Automated sulfur dioxide flux monitoring at Asama volcano, Japan

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Asama volcano located in central part of Japan is one of the active volcanoes continuously emitting volcanic plume. Sulfur dioxide flux of the volcano has been measured using COSPEC (Correlation Spectrometer) since 1970s, and recently using COMPUSS (Compact UV spectrometer system). The volcano emit a few hundred ton/day of SO_2 during the quiescent period and several thousand ton/day during active period (e.g., JMA web page*).Because, the past SO_2 flux measurements were carried out intermittently on an irregular base, it is not well constrained when and how the flux increased at the beginning of the active periods. We need to have more frequent measurements to relate the SO_2 flux with other geophysical observation data and to understand the degassing activities during the changes of the activity of the volcano.

We installed automated scanning system with a USB2000+ spectrometer (Ocean Optics Inc.) for SO_2 flux measurement in the end of July 2011 at Asama volcano observatory (Earthquake Research Institute, the Univ. of Tokyo) located about 4 km east of the summit crater. The scanning system used at the volcano is 45 degrees forward looking system which intended to cover relatively wide wind direction range with one instrument. For the plume speed, we use wind speed data at plume height from GPV (Grid Point Value) data based on MSM (MesoScale Model) provided by Japan Meteorological Agency.

The volcano has been in quiescent period for the last three years. The observed SO_2 flux usually showed 2-3 kg/s which corresponds to typical SO_2 flux of the quiescent period and agrees well with the results of traverse data measured by JMA (JMA web page*). Kazahaya *et al.* (2011) reported that the volcano emits a large amount SO_2 after very long period seismicity occurred beneath the crater bottom. Our flux data sometimes exceeded 10 kg/s for a short period during the day, which may be related to the seismicity. We will discuss about present status of the automated monitoring at Asama volcano and about these short period flux increases in relation with seismic activities of the summit area.

*JMA web page: http://www.seisvol.kishou.go.jp/tokyo/306_Asamayama/306_So2emission.htm

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Inventory of gas emission rate measurements from volcanoes of the global Network for Observation of Volcanic and Atmospheric Change (NOVAC) - present status of the network and some study cases

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Measuring the magnitude, intensity and distribution of volcanic gaseous emissions is important for a number of reasons. On one hand, it provides information on the amount of magma involved in an eruption, as well as on the conditions in the conduit and eruptive vent that determine if magma would erupt explosively or effusively. On the other hand, volcanic gases may have an important impact on the surrounding human and natural environment, either directly for the case of acid, corrosive or suffocating species; or indirectly, due to their role in atmospheric chemistry, radiative balance and potentially climate on different scales. Despite of its importance, continuous monitoring of volcanic gases has traditionally not been the major focus of volcanological studies, due mainly to technological, logistical or economical reasons. This situation is changing in recent years, due to the advent of robust, affordable, automatic remote sensing instruments, like the Scanning Mini-DOAS. This instrument is capable of measuring the emission rate of SO2 emitted by a volcano by the scanning-DOAS method with sufficient accuracy to detect passive emission plumes a few km downwind their sources.

NOVAC, the Network for Observation of Volcanic and Atmospheric Change, was initiated in 2005 as a 4.5-years-long project financed by the European Union. Its main purpose was to implement a global network for the study of volcanic atmospheric plumes and related geophysical phenomena by using the Scanning Mini-DOAS instrument. Up to 2013, 68 instruments have been installed at 26 volcanoes in Central and South America, Italy, Democratic Republic of Congo, Reunion Island, Iceland, and Philippines, and efforts are being done to expand the network to other active volcanic zones. NOVAC has been a pioneer initiative in the community of volcanologists, involving research institutes and volcanological observatories in 18 countries.

We present the results of the batch evaluation of measurements of SO2 gas emission rates carried out within NOVAC, which for some volcanoes represent a record of more than 7 years of continuous monitoring, with an average of 40 flux measurements every day. The network comprises some of the most strongly degassing volcanoes in the world, covering a broad range of tectonic settings, levels of unrest, and potential risk. Besides showing the present status of the global database, the source strengths and statistical distribution of emissions from the volcanoes in the network, some results of specific studies are presented, including a complete tracking of the recent reactivation of Nevado del Ruiz volcano, the characterization of open-closed degassing regimes of Tungurahua volcano, and the long-term variations of gas emissions from Nyiragongo volcano.

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Intercomparison between ground-and space-based measurements of SO2 at Popocatepetl volcano casts light into the several meteorological, instrumental and systematic biases of remote sensing.

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Popocatepetl has been continuously degassing copious amount of sulfur dioxide into the high troposphere of Mexico. Since the reawakening of the volcano in 1994, the cumulated SO_2 emissions have exceeded the SO_2 mass produced by the Pinatubo eruption in 1991, the largest episodic release of volcanic SO_2 on-record. The volcano is equipped with a permanent network of scanning mini-DOAS that provide an estimation of the SO_2 emission rate every five minutes, during daytime. Traverses with COSPEC and mobile mini-DOAS spectrometers, and, more recently, UV camera measurements, are also conducted regularly. The permanent, large, and high altitude SO_2 plume is also an ideal target for satellite-based measurements. We used ASTER and OMI, the two most effective satellites for measuring passive degassing, to reconstruct long term space-based databases of SO_2 emission rates. During the last, still ongoing, high degassing period, the SO_2 plume could often be tracked as far as Florida or the Bahamas Islands. Comparing the datasets of SO_2 emission rates from the different techniques brings into light some significant discrepancies, which must reflect some systematic methodological errors. We carefully investigated the potential causes to these discrepancies and propose explanations and solutions to reduce the methodological issues.

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Satellite-based assessment of global volcanic degassing

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Satellite observations by hyperspectral ultraviolet (UV) and infrared (IR) sensors over the past decade have afforded tremendous insights into the spatial and temporal variability of global, subaerial volcanic degassing. Commonly cited volcanic emissions inventories are still largely based on infrequent ground-based gas measurements and have not been updated in recent years. We use 8 years of sulfur dioxide (SO_2) measurements by the Ozone Monitoring Instrument (OMI) on NASA's Aura satellite to assess the spatial and temporal variability of volcanic SO_2 degassing between 2004 and 2012. We focus on passive (lower tropospheric) degassing, which is the major component of total volcanic emissions to the atmosphere on a time-averaged basis, but poorly constrained. Synergy between OMI and infrared (IR) satellite sensors (e.g., Aqua/AIRS) in the A-Train satellite constellation provides constraints on the vertical distribution of SO_2, which is critical for assessing the potential climate impacts of volcanic emissions. OMI measurements are most sensitive to SO_2 emission rates on the order of 1000 tons/day or more, and thus the satellite data provide new constraints on the location and persistence of major volcanic SO_2 sources. Time-averaging of OMI SO_2 data provides information on weaker SO_2 degassing. We find that OMI has detected non-eruptive SO_2 emissions from at least 60 volcanoes since 2004. Results of our analysis reveal the emergence of several dominant tropospheric SO_2 sources that are not prominent in existing inventories (Ambrym, Nyiragongo, Turrialba), the persistence of some well-known sources (Etna, Kilauea) and an apparent decline in emissions at others (e.g., Lascar). The OMI measurements provide particularly valuable information in regions lacking regular ground-based monitoring such as Indonesia, Melanesia and Kamchatka. We describe how the OMI measurements of SO_2 total column, and their probability density function, can be used to infer SO_2 emission rates for compatibility with existing datasets. We also discuss the potential biases in the OMI measurements due to latitudinal variations in ozone abundance, UV irradiance and cloud cover. Our analysis underlines the critical role of hyperspectral UV satellite observations in assessing global volcanic degassing rates, particularly for remote and/or unmonitored volcanoes.

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Interactive mapping of volcanic emissions with high-performance radiative transfer modeling tools

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The estimation of plume composition from radiance measurements is based on the use of radiative transfer (RT) modeling to fit the observed radiance spectra. In the thermal infrared (TIR), we must account for the temperature, emissivity, and elevation of the surface beneath the plume, plume altitude and thickness, and local atmospheric temperature and humidity. Our knowledge of these parameters is never perfect, and interactive mapping allows us to evaluate the impact of these uncertainties on our estimates of plume composition.

To facilitate this interactive mapping, the Jet Propulsion Laboratory (JPL) and Spectral Sciences, Inc. (SSI) are developing a new class of mapping tools based on the implementation of RT modeling on graphics processor (GPU) hardware. We will achieve a 100-fold increase in processing speed, relative to conventional CPU-based processing, and thus enable fully-interactive estimation and visualization of plume composition. The heritage for our new tools is based on the Plume Tracker toolkit, developed at JPL, and MODTRAN RT model, developed by SSI. Plume Tracker integrates retrieval procedures, interactive visualization tools, and an interface to a customized version of MODTRAN under a single graphics user interface (GUI). Our new tools will incorporate new adaptations of MODTRAN to optimize modeling of the radiative properties of chemical and aerosol clouds.

This presentation will include a review of the foundations of plume mapping in the TIR and examples of the application of Plume Tracker to ASTER, MODIS, and AIRS data. We will focus on our current efforts to validate the Plume Tracker retrievals for ASTER data acquired over the Turrialba and Kilauea Volcanoes in Costa Rica and Hawaii, respectively. Finally, we will discuss the application of our tools to data from new and future instruments, such as the airborne Hyperspectral Thermal Emission Spectrometer and TIR data from the upcoming Hyperspectral and Infrared Imager mission.

Portions of this research were conducted at the Jet Propulsion Laboratory, California Institute of Technology, under contract to the National Aeronautics and Space Administration.

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An integrated study of sulphur dioxide emissions from Tungurahua volcano, Ecuador

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Tungurahua is a stratovolcano in Ecuador, with a long-term mean SO_2 output of 1458 $\pm$ 2026 t/day. Since 2006, SO_2 emissions have been continuously monitored by UV DOAS spectrometers of the NOVAC programme. Tungurahua's SO_2 emissions have also been observed by the satellite-based UV spectrometer OMI (Ozone Monitoring Instrument). Tungurahua is therefore an ideal location for comparing ground- and satellite-based estimates of volcanic SO_2 emissions. Although OMI SO_2 retrievals for continuous tropospheric degassing are not yet validated, the dataset represents a large and mostly untapped resource for volcano monitoring, particularly in remote or inaccessible regions.

This study aims to improve agreement between the DOAS and OMI SO_2 datasets for Tungurahua, and gain new understanding of why differences arise. Uncertainties affecting comparison between the datasets include: the different natures of the quantities typically measured (flux vs column concentration); the impact of local atmospheric and meteorological conditions (e.g. clouds masking volcanic plumes; humidity and temperature promoting rapid loss of SO_2 via oxidation to sulphate or by various wet/dry deposition processes; wind dispersal of plumes); and differences in the spatial/temporal resolution of measurements. We present a novel numerical modelling-based study of volcanic SO_2 emissions from Tungurahua using the atmospheric chemistry/transport model REMOTE, which has already been used to investigate post-emission SO_2 dispersion from volcanoes in Nicaragua and Indonesia. We also investigate the use of derived fluxes from instantaneous satellite scenes to provide better agreement with ground-based gas emission measurements, and a detailed assessment of the principal errors in each dataset is presented.

Much better agreement between satellite- and ground-based observations of SO_2 emission are found when using OMI derived fluxes, rather than mass burdens, for comparison to DOAS-measured fluxes. Where possible therefore, these derived datasets should be used in assessing volcanic SO_2 output. Simulations of plume dispersal by the REMOTE model agree broadly with OMI observations. Simulations of daily SO_2 mass burden in the model domain record significant variability in the extent of atmospheric plume processing, and this variability shows limited agreement with the OMI mass burden time series. This suggests that simulations of processing may be able to predict days on which potential for satellite-based detection of SO_2 is improved or limited. Further simulations are proposed to address this further. Calculated SO_2 loss rates are in agreement with previous work at similar volcanoes, and the relative importance of oxidation, deposition and transport processes in the removal of SO_2 are assessed. Diurnal variations in these processes do not appear to be significant.

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Detection of volcanic CO2 in the August 2008 Kasatochi eruption plume by SCIAMACHY measurements

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Volcanic emissions likely dominate the carbon dioxide (CO_2) flux from the Earth's deep interior to the surface, and yet current estimates of global volcanic CO_2 emissions are highly uncertain due to the temporal and geographical limitations of volcanic gas measurements. The only means to fully monitor gas emissions from the approximately 1500 active volcanoes globally and on a regular basis are space-borne remote sensing observations. To our knowledge, direct detection and quantification of volcanic CO_2 from satellites has not yet been reported. Here we take a step toward this goal and report for the first time on statistically significant enhancements of dry-air columnar averaged CO_2 mixing ratios (XCO_2) derived from SCIAMACHY (SCanning Imaging Absorption SpectroMeter for Atmospheric CHartographY) measurements found in the August 2008 eruption plume of Kasatochi volcano (Alaska). Applying a threshold on coincident SO_2 retrievals allows us to discern plume pixels from background pixels in the SCIAMACHY data set. We find that over the study region of North America (30–85N, 50–175W) the XCO_2 of the Kasatochi plume pixels significantly exceed those of the background pixels. Evidence that volcanic CO_2 was detected by SCIAMACHY is found by focusing on individual days when the plume was located over North America. For example, while the XCO_2 enhancement is stable over time SO_2 decreases due to its much shorter atmospheric lifetime. We observe statistically significant correlations between SO_2 and XCO_2 in the plume for almost every day but CO_2:SO_2 ratio increases with time depicting the faster chemical loss of SO_2 in the atmosphere. Using alternative SO_2 products to classify plume/background pixels from GOME–2 and OMI leads to the same findings. We roughly estimated the amount of the Kasatochi released CO_2 based on the remote sensing data and found a significantly higher mass burden compared to bottom-up estimates, for example from analyzing melt inclusions. The sources of this discrepancy are currently under further investigation. Taken together, we conclude that the observed enhancement XCO_2 in the volcanic plume pixels can very likely be attributed to CO_2 emissions from the August 2008 eruption of Kasatochi volcano. Further research, including a combination of ground-based measurements and inverse atmospheric modeling as well as a dedicated sensitivity analysis is required to refine and validate our estimates of CO_2 emissions.

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Volcanic eruption clouds in southwest Japan observed from the ground and satellites

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Results of ground observation network of eruption clouds at volcanoes in southwest Japan in these several years are summarized, and compared with satellite images for large scale eruptions. Automatic long-term camera recording systems have been installed at Aso, Kirishima and Sakurajima volcanoes in mainland Kyushu, and at insular volcanoes Satsuma-Iojima and Suwanosejima south of Kyushu. Some of the systems are connected with Internet for real-time monitoring.

White vaporous plumes, with the heights about 200-300 m or less, were often observed at Aso volcano from the site 3 km west of the crater since May 2009.

Kirishima-Shinmoedake volcano experienced subplinian eruption on 26-27 January 2011, ejecting huge amount of ash clouds easily observed in satellite images of MODIS, MTSAT etc. A complete interval record of the onset and development of the eruption was obtained at 50 km away from the crater by using a video camera with the NIR mode in spite of poor visibility condition. The change of white vaporous clouds since 2008 to continuous ash plumes was observed on several days prior to the big eruption, indicating the magma intrusion to the surface. After the climax of the eruption, isolated strong vulcanian eruptions happened occasionally until September 2011.

At Sakurajima volcano, eruptive activity of Showa crater near the summit started in 2006 and strongly increased since 2009, while Minamidake crater at the southern summit was rather dormant in this century. Multi-point automatic recordings of Sakurajima plumes have been conducted at the sites 10-17 km away from the crater in different directions, so as to obtain stereographic features of eruption clouds and their dispersion patterns with wide coverage. The records of the plumes were utilized in analyzing the surface concentration of sulfur-dioxide at the stations around the volcano.

Automatic camera recording at Satsuma-Iojima was conducted during 1998-2007 at the site 3 km west of the Iodake summit crater. It was found that the crater was almost always ejecting white or light-gray clouds with rather constant strength, while explosive eruptions were rarely seen.

Network-camera monitoring of Suwanosejima volcano was done during 2002-2007 at a site 25 km NE in Nakanoshima Island. The NIR mode of the camera was very effective for the observation over the sea recording many explosive eruptions, which were also detected in satellite images. In 2008, the system restarted at a new site 5 km SSW from the crater inside the same island. The eruptive activity of Suwanosejima gradually decreased in late 2000s.

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Tracking of Rock fall and Pyroclastic Flow Events using Infrasound Arrays at Volcan Santiaguito, Guatemala

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Volcan Santiaguito is an active andesite/dacite dome complex in Guatemala characterized by small explosive eruptions every 0.5 - 2 hours, daily pyroclastic flows, frequent block-and-ash flows, and rock falls, including many from the neighboring Santa Maria volcano edifice. This high level of activity, along with exposure of the dome area makes Santiaguito an excellent laboratory for the study of gravity flow events using acoustic sensors. Array processing is used to identify and distinguish these events, and to track their movement through time.

We deployed arrays of two different types of infrasound microphones around Caliente, Santiaguito's current eruptive center, in January and November 2012 to record rock fall, block-and-ash flows, and pyroclastic flows. The January Array consisted of three MEMS differential pressure transducers, which possess a flat amplitude response in the band of interest (about 50 s to 50 Hz), making them ideal for waveform analysis. In november, we deployed an array consisting of eight electret condenser microphones (ECMs), characterized by a high signal-to-noise ratio, which enhances their overall detection capabilities.

We focus on the MEMS infrasound array recordings of January 2012 and corroborate analyzed signals with observations from a broadband seismometer, and one continuous time-lapse camera recording at 5 s intervals. The array was located approximately 2.5 km south and 1,000 m below the dome, with a clear view of the active slope. We locate events by conducting slowness searches for candidate sources located on the surface of the Santiaguito dome edifice. We find that the MEMS array is capable of effectively locating most moving sources of sound (i.e., block-and-ash and rock fall) for events detected by camera. The seismometer also detected rock fall events, but a single instrument is incapable of detailed source localization.

For comparison purposes, another slowness search was conducted using the November 2012 ECM array, located 1 km east, and approximately 250 m below the summit of Caliente, in view of the active south-eastern slope. Microphones were placed around the central logger with an aperture of 100 m. During he 30-hour deployment, the team observed and logged many rock falls, pyroclastic flows and small explosions (often triggering flows or rock falls), though events occurring overnight were not noted. Analysis shows movement of gravity flow events as they travel down slope with velocities from 15 to 35 m/s. This study verifies the ability of MEMS and ECM acoustic arrays to detect multiple types of events, and track their propagation through time.

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Monitoring the 3D structure of diffuse volcanic ash clouds : a case study after the 2011 Puyehue-Cordon Caulle Eruption

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Volcanic eruptions of the past few years have highlighted particular weaknesses in the current infrastructure used to monitor volcanic ash for aviation. In addressing these weaknesses, recent reports from the International Civil Aviation Organization have notably stressed the importance of improving our understanding of the vertical structure of volcanic ash and how its persistence at cruise levels for several weeks can affect air traffic. Through its aerosol and cloud profiling capability, space-borne lidar represents a very promising technique to address some of these concerns. In June 2011, a persistent volcanic ash cloud from the eruption of the Puyehue-Cordon Caulle volcano disrupted the air traffic in most of the southern hemisphere. The resulting volcanic ash clouds which were present near the tropopause between 30000-45000 ft. , could be observed by the CALIPSO space-borne lidar for several weeks between 40S-70S latitude. We show here how the optical parameters obtained from CALIPSO can be used to detect volcanic ash. Notably, the color ratio between the 1064 and 532 nm channels exhibited significant lower values (0.3-0.4) for ash relative to unity that are typically observed for ice clouds. Based upon this and other optical properties, the volcanic ash clouds were isolated in the CALIPSO dataset and used to initialize a forward trajectory model. A domain-filling approach was then developed to reconstruct maps and cross-sections of volcanic ash backscatter with a better temporal and spatial continuity than using CALIPSO alone. Despite limitations of the CALIPSO lidar sampling and the possible confusion of volcanic ash with dust in the low troposphere, this tool could nevertheless provide a step forward for the Volcanic Ash Advisory Centers to improve volcanic ash advisories, especially for extensive zonal dispersion regimes. Future research to understand how limb observations from the upcoming SAGE III/ISS mission could also be used to detect volcanic ash clouds and be combined with trajectory models to provide additional improvements.

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Measurement of Plume Growth Rate From Satellite Imagery for ESP Estimation

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The eruption of Eyjafjallajokull, Iceland in April and May, 2010, brought to light not only the hazards of airborne volcanic ash but also the importance of Volcanic Ash Transport and Dispersion models (VATD) to estimate the concentration of ash with time. These models require Eruption Source Parameters (ESP) as input, which typically include information about the plume height, the mass eruption rate, the duration of the eruption and the particle size distribution. However much of the time these ESP are unknown or poorly known a priori.

Using satellite images, we show that the mass eruption rate can be estimated from the downwind plume or umbrella cloud growth rate. A simple version of the continuity equation can be applied to the growth of either an umbrella cloud or the downwind plume. The continuity equation coupled with the momentum equation using only inertial and gravitational terms provides another model. Numerical modeling or scaling relationships can be used, as necessary, to provide values for unknown or unavailable parameters. Use of these models applied to data on plume geometry provided by satellite imagery allows for direct estimation of plume volumetric and mass growth with time.

This methodology was tested by comparing our results with five well-studied and well-characterized historical eruptions: Mount St. Helens, 1980; Pinatubo, 1991, Redoubt, 1990; Hekla, 2000 and Eyjafjallajokull, 2010. The methodologies yield results comparable to or better than currently accepted methodologies of ESP estimation. We then applied the methodology to umbrella clouds produced by the eruptions of Okmok, 12 July 2008, and Sarychev Peak, 12 June 2009, and to the downwind plume produced by the eruptions of Hekla, 2000; Kliuchevsko'i, 1 October 1994; Kasatochi 7-8 August 2008 and Bezymianny, 1 September 2012.

The new methods allow a fast, remote assessment of the mass eruption rate, even for remote volcanoes. They thus provide an additional path to estimation of the ESP and the forecasting of ash cloud propagation.

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Eruption of Nabro volcano, 2011: Evidence for early injection of sulfate into the stratosphere

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The eruption of the Nabro volcano (Eritrea), which started on June 12, 2011, caused the introduction of large quantities of SO_2 into the lower stratosphere. The resulting sulfate aerosols could be detected for several months following the eruption. It is generally assumed that the formation of sulfate aerosols in the stratosphere takes about a month, but in plumes from explosive eruptions, significant amounts of aerosols have been seen to form within a few hours. Neglecting such rapidly formed sulfate aerosols, e.g. in climate model simulations, causes an appreciable underestimation of the direct radiative effect of volcanic aerosols.

We here show that a significant amount of sulfate aerosols was present in the lower stratosphere within hours of the onset of the eruption of Nabro. Evidence comes from measurements by the SCIAMACHY instrument on ENVISAT, which was one of the first satellite instruments to capture the volcanic plume. Its unique combination of measurements in nadir and limb geometry allows the unambiguous discrimination between volcanic ash and sulfate aerosols (via the nadir UV Aerosol Indices) and the determination of aerosol layer top height (from limb measurements). The findings are in agreement with previously published ground-based lidar data.

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Direct airborne in-situ aerosols measurements of the Mt. Sakurajima eruption plume and remote sensing plume tracking

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Volcanic eruptions can influence the radiative balance of the atmosphere and can have strong impact to the economy, as it became evident during the Eyjfjallajoekull eruption 2010. The recent eruptions of Icelandic volcanoes demonstrated the strong effect of heavy ash loaded plumes. In order to determine the temporal and spatial dispersion of the plume the liable authorities (VAAC) use a dispersion model and correlate the results with satellite informations. During these eruption periods the simulations often overestimated the concentrations. Since 2011 limit ash concentration values exist for the air traffic. However, so far not many in-situ measurements, which were performed in high concentrations of the plume, are available to evaluate these models or to investigate their accuracy.

To validate the model and satellite results it is necessary to correlate the results with reliable airborne in-situ data and to quantify the down-wind characteristics of gases and particles in the plume and the spatial distribution of the plume emitted by the volcano.

In January 2013 airborne in-situ particle and remote sensing SO2 measurements were performed in the emissions from Sakurajima Volcano Japan, with a light aircraft Cessna 172. In-situ particle characteristics were measured using a Grimm 1.029 SkyOPC (microparticles 0.25-32 microns) and a Turnkey dustmeter (DustMate; microparticles 0.5 -20 microns). For each system a different inlet was used to avoid systematic errors. In parallel to the in-situ measurements the SO2 column density was measured using a vertically pointing differential absorption spectrometer (DOAS). A GPS was used for positioning the aircraft.

Through down wind transect measurements below and through Sakurajimas plume, aerosol concentrations up to 15 and 20 mg/m-3 were detected within the dispersing plume. By the use of a combination of in-situ and DOAS measurements the plume boundaries were tracked.

During the research flights the distance dependence of the aerosol size distribution could be investigated as well as the dispersion of the plume.Moreover, by parallel measurements a separation of the ash and SO2 into two plumes could be detected in horizontal and vertical direction.

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Operational challenges in Volcanic Ash Advisory Centre remote sensing

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Significant volcanic eruptions cause high workloads in Volcanic Ash Advisory Centres (VAACs). In this environment, the correct interpretation and fast assimilation of data of all kinds, much of which may be contradictory, is essential for prompt analysis and preparation of evidence based advice to the aviation industry. The use of remote sensing data in VAAC analysis is affected by the trust that the operational team has in those data, easy access and straightforward interpretation of the data, and embedding of the data in operational procedures.

The Darwin Volcanic Ash Advisory Centre has, since 1993, relied heavily on a combination of pattern analysis and reverse absorption remote sensing for most of its operations, and preferably using geostationary data to ensure timeliness. Increasingly, higher resolution MODIS infrared data and SO2 data such as from AIRS or GOME 2 is used to supplement and assist in reinterpreting geostationary imagery, particularly when these images are easy to access or automatic alerting systems are in place. For example, an automated SACS alert during the Soputan eruption of 27 August 2012 was extremely useful. However, the experiences of recent eruptions such as from Soputan and Merapi in Indonesia demonstrate that, on many days, remote sensing must be supplemented by timely and accurate ground and air based reports for effective VAAC operations. Image frequency, cloud, sub resolution eruptions, and water entrainment into the eruption plume all remain major issues.

Many eruptions are identified first on satellite imagery, particularly from more remote volcanoes such as Manam in Papua New Guinea. The introduction of the Himawari 8 satellite in the Asia Pacific Region will increase the chances of eruption detection. In order to fully take advantage of these new data, a greater reliance will need to be placed on automatic monitoring algorithms, whilst recognising that many eruptions are not easily distinguishable from non volcanic convection in their early stages, particularly in the moist tropics but also elsewhere. Long term observations of Mt Sakurajima in Kagoshima, for example, show that volcanic eruption clouds will change character according to the season. The role of the human analyst will remain important in VAAC operations for the foreseeable future.

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Global and regional patterns of volcanic deformation.

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A truly global dataset is required to characterise the global distribution and probability of volcanic unrest and identify the mechanisms responsible. The scope of satellite observations mean that it is now possible to study volcanoes on both regional and global scales and throughout their eruption cycles. Volcanic deformation is one of the a key parameters to understand in order to interogate the causes of volcanic unrest with the advent of satellite-based InSAR capabilities enabling regional-scale surveys of such deformation to be undertaken. These studies are beginning to hint at striking trends in the distribution of volcanic deformation.

A systematic InSAR survey of the Central American Volcanic Arc shows a significant lack of magmatic deformation, that may be indicative of differences in magma storage or degassing processes relative to other well-studied continental arcs. We expect that if magmatic volcano deformation were spread evenly across historically active volcanoes worldwide, there would be less than one percent probability of none of Central America's 26 volcanoes deforming. At the opposite extreme, the East African Rift has few historically recorded eruptions but >10 volcanoes are shown to be deforming.

Globally, InSAR has detected deformation at 140 volcanoes and counting. In this presentation, we will combine information from a series of systematic surveys, to produce a catalogue of volcanoes at which InSAR observations have been reported, including those at which measurements revealed no deformation. We then use these values to assign probabilities to a Bayesian Belief Network to allow satellite observations of deformation to be robustly included in probabilistic hazard assessments. Our preliminary findings are i) the most common observation is that the volcano showed no deformation and did not erupt (not surprising given the typically long repose periods); ii) Fourteen volcanic eruptions have been reported at which no deformation was observed; iii) For magmatic deformation, there are roughly twice as many records of deformation without eruption as those associated with eruptions; iv) a growing number of measurements indicate the prevalence of non-magmatic deformation. We will discuss the initial implications of these findings and develop a framework for the future interpretation of InSAR signals at volcanoes.

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Deformation on the lava surface within the crater at Kirishima, Shinmoe-dake volcano, detected by InSAR and PSInSAR

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Shinmoe-dake in the Kirishima volcano group is located in southwestern part of Japan. In January 2011, eruptive activities started from the Shinmoe-dake crater and resulted in sub-Plinian and Vulcanian eruptions and a rapid accumulation of lava within the crater. GPS and DInSAR data revealed pre-eruptive inflation, co-eruptive deflation, and post-eruptive inflation centered on 5km west of the crater. The eruption phase ceased by the beginning of September, and the post-eruptive inflation also ceased by November 2011. After the 2011 eruption, monitoring by TerraSAR-X have continued. A surface deformation on the lava within the crater after September 2011 revealed a continual shortening of satellite-ground distance even after the end of the main activity. This LOS shortening means uplifts of the lava surface. We estimated the volume increase of the lava after November 2011, using DInSAR processing of TerraSAR-X data, and concluded that the volume increase still continued in January 2013. The volume change rate has decreased with a small fluctuation as an overall trend. PSInSAR and long-term DInSAR results show LOS elongation including a subsidence in the northeast flank of the crater. It is interpreted that the subsidence is caused by deflation of a shallow deformation source located just beneath the crater. Although total amount of effused lava after November 2011 was larger than a volume decrease of the shallow source estimated from the deflation deformation, continual injections from the deeper source can account for the difference. PSInSAR results also revealed that the subsidence ceased in October 2012. It is interpreted that volume of injection and effused lava achieved an equilibrium condition.

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Monitoring and Modeling the Surface Deformation around Mud Volcano of Sidoarjo, East Java, Indonesia

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On May 29th 2006 the mud volcano started to erupt in the sub-district of Porong, in Sidoarjo, East Java, Indonesia. An almost continuous eruption of a mud, water and gas mix has occurred since then and has triggered vertical and horizontal ground displacements around it. The surface deformation phenomena around the mud volcano has been monitored since June 2006 using several geodetic techniques, namely GPS surveys, GPS continuous system, Leveling and InSAR. In the early development of mud volcano, the observed vertical and horizontal rates up to about 4 cm/day and 1 cm/day respectively, were observed around the mud volcano area. Nowadays, about seven years after the eruption, the observed surface deformation is showing an exponential decay pattern, with the rates of about several mm-cm/year. Deformation source modeling suggested that surface deformation occurred due to the combination of the near surface and subsurface collapses of the overburden due to outflow of mud from the subsurface, and loading from weight of mud and man-made dykes. The model also predicted that after about 20 year, the surface deformation will reach the negligible level which is less than 1 mm/year.

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Effects and extent of pyroclastic and lahar deposits of the 2010 Merapi eruption in one active catchment analyzed from HSR imagery

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The 26 October-23 November 2010, eruption is Merapi's largest event (VEI 4) over the past 140 years. We assessed the extent and effects of the deposits from pyroclastic density currents (PDCs) and lahars from this eruption, using high-spatial-resolution (HSR) imagery (from GeoEye and SPOT-5 satellites). We have mapped PDC deposits in particular the longest pyroclastic flows and most widespread pyroclastic surges across the Gendol-Opak catchment on the Merapi's south flank. We investigated the relationships between the topography, the morphology of the river channel, and the apparent behavior of the PDCs, as deduced from over-banking processes. We show that HSR imagery enables mapping with unprecedented detail the effects of the 2010 eruption across the most devastated catchment on Merapi.

The 2010 pyroclastic deposits cover an area of ~27 km^2 in the Gendol-Opak catchment, i.e. 35% of the total deposit area. From observed thickness of deposits in the field, we estimate the volume of PDCs mantling the south flank to range between 62 and 82 million m^3 i.e. about 70% of the entire volume of 2010 PDC on Merapi. We analyze how unconfined PDCs with over-bank and veneer facies, as well as two types of surges have mantled widespread areas on both sides of the Gendol valley which contain the confined PDC deposits. Geometric and geomorphic characteristics that allow over bank and veneer deposits beyond the main valley are: limited cross-sectional areas under 1500 m^2 and the decreasing longitudinal rate of channel confinement. Subsequent lahars six months after the eruption have devastated several villages along the Gendol River 20 km from the summit on the ring plain where 66 houses in an area 0.16 km^2 were destroyed and led to the evacuation of 300 people. Small areas down-valley was affected by over-bank lahars once pyroclastic deposits were remobilized 3.8 km farther than the PDC front. The over-bank and avulsed lahars can be attributed to low-gradient (0.04 m/m), meandering river (sinuosity index of 1.25) across the lowest-angle (<2°) ring plain and the limited capacity (200-300 m^2) of river channels. Lahars now threaten the area of the iconic Prambanan temple farther down the Opak River.

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HotVolc: A satellite-data-driven Web Map Service for real-time monitoring of active volcanoes

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We have developed a web-based, satellite-data-driven, system (named HotVolc, http://www.obs.univ-bpclermont.fr/SO/televolc/hotvolc/) for real-time tracking of volcanic events (both explosive and effusive). For detection of volcanic hot spots (associated with effusive eruptions) and clouds (associated with explosive eruptions) the system uses mid- and thermal-infrared data provided by the Eumetcast broadcast system. Our system relies mainly on SEVIRI/MSG sensor but could be extended to other sensors flown on both geostationary satellites and polar orbiters, the system uses data acquired in real-time (at rates of up to 1 image every 5 minutes), to process and convert satellite-sensor hot spot data to products of use to the volcanological and hazard response community. HotVolc is thus designed to provide higher-order products (such as maps and derived quantitative parameters) of use to the scientific community, observatories, and decision makers. These products are either routinely calculated, or processed on demand. We currently provide: (1) an ash-index map that uses a three-band method that allows ash cloud with minimisation of artefacts, (2) a thermal-index allowing detection of thermal anomalies associated with lava flows, lakes and domes, (3) an SO2-index to assess sulphur dioxide loads associated with thin gas-ash clouds, and (4) a three-channel colour composition that allows discrimination between meteorological and volcanic clouds.

HotVolc is operated by the Laboratoire Magmas et Volcans (LMV) at the University of Blaise Pascal (Clermont Ferrand, France), as a part of a wider remote sensing project initiated in 2006 by the Observatoire de Physique du Globe de Clermont-Ferrand (OPGC). It was subsequently used to track ash clouds during the Eyjafjallajokull eruption in 2010, as well as a number of other explosive events in Iceland and Italy between 2008 and 2013.

We present an overview of the system, with an emphasis on new features recently implemented through integration of HotVolc products with the Web Map Service (WMS). WMS was developed by the Open Geospatial Consortium (OGC) and is now a standard protocol for serving geo-referenced data. It is widely supported by most GIS clients. WMS is particularly well adapted to ingestion of geo-referenced satellite-data-derived products.

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Pulsating Magma Output Detected by Helicopter Thermal Surveys: the 2011-2012 El Hierro Submarine Eruption Test Case, Canary Islands

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The use of a hand-held thermal camera during daily helicopter flights carried out to monitor the 2011-2012 submarine volcanic eruption at El Hierro, Canary Islands, allowed us to estimate for the first time the daily erupted magma volume from a submarine eruption. Temporal evolution of estimated magma volume erupted from October 18, 2011 until February 12, 2012, is in a good agreement with the observed changes in the effusive dynamics of the submarine eruption. Three peaks have been recorded in the output rate pattern. The first one occurred on October 20, 2011, during the initial phase of the eruption and few days after the appearance of floating volcanic rocks (restingolite pyroclasts). The second peak and the highest occurred in November 8, 2011, one day after the maximum gas discharge rate observed due to both strong explosive and effusive activity. The third peak was recorded on January 6, 2012, and suggests a new input of gas-rich magma feeding the eruption before its decline. Thermal imagery by helicopter proved to be a fast, cheap and reliable technique of monitoring volcanic eruptions, even when they occur on the shallow sea floor.

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Active submarine volcano monitoring with satellite optical sensors

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Shallow volcanic activities near island arc, where one tectonic plate subducts under another plate, interfere with the aircrafts or vessels near the activities, and sometimes trigger tsunami. More than 40 submarine volcanoes shallower than 200m exist mainly West Pacific. Only few submarine volcanoes are monitored periodically. Monitoring submarine volcano is not an easy task compared with land volcano because it is covered by seawater and located in remote area. Satellite optical sensors are powerful tools for monitoring submarine volcanic activities such as discolored seawater, floating material and volcanic plume. Fukutoku-Okanoba submarine volcano, which is located 1,300 km south of Tokyo, is one of the most active submarine volcanoes in Japan. Brightness and color survey of discolored seawater can be done quantitatively by satellite remote sensing even in remote area with low cost. Brightness and color change analysis of discolored seawater was conducted at Fukutoku-Okanoba submarine volcano using ALOS AVNIR-2 satellite optical sensor with 10m ground resolution and three bands in visible region. The brightness was increased and the color was changed from blue to green according to the volcanic activity. It means that submarine volcanic activities can be monitored with satellite optical sensors.

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Volcanic eruption monitoring by thermal image correlation: Pixel offsets show episodic dome growth of the Colima volcano

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Estimating the magnitude of dome eruptions is one of the main challenges in volcano monitoring. Although modern monitoring networks are in place at many dome-building volcanoes, the type and occurrence of explosive activity and the scale of the eruptions are commonly estimated by visual inspection. Quantifying the deformation of dome-building volcanoes and the occurrence of explosions is highly valuable, not only for enabling the provision of early warnings but also for facilitating an understanding of the physics of explosive volcanoes, as demonstrated by this study of one of the most active volcanoes in Mexico. The Volcan de Colima is currently experiencing a phase of viscous dome growth, which is associated with daily episodic Vulcanian eruptions and rock falls. Little is known about the dynamics of this dome, its growth rates, or the scale of the associated explosions. We present the results from an analysis of nighttime time-lapse infrared images and compare these data with local seismic amplitude recordings. For detected digital image correlation, we track temperature features in infrared images. Images taken before and after the explosions reveal the location of the hot dome to be subject to significant and systematic lateral pixel offsets. Dome deformation is shown to occur intermittently every 3-4 h, with lateral displacements exceeding 0.3 m within periods of less than 120 s. Only the thermally elevated regions of the western dome, which may represent a coulee-like flow, are displaced and are often, but not always, associated with seismic amplitude peaks. Therefore, our analysis of the infrared image correlation suggests the occurrence of aseismic dome-deformation episodes, thereby challenging the current understanding of dome growth and the appropriateness of commonly used volcano surveillance techniques.

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High spatio-temporal resolution photogrammetry of active dome growth, Santiaguito Dome, Guatemala

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Synchronized photogrammetry observations show surface velocities of greater than 2 meters per hour on the Santiaguito lava dome during January and November 2012 that vary through time and space. We used an array of 5 radio triggered cameras to collect synchronized images of the lava dome at 1 minute intervals. The Canon T2i cameras were equipped with 200 mm lenses and spaced such that from a distance of about 2.7 km the array had a total angular aperture of about 7 degrees and individual images have a nominal resolution of 0.05 meters per pixel. Using cross correlation of the images we constructed 3D point clouds of the dome at each time with nominal point spacing of about 0.25 meters. Tracking each point through space and time provides a 3D velocity field of the dome with 1 minute temporal resolution. We estimate velocity detection limits of about 0.1 meters per minute for instantaneous velocities and 0.01 meters per minute for those averaged over greater than 1 hour. Use of three and multi camera techniques improves spatial resolution compared with a two camera technique, but the latter offers computational times that are feasible for real-time monitoring (e.g. less than 1 minute for each image pair on a workstation laptop computer). The largest variations in velocity occur near the dome summit where up to 5 meters of inflation-deflation can occur in as little as 10 minutes in a 15-20 meters diameter region. Inflation deflation cycles fall into two main groups: inflation followed by an explosion and rapid deflation, or inflation followed by slow deflation and passive degassing. As other velocities radiate from the region of inflation deflation, this region likely overlies the conduit. Local deflation events are often correlated with inflation of the greater Santiaguito dome as measured by tiltmeter. Velocities in the region south of the likely conduit are steadier with peak velocities of about 2.7 meter per hour, representing effusion of lava flows down the south flank. Our work demonstrates how an array of consumer grade DSLR cameras may be used to collect high frequency, quantitative observations of rapidly flowing or deforming lava flows. These data provide constraints on conduit geometry and processes, and lava effusion rates.

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Oblique photogrammetry to measure lava volumes and extrusion rates

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Measurements of the volume and rate of growth of active lava flows and domes are key parameters of volcano monitoring. Often such measurements are hard to obtain quickly during eruptions due to hazardous conditions, lack of resources, or time constraints. Oblique photogrammetry is a powerful tool for monitoring volcanoes and characterizing topographic change, which provides an advantage of near-field remote sensing when conditions are unsafe. Traditionally, photogrammetry has been limited in versatility, due to the intensive data acquisition and processing needed to achieve high accuracy. However, considerable improvements in camera technology and photogrammetry software have dramatically reduced acquisition and processing time, and have moved oblique photogrammetry to a near real-time monitoring technique. Oblique photogrammetry provides a cost-effective means of producing topographic models, by utilizing imagery from standard digital cameras and by processing models using consumer grade software. From manual interpretation to automated pixel matching algorithms, oblique photogrammetry has proven successful at providing critical data during both routine monitoring and crisis response in varying conditions and types of eruptions. We present results from oblique photogrammetry surveys at Mount St. Helens, Redoubt Volcano, Kilauea Volcano (all USA), and Chaiten Volcano, Chile and discuss the practical strengths and weaknesses of this method, challenges encountered during each application, and suggested improvements for future surveys. The motivation behind improving our ability to measure the rate of lava extrusion is to better understand eruption dynamics, and particularly during lava dome effusion, to constrain the volume of potential collapsible material and measure effusion rate changes that may signify a transition from effusive to explosive activity.

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Volcanic deposit mapping using surface roughness textures

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Spectral remote sensing is well suited for differentiating regions based on chemistry and mineralogy. The addition of quantitative morphologic analyses augments spectral interpretations as compositionally identical materials can have quite distinct morphologies. This is especially relevant for volcano remote sensing where vastly different emplacement mechanisms can produce deposits with the same mineralogy. For example: effusive lava flows and explosive pyroclastic flow and fall deposits all of the same composition are common at stratovolcanoes.

Here, LiDAR and radar data are used to quantitatively differentiate volcanic facies based on patterns in surface roughness. Roughness elements consist of primary volcanic features and clasts (e.g., pumice-lobes, blocks, and bombs) as well as erosional features (e.g., remnant mounds and channels). The distribution of these features produce roughness textures (i.e., patterns) that depend on the local depositional and erosional history.

At Mount St. Helens (46.251, -122.202), roughness textures are derived from a ∼2 m spaced LiDAR point cloud, acquired in 2004 by the USGS, Puget Sound LiDAR consortium, and NASA. Point data covering the ´Pumice Plain´are processed in ITT- ENVI to produce roughness rasters with 5 m resolution. In Southeast Asia, roughness is derived from 5-15 m resolution space-borne radar backscatter images of active and potentially active volcanoes (i.e., Mayon (13.257, 123.685), Barren Island (12.278, 093.858), Doro Maria (-08.4833, 118.9) and Sengeang Api (-08.2, 119.067)). In all cases, textural statistics (e.g., Entropy (ENT), and Homogeneity (HOM)) are calculated from roughness rasters to produce maps of roughness textures.

Roughness textures are based on statistical measures of the distribution of roughness elements on the surface of volcanic deposits, within discrete geomorphic units. These include: primary eruptive deposits (lava flows, domes, debris avalanche deposits, pyroclastic fans, and pumice lobes), modified volcaniclastics (e.g., lithic rich lobes, lithic armored pumice lobes, and steep walled channels), and landforms (e.g., collapse scars and craters). Each geomorphic unit has a unique set of roughness textures that are a result of the depositional conditions and erosion. Textural segmentation of roughness maps is demonstrated to be a useful tool for volcanic deposit mapping using both radar and LiDAR data. A similar approach could be used in many other applications (volcanic or non-volcanic) to differentiate geomorphic units and quantify the degree of modification from erosion.

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The crucial role of digital elevation modeling to study Nyiragongo and Nyamulagira volcanoes (North Kivu, Democratic Republic of Congo)

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The Virunga Volcanic Province (VVP), in the western branch of the East African Rift System, is one of the most active volcanic zones in Africa. Two of the height main volcanic edifices are currently very active, namely Nyiragongo and Nyamulagira. In regions where field investigations are problematic, remote sensing proved to be efficient for studying and monitoring volcanic activity. This is the case in the VVP, which is affected by recurrent periods of political unrest.

The presentation focuses on the study of Nyiragongo and Nyamulagira volcanoes (Eastern DR Congo) using digital elevation modeling. Stereo-photogrammetry, SAR interferometry and close-range photogrammetry are used to produce metric to sub-metric digital elevation models (DEM):
New generation of very high resolution (1 to 6 m) DEM are produced based on Pleiades (optical) and TanDEM-X (radar) satellite imagery. These DEM offer new perspectives compared to previous available DEM of the VVP (e.g. SRTM and ASTER). These new very high resolution DEM are exploited for 1) quantitative geomorphological investigations and 2) as input for lava flow modeling. For the first time, metric structures, such as small cones, thin lava flows and lava channels, can be studied in the VVP. The influence of these small reliefs on lava flows is assessed using flow modeling.
These DEM analyses efficiently complement the space-borne techniques, the ground-based techniques and fieldwork for the study of volcanic activity in the VVP.

A stereographic time-lapse camera (STLC) system was developed and installed inside the main crater of Nyiragongo. The STLC system takes pairs of images at a given time rate. Each pair of mist-free pictures enables the production of a 3D model of the lower part of the main crater. This technique aims at accurately estimating volume and surface changes linked to lava lake activity and its level fluctuations. First results of this innovative technique, which is still under development, indicate a great potential to study permanent lava lakes.

The present work is performed in the frame of various projects and initiatives launched by the GORISK Scientific Network (www.ecgs.lu/gorisk/) and mainly funded by the FNR-Luxembourg (including the AFR PhD grant 3221321) and the Belgian Science Policy.

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Monitoring changes in the active lava lake and Inner Crater at Erebus volcano, Antarctica using terrestrial laser scanning

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Active lava lakes are a rare and poorly understood phenomenon that provide unique opportunities to monitor the volcanic activity of an open magma conduit. We used an Optech ILRIS-3D terrestrial laser scanner (TLS) to monitor surface area and elevation changes of the active lava lake located within the Erebus Inner Crater and to detect deformation of the crater floor over four austral summer field seasons, from 2008 - 2012. TLS systems provide a portable tool for data collection in areas inaccessible due to terrain, heat, or volcanic gas emissions. The Erebus lava lake was scanned from the crater rim, 300 meters above the lava lake. Four to eight hours of continuous data were collected each season, despite sub-optimal conditions including minimally-reflective snow and ice, temperatures below operating specifications, and plume moisture. Raw point clouds were imported into PolyWorks where a matrix transformation and translation were applied. Alignments were further constrained by manually choosing stable reference points above the crater floor. Using the point cloud and GPS data, we saw a yearly 2-3 meter decrease in the average lava lake elevation and a meter-scale deformation of the crater floor. We scanned the lava lake continuously at 30 second intervals to obtain a time-series of elevation changes of the lava lake surface. The average elevation of five, meter-square areas on the lake surface was plotted against time. Elevation changes were cyclical and on the order of 0.5-1 meter, although bigger changes were seen during one eruption from the lake. Time-series plots showed a periodicity of 18 minutes in elevation changes for the lake in 2008 and 2009 and 13-11 minutes for 2010 and 2011. The decrease in the periodicity corresponds to a reduction in the lava lake surface area. Surface area of the lake was 1700 square meters in 2008 and 2009, but reduced to 800 square meters in 2010 and 500 square meters in 2011. These results show TLS to be effective in determining a continued reduction in volcanic activity and provide insight into the dynamics of the conduit system.

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A low-cost SO_2 imager with the use of digital cameras of consumer use

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Sulfur dioxide in volcanic plumes is generally hard to recognize with human eyes. In recent years, ground-based remote sensing of SO2 is mostly performed with DOAS instruments which measure the UV spectra along the line of sight (e.g. McGonigle et al., 2002). Besides, so-called SO2 cameras which composed of a CCD device and band-pass filters have been developed for imaging the SO2 concentration in a plume (e.g. Mori and Burton, 2006). The prime feature of the latter system is the visualization of SO2 gas as a snapshot, in which a plume shape is instantly recognized. Such an easy visualization of SO2 may contribute to the quick awareness of harmful gas from the vent as well as to the monitoring of volcanic activity. However, high-spec CCD devices are generally expensive and this is one of the reasons that prevent such SO2 cameras to be widely used by non-specialists. In this study, we produced an SO2 imager of a low-cost version by means of digital cameras of consumer use.

In our system, we introduced the model D70 (Nikon), as a light-receiving CCD device. The dimension, number of pixels, and brightness resolution of the CCD are 23.7 by 15.6 mm, 6.27 M pixels, and 12 bit, respectively. Some modifications are necessary in order to enable the camera to sense the UV lights. First of all, a built-in optical low-pass filter must be removed manually. Appropriate lens and filters which permit UV bands should be chosen. We used a compound lens (Nikon UV-105 mm, F4.5) and band-pass filters (FWHM: 9 nm, max transmission rate: 65%, blocking: 10^{-5}) to extract the 310 and 330 nm bands separately, with additional two band-pass filters for each to cut unwanted wavelengths. The former band has a higher absorbance by sulfur dioxide than the latter. We adopted simultaneous shooting system with the use of two cameras to overcome a somewhat long exposure time (5 to 10 sec) required. Additional ND filters were added to adjust the exposure times of the two bands to be approximately the same. Since images can be taken in the same way as ordinary photographing and stored in the build-in memory card, this device can operate without external power or control PCs, and thus, is suitable for mobile use.

Calibration of our device with SO2 cells of known column concentration confirmed a comparable absorption coefficient to the device which was previously invented by Mori and Burton (2006). We also performed a field test of the system in Sakurajima volcano, southwestern Japan and confirmed its validity as an SO2 imager. However, a special care with the UV scattering in front of a plume (e.g. Mori et al., 2006) is necessary for fully quantitative applications in a field operation. A simultaneous operation with DOAS system might be another option to ensure the quantitative capability. Meanwhile, further cost-down is also possible by replacing an optical system into a single silica lens by compromising on the optical distortion and aberration.

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Separate quantification of volcanic gas fluxes from showa and minamidake craters at sakurajima volcano, japan

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Measurements of volcanic gas emission are crucial for monitoring of volcanic activities. Volcanic gas emission data reflect the amount of degassed magma within the volcano and conditions of the conduit. At a volcano with multiple craters, a separate estimate of the gas fluxes from different craters is needed. However, it is difficult to measure volcanic gas emissions from multiple craters separately by means of conventional observational methods. When observing volcanic gas emission from the leeward, the volcanic plume observed is mixture of emissions from multiple sources. In this study, we present separate quantification of volcanic gas emissions using a UV camera observation system.

We conducted volcanic SO_2 measurements from 2007 to 2010 at Sakurajima volcano, Japan. The UV camera observation system was used to visualize SO_2 in the volcanic plume (e.g., Mori and Burton, 2006). By analyzing UV images obtained by the UV camera system, we succeeded separate quantification of SO_2 fluxes from two craters of the volcano: Showa crater and Minamidake crater. Sulfur dioxide flux from Showa crater showed a variety from a few hundred to several thousand ton per day. In contrast, that of 100-500 ton per day from Minamidake crater remained at a lower level. Within the observation period, the amount of degassed magma beneath Showa crater should have varied corresponding to the intensity of volcanic activities and number of eruptions. On one hand, degassing conditions of Minamidake crater have kept stable in this period.

Conventional volcanic SO_2 observations using a UV spectrometer have been conducted after 2003 (e.g., Mori et al. 2008). The sum of SO_2 fluxes from both craters has been collected by means of the conventional methodology. The result showed a diversity of SO_2 emission in 2007-2010. Since SO_2 flux from Minamidake crater have remained stable, this variation of SO_2 emission in 2007-2010 was controlled mainly by degassing activities of Showa crater, not by those of Minamidake crater.

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Yearly averaged BrO and SO_2 emissions from Ambrym volcano as seen by the GOME-2 satellite instrument

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Since bromine monoxide (BrO) of volcanic origin was detected for the first time in the plume of the Soufrière Hills volcano by ground-based differential optical absorption spectroscopy (DOAS) measurements in 2003, this species has been regularly observed by ground-based instruments at several quiescent-degassing volcanoes worldwide. Recently, the Global Ozone Monitoring Experiment satellite instrument (GOME-2) has proven to be capable of monitoring volcanic BrO in volcanic plumes also from space, during both, minor and major eruptions. However, long-term measurements of BrO at continuous passively degassing volcanoes are usually only provided from ground-based observations due to their higher sensitivity to weaker emissions.

Here, we present the first space-based observations of enhanced BrO abundances in the vicinity of the mostly quiescent-degassing Ambrym volcano (Vanuatu) by yearly averaged GOME-2 satellite data in the years 2007-2012. The observed spatial BrO distribution in the plume is compared to the corresponding mean distribution of volcanic sulphur dioxide (SO_2), which is commonly used as a tracer for volcanic emissions due to its relatively long lifetime and strong absorption features in the UV wavelength range. The averaged data shows distribution patterns of both species up to distances of $\approx$ 100 km from the volcano and a clear linear correlation with mean BrO/SO_2 ratio of $\approx 5 \times 10^{-5}$ to 1×10^{-4} throughout the investigated time period. In addition, an estimation of the lower limit of the total sulphur and bromine emissions will be given.

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Non negligible passive degassing from Kerinci, the greatest volcano in Indonesia

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Kerinci is a massive 12 x 25 km wide volcano situated in the central part of Sumatra. It is one of the most active volcanoes in Indonesia. At least 31 moderate eruptions were reported to occur since 1838. Kerinci is also the highest active volcano of Indonesia, culminating at 3805 m a.s.l. Accessing the summit of this edifice requires at least 2 days of expedition with camping gear and intense climbing, under ambient temperature that can descend lower than 10 degree celsius with humidity close to 100 percent at day break. Due partly to this access difficulty, little is known about this volcano.

In order to gain insights into the activity of this volcano, a set of remote sensing tools, including DOAS, thermal Infrared camera and ultraviolet camera, were deployed at the summit and about 8 km from the crater, in April 2012. Measurements results indicate for the first time that Kerinci volcano is releasing about 10 tons of sulfur dioxide daily into the atmosphere. Results further suggest that Kerinci continuous degassing is sustained by regular puffs, suggesting successive arrival of gas bubbles at the surface. Henceforth, with its regular eruption and its continuous passive degassing, Kerinci is a non negligible source of volcanic degassing, an example to be consider for the numerous yet little known Indonesian volcanoes whose contributions to the atmosphere should be integrated in volcanic emission inventories.

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Measurements of BrO/SO_2 ratios at Popocatepetl from 2007 to 2012

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We present results from 6 years of scanning DOAS measurements at Popocatepetl, a Stratovolcano located about 60 kilometers to the southeast of Mexico City in the Trans-Mexican Volcanic Belt. The four DOAS instruments have been primarily used for monitoring SO_2 fluxes during the time period; the collected spectral data has been reevaluated to quantify, besides the SO_2 column concentrations, also the ones of BrO. Changes of the ratio of the two species are discussed in the context of the volcanic activity.

Special emphasis is put on the early 2012 volcanic crisis, when high overall gas fluxes were observed, which also included a high bromine output.

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Estimating emissions and lifetime of SO2 from space: A case study of the Kilauea Volcano

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Satellite observations of atmospheric trace gases have revolutionized our insights regarding the location and amount of various pollutants. In addition, it has been demonstrated recently that atmospheric lifetimes can be derived by analyzing the downwind decay of point sources.

Here we present an analysis of the downwind evolution of the SO2 plume from the Kilauea volcano (Hawaii) in 2008. Both the SO2-patterns observed from space (GOME-2) and the wind fields according to ECMWF stay rather stable over several months, making this an ideal case for lifetime determination. Using a relatively simple mathematical analysis, an e-folding lifetime of SO2 and the total release of SO2 can be estimated simultaneously on the basis of monthly mean SO2 maps and wind fields.

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Ultraviolet camera monitoring of SO2 emissions from Volcan Villarrica, Chile 2012 - 2013

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Ultraviolet cameras are increasingly recognized for their unparalleled ability to image the entrainment of volcanic SO2 into the atmosphere and to measure emissions at high temporal resolutions (1–3 Hz). A particular benefit can be in resolving emissions from multiple sources at a given volcano and partitioning the overall SO2 budget between them. Other spectroscopic techniques such as the Correlation Spectrometer and compact UV spectrometers typically only provide an integrated measurement for all sources present.

During February to March of 2012 and 2013, high temporal resolution SO2 degassing data were collected at Volcan Villarrica using a setup of one to three simultaneously operating ultraviolet cameras. The persistent gas plume at the dominantly basaltic to basaltic–andesitic Villarrica offers an excellent field laboratory setting to test novel instrumentation. These data were collected as part of a broader multiparameter study to characterize shallow degassing processes, and thermal and particle emissions at Villarrica. Preliminary results from these two campaigns highlight interannual variations as well as variability on weekly–daily timescales.

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GROUND-BASED IMAGING OF VOLCANIC PLUMES

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This presentation will provide an overview of how an imaging interferometer can be used to provide high spectral and spatial resolution image data regarding the composition of volcanic plumes from the ground. The technique we describe offers the possibility to allow high spectral resolution imaging of volcanic emissions in the thermal infrared, a region in which silicate ash, sulfur dioxide and carbon dioxide have spectrally distinct (and measureable) absorption features. The instrument acquires approximately 40 separate spectral bands in the 8 to 14 micron wavelength region, at 15 wavenumber resolution. Rather than using filtering or dispersion to generate the spectral information, the instrument uses an interferometric technique. Light from the scene is focused onto an uncooled microbolometer detector array through a stationary interferometer (Sagnac configuration), causing the light incident at each detector at any instant in time to be phase shifted by an optical path difference that varies linearly across the array in the along-scan dimension. By scanning across the plume at 30 Hz (equal to a spatial sampling of one pixel per frame), an interferogram can be generated for each scene element.

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Remote sensing of volcanic gases using wavelength-tunable mid-infrared laser

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In recent years, the need for research on natural disasters is growing urgency. Various researchers have actively carried out observed activities such as volcanic eruptions and gas research to elucidate the mechanisms of volcanic eruptions. Measurement of volcanic gases is of great help in order to observe the volcanic activity. Component of volcanic gases is due to the movement of underground magma. For example, Gases from magma coming up from deep underground contains many H2O than DHO. We depending on the percentage of the DHO and H2O in the water vapor contained in the volcanic gases, it is seen lifting movement of magma underground.

Observation of volcanic gas might be the best efficiency that is directly observation in the active volcano. However, the direct observation has significant risk of danger.

We have a tunable laser technology was originally developed by RIKEN. Raman LiDAR or LAS can be used to utilizing this technology to observe the composition of the gas phase chemistry is possible.

For example, the absorption spectra of major pollutant substances (H2O, DHO, NO, NO2, CH4, CO2 etc.) are generally detectable in the mid-infrared (IR) range from 3 to 5 um. On the other hand, absorption spectra of chemical agents are also observed from 6 to 11 um. To remotely conduct the identification of chemical agents, the development of LiDAR system equipped with a high-energy tunable mid-IR coherent light source as a transmitter is one of urgent issues for a safe observation of volcanic gas.

Optical parametric oscillation (OPO) is required to accomplish high-energy (10 mJ) pulsed oscillation in a mid-IR wavelength range using a tunable high-energy pulsed laser. Especially tunable lasers in the range from 2 to 3 um are useful as a pump source to generate mid-IR wavelength exceed 5 um in OPO. Moreover, rapid tunability is an attractive element in tunable lasers for real-time LiDAR environmental detection.

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Remote sensing of vapor phase chemical agent using wavelength-tunable laser

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In recent years, the need for research on natural disasters is growing urgency. The Lidar technique is a powerful means for range-resolved environmental remote sensing. The technique is especially useful in polluted areas and to implement anti-crime and anti-terrorism for a safe and secure society.

We have a tunable laser technology was originally developed by RIKEN. Raman Lidar or LAS can be used to utilizing this technology to observe the composition of the gas phase chemistry is possible.

This technique of measurement is of great help in order to observe the volcanic gases etc..

For example, the absorption spectra of major pollutant substances (H2O, DHO, NO, NO2, CH4, CO2 etc.) are generally detectable in the mid-infrared (IR) range from 3 to 5 um. Remote sensing spectroscopy using the molecule-specific absorption spectrum are DIfferential Absorption Lidar (DIAL), Laser Absorption Scattering (LAS) and etc..

On the other hand, Raman scattering is caused by incident light of wavelength-specific to molecules. Energy difference of the incident light and the light that is scattered by the Raman effect corresponds to the energy of the electron level, or level of vibration level and rotation in the material and crystal molecules. In order to have a specific vibration energy according to structure of molecules, is used to identify a substance, such as by using a laser is a monochromatic light source and crystal molecule. Remote sensing spectroscopy using the Raman effect is a Raman lidar.

It is necessary to control the wavelength of the laser arbitrarily for the both techniques. Must be considered the observation wavelength in the atmospheric absorption or the reaction of the object.

I report about the remote sensing technique that uses laser technology and its technology to control wavelength of the laser.

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Behaviors of volcanic ash, SO2 and sulfate aerosol: A perspective from research results on academic journals

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Articles for the studies on volcanic eruption clouds (ECs) using satellite-borne instruments are selected from 3 academic journals to clarify various behaviors of volcanic ash, SO2 and aerosol and to know the influence of volcanic aerosol on ash and SO2 measurements. Journals (J) are the following 3: J of Geophysical Research (JGR-B: Solid Earth and JGR-D: Atmospheres), Bulletin of Volcanology (BV) and J of Volcanology and Geothermal Research (JVGR). The periods investigated are from 1965 to 2012 for JGR-B, JGR-D and BV and from 1976 to 2012 for JVGR, respectively. Number of the papers selected is 355, and 297 of them discussing satellite data analyses and models are investigated here. They are classified into 6 categories; EC detection / discrimination (number of papers; 19), ash extent and mass measurements (81), SO2 extent and mass measurements (59), aerosol extent and mass measurements (71), EC development models (30) and EC trajectory models (37).

At early stage of the studies, detection and tracking of ECs are actively conducted. Then, the techniques of ash discrimination from meteorological clouds, SO2 extent detection at ultraviolet wavelength region (WR) and estimation of ash particle size and mass loading are developed. Ash and SO2 tracking and estimation of their mass loadings are introduced using infrared WR, and retrievals of volcanic sulfate aerosol generated from SO2 are successively proposed. Volcanic sulfate aerosols are monitored by space-borne lidars. Measurements of SO2 clouds at the upper troposphere and the lower stratosphere (UTLS) and the boundary layer (BL) are successfully conducted. EC models and trajectory models are actively developed.

Research results show that ash and SO2 collocate together for several hours to three days after eruption onsets. ECs injected at high altitudes are affected mainly by wind shear and show complicated extents, and separation of ash and SO2 clouds in different directions are confirmed. Usually, SO2 gases in ECs change to sulfate aerosols at early stage after eruption onsets, and cover widely dispersed areas of ash and SO2.

When the measurements of ash and SO2 mass loadings are conducted one to two days after eruption onsets, the increased volcanic aerosol may cause masking of ash and SO2 extents, and may bring misunderstanding for detection of ash and SO2 distributions, and for estimation of their mass loadings. To prevent false analyses, plural satellite data are necessary for the validation of measurements. Recent satellites are equipped with high-resolution, multi-spectral and hyper-spectral detectors and space-borne lidars. Using those data, further developments of the techniques of data processing are required. In addition, ash detections in thick and opaque ECs and in ice rich ECs generated soon after eruption onsets are essential for urgent issues of VAAs (Volcanic Ash Advisories) and ash trajectory models. They are vital to mitigate the aerial volcanic hazards.

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The NASA Volcano Sensor Web (VSW): recent observations, activity and network expansion

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Spaced-based assets, ground-based sensors and automatic data processing algorithms have been incorporated into a sensor web that is capable of volcano monitoring with global coverage [1-4]. The NASA Volcano Sensor Web (VSW) uses the Earth Observing-1 (EO-1) spacecraft as the principal space-based observation platform to quickly react to detections of pending or ongoing volcanic activity. EO-1 is also used as a test bed for testing new onboard data processing and flight operations software [1,3]. This successful autonomy initiative has demonstrated that re-tasking of spacecraft can be very fast and completely automated, and the additional use of advanced autonomy and improvements in data transmission from EO-1 have greatly increased the speed at which data is acquired, downlinked and processed, and the resulting products (including hot pixel location, and the distribution and magnitude of thermal emission) created and delivered to end-users. The VSW was linked into the Icelandic Meteorological Office SIL seismic network [6] in 2011 and was triggered by increased seismic activity at the start of the Grimsvötn 2011 eruption [5]. In late 2012 the VSW incorporated seismic alerts for the Ecuadorian volcanoes Reventador, Tungurahua and Cotopaxi, with expansion to other volcanoes under evaluation. Also since late 2012, acoustic sensors on Etna [7] generate regular activity status alerts which are used to autonomously trigger requests to the EO-1 observation planner. The streamlining of EO-1 operations (a result of the autonomy initiative) means that re-tasking spacecraft manually is now a quick and easy task. This has led to multiple observations of eruptions around the world, including over 50 observations during the 2010 Eyjafjallajökull, Iceland, eruption, and observations of Puyehue Caulle Cordon, Chile, during 2011 and 2012, and the ongoing (at time of writing) eruption of Tolbachik, Kamchatka, and many others. Since mid-2004 over 4000 EO-1 observations of volcanoes have been obtained via ASE, VSW, and other scheduled requests. The VSW is responsible for over 1750 of these observations. The autonomous systems, data processing techniques, and workflows developed for the VSW will enable more efficient operation of future missions, and increase mission science return. References: [1] Chien, S. et al. (2005) JACIC, April 2005, pp. 196-216. [2] Chien, S. et al. (2005) IEEE Intelligent Systems, 20, no. 3, 16-24. [3] Davies, A.G., et al. (2006) RSE, 101, no. 4, 427-446. [4] Davies, A.G. et al. (2006) EOS, v. 87, no. 1, 1-5. [5] Davies, A.G., et al. (2013) JGR, under revision. [6] Böðvarsson, R. et al. (1999) Phys. Earth Planet Inter., 113, 89-101. [7] Marchetti, E., et al. (2009) GRL, 36, no. 19, L19308. Acknowledgements: Part of this work was performed at the Jet Propulsion Laboratory, California Institute of Technology, under contract to NASA. © 2013 Caltech. EO-1 is managed by the NASA Goddard Space Flight Center.

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REALTIME MONITORING OF ACTIVE VOLCANOES IN EAST ASIA USING MODIS AND MTSAT DATA AND ITS ADVANCEMENT BY GCOM-C1 SGLI

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There are many active volcanoes distributing in east Asia, however, most of them are not well monitored. Monitoring volcanoes is a key issue for disaster mitigation. Practically, it is not realistic to install ground-based instruments to all of the active volcanoes, because of the cost and manpower for maintenance. Satellite remote sensing is the only way to monitor these volcanoes existing in such wide areas. We developed a monitoring system based on infrared images from Moderate Resolution Imaging Spectroradiometer (MODIS) and Multi-functional Transport Satellite (MTSAT), and are currently observing 147 active volcanoes of this region. In this system, observed results are immediately uploaded to the website, so that the information can be widely used. Unfortunately, resolution of MODIS and MTSAT is not sufficient for observing detailed situation of eruptions (MODIS: 1km, MTSAT: 4km). Japan Aerospace Exploration Agency (JAXA) is lunching the GCOM-C1 satellite carrying Second Generation Global Imager (SGLI) of which 1.6um, 11um and 12um channels possess 250m resolution, in 2015. Such high resolution infrared images are useful for observing effusing process of small scale lava flows or distribution of small pyroclastic flows. We worked on improving observation capability of the current system, utilizing images from SGLI, and developed a method to detect and monitor pyroclastic-flows generation associated with growth of lava dome. The concept is as follows. As the lava dome grows, the marginal parts of the dome collapse to generate pyroclastic flows. These pyroclastic flows spread and accumulate on the slope. The surface temperature is much lower than that of the dome growth area, because of effective cooling in flowing process. On the 1.6um images, the dome growth area will be radiant, however the depositional areas of pyroclastic flows will not be visible, because of the detection limit of this channel. On the other hand, on the 11um images pyroclastic flow deposits will be radiant, as well as the dome growth area - 11um channel is sensitive to low temperature. Accordingly, size of thermal anomaly will be larger on the 11um than on the 1.6um images here. In contrast, in the case of activities without pyroclastic flows, both on the 1.6um and 11um images, the sizes of thermal anomaly will be about the same, because of no hot materials existing around the lava dome. We tested this discrimination method, using simulated SGLI data produced from Landsat TM of the Unzen 1991-1992 activity. The results showed that activities with pyroclastic flows have systematically higher 11um /1.6um size ratios than those without pyroclastic flows, as expected. We plan to add this discrimination method to the system for realtime monitoring pyroclastic-flow generation. Pyroclastic flows are most destructive volcanic phenomena, so, this kind of information will be useful for mitigation of volcano-related disasters in east Asia.

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Development of a remote multi-sensor global monitoring system for active volcanoes

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The complexity of active volcanic systems produces a vast array of eruptive phenomena; some persistently active volcanoes display combinations of effusive activity such as passive degassing, lava flows, lava fountains and lava lakes, while others display more explosive strombolian and vulcanian characteristics. Satellite remote sensing techniques provide the opportunity to monitor activity without the requirement of costly ground-based instrumentation or monitoring networks. Two datasets commonly utilised for satellite-based volcano monitoring are sulphur dioxide (SO_2) measurements using ultraviolet (UV) wavelengths and thermal anomaly detection using thermal infrared (TIR) wavelengths, but there have been few efforts to combine these techniques. We focus on operational SO_2 measurements made by the Ozone Monitoring Instrument (OMI) on NASA's Aura satellite, and TIR MODVOLC data derived from the Moderate Resolution Imaging Spectroradiometer (MODIS) on the Aqua platform. Both Aqua/MODIS and Aura/OMI are in NASA's A-Train satellite constellation, providing daily, near-coincident observations of SO_2 emissions and heat flux at active volcanoes facilitating coupled analysis of the information obtained from these datasets. Our goal is to develop a technique to classify and monitor volcanic activity autonomously using OMI, MODIS and (ultimately) other satellite datasets. In order to characterize the style of eruptive activity based on satellite observations alone, we will first compile a database of OMI and MODIS observations for periods of well-documented volcanic unrest, and analyze their temporal variability. Time-series analysis techniques including Fourier functions, power spectral density and wavelet analysis will be utilised to identify the presences of cyclical patterns in the OMI and MODIS data from the selected locations. Select volcanic targets will be assessed representing diverse locations and styles of activity in order to test the developed methodology. Kilauea (Hawaii) will be incorporated due to its well-established eruption record compiled by the Hawaii Volcano Observatory (HVO) providing an invaluable source of observations to validate the technique. Popocatepetl (Mexico) will be analysed to represent the complexities associated with the presence of both natural and anthropogenic sources of SO_2, testing the validity of the methodology when sources of SO_2 are not purely volcanic. The ultimate aim of this project is to develop a more robust multi-sensor satellite monitoring and alert system than currently exists.

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Monitoring of Merapi Volcano in Indonesia using Remote Sensing Data

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We study Merapi volcano that erupted from November 1994 to October 2010 in Indonesia. We collected LANDSAT TM and ETM+ data to understand pyroclastic flow deposit area from and monitor volcanic activity of Merapi, Indonesia from 1994 to 2012. Supervised classification is executed for atmospheric correction using COST model. While western part of this volcano represents pyroclastic flow deposit until 2005 southern part pyroclastic deposit area is stronger than western part of this volcano after 2006 eruption by LANDSAT TM and ETM+ data analysis with thermal band combination. JERS-1 and TerraSAR-X data agree to pyroclastic flow deposit area with LANDSAT data. For time series analysis, we generate interferograms with ALOS PALSAR data from 2007 to 2011. This result is very efficient to monitor volcanic activity and understand dynamic system of magma movement.

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Identification of long- and short-term eruptive trends using satellite TIR records of Merapi Volcano, Java, Indonesia

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Merapi is a 2968 m high volcano located in the Central Java Province of Indonesia and one of the countrys most active volcanoes. Episodes of basaltic-andesite dome growth are periodically interrupted by explosive eruptions, which have caused at least 429 fatalities in the last 20 years alone. We use thermal infrared (TIR) images from the Moderate Resolution Imaging Spectrometer (MODIS) and Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER) instruments to measure heat flux at Merapi Volcano over the time period from 2005-2012. We also estimate effusion rates at the vent from the heat flux values using the method of Harris and Ripepe (2007, Geophys. Res. Let. 34). Our data set includes over 1500 MODIS images and over 40 ASTER scenes that allow us to observe trends in volume flux at the vent over time. The result is an 8-year record of heat flux at Merapi that includes a typical Merapi-style, dome-building effusive eruption in 2006 and the explosive VEI 4 eruption of 2010. We are able to confirm the accuracy of heat flux measurements and effusion rate estimates from TIR data by comparison with a limited number of ground observations from the 2006 and 2010 eruptions. Nightly MODIS images create a dense record of heat flux that can show both long-term trends and the rapid onset of eruptions. Long-term trends include volume flux changes that may represent precursory events and post-eruption high-flux rebound, as well as background volume fluxes similar to previous studies (e.g. Siswowidjoyo, 2005, Bull. Volc. 57). The higher resolution ASTER images allow detection of source details that cannot be resolved in the lower-resolution MODIS images, such as differentiation between accelerated dome growth and dome collapses that create widely distributed hot pyroclastic deposits. We also demonstrate the limits of satellite TIR monitoring, which is primarily restricted by frequent cloud cover blocking the view of the volcano during the rainy season. Additionally, the presence of an ash plume during the 2010 explosive eruption severely limited our ability to observe that event. Satellite TIR monitoring of volcanic activity is best suited to observe ongoing effusive activity and to some extent, pre- and post- eruptive trends. The ability to correlate satellite TIR observations with specific events and types of activity at Merapi can be applied to other similar volcanic systems. More detailed interpretation of the TIR images captured by MODIS and ASTER can improve monitoring and hazard assessment at other potentially dangerous volcanoes that are not as well observed as Merapi.

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Near real-time monitoring of Taal volcano from space by means of an automated hot spot detection system

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An automated satellite monitoring system, based on the RST_{VOLC} detection algorithm, has been designed, developed and implemented at laboratories of Institute of Methodologies for Environmental Analysis (IMAA) of the National Research Council (CNR) to monitor Taal volcano (Philippines) in near real time. This system, developed in the framework of a collaboration project between PHIVOLCS (Philippine Institute of Volcanology and Seismology) and EMSEV (Electromagnetic Studies of Earthquakes and Volcanoes, http://www.emsev-iugg.org/emsev/), automatically processes infrared data provided by Japanese geostationary satellites (MTSAT - Multifunctional Transport Satellites) to promptly identify anomalous variations in the MIR (Medium Infrared) and TIR (Thermal Infrared) signals, associated to possible thermal unrest phases of volcano. The system is capable of analyzing the infrared satellite signals at 1 hour of temporal sampling. In addition, in case thermal anomalies are detected, e-mail alerts reporting position, date, time and relative intensity of anomalies (in terms of RST_{VOLC} index values) are produced and sent a few minutes after data acquisition, providing timely information about possible thermal activities in progress at volcano. From January 2011 to October 2012, the system has worked in almost continuous way, processing more than 18 months of data. In this period, no statistically significant thermal anomalies were detected, although some seismicity activity was recorded. But during that period, no large thermal anomaly was detected on the ground.

In this work, a summary of the activities carried out and the results achieved is reported. In particular, performances of the system are analyzed, also assessing operational capabilities, drawbacks and potential of satellite observations as an additional tool contributing to provide prompt and accurate information about possible unrest of active volcanoes, in the framework of an integrated and operational warning system.

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Estimation of clast-size distribution and eruption energy partition from the thermal images of debris ejected by dome-destruction explosions: Applications to Colima and Popocatepetl volcanoes

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Sequential thermal images of the cooling of clasts ejected by explosions at Popocatepetl and Colima volcano, Mexico, during periods of high lava-dome destruction activity (1998-2002 and 2005-2007 respectively) are used to estimate the relative thermal energy release by eruptions, and the degree of conversion into mechanical energy spent in the fragmentation of the ejecta. The cooling rate from successive thermal images, obtained immediately after explosions, is measured on selected pixels of the thermal images where ejected fragments have been deposited on the volcano flanks. The observed rate of cooling is then compared with different possible distributions of hot-fragment sizes in the pixels. The optimal fitting of a fragment distribution reveals the degree of fragmentation of individual explosions, and the use of a model of the cooling process allows estimating the relative proportion of thermal energy released on the area covered by the image. The sequence also provides information about the kinetic energy of the ejected tephra. In addition, the results indicate that the radiative thermal conductivity plays a significant role in the outer shell of the fragments, suggesting a free mean path of thermal infrared photons in the range of a few centimeters.

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Pyroclastic flow and lahar hazards in populous, developing regions: Integrated TIR and SAR data analysis

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Using both thermal infrared (e.g., ASTER and Landsat) and radar sensors (e.g., RADARSAT-2 and TerraSAR-X) there is an opportunity to forecast future explosive volcanic activity in highly populated, developing countries. The research proposed here will refine models of surface composition and roughness on existing pyroclastic flow and lahar deposits at Merapi volcano in Indonesia and Shiveluch volcano in Russia. Each volcano has had numerous eruptions in the past decade that have produced many sizes and styles of flow deposits. It is hypothesized that through testing current remote sensing methods on these deposits, future eruptions can be better constrained at other volcanoes in different climates. Reduction of risk to people and property can be achieved by quantifying volcaniclastic and pyroclastic deposit pre-eruptive magma composition and crystal content, and volatile content and degassing conditions through deposit surface roughness. These conditions give insight to the magma system evolution, and future eruption style to aid in disaster management and decision-making (using digital elevation models combined with the results of the flow surface data modeling). Compositional data and crystal content will be derived using satellite thermal infrared spectral deconvolution methods described by Ramsey and Christensen (1998). Micron-scale surface roughness will be quantified by improving the vesicularity model developed by Ramsey and Fink (1999) using a two-component spectral deconvolution model applied to thermal infrared wavelengths. These results will be extended to larger morphology and block size measurements derived from radar (SAR) and thermal inertia data of the same flows and subsequently compared to previous ground and lab based studies of these deposits. This research aims to improve remote sensing modeling of explosive eruptions by also testing in humid climates with high cloud cover, increased vegetation, and commonly increased populations in harm's way. The data produced by this research will therefore be linked to past volcanic activity, and then incorporated with topographical data for volcanic hazard application to assess risk to local populations.

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Numerical Simulation of Volcanic Ash Dispersion due to the Explosive Eruption of the Mt. Baegdu

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Numerical Simulation of Volcanic Ash Dispersion due to the Explosive Eruption of the Mt. Baegdu

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Abstract: Mt. Baegdu located in the north part of the Korean peninsula is known with rest volcanic activity, but recently various precursory signs appear so that the requirements to develop for the manual according to prevent the disasters after the volcanic erupted is getting increased. In order to clarify the characteristics of dispersion of volcanic tephra emitted from the Mt. Baegdu with various eruption environment, numerical analysis were performed using numerical models, Weather Research and Forecast (WRF) and FLEXPART. In this study, the amount of deposition erupted volcanic ash was calculated by the emitted amount at each intensity of the discrete eruption and the amount of its dispersion based on the various assumptions. Especially, these assumptions were made that the volcanic ash released from the Mt. Baegdu in the atmosphere, then transported with wind field, so that they could be affected to overestimate by the various factors. This study is based on the meteorological field which is predicted the direct damage by the volcanic ash from the Mt. Baegdu. Volcanic ash tends to be deposited easily in the eastern coastal area such as Gangneung and Busan, because of the inflow of ash from the East Sea and barrier effect of the Taeback Mountains along the east coast of the Korean Peninsula. Accumulated amount of ash deposition can be increased in short period in several urban areas. This study aims to quantify the disaster for the prevention after the Mt. Baegdu erupted, which can be used to make a predicting scenario according to damage from ashfall and applied as major fundamental references.

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Balloon-borne Observation of Volcanic Ash from Shinmoe-dake (Kirishima) Volcano in March 2011

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Tephra which is released into the atmosphere will cause various damages in wide region such as cancellation of aircraft operations in wide area not only on the society in the neighbor district. Ash plume observation by airbone in-situ measurement was to be performed at the time of the 2010 Eyjafjallajokull eruption in Iceland, Operations within volcanic plume on the vicinity area has not been performed because there is a risk of failure of aircraft. We have tried to observe the interior of ash plume of vulcanian eruption of Shinmoe-dake(1421m a.s.l.) using the balloon sonde designed for meteorological measurement. The rising speed of the balloon is 6 meters per second. Two types of monitoring devices are used in addition to normal weather sonde. Hydrometeor videozonde (HIVIS) is a device that wirelessly transmits captured videimage particles adhered to the film coated with silicone oil. The HIVIS covers the size range of 10 micro meter to 2 mm. Aerosol sonde (OPC) irradiate a continuous laser beam to the particles contained in the pumped air and measures the intensity of the forward-scattering light by photodiod. The OPC covers nominally the size range of 0.3-10 micro meter (8 channels).

The observation was carried out in late March 2011. The height of the plume was 4700m a.s.l. obtained from radar observations of the eruption on March 23, which is the only eruption that occurred during this period. The total amount of tephra erupted in the 23 March eruption is about 5x10ˆ6kg. In the balloon release after the eruption from the site of the 18km downwind of the vent, volcanic ash particles have been detected. In the range from ground level(162m) to 1800m altitude, the size of coarse particles reached about 30-80 micro meter. The proportion of particles of about 3-10 micro meter was relatively high in the range of 1800-6000m altitude. Altitude above 6000 m, particles were composed of less than 10 micro meter. Probably coarse particles of low altitude are volcanic ash origin, however these are considered reworked particles and/or ash released from subsequent weak ash emission in the crater because unfortunately the observation started two hours after the main ash emission period of the eruption. Particles of the middle to high altitude range are considered likely to contain particles Yellow Dust origin.

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Characterizing the October 2010 Lava Flow of Piton de la Fournaise using Space-based data

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Over the past five decades, the use of space-based data has proven its ability in imaging and analyzing the Earth's surface. As a result, it has become a powerful tool, most importantly in volcano monitoring and hazard mitigation. Here, we present the co-eruptive and post-eruptive behavior of the lava flow of Piton de la Fournaise active during the October 2010 through integrated use of InSAR (i.e. TerraSAR-X and COSMO-SkyMed) and thermal (i.e. MODIS) remote sensing data. Horizontal and vertical displacement maps derived from syn-eruption TerraSAR-X data shows that the October 2010 eruption was related to the injection of a dyke. It extended to SSE direction from the summit breaking the surface at 2000 m a.s.l.. Analysis of the post-eruption data involved phase unwrapping, detrending, phase inversion and application of corrections to take into account bad unwrapping of a large database of COSMO-SkyMed interferograms. This revealed that the lava flow subsided at a maximum rate of 13.5 cm/yr and deformed, mostly eastward, at a maximum rate of 4 cm/yr. The slope of the volcano is assumed to be the cause of the East-West displacement of the lava flow (i.e., deformation is gravity-driven), whereas the subsidence can be attributed to: 1) poro-visco-elastic relaxation of the substratum and the lava flow due to the gravity load and compaction, 2) thermal contraction of the lava flow during cooling, and 3) other non-linear processes occuring within, and beyond, the lava flow. In addition to the deformation, we produced a thickness map which illustrated the extent and boundary of the emplaced lava flow. We derived a DRE volume of 3.06 ± 0.19 Mm^3 from the lava thickness map after considering a vesicularity of 20 percent. The InSAR characterization results were cross-validated with results obtained from converting MODIS spectral radiance data to lava discharge rates during the eruption. This integration of the MODIS-derived discharge rates through time also gave a volume estimate of 3.0 Mm^3. The discharge rate time series also revealed a waxing-waning behavior, which also implies eruption from a pressurized (dyke) source.

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Remote temperature sensing of active fumaroles using hydrogen isotopes of molecular hydrogen in volcanic plumes: Temporal variation in the temperature of fumaroles in Aso volcano

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In high-temperature volcanic fumaroles (>400℃), the isotopic composition (δD value) of molecular hydrogen (H_2) reaches equilibrium with that of the fumarolic H_2O under the outlet temperature so that the δD value of fumarolic H_2 is a function of fumarolic temperature. Combining this temperature-dependent variation in δD value of fumarolic H_2 with our high-sensitivity mass spectrometric technique which enable us to deduce the δD value of fumarolic H_2 from trace H_2 in the volcanic plume, we can determine the temperature at volcanic fumaroles remotely. We have applied this methodology (HIReTS: Remote Temperature Sensing using Hydrogen Isotopes) to the volcanic plume emitted from the Crater 1 of Mt. Naka-dake, Aso volcano (Japan), where direct measurement on fumaroles was impractical. The average H_2 concentration of the plume samples (n=12) taken at the crater rim was 1.2 ppm (from 0.54 ppm to 2.3 ppm), while that taken apparently outside the volcanic plume was 0.53 ppm. We estimated that the δD value of the fumarolic H_2 to be –172±16‰and the outlet temperature to be 868±97℃ during the first observation in Nov. 2010. While the temperature was much higher than the highest temperature of the fumarolic area determined remotely using a dedicated IR thermometer (ca. 300℃), we concluded that our temperature was a reasonable and reliable estimate of the outlet temperature. Besides, subsequent periodic observations on the same crater using HIReTS revealed ca. 80 ℃ increase in the temperature that was not detected by the IR thermometer. The HIReTS is the reliable method to determine temporal variations in fumarolic temperature remotely.

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Evolution of the lava dome in the 2011 Shinmoe-dake (Japan) eruption revealed by spaceborne SAR imagery

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SAR observations to investigate the 2011 Shinmoe-dake (Japan) eruption were carried out by several SAR satellites. We found temporal change of a crater shape in their SAR images. A convex shape appeared in the PALSAR image acquired on January 27, but it is unclear whether this shape indicates lava. A larger convex shape that does indicate lava could be identified in SAR images acquired after that, and it seems to have grown progressively. Estimating topography so that the simulated intensity image corresponds to the acquired one, we estimated that lava grew from the night of January 28 until January 31 with a constant effusion rate of 89.2 m^3/sec. The lava volume of 15 million m^3 estimated from the TerraSAR-X image of February 1 was in good agreement with that of airborne SAR observation by the Geospatial Information Authority of Japan. From the estimated lava effusion rate and lava-covered area, we estimated that lava viscosity was less than 2.1 GPa·sec, suggesting the potential to form a lava flow. Furthermore, we corrected the foreshortening distortion using the estimated topography and suggested that the lava effusion point was around the crater lake.

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Geomorphic analysis and numerical flow simulations from the 2012 Te Maari eruption from Mt. Tongariro, New Zealand.

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Data from LiDAR and RTK GPS, remotely sensed data and numerical computer simulations have all been combined to determine geomorphic change and volcanic hazard from the 6th August 2012 eruption from the Te Maari Craters of Mt Tongariro, New Zealand. The small phreatic to phreatomagmatic eruption and resulting landslide/debris flow was not considered in the hazard analysis of the Tongariro Volcanic Centre. The Titan2D computational flow model was applied to scenarios developed around historic eruptive centres to create a mass flow hazard zone for public hazard maps. Titan2D model parameters were determined from current geomorphologic conditions from the Te Maari Craters and from past experiences in hindcasting expected mass flow products from this complex. With no validation available from past events, hazards analysis of the simulations focused on maximum run-outs and maximum inundations areas. The subsequent 6th August phreatic to phreatomagmatic explosions altered the landscape with newly established volcanic vents and potentially unstable craters. This eruption also displaced 320,000 m3 of material from the flanks of the vent area in the form of a landslide, generating a small debris flow that flowed 2.5 km from source and blocked a valley system. These geomorphic changes were characterised by RTK-GPS surveys and LiDAR. The damming of the valley and the formation of a lake behind the dam presented a changing hazardscape, which is continually altered by the rapidly evolving landscape and the ever-changing geomorphic conditions. Computer simulations and their results can be combined with present topographic measurements to provide signals to predict landscape changes over time.

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Stability assessment of Unzen lava dome by long and short range displacement monitoring

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The eruptions of Unzen volcano occurred in 1990, leading to the recurrent formation and collapse of lava dome that almost ceased by 1996. Although these hazardous failures of the dome have ceased, the large remaining lava dome(100 million cubic m) that exist along the steep slope, pose threat to the public. Hence, Unzen Restoration Work Office (Ministry of Land, Infrastructure, Transport and Tourism) has been monitoring the lava dome, by surveillance cameras, vibration sensors, and electronic distance measurements (EDMs), in order to ensure the safety of the public. This presentation mainly reports the recent results of monitoring the movements of the lava dome.

One of the ongoing main monitoring methods for detecting the movements of lava dome is the automatic long distance EDM of the eight reflecting prisms placed at near the end of the dome. The results, obtained with the two EDM stations at 3 km and 3.5 km from the dome, suggest that the eight prisms are continuously moving at a rate of 50 mm to 100 mm per year. The vertical component of the displacement, however, is not clear due to limitation with the accuracy in measuring the change in elevation of the eight prisms. On the other hand, the manual short range EDM, performed at a distance of approximately 500 m from the end of the dome, was able to measure the vertical displacement component and indicated that the dome may be moving downward at an angle close to that of the original slope surface before eruption.

While the results of automatic EDM provide valuable data in help revealing the mechanisms of the movements of the lava dome, the noise due to climatic variation is relatively large such that it is difficult to examine whether the increase in the displacements are associated with the rainfalls or earthquakes. Moreover, the measured displacements are limited to those obtained by the eight prism points on the large lava dome and therefore it is not clear whether the whole lava dome is deforming or there are areas more active than other areas.

Recently, ground based synthetic aperture radar has become available for monitoring of landslides. This radar has been scanning the lava dome of Unzen volcano at distance of approximately 3.5 km since October 2011. The scanned area of roughly 800 m by 400 m is resolved into 20,000-30,000 pixels, allowing coverage of wide areas that cannot be measured with EDM. The displacement maps, corresponding to 1 year of measurement, show that there are areas with larger movements than the other areas. It was also found that the variation in the GBSAR, due to the climatic effects, is smaller than that of the EDM and permits detection of change the displacement velocities, which were not easily performed with the EDM. Thus, GBSAR is expected to be a viable method to assess the deformation mechanisms of the lava dome in more detail and also to detect precursor of instability for early warning purpose.

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Application of the Kinect sensor to analogue modeling of volcanic deformation

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The Kinect is a USB-input motion capture device originally intended for the Microsoft XBOX system. The device comprises a visible (RGB) camera and an infrared (IR) camera, refractor and light emitter emitting a known structured light pattern at the near-IR wavelength of 830 nm, plus a three-axis accelerometer and four microphones. Although designed for use with videogames, the Kinect can be exploited as a short range, low-cost camera-type laser scanner by scientists in various fields. In fact, thanks to the effort of the online developer community, by combining the IR pattern emitted by the projector and received by the camera we are able to quantify the distance from the Kinect to objects within its field-of-view.

Measuring and monitoring 3D surfaces is critical to many studies in the earth sciences, including volcanology. We envisage several possible applications of the small-scale, precise topographic data acquired by the Kinect in this field, including mapping inactive lava tubes, capturing topographic data on the outcrop scale, and mapping surface roughness variations on volcanic mass flow deposits. The Kinect's main limitations for exploitation in this field are its limited field-of-view, operating working distance (i.e. from 0.5 to 5 m), precision and accuracy of the measured distance, which ranges from 1 mm to 8 cm at 0.5 and 5 m, respectively. Moreover, environmental factors can limit its usage in the field. For example, the presence of other strong IR sources such as bright sunlight can saturate the sensor, and surfaces that absorb IR radiation cannot be accurately detected.

However, remarkable results can be obtained in visualizing and quantifying the deformation of analogue volcano models in the lab. As a demonstration, we will present a novel application of the Kinect as a tool for 2D quantitative analysis and 3D visualization of laboratory analogue models of volcanoes. We will describe the calibration process for the RGB and distance images to the color spectrum and modeling materials and demonstrate its effectiveness in quantifying deformation in analogue modeling experiments.

Besides being lighter, smaller and therefore more portable than equipment commonly used to collect field data, data can be recorded with free and open source software, demonstrating the cost-effectiveness of the Kinect, in particular where conditions may be unsuitable for the deployment of more costly instruments.

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X-Band SAR topography changes for pyroclastic density current volume estimation: the 2010 Merapi eruption case study

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Pyroclastic density current deposits remobilized by water during period of heavy rainfall trigger lahars (volcanic mudflows), affecting inhabited areas at considerable distance from volcanoes, even years after an eruption. Here we present an innovative approach to detect and estimate the volume of pyroclastic density current (PDC). We use an airborne Digital Surface Model (DSM) acquired in 2006 and compare it with a post eruption DSM retrieved by means of SAR interferometry (COSMO-SkyMed data) estimating the volume of PDC along the Gendol river (Kali Gendol, KG) deposited during the 2010 Merapi eruption. Results show PDC thicknesses of up to 75 m filling canyons and a volume of about 40 x 106 m3, mainly along KG, and at distances of up to 16 km from the volcano summit. This volume estimation corresponds to the possible volume of removable material along the KG due to the 2010 eruption. The PDC volume estimation is critical for volcanic hazard mitigation, especially for lahar occurrences during rainy season at Merapi. Our technique can also be applied at other active volcanoes to evaluate lahar hazards.

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Evaluation of volcanic activity by using LiDAR Data in Aso Volcano, Japan

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It is generally more difficult to collect geological information about a volcano with an old formation age, owing to erosion or deposition of ejecta. Therefore, it is necessary to develop a new investigation method as an alternative to a conventional geological survey. Sakagami and Sasaki (2010) performed a terrain analysis with a terrain model with various resolutions (DEM and DSM) on four volcanic edifices in the Aso central cones (Komezuka, Oujoudake, Kijimadake and Kusasenrigahama). As a result of analyzing the dissection degree of volcanic edifices, we revealed that the standard deviation of the laplacian was most suitable to evaluate the relative ages of four volcanoes. The formation age of Komezuka, which was unknown at the time, was estimated to be about 2.4 ka, based on the standard deviation of the laplacian, the formation ages of which were known from previous reports. The formation age of Komezuka was determined by Miyabuchi (2010) to be about 3.3 cal. ka. It showed no significant difference from the formation age estimation result achieved by Sakagami and Sasaki (2010). A high-resolution terrain model generated from an airborne laser scanner, were therefore considered suitable for the assessment of volcanic activity.

In this study, an existing volcanic crater terrain was considered to be one of the indices for assessing volcanic activity; this volcanic crater terrain data was extracted using a high-resolution terrain model generated from an airborne laser scanner. The diameter of the volcanic crater was measured using the extracted a high-resolution terrain model. And, we estimated the amount of ejecta using the method of Sato and Taniguchi (1997). Based on the results, we interpreted some new volcanic crater terrain at Kijimadake and Kusasenrigahama, which have not been reported in the previous studies. The amount of ejecta was calculated based on the volcanic crater diameter while interpretation of geographical features and was found to be similar to the amounts of ejecta derived by previous geological surveys. Furthermore, we obtained by estimating the assumed amount of ejecta in Komezuka, which had previously been unresolved. We estimated the maximum ejecta amount from each volcano using our method. When we are not able to obtain enough geological information, it is possible to evaluate of volcanic activity using this method.

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Monitoring of geothermal activity in the ice-covered Katla caldera, Iceland, 1999-2012

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The upper parts of the Katla central volcano are covered by the 600 km2 Myrdalsjokull ice cap. The central part of Katla is a large (100 km2) ice-filled caldera. Eruptions in Katla occur about twice per century, typically phreatomagmatic explosive events of size VEI 3-4. The eruptions melt quickly through 400-600 m thick ice in the caldera before the onset of the subaerial explosive phase. During the typically 1-8 hour long subglacial phase large volumes of ice are melted, leading to catastrophic outbursts floods (jokulhlaups) with peak discharge of order 100,000 m3/s. Katla is located on the south coast, close to inhabited areas and because of the jokulhlaups it is regarded one of the most dangerous volcanoes in Iceland. As a consequence, Katla is monitored with a network of seismometers, continuously recording GPS and automated monitoring gauges are located in rivers that drain the ice cap. In addition, a monitoring program was set up in 1999 to survey ice surface profiles from low-flying aircraft across 17 depressions formed by geothermal activity under the ice. Although most depressions only have minor crevassing at the surface and lack vertical ice walls, it is customary to use the term ice cauldrons when referring to these depressions. On board the aircraft ground clearance radar coupled with kinematic GPS is used to map the surface profiles. The elevation accuracy from the surface profiles is 2-3 meters, allowing changes in ice surface between successive surveys in excess of 5 meters to be resolved. The surveying since 1999 covers two periods of enhanced unrest in Katla, 2001-2004 and 2011-2012. Both unrest periods were characterised by increased geothermal activity, manifested in increased depth and width of ice cauldrons. Some of the cauldrons have showed evidence of periodic accumulation of water at the bottom in winter and drainage in summer. Within the 13 year long survey period, two unusual jokulhlaups with discharge of a few thousand m3/s have occurred (1999 and 2011) when sudden increase in thermal activity lead to rapid growth of water bodies under cauldrons. The formation and size of such subglacial bodies is difficult to monitor with only ice surface profiling. Steps are being taken to supplement the airborne surveys with ground-based radio echo surveys. This will make it easier to detect cauldrons with unusual accumulation of water, as the ones that drained in the jokulhlaups of 1999 and 2011.

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Documenting dome and glacier changes from the 2004-2008 eruption at Mount St. Helens, USA

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During the 2004-2008 eruption at Mount St Helens, WA, 26 digital elevation models (DEMs) were created from vertical aerial photographs. These DEMs were used to track volume and rates of growth of a new lava dome as well as changes in Crater Glacier, which was displaced by the growing lava dome. The estimated dome volume reached a peak in early September, 2007, of about 95 x 10^6 m^3. More recent estimates of the dome volume decreased to about 90 x 10^6 m^3, the decrease presumably due to settling and compaction of abundant dome rock talus. These estimates are approximations of total volume, because, the dome bore and grew through Crater Glacier, leaving us to assume the dome had vertical sides beneath the glacier surface. Rates of dome growth decreased from about 6 m^3 / sec early in 2004, to about 0.1-0.2 m^3 / sec in early 2008 as the eruption waned. Constructing and differencing of consecutive DEMS was used to track dome growth as part of a multidisciplinary monitoring effort throughout the eruption. The dome-volume estimates also served as a key data set to constrain seismogenic extrusion models and to compare against geodetic surface-deflation volume to constrain magma chamber behavior.

As the dome grew, it split Crater Glacier into a two parts, and squeezed east and west arms of the glacier against the crater walls. DEMs showed the glacier arms nearly doubled in thickness and then thinned as the glacier ice flowed downslope to the north. Despite early explosions through the ice and exposure of the glacier to extruding hot dome rock, the glacier lost only about 15% of its pre-eruption volume (from about 70M m^3 to 60M m^3). By 2012, the glacier volume had regained about 91% of its pre-eruption volume (to about 64M m^3).

Photogrammetric software that uses robust image-matching algorithms to produce 3D surfaces automatically from overlapping photographs is now a mainstay of our ongoing volcano monitoring. Vertical aerial photographs are taken annually at a consistent 1:12,000 scale in the autumn at the time of maximum glacier ablation; prior to new winter snow. With overlapping pairs of photographs and carefully planned GPS ground control, we use the software to generate surfaces in minutes that extend over the entire 1980 crater. Preliminary tests show that surfaces generated from those images are of comparable resolution and accuracy to those generated from vertical aerial photographs. Oblique hand-held images offer ease of image capture and unobscured views at times when steam plumes and clouds obstruct vertical aerial photography, a common obstacle early in the eruption. The combined use of vertical and(or) oblique photographs provide substantial flexibility to our monitoring program. These technological advances have repositioned photogrammetry into the realm of near real-time monitoring and hazard assessment.

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Geomorphic constraints on the Pleistocene growth of Uturuncu Volcano, Bolivia

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The Altiplano-Puna Volcanic Complex (APVC) in southern Bolivia repeatedly sourced large-volume ignimbrite eruptions over the last 11 myr. Though eruption rates have waned since 3ma, given the cyclic nature of eruptions in this region it is uncertain whether or not future eruptions of similar scale (VEI 8 and above) will occur. Moreover, InSAR studies at Uturuncu Volcano, Bolivia reveal surface inflation over a 70 km area, with a central uplift rate of 1-2 cm/yr and a corresponding magma chamber growth rate of 1m3/s sustained over the 14 years of available data. A key question still remains for Uturuncu Volcano: what does this modern unrest mean in terms of the volcano's magmatic evolution, and consequently its eruptive stability? As silicic magma chamber evolution is a subject of much debate, real-time observations of this system's evolution may help constrain future modeling efforts. Here we investigate the evolution of Uturuncu Volcano using geomorphology. Geomorphic processes operate on timescales similar to those of magma chamber growth (10 ˆ4-10 ˆ5 yrs), and the APVC has had a rich history of Pleistocene lakes whose shorelines can be used as markers to measure surface deformation. Lakes near Uturuncu are experiencing uplift gradients from the modern deformation field, which drives shoreline tilting away from the volcano. If this deformation is sustained on timescales greater than 10 ˆ3 yrs, then we expect to observe Pleistocene shorelines to be tilted on the order of 1-10's of meters. Alternatively, if we observe no measurable tilting then the modern defomration must either be a recent or perhaps periodic phenomenon. We focused our field efforts on two lakes adjacent to Uturuncu: Laguna Mama Khumu and Laguna Loromayu. Here we surveyed shorelines and deltas using differential GPS, characterized the stratigraphy of multiple shoreline fatures, and collected samples for OSL dating. OSL ages for the Loromayu shoreline sequence show highstands of Tauca age (e.g., Placzeck et al., 2006), suggesting a regional basinal response to climate. Differential GPS surveys of Mama Khumu shoreline features show no discernable tilting of lake shorelines, which suggests no sustained long term surface deformation associated with magma intrusion. Additionally, river longitudinal profiles from a photogrammetry-derived 5m digital elevation model yield no easily-interpretable evidence for sustained surface uplift. Together, these observations imply a relatively stable topography at Uturuncu over the late Pleistocene. The recent decadal uplift here thus likely reflects a transient inflational pulse rather than a snapshot of long term tumescence.

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Dome contraction at Colima Volcano in 2012 as constrained by TerraSAR-X interferometry

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Colima is one of the most active volcanoes in Mexico. It has been proposed that its activity is marked by 100-year cycles which terminate in a large Plinian eruption, and that we could be approaching the end of the current cycle. Since the beginning of the most recent eruptive period in 1998, the type of activity has been varying between smaller explosions, dome growth and dome collapse, some of these leading to pyroclastic flows. The current dome at Colima began growing in 2007, but the steep slopes and explosive nature of the volcano limit the possibilities for monitoring it directly. However, measuring deformation in this region is important to determine the rate of the ongoing eruption and the stability of the dome. In June 2011, the seismic and magmatic activity at Colima decreased significantly and remained low until January 2013, when a series of four significant explosions took place, preceeded by seismic premonitors ranging from significant to almost none.

We have acquired TerraSAR-X data in spotlight mode for ascending and descending tracks over Colima, obtaining a high spatial resolution of up to 2 m, and a temporal resolution of up to 11 days. We generated interferograms using DORIS and subsequently analysed the time series of the deformation pattern with the small baseline approach implemented in the StaMPS software, also applying a linear atmospheric correction for each small baseline interferogram. In combination with a high resolution LIDAR digital elevation model the spotlight data allows the detection and quantification of slow deformation in the region of the dome in an unprecedented spatial and temporal resolution, considerably higher than those achieved by other methods.

Here we present the time series of the dome deformation between February and December 2012. The velocities in either look direction reaches up to 10cm/year in line of sight, the maximum subsidence being directed towards the centre of the dome, but very low velocities at its borders. The data suggests that the strong explosion in January 2013 occurred after months of dome contraction. We present a model to explain the pattern of dome contraction rates in an attempt to explore how localisation and geometry of the deeper conduit might be inferred from the space geodetic data.

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Time Series Analysis for Sinabung Volcano in Indonesia using InSAR Technique

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Sinabung volcano erupted August 29, 2010 at Sumatera Island in Indonesia. After about 400-year dormancy, Sinabung volcano erupted on August 29, 2010. Small BAseline Subsets (SBAS) technique can measure time series surface deformation between 2007 and 2011 Advanced Land Observing Satellite (ALOS) PALSAR data precisely. Sinabung volcano has gradually inflation of volcano crater for around 3 years and drastically uplifts transition to top of the mountain during the 6 months before the eruption. The source of inflation is located about 0.3-1.3 km below sea level directly underneath the crater. This remote sensing method to detect dynamic volcano monitoring is one of efficient way for acquiring results of characteristics and surface deformation with time of active volcanoes.

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