit and phasing

The preferred option provides a passage every 3 days in sight of any spot of the world, with a pass better than 10° from the vertical every 15 days. These figures are achieved for a 661 km altitude and 98.034 orbit inclination.

C.2.5.2 - Observation geometry

The observations will be performed in along track stereoscopy, with a lateral aiming capability of 40° . The images will be acquired by sets of three: one at the closest point of the spot, one before and one after, separated from 10°-15° from the direction of the first image. Large stereo angle will require more time for stereo data acquisition along the track, thus less time for data downloading to the receiving station and less observable targets on one pass. If stereo angle larger than 15° are necessary, they will be obtained by using different passes on the same track. The acquired area will be 6 km x 6 km at the nadir, with one large spectral band (0.4 µm to 1 µm) only. One satellite alone will allow for the observation in the worst case of one given spot every 3 days, in stereoscopy and in near-IR night acquisition as well. Every 15 days a scene will be accessible with the optical axis closer than 10° from the nadir, providing the best quality possible of the DEM. In each orbit, considering the dead times requested for aiming the platform, a maximum number of three spots will be acquired on day time, and the same for night time as well. The following numbers characterise the acquisition time and the minimal geometrical separation of two consecutive targets to be observed during a given pass:

- Duration of one stereo scene acquisition (with images taken at ± 15° angles), according to the speed of mirror rotation and satellite velocity: 43s.
- Minimum distance between two targets when stereo scenes are acquired: 250km. A daily survey of several volcanoes located close one to the others is not compatible with the stereo imagery.
- When stereo imagery is not mandatory, a group of close volcanoes can be monitored on a daily basis, the capability decreasing from the case of ~N/S orientation to the case of ~E/W orientation.

The geometric calibration will be performed in flight and without special equipment, as a result of the automatic correlation of several sets of 3 images in good geometric configuration (areas close to the nadir of the satellite, chosen in mountainous areas of Europe). Radiometric calibration will be performed on homogeneous places, from time to time, in order to check the sensitivity evolution of the CCD pixels.

C.2.5.3 - Scale and spatial resolution, spectral characteristics.

The requested ground pixel size is 1.5 m at the nadir and the basic footprint 6 km x 6 km. The use of a panchromatic CCD camera with high a dynamic range (11 bit effective) will allow DEM generation in daytime images. The expected DEM accuracy is 1 m with 3 converging sights. The camera will work on the full bandwidth possibilities of Si CCD, from 0.4 µm to 1 µm in a pure panchromatic mode. With respect to a classical push-broom technology, the CDD matrix allows significant reductions of camera weight and constraints on satellite pointing stability during image acquisition. The 11 bit dynamics will allow to correlate images even in areas where the target contrast is too low for 8 bits images and to map hot areas on night-time images.

C.2.5.4 - DEM generation

Along-track stereo data for DEM generation will be acquired using images from one single pass or images from different passes on one track. Across-track stereo using images from different tracks will be provided as well. Single-pass along-track stereo obtained by forward-backward motion of the on-board mirror will be used to provide high temporal monitoring rates for the highly active volcanoes.

Combining stereo images acquired at different passes along a given track and combining across-track stereo images will reduce the need for mirror rotations and will increase the observation capability of the satellite. This method will be applied for the routine observation of currently less active volcanoes.

DEM accuracy will depend on the accuracy of the orbit data, aiming accuracy and geometric camera calibration. Along track stereo will be favourable for automatic image correlation, since images are acquired nearly simultaneously. Spatially continuous snow coverage is a known problem for image matching algorithms, but will be rare on highly active volcanic areas.

C.2.5.5 - Night data

Night acquisitions involve the problem of accurate pointing / accurate geocoding of the images. Several methods may be used to improve the accuracy of the night data geocoding:

1) Accurate orbit control (*see C.3.1*)

2) Geocoding based on identified targets in the images. This can be either artificial lights installed in the image area for the specific purpose of the experiment or urban or peri-urban well identified lights. In the latter case, the acquisition of more than one image along the track may be necessary for geocoding purpose (6 x 6 km will in general not be enough to see inhabited areas).

3) Stereo acquisition of data during night-pass and use of a recent DEM produced at day-pass to constrain the location of the night images. This possible method would imply further research to be validated.

C.2.6 - Data download

C.2.6.1 - Volume of data

The volume of data is estimated for a 4096 x 4096 CCD matrix (area of 6x6km and a pixel size of 1.5m, an average compression ratio of 1.25 and a dynamics of 12 bits.

- Size of one full stereo scene: 3 visible images (+10°, nadir, -10°) = 3 x $(4096)^2$ x (12/8) / 1.25 = 60 Mbytes
- Size of one non-stereo scene = 20 Mbytes
- Size of one "quick-look" scene with resolution lowered by x10 (for mission control and quick centralised archiving system): 0.6 Mbytes

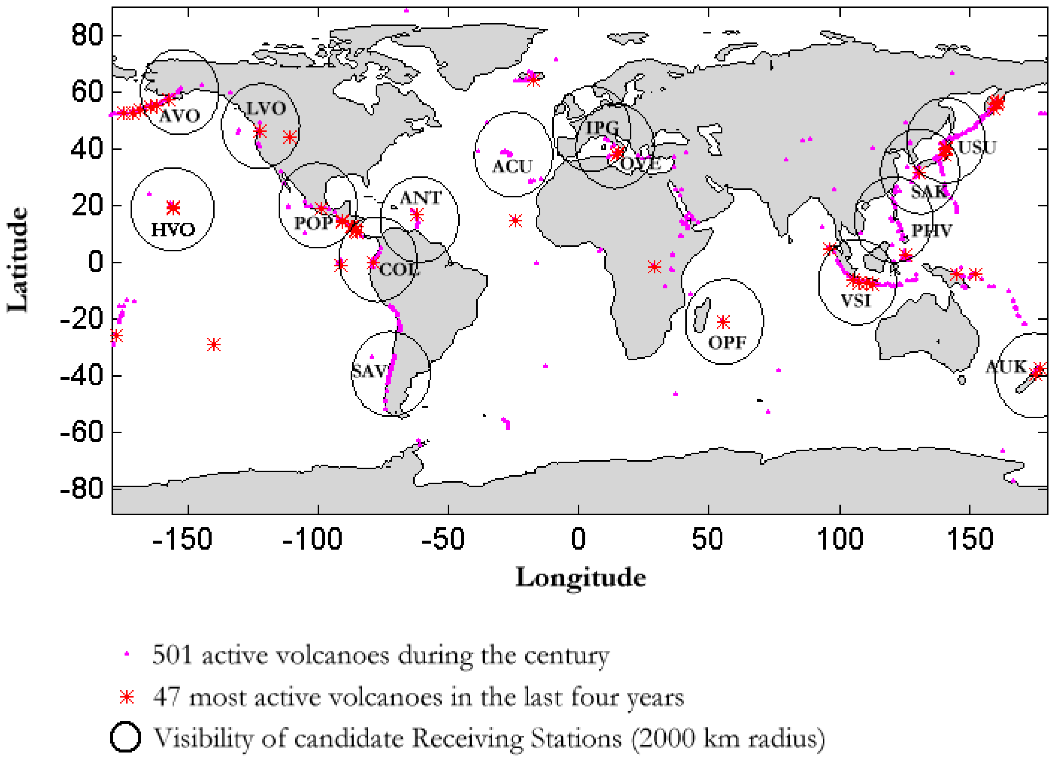
C.2.6.2 - Data download

- L band channel at 3 Mbits/s (*see C.3.3 for more technical information*)
- Time requested to download one full stereo scene (including quick-look): 55s (assuming 15% extra time)
- 15 receiving stations installed in the major volcanological observatories around the world + 1 master station
- Percentage of the satellite orbit visible from one receiving station: 9 to 12% (for 12 to 15 stations), 10% assumed
- Maximum number of scenes downloadable per day: 24h x 10% / 75s = 115
- Scenes downloaded daily according to the mission tasks: 30 + 40/7 + 500/365 = 37. The redundancy of 3 with respect to the maximum possible allows to start the mission with a reduced number of ground beacons and to monitor on demand other sites (landslides, earthquake areas, …).
- Daily amount of data recorded on board: 37 x 60 Mbytes = 2.22 Gbytes/day. Data archive on DVD-ROM and CD-ROM.

C.2.7 - Ground segment

12 to 16 receiving stations are necessary to ensure suitable coverage of the most active volcanic areas worldwide. The receiving stations will be installed in major volcanological observatories (see table below). The images and products will be added to a central database via Internet. Assuming 12 ground stations, and 37 full scenes per day, the total amount of data is about 2.2 Gbytes/day. A package of software will be provided together with the receiving stations in order to allow a real time processing of the data for DEM production. A master station will be operated in one control centre in Europe. This centre will be responsible for the precise orbit and ephemeris calculation and for the observation schedule. This centre will be linked to a control centre in charge of the data up-link for satellite maintenance and programmation.

Distribution of the active volcanoes on the Earth & Possible ground segment configuration



Observatory	Code	Country	Longitude	Latitude
IPG Paris	IPG	France	5° E	47° N
Universidade dos Açores	UAC	Portugal	25° W	38° N
Obs. Volcanologique Antilles	ANT	France	61° W	15° N
Obs. Volcanologico y Sismologico	COL	Columbia	77° W	1° N
Popocatepetl Volcano Obs.	POP	Mexico	100° W	20° N
Long Valley Caldera Obs.	LVO	USA	122° W	48° N
Alaska Volcano Obs.	AVO	USA	153° W	60° N
Hawaiian Volcano Observatory	HVO	USA		
Univ. Aukland	AUK	New Zealand	175° E	40° S
Usu Volcano Obs.	USU	Japan	141° E	43° N
Sakurajima Volcano Res. Center	SAK	Japan	131° E	32° N
Volcanological Survey of Indonesia	VSI	Indonesia	107° E	7° S
Philippines Volcano Observatory	PHV	Philippines	121° E	15° N
Southern Andes Volcano Observatory	SAV	Chile	72° W	39° S
Obs. Volc. Piton Fournaise	OPF	France	56° E	21° S
Istituto Internazionale di Vulcanologia	IIV	Italy	15° E	37° N

Table 7

C.2.8 - Identification of geophysical products, necessary data and development of necessary algorithms.

The only geophysical product requested to exploit data is the accessibility to precise GPS orbits. This is provided since 1992 on a routine basis by IGS centres and should not create any access problem for scientific community in the next years.

For the exploitation of observed data, it will be convenient to put together some software tools for which various sources, either as university or as commercial products :

- GPS computations

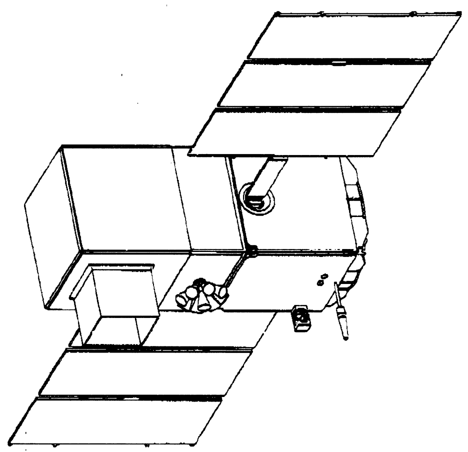
- DEM computation software through images automatic correlation : softwares that are proposed at least by DLR and IGN as well.

More specific softwares will have to be developed for the absolute positioning of images through the computation of GPS and for the image geo-referencing using identified target on the ground or using correlation methods (*see also C.2.5.5*). This software will be developed in collaboration between IPGP, DLR, OU.

C.2.9 - Calibration and validation

In order to assess the accuracy of the system and thus to ensure the delivery of calibrated data, the science team will promote the realisation of specific ground truth campaigns on a few chosen targets where reliable ground data is available. Such ground truth will concern:
1) The accuracy of the DEM generation. This can be done partly in places accessible to extensive ground measurements, away from active volcanic centres. However, it is advisable that volcanic areas are used as test areas as well (maybe at less active volcanoes) to assess DEM accuracy at the surfaces of interest (different morphology and coverage may afford slightly different approaches for matching).
2) The effective spatial resolution and level of detection for ground deformation monitoring. Both volcanic areas and landslides area will be investigated. The relation with the viewing angle is an important issue to be validated too.
3) The effective spatial resolution and level of detection for thermal mapping and flux quantification.

C.3 - TECHNICAL CONCEPT



C.3.1 - Overview

SVO will be built around the PROTEUS platform developed by Alcatel Space.

The payload includes a high resolution camera with a lateral orientation capability of ±40° with respect to the nadir direction, and an along track stereoscopic capability, with a ground pixel of approximately 1.5 m wide for a footprint of about 6 km x 6 km at the nadir, in a panchromatic large spectral band from 0.4 to 1 µm, with a TDI capability adjustable in a large set of values (from a few to about a hundreds pixels, the maximum number depending on the pointing stability (RPE) of the platform). The requested dynamic range is 12 bits (11 useful bits), in order to accept the very strong contrasts of such images. The compression rate expected for such conditions will be very low (around 1/1.5 typically). Given the stability of the PROTEUS platform (*see C.3.3*), very long TDI could be used during night passes (*see C.3.2.5*), especially when a degradation of the resolution (6 m instead of 1.5 m) will compatible with the scientific goal.

The platform will provide an altitude and orbit control allowing to aim at a given spot with an accuracy better than 600 m at the nadir. On another hand, the orbit and the exact position of the optical axis will have to be known off line so as to allow for a superposition of the night and day images at better than 5 metres. This implies an orbit knowledge within 1m. This accurate orbit will be calculated off-line using precise IGS orbits of the GPS satellites.

No actuator will be operated during image acquisitions.

The platform will have enough power autonomy for acquisition and transmission to the ground station of one image in the shadow zone.

The SVO system will work only with direct reception stations.

The relative simplicity of the proposed system allows to imagine that future other missions using the same method for high resolution imagery could have their weight progressively reduced so as to allow cheaper launches (like the planned ASAP or ASAP-twin launches). This aspect is important in the perspective of a complete constellation of satellites dedicated to environmental hazard monitoring.

C.3.2 - The Camera

C.3.2.1 - Instrument aiming

Lateral spacecraft aiming and along track scanning mirror

The lateral aiming capability will be obtained by a general rotation of the platform with respect to an axis parallel to the ground speed vector. The acceptable aiming delay is around 0.3° per second of direction change, and this function will be obtained by a proper operation of inertial wheels of the platform.

The along track aiming will be obtained by the proper rotation of a tiltable (scanning) mirror in front of the telescope.

Option of complete spacecraft pointing
A tiltable scanning mirror in front (objet side) of the 35 cm optics would be at least of 40 cm and have a mass of about 10kg, this is comparable with that of the CCD camera itself. The solution of pointing the complete spacecraft is an alternative option.

C.3.2.2 - CCD matrix

The camera will be built around a 4096 x 4096 Kodak CCD matrix (KAF-16800), with pixel size 9 µm x 9 µm. The maximum electron capacity per pixel is 80 000 and the noise current is 20 electrons/pixel/second at a temperature of 20° (very low). The environmental conditions around volcanoes are such that it is advisable, even if not fully compulsory, to use matrix with an anti-blooming capability. In some sites close to the sea or with a lake, the water surface will be close enough for the Sun specular reflection to make the camera impossible to use. Such a situation will not be very frequent. Kodak company is ready to provide the matrix with an anti-blooming, which will result in a sensitivity loss, but not at a prohibitive level (around 30%). No spectral filtering will be performed to limit the sensitivity in the IR band.

C.3.2.3 - Telescope

The telescope optics, in order to overcome the diffraction limits, will need to be at least 35 cm in diameter (entrance pupil). The requested focal length for 1.5 m ground pixel size is 4.1 metre, which means an aperture ratio of f/12 (for a 685km orbit). This corresponds to an instantaneous FOV (IFOV) of about 2.2 µrad (0.5 arcsec). Analysing various telescopes suitable of fulfilling the above requirements, the minimum achievable mass of the camera including the optics, shutter unit and the FPA with read-out electronics and the interface to an (external) image data buffer (but excluding the front-end scanning mirror) could amount to about 8 to 10 kg only if a compact optical and mechanical configuration is chosen. An appropriate design would require the application of highly aspherical optical surfaces (mirrors), the use of light-weight construction materials (e.g. carbon-enforced Silicone Carbide [C/SiC], or Zerodur), and a careful thermal control of the optics and mechano-optics.

C.3.2.4 - Shutter

Slit shutter option

The shutter will be placed in the narrowest part of the optical beam. As the TDI requires the columns of ground pixels to be oriented parallel to the speed of the satellite with respect to the ground, a slit shutter will be usable. The slit motion will be parallel to the projected velocity vector, so as not to deform the image geometry significantly. The number of TDI stages will then be adjusted to the duration of a complete motion of the slit in front of the CCD. The shutter may be purely electro-mechanical, and then it will be possible to use a classical slit shutter that will be pressurised at 1 bar in an optical box. Some technical publications propose to use liquid ferroelectric crystals (which would in any case lose around 60% of the incoming light), but this in turn implies that the system stays within a quite limited temperature range, and then the obturation itself is not perfect, specially in the IR part of the spectrum. This device cannot thus be used without a mechanical shutter, that as a counterpart will be allowed to be slower (e. g. a rise or fall time around 20 ms or more could be acceptable).

For a slit shutter with a movement time of 4 ms (which is a very common specification for 24x36 film cameras), the blurring due to the movement will be 7 km/s x 0.004 s = 28 m at the nadir, i. e. ~ 20 pixels. This implies that the alignment of the ground pixels columns relatively to the velocity vector can be adjusted within 1/40th of a radian, which is far from the limits of absolute orientation guaranteed by the platform PROTEUS (0.05 or 0.9 mrd).

Central shutter option

The relatively small size of the Kodak CCD (37 mm x 37 mm) would allow to use an iris diaphragm (central shutter) with minimum exposure time of about 1ms instead of a slit shutter. The mass and effort to integrate the shutter would be almost the same as for the other option.

C.3.2.5 - Exposure time and detection level for the thermal mapping

The normal daylight exposure time at f/12 is close to 3 ms, and thus is perfectly compatible with the slit shutter already mentioned.

For the night observation of lavas, the integration times will be much longer, and there lies the interesting feature of large CCD. For example, for lavas at 700°C or 1000K, Planck's law for the black body, and the quantum efficiency of the Si CCD are listed below :

Wavelength (µm)	0.6	0.7	0.8	0.9	1
Quantum efficiency (Rq)	0.4	0.4	0.4	0.25	0.05
Spectral luminance of black body at 1000 K (L) *(in $W.m^{-2}.srd^{-1}.\mu m^{-1}$)*	0.05	0.8	7	20	70
Rq x L	0.02	0.32	2.8	5	3.5

Table 8

Within an hypothesis of a Lambertian emission, and transformed for a camera with a quantum efficiency of 100%, the emittance is M = 3.14 L, and at 1000° K the total emittance will be around 2.5 $W.m^{-2}$.

This figure is comparable with daytime radiance across the panchromatic domain, with a solar illumination corresponding to 2 air-masses (sun at 60 from the zenith), from a surface having an albedo of 0.15 (lavas) and a negligible illumination due to the atmospheric diffusion (which will be the case for very high volcanoes). The total emittance transformed for a 100% quantum efficiency camera will be :

1200 ($W.m^{-2}.\mu m^{-1}$) x 0.15 (Albedo) x 0.4 (mean quantum efficiency) x 0.5 (µm of wavelength) x 0.5 (cos(60°) , mean

inclination of sun rays) that gives a total of 120 $W.m^{-2}$
Thus for a 1.5 m pixel containing a homogenous surface at 700 C, the maximum exposure time for full dynamics (11 bits allow for 4000 true grey levels) will be 50 times longer than during daylight, that is 150 ms or 700 TDI pixels. If, as is more likely, only 1% of the surface was at 700 C and the rest was too cold to be radiant, these conditions would give a DN of 40, which is still well above the noise level. On another hand, we note that the pixel size requested is 5 m and that we find here 1.5 m. So if it was necessary to use a very long TDI (the platform stabilisation is accurate enough for 1100 pixels of TDI), a misalignment giving 3 pixels of blurring would be acceptable, and thus TDI of more than 2000 pixels would be possible.

These computations show that the TDI mode, used with a reduced dynamics, should allow to see even lavas at 500 C (25 times less signal than at 700 C). This is compatible with the observation of lava channels, hot fissures in lave domes or the inner part of strombolian cones that are very hot in areas of limited extension only, and that would not been observable on large pixel not fully covered by hot material.

C.3.3 - On board data handling and down-link

C.3.3.1 - Buffers and image compression

The buffer is requested between CCD camera, whose readout speed is close to 5 MHz (i. e. 3.5 s for the 16.7 millions of pixels), while allowing the use of image compression algorithms in real time. It will not be very important, less than 32 Mbytes.

The onboard memory will have to store GPS data before re-emission towards the master reception station, once every day.

C.3.3.2 - Data down-link

The bandwidth of data transmission will be designed taking into account the time available between two stereoscopic image acquisitions of the same spot. If the stereoscopic ratio (base over distance) is around 1/5 (an optimum for DEM in areas where deep slopes occur), the acquisitions will be with the satellite in positions differing at least of 130 km from each other, i. e. 18 seconds. An image represents at least 4096x4096x12(bits)/1.5(compression), around 125 Mbits. A L band data download at 3Mbits/s using the new generation of HRPT technology is compatible with the data acquisition rate and satellite speed over target. Present L band transmission allow rates of 0.5 and 1Mbit/s (0.65 Mbits/s for a VEGETATION), but it is expect that the new generation of HRPT technology, developed for the distribution of meteorological data at low orbit, will permit rates of up to 3Mbit/s in the next few years. With respect to the X band, the use of the L band allows a significant reduction of cost.

C.3.3 - Spacecraft description

The SVO spacecraft will use a recurrent PROTEUS platform. Its shape is cubic (nearly 1m side) without central structure, and all the equipment units are accommodated on the four lateral panels and on the lower plate. The interface with the launcher is realised through a specific adapter bolted at the bottom of the structure. The mechanical interface with

the payload is provided through the four upper corners of the platform.
The platform thermal control is sized to withstand the highest thermal environment loads extracted from the PROTEUS mission domain. The concept uses passive SSM radiators and an active regulation, heaters being monitored by the central computer.
Electrical power is generated by a symmetrical two wings solar array covered with classical Silicon cells, providing about 800W when facing the sun. It is distributed through a single non regulated primary electrical bus (21/35 volts) using a recurrent Spot4 NiCd battery.
The on board control and command chain relies on a fully centralised architecture. The main function devoted to this chain are the following:

- satellite modes management: automatic modes transmission and routines,
- failure detection and recovery: monitoring and switching to the SHM if needed,
- on-board observability: housekeeping telemetry permanently registered,
- satellite commandability: managing of the telecommands sent by the ground either to hardware or software.

The DHU (Data Handling Unit) performs most of the main tasks through the central 3-1750 processor running the satellite software. It supports also the management of the communication links with all the satellite units either via point to point lines or via a MIL-STD-1552 bus. It generates a clock reference, manages data storage and insures telemetry frame decoding. Finally, it distributes power towards platform and payload equipment.

There are five distinct AOCS modes: Star Acquisition (STAM), Normal Operations Mode (NOM), Orbit Correction Mode with 2 or 4 thrusters (OCM2, OCM4) and Safe Hold Mode (SHM). In NOM, a zero-momentum three-axis control with four reaction wheels and a gyro-stellar attitude determination provide a typical pointing performance better than 0.1 degree (3 sigma). In SHM where satellite is sun pointing, coarse sensors and magnetometers provide attitude measurement and magneto torquers generate torques. In addition, two among the four reaction wheels are used to provide gyroscopic stiffness. The following table summarises the PROTEUS platform's main characteristics:

Dry mass	245 kg
Size (without solar array)	0.95 m x 0.95 m x 1.00 m
Hydrazine capacity	30 kg
Maximum average power consumption	170 W
Lifetime	Up to 5 years
Down-link rate	650 kb/s in S band, up to 100 Mb/s in X band

Table 9: Main characteristics of the PROTEUS platform

The platform provides a wide range of payload pointing capabilities, the accuracy of which is mission dependent:

- Earth and Anti-Earth pointing
- Inertial pointing

	Roll	Pitch	Yaw
Earth	0.035°	0.04°	0.035°
Inertial	0.02°	0.027°	0.02°

Table 10: Pointing accuracy

The platform is designed to be compatible with various orbits, with altitudes ranging from 500 to 1500 km, for any orbital plane inclination.

The standard payload mechanical interface consists in 4 mechanical links at the 4 upper corners of the platform.

A MIL-STD-1553 bus line is available for standard payload command-control and data retrieval. Numerous acquisition (48 analog and 12 serial lines, 8 logical status, 24 relay status, 48 temperature acquisitions) and command (48 relay commands, 8 serial commands, 16 open-collector types) lines are provided for the payload. Data Handling Unit Software, memory and computing power ressources are allocated for the payload. A standard 2 Gbits End of Life payload data storage capacity is provided. The down-link rate is 650 kbits/s using the S-band telecommunication system. As the SVO mission requires a higher rate of data download (*see C.2.6.1*), we expected to be able to use the new generation of L band transmitters using the HRPT technology at a rate of 3Mbits/s.

In the Payload part of the payload we find the following:

1) a mechanism with a flat mirror for stereoscopic observation of the Earth
2) a CCD camera system that includes:
- a Ritchey-Chretien telescope
- a mechanical shutter
- a focal plane unit
- a video chain with buffer memory and data compression

3) a L-band telemetry

C.3.4 - Launch vehicle

The PROTEUS platform is designed to be compatible with several existing or currently developed launchers such as: Taurus, Delta 2, LMLV1 & 2, Cosmos, Rockot, PSLV, Soyouz and Ariane 5. The stowed platform is then compatible with small launch vehicles fairing diameters of 2m. For SVO, we propose the use of the Rockot

C.3.5 - Mission operations

C.3.5.1 - Mission control and up-link operations

The CNES Aussaguel centre may provide the workmanship for the up-link and down-link data transmission. Some specific equipment are requested to allow for routine operations, due to the high degree of activity on this site already achieved now. Considering the duration of the antenna use requested (a few minutes every day), it is not possible to know whether a new antenna will be requested at the launch date for the 2 years of operation. Thus the cost lies between 0.3 ME (only the command software) and 1.2 ME if a new antenna is requested. The routine operation may be supported by CNES.
Mission parameters like precise orbits as well as the data acquisition sequence will be delivered by the institution in charge of the "mission planning and orbit maintenance", in order to reduce the services requested to the agency for the mission operation (see C.3.5.3 below).

C.3.5.2 - Orbit maintenance

The satellite orbit will be provided by a classical onboard GPS receiver. Data will be downloaded to the mission control station, once every day. Broadcast orbits of the SVO satellite will be uploaded on a daily basis to the satellite for direct download to the receiving stations together with the images. This will improve the accuracy of image geo-referencing and quick DEM generation. Broadcast orbits as well as off-line precise orbits of the SVO satellite will be available via Internet at the data archiving station.

C.3.5.3 - Mission planning and orbit maintenance

This task will be performed by an European research group on a voluntary basis, after diffusion of an A. O. The institution in charge of the "mission planning and orbit maintenance" will operate a main receiving station. It will allow, using the various programmation requests emanating from the different groups operating reception stations, to program the image acquisitions limiting as much as possible programmation conflicts, under the chairmanship of a scientific committee formed by various researchers implicated in this project. It will receive the GPS data stored on board, and with these data the precise orbit and the ephemeris will be computed. The use of this main station will considerably limit the services requested from CNES to operate the satellite.

C.3.6 - Ground operations

C.3.6.1 - Distributed reception stations

The visibility zone, with a limit elevation angle of 20° and an altitude of 685 km for the satellite, has a radius around 1470 km. In the case of Indonesia for example, it means that a station in Yogjakarta may allow the observation of all active volcanoes of the country.

If possible, reception stations should be designed without requirement of a directive antenna so as to limit their cost.

In the reception stations will be installed a software allowing DEM computations using the stereoscopic images, an image processing software allowing to use the precise GPS orbits (downloaded from IGS web sites), the star images and the DEM of the zone so as to provide a correct superposition of day and night images in the same reference frame.

C.3.6.2 - Data archiving and on line data access

A general database of acquisition world wide will be accessible at IPGP via Internet. On line data access to the RAW data (images) and to the products (DEM, thermal anomalies maps) will be accessible via Internet as well. If successfully implemented by this time, the ISIS (Interactive Satellite Image System) system (presently EU-DGIII project) could be used as one of the gateways to the SVO data.

C.3.7 - Maturity of the requested technology

C.3.7.1 - On board instrumentation

The camera using a Kodak matrix 4k x 4k is based on airborne developments (including TDI), operated on an operational basis since 1997. The CCD technology is the same as the one used in 2k x 3k of IKONOS satellite. The telescope is a classical spatial subsystem (we may cite the C/C telescope from Alcatel Space and the Ritchey-Chrétien telescope from DLR).

The proposed shutter is a slit shutter pressurised under inert gas. The proposing team has no experience concerning the spatialisation of such a component at that time.

The scanning mirror is also a classical spatial subsystem, widely used in imaging satellites.

The GPS receiver has been used for various spatial missions (Topex-Poséïdon, Jason, …)

The other instruments belong to the PROTEUS platform and thus will not be discussed here.

C.3.7.2 - Reception stations

The direct reception stations are classical subsystems, and are based on common industrial fabrications. About eight of them could be financed by ESA, and the other could be founded by other agencies or European funding (for the European stations for example).

C.3.7.3 - Algorithms

The requested algorithms for data processing are the ones relative to DEM processing, and to the computations of superposition of daylight and night images, which are basically geodetic and photogrammetric computations.

- For the algorithms of automatic image correlation, they have been put into production at IGN-France as early as the SPOT 1 launch. A good experience is available on this topics in several large european laboratories, in particular DLR and IGN. This experience covers software for image correlation, but also on photogrammetric software for object point calculation, orthoimage computation, map projection, and image mosaicking.
- For geodetic computations, orbit computations are performed on a routine basis at ESA and at CNES, and a large scientific community is ready to invest time on this topics, based on the software tools existing in many laboratories.

C.4. Mission Elements and Associated Costs

Alcatel Space (Cannes) has a thorough experience in the design and development of optical earth observation payloads and platforms. In particular, it realised the VEGETATION and MERIS as well as HELIOS cameras. It is also developing the multimission PROTEUS platform which will first fly in 2000 for the JASON mission. The development of this platform has involved several European partners (60% Europe, 35% France).
For the SVO project it will provide support for visible and infrared instruments and for the overall platform, satellite and system design.

Command and acquisition station

The general SVO concept is based upon direct reception of images directly by the teams collaborating to the project. Thus the main station has only the following roles :
1) reception of GPS orbitographic data of the last 24 hours, so as to compute precise orbits off-line, and to compute broadcast ephemeris that will be uploaded to the satellite for diffusion to the users with the images.

Mission element		Implementation	Assumed Funding Source
Science preparation	Scientific definition studies	IPGP, ESGT, INSU, OU, IIV	ESA, EU funding, national funding
	Campaigns	IPGP	EU funding, national funding
System engineering and assembly integration and test		ALCATEL	ESA
Space segment	Instrument(s)	ALCATEL, DLR, IGN	ESA
	Platform	ALCATEL	ESA
	Launcher	Small launchers, or ARIANE 5 dual launch	ESA
Ground segment facilities	Command and acquisition stations	ESA, IPGP, major volcanological observatories	ESA, EU funding, non EU funding (world bank …)
	Operations centre	CNES	ESA
	Processing and archiving	IPGP	ESA, EU funding, IPGP
Mission control and data exploitation	Mission Control	CNES	ESA
	Data utilisation	World scientific community	Various national, EU funding, and non EU funding

Table 11 - Mission implementation and funding

Mission element		Costs Estimates (Mecu)
Science preparation	Scientific definition studies	2
	Campaigns	
System engineering and assembly integration and test		8
Space segment	Instrument(s)	20
	Platform	17
	Launcher	15
Ground segment facilities	Command and acquisition stations	5
	Operations centre	2
	Processing and archiving	2
Mission control and data exploitation	Mission control	2
	Data utilisation	

Table 12: Cost Estimates

2) commands of programmation for the observation of the various sites in the world. The demands will be received by the SVO operational centre team, this team will check that the demands are compatible with each other and transform them into programmation commands. These commands will be stored on board for the next 24 hours and trigger the image acquisitions and transmissions.

The costs of this station will be shared by the SVO operational centre (that will be operated free of charge on a voluntary basis) and the operating centre, that may be provided by the CNES in Aussaguel.

Receiving stations

The estimated cost of the receiving L-band stations will be 0.25Mecu/station (for the expected new generation of HRPT stations at 3Mbits/s)

Processing and archiving

The SVO operational centre will archive the images and the precise orbits (computed off-line). The images acquired in each observatory will be stored also locally.

Software development

For the software development, that include the software for direct reception stations, the operational centre software for orbit computation and commands planning, the cost is estimated to 1 ME.

Financial support other than ESA

CNES support: The science team has been advised by CNES that the SVO project will be considered by the agency for appropriate support necessary for the implementation of the proposal in case of selection by ESA. Mission control operation, Operation Centre as well as support to the instruments implementation are primarily concerned.

EU support: A support of the EU to the SVO project may be obtained within the future 5th Framework (activities related to the monitoring and prevention of risks in Europe using remote sensing techniques are mentioned in the preliminary framework programme). In the case of SVO, science preparation, data acquisition and data utilisation may be relevant to this EU programme. The experience of the EU Joint Common Centre (JRC) of Ispra that has already developed a strategy for remote sensing data management/dissemination though its Centre for Earth Observation (CEO) may help the SVO team for the definition of its ground segment.

C.5 - Implementation

C.5.1 - Proposed cooperation arrangements

C.5.1.1 - Science team roles

IPGP (Pierre Briole) will act as principal investigator of the science project. According to the scientific objectives of the project (*see C.1.3*), further prospective analysis of the scientific interests of the mission will be placed under the leadership and responsability of Co-I according to the following possible configuration:
Volcano topography monitoring: IIV
Thermal volcano monitoring: OU
Landslide monitoring: LCPC
Mudflows: CVUC
Fault mapping and earthquake study: IPGP
Comparative Planetology: DLR

C.5.1.2 - Interface science - instrumentation to meet science objectives

Coordination of the interface between science and instrumentation configuration necessary to meet science objectives will be placed under the joint responsability of IPGP (Pierre Briole) and ESGT (Michel Kasser). They will ensure an efficient communication of the information and reciprocal feed-back between Co-I both on the science side and instrumental side.

C.5.1.3 - Instrumentation team roles

ESGT (Michel Kasser) will be responsible of the coordination between the partners involved in the technical part of the project (DLR, IGN, ESGT) and Alcatel Space.

C.5.2 - Requirement for data from other sources

No data from other sources are required for the implementation of the project.

Annex 1 - Team Composition

The science team includes several research groups that are leaders in the field of volcanology in Europe and that have already a strong background of scientific cooperation. Other partners (DLR, IGN) have a very high experience on airborne and satellite imagery, and also a large background of collaboration with the geophysical community. Given the fact that the technological feasibility of the satellite appears reasonably high, the large experience of Alcatel coupled with the competence/complementarity of the science team ensures a high level of feasibility to the project.

Project proposer

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Science team

Institut de Physique du Globe de Paris (IPGP) - F

- Prof. Pascal Bernard - Head of the Laboratoire de Sismogénèse
- Dr. Jean-Louis Cheminée - Head of the Observatoires Volcanologiques, chairman of the WOVO
- Prof. Michel Diament - Head of the Laboratoire de Gravimétrie et Géodynamique
- Prof. Philippe Lognonné - Head of the Département d'Etudes Spatiales
- Prof. Paul Tapponnier - Head of the Département de Tectonique
- Ing. Jean-François Karczewski

IPGP is the largest centre for earth sciences in France. It is in charge of the monitoring of the French active volcanoes. It has a long and wide background in volcanology including instrumentation, multi-parameter monitoring, SPOT and ERS SAR Interferometry images processing and interpretation, field intervention during eruptions, collaboration with several countries for the volcano monitoring and risk mitigation (Italy, Greece, Indonesia, Central-America,…). IPGP has also experience in space missions (MARS 94, DEMETER).

Ecole Supérieure des Géomètres et Topographes (ESGT) - Le Mans - F

- Prof. Michel Kasser - Director

At ESGT, Prof. M. Kasser is specialist of airborne and satellite instrumentation, and has promoted the use of CCD cameras for airborne photogrammetric imagery in close relations with LOEMI of IGNF.

Institut Géographique National (IGN) - Saint Mandé - F

- Ing. Christian Thom
- Dr. Nicolas Paparoditis

IGN-France, Christian THOM. At IGNF, the LOEMI Laboratory has built several airborne CCD cameras using KODAK chips (KAF 6300 and KAF 16800) and promoted their operation for imagery devoted to orthophotography and photogrammetric applications, since 1996.

Bureau de Recherches Géologiques et Minières (BRGM) - F

- Prof. José Achache - Scientific director

Laboratoire Central des Ponts et Chaussées (LCPC) - F

- Dr. Durville

Open University (OU) - Milton Keynes - UK

- Prof. Peter W. Francis
- Dr. David A. Rothery

The Open University is the leading European institution for the infrared study of volcanoes, from satellites and ground-based observations. Francis and Rothery of the Open University developed the use of short wavelength infrared data from satellites for monitoring and modelling surface magmatic activity at, and have used Landsat TM, ATSR, AVHRR and JERS data to study volcanoes in volcanoes in Europe, South America, Central America, Africa, Antarctica and Hawaii. Their group, plus two former students of theirs (Oppenheimer and Wooster, see below) will provide the Science’s Team’s main expertise in interpreting the night-time thermal data.

Cambridge University (CU) - Cambridge - UK

Dr. Clive Oppenheimer has been a lecturer in the Department of Geography at Cambridge University since 1993 has worked with Landsat TM and ADEOS data for thermal study of lava lakes and crater lakes, as well as being familiar with Indonesia and the Philippines and an expert on volcanic gases.

Kings College London (KCL) - London - UK

Dr. Martin J. Wooster has been a lecturer in the Department of Geography at Kings College London since 1998. He is an expert in using ATSR data for volcano monitoring, and has close collaborative ties with Japan.

Deutsches Zentrum für Luft und Raumfahrt (DLR) - Berlin - D

- Prof. Ralf Jaumann
- Dr. Ernst Hauber
- Dr. Klaus Gwinner

The Institute of Planetary Exploration (part of DLR, German Aerospace Center) investigates the origin and development of planets, moons, and small bodies in the Solar System by ground-based and spacecraft observations as well as laboratory experiments and in-situ studies combined with theoretical modelling. This includes the design and development of modern remote sensing experiments and the implementation of quantitative data processing techniques. DLR will contribute to the SVO in three main aspects: (1) The extensive experience in instrument design (e.g.: DLR has built the High Resolution Stereo Camera HRSC for the Mars 96 and Mars Express missions) will support the development of the SVO camera. (2) For the analysis of HRSC images, a unique data processing system for automated generation of Digital Elevation Models (DEM) was developed by DLR and the Technical University of Berlin. DLR will participate in the software generation for analysis of topographic data provided by SVO. (3) Comparative planetology often uses terrestrial analog features in the interpretation of planetary surfaces. This approach has been applied by DLR to volcanic phenomena in recent flight campaigns over active volcanoes in the Aeolian Islands (Italy). Scientific investigation of terrestrial volcano topography provided by SVO will extend our understanding of planetary volcanism.

Istituto Internazionale di Vulcanologia (IIV) - Consiglio Nazionale delle Ricerche (CNR) - Catania - I

- Dr. Mauro Coltelli colt@iiv.ct.cnr.it
- Dr. Giuseppe Puglisi geo@iiv.ct.cnr.it

The Instituto di Vulcanologia Catania (IIV-CNR) is responsible of the monitoring system of the active Italian volcanoes (Mt. Etna, Stromboli and Vulcano islands). Furthermore it carry out several studies relevant to the recent volcanism of the different volcanic district of Sicily and surrounding islands (Aeolian Island, Ustica, Pantelleria, Iblei) and its relationship with the geodynamic framework of the central Mediterranean

Sea. With regard to the remote sensing applications in volcanology, the IIV-CNR has been involved in several national and international projects concerning the ground deformation monitoring using SAR techniques (in EC projects with IPGP and POLIMI and NASA project with JPL and IRECE-CNR), the volcanic gas emission detected with COSPEC (in EC projects with OU and CNRS) and DEM production using SAR and photogrammetric techniques (with IPGP, DLR, and OU). Particularly useful for the present ESA proposal is the activity recently carried out together with the DLR (Germany) in several high resolution airborne surveys of Mount Etna using CCD cameras developed partly for space applications.

Università della Calabria & Dipartimento della protezione civilà (Presidenza del consiglio dei ministri) - I

- Prof. Fabrizio Ferrucci

Fabrizio Ferrucci has a strong background in geophysics, applied geophysics and volcanology. He has been and is in charge of several EU project related to volcano risk and to civil protection problems related to environnemental hazard.

Centro de Vulcanologia - Universidade dos Açores (CVUA) - Ponta Delgada (P)

- Joao Luis Gaspar, Director
- Dr. Gabriela Queiroz
- Ing. Antonio Neves Trota

The CVUA is a multidisciplinary research unit directed at the development of Earth Sciences in the field of Volcanology.

Presently the CVUA coordinates the Azores Volcanological Monitoring System (SIMOVA) and the Azores Seismological Surveillance System (SIVISA), being the later in cooperation with the Meteorological Institute. This is achieved taking in account the maintenance of several surveillance networks and the integrated analysis of geophysical, geodetic and geochemical data. A Geographic Information System to facilitate data processing is now under installation.

The CVUA is than responsible to support scientifically the Azores Civil Protection Service (SRPCA) before, during and after natural disasters. It draws scenarios for the evolution of the eruptive crises and for their implications regarding civil protection actions and povides recommendations to the authorities regarding the precaution measures for the mitigation of volcanic risk.

CNES

The science team has been advised by CNES that the SVO project will be considered by the agency for appropriate support necessary for the implementation of the proposal in case of selection by ESA.

Industrial team

Alcatel Space Industries

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Annex 2 - Abbreviations

AIRS:	Atmospheric Infrared Sounder
ASTER:	Advanced Spaceborne Thermal Emission and Reflection Radiometer
CNES:	Centre National d'Etudes Spatiales
DEM:	Digital Elevation Model
DHU:	Data Handling Unit
DHUS:	Data Handling Unit Software
DLR:	Deutsches Zentrum für Luft und Raumfahrt
EOS:	Earth Observing System
EOSP:	Earth Observing Scanning Platform
ERS:	European Space Agency's Remote-Sensing Satellite
ESA:	European Space Agency
EU:	European Union
GOES:	Geostationary Observational Environmental Satellite
GLAS:	Geoscience Laser Altimeter System
GPS:	Global Positioning System
IAVCEI :	International Association of Volcanology and Chemistry of the Earth Interior
IGS:	International Geodesy GPS Service
IIV:	Istituto Internazionale di Vulcanologia
IPGP:	Institut de Physique du Globe
ISIS:	Interactive Satellite Image System
ISCCP:	International Satellite Climatology Project
MISR:	Multi-Angle Imaging SpectroRadiometer
MLS:	Microwave Limb Sounder
MODIS:	Moderate-Resolution Imaging Spectroradiometer
MTPE:	Mission to Planet Earth
NASA:	National Aeronautics and Space Administration
NOM:	Normal Operation Mode
OCM:	Orbit Correction Mode
SHM:	Safe Hold Mode
SPAT-DEM:	Single-Pass Along-Track DEM
STAM:	Star Acquisition
SAGE:	Stratospheric Aerosol and Gas Experiment
TDI:	Time Delay Integration
TES:	Tropospheric Emission Spectrometer
VAAC:	Volcano Ash Advisory Centres (see also http://disaster.ceos.org/newash.htm)
WOVO:	World Organisation of Volcano Observatories

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Annex 4 - Recent and future remote sensing mission useful for volcanology

Mission Name	Country	Description	Date of activities	Web reference
NOAA AVHRR	USA	Primarily meteorology secondary use for volcano ash plume and hotspot alert	since 1960s	http://www.arl.noaa.gov/ready-bin/vaftad.pl
SPOT	France	Earth observation. Stereo capability allows DEM generation	Since 1986	http://www.spot.com/
Landsat	USA	Terrestrial resources monitoring	since 1972	http://geo.arc.nasa.gov/sge/landsat/landsat.html
JERS	Japan	SAR and optical. Low data quality makes IR data of qualitative value only	1992	
Meteosat	Europe	Meteorology	Present	http://www.esa.int/
ERS	Europe	Earth observation SAR capable of DEM generation and deformation monitoring, ATSR capable of thermal monitoring	Present	http://www.esa.int/
GOES	USA	Primarily meteorology, Secondary use for volcano hotspot alert	Present	http://rsd.gsfc.nasa.gov/goes/
Radarsat	Canada	Earth Observation. SAR penetration of clouds useful for volcanoes.	1995 - 2000	http://radarsat.space.gc.ca/
EOS	USA	long-term global observations of the land surface, biosphere, solid Earth, atmosphere, and oceans Inderdisciplinary Science team for volcanology	1999-	http://eospso.gsfc.nasa.gov/ http://www.geo.mtu.edu/eos/
Envisat	Europe	Earth observation, as for ERS	May 2000	http://envisat.estec.esa.nl/

Table 13