



SESAR Engage KTN – catalyst fund project final technical report

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Coordinator:	Royal Belgian Institute for Space Aeronomy (BIRA)	
Consortium partners:	EUROCONTROL, consultancy ROLLS-ROYCE	
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1. Abstract and executive summary

1.1 Abstract

Volcanic emission is a threat to ATM and the safety of flights. Early warnings is an essential source of information for the stakeholders. The OPAS Engage-KTN project is the development a SWIM TI Yellow Profile service providing information (notification & data access) about volcanic SO₂ height. The OPAS service considers observations from 3 hyperspectral satellite sensors (TROPOMI, IASI-A and IASI-B), respectively operating in the ultra-violet and infrared ranges. These instruments represent the state of the art of satellite SO₂ measurements. The IASI sensor already provides well recognised estimations of SO₂ height, which is available in SACS early warning system and contributes to the OPAS service. The outcome of the OPAS project is the new algorithmic development (iterative SO₂ optical depth fitting) of TROPOMI SO₂ height retrievals, the creation of alerts and the access to tailored information, i.e. SO₂ contamination of flight level and improved mass loading estimates.

1.2 Executive summary

Natural airborne hazard can affect the good proceedings of long-line flights, being a possible threat to the health of the passengers, affecting the Air Traffic Management (ATM) and causing potential damage to aircraft engines. For this reason, it is essential to give access to the stakeholders to global Earth observations from satellite, with the objective to generate prompt alerts, e.g. of the emission of gas and aerosols from a volcanic eruption. The availability of relevant information is critical for enhancing situational awareness and providing resilience in crisis.



The OPAS Engage-KTN project aims to develop a new type of early warnings and the delivery of tailored information to avoid the contamination of sulphur dioxide (SO₂) during longlines.

The type of alert developed by the OPAS project is the plume height of SO₂ emitted by a volcanic eruption. The knowledge of the height of the volcanic plume is essential for the good proceedings of a flight. The SO₂ height is often a good proxy of the height of volcanic ash, which is known for being a potential source of damage on aircraft. The ash (and its height) is notoriously difficult to measure. A recent study achieved by Rolls-Royce, shows the impact of the SO₂ exposure and the sulphur damage to engines has been diagnosed for several hundred of flights. This highlights the critical interest for the stakeholders to get information on the SO₂ plume height to avoid contamination.

The OPAS ('Operational alert Products for ATM via SWIM') project uses data from 3 satellites sensors:

- TROPOMI on board Sentinel-5 Precursor platform (S5P)
- IASI-A & IASI-B, respectively on board MetOp-A & MetOp-B

These 3 hyperspectral instruments, operating respectively in the ultra-violet and infrared ranges, contributes significantly to the state of the art of SO₂ measurements from satellite.

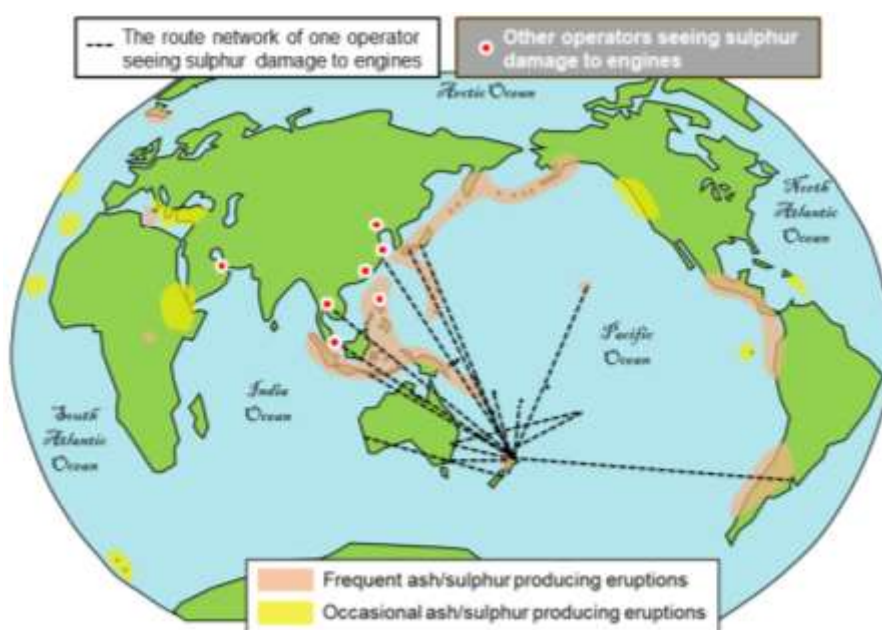
The outcome of the OPAS project is the new algorithmic development (iterative SO₂ optical depth fitting) of TROPOMI SO₂ layer height retrievals (SO₂ LH). This algorithm is operationally running at BIRA by using the spectral radiance provided by the ESA hub. In addition, the OPAS project developed a new type of warnings, the SO₂ LH from TROPOMI, used by an existing Early Warning System (EWS), i.e. the Support to Aviation Control System (SACS; <http://sacs.aeronomie.be>). This system is dedicated to aviation and ATM. SACS was initially developed by ESA (2002-2014) and recently upgraded in the frame of EUNADICS-AV project (European Natural Airborne Disaster Information and Coordination System for Aviation; <http://www.eunadics.eu>). The IASI sensors already provide well recognised estimations of SO₂ LH and alerts, which are used by the SACS EWS. The outcome of the OPAS project is the improvements of the SO₂ LH alerts (TROPOMI and IASI) by providing tailored information, i.e. SO₂ contamination of flight level (FL) and improved SO₂ mass loading.

The OPAS Engage-KTN project has developed a SWIM Technical Infrastructure Yellow Profile service. The OPAS SO₂ LH notification SWIM service allows subscribers to receive warnings with information on the height of volcanic plume (emission of SO₂ from an erupting volcano) and the associated SO₂ contamination of FL. The subscriber receives an email notification that provides access to datasets of SO₂ LH from 3 satellite instruments (via https connection). These datasets are characterised based on metadata and provided in NetCDF format.

2. Overview of catalyst project

2.1 Operational/technical context

Volcanic emissions (gas and particles) can affect long-line flight, being a possible threat to the health of the passengers, affecting the ATM and causing potential damage to aircraft engine. A recent study achieved by Rolls-Royce, shows that the impact of the SO₂ exposure and the sulphur damage to engines has affected hundreds of flights in the last decade.

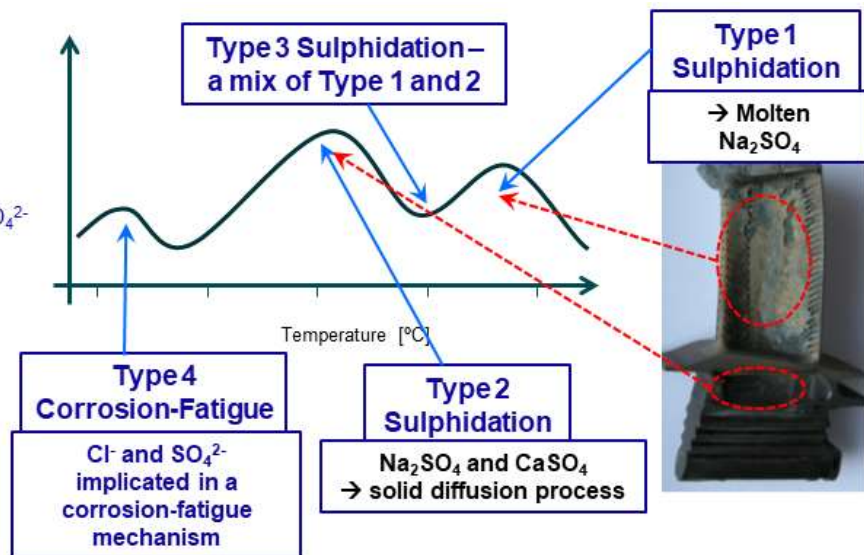


This map illustrates World areas with occasional and frequent volcanic emissions, and an example of a route network and operators seeing sulphur damage to engines.

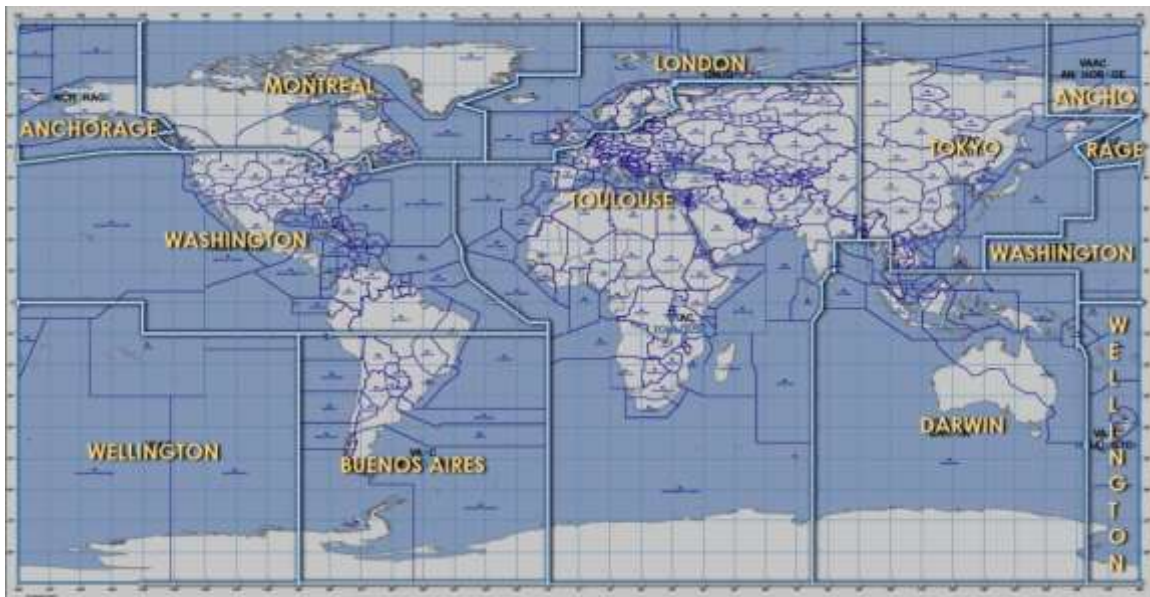


Sulphidation Mechanisms

- Sequence of contamination exposure: Na/Ca, then $\text{SO}_2/\text{SO}_4^{2-}$ and potentially Cl^-
- Chronic versus acute SO_2 exposure



This figure illustrates 4 types of sulphidation mechanisms identified in a communication from Rolls-Royce. The cost of the maintenance contract for the stakeholders and the turbine maintenance costs for the aircraft manufacturers, on the top of the safety and the health problem for the passengers during a long-line flight, is the main motivation for the OPAS team. This recent communication from Rolls-Royce is a very convincing introduction to the problem addressed by the OPAS project, i.e. the transfer to ATM stakeholders of information related to volcanic SO_2 (height and mass loading).



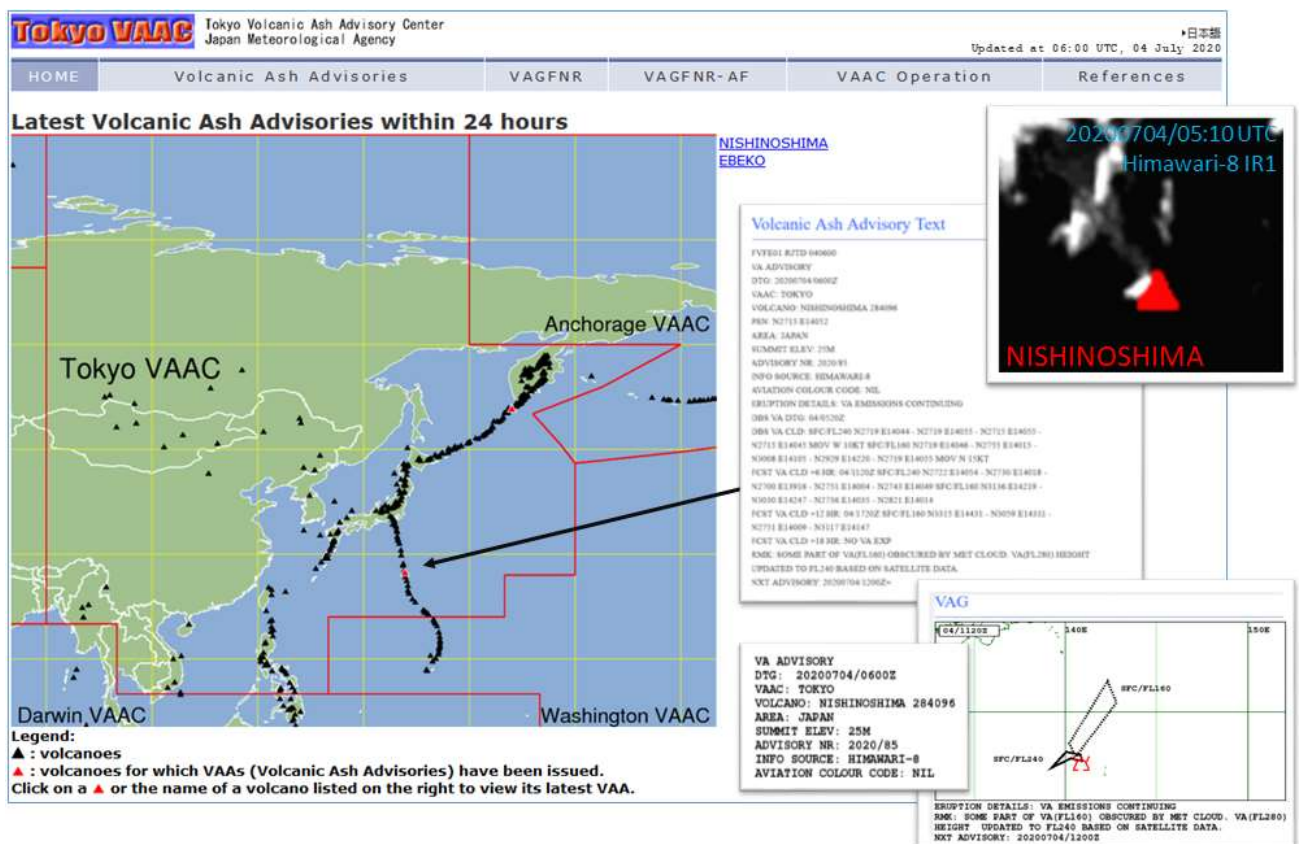
Region of responsibility of the 9 VAACs.

The operational environment to enhance situational awareness and provide resilience in case of volcanic emissions affecting ATM, is the following: nine VAACs (Volcanic Ash Advisory Centres) have been designated by the International Civil Aviation Organization (ICAO) to provide their expertise to civil aviation in case of significant volcanic eruptions. Each VAAC is a meteorological centre (Civil Aviation Authority) designated by regional air navigation agreement to provide advisory information to Meteorological Watch Offices (MWO), area control centres, flight information centres, world area forecast centres and international OPERational METeorological information (OPMET) databanks regarding the lateral and vertical extent and forecast movement of volcanic ash in the atmosphere following volcanic eruptions.

The role of the VAACs is to provide:

- Volcanic Ash Advisory (VAA), an advisory information regarding the lateral and vertical extent and forecast movement of volcanic ash in the atmosphere following volcanic eruptions.
- Volcanic Ash Graphic (VAG), associated to the VAA, showing ash observations and forecasts.
- ASHTAM, provided in the VAA, are special series NOTAM (Notice to Airmen) notifying by means of a specific format change in activity of a volcano, a volcanic eruption and/or volcanic ash cloud that is of significance to aircraft operations.
- Volcanic Ash SIGMET, provided with the VAA, reports the presence of volcanic ash conditions.

A SIGMET (SIGNificant METEorological conditions), provided by a MWO, is an information concerning en-route weather phenomena which may affect the safety of aircraft operations.



Example of the VAA/SIGMET from Tokyo VAAC for the on-going eruption of Nishinoshima volcano (at 21:03 UTC on 4 July 2020). http://ds.data.jma.go.jp/svd/vaac/data/Archives/2020_vaac_list.html

The contamination of air by a volcanic SO₂ plume is considered as an atmospheric phenomena in the IWXXM (ICAO Meteorological Information Exchange Model). A specific consideration of the SO₂ cloud may occur in the future within the ICAO. The exchange of information on the SO₂ cloud is not part of the task of the Volcanic Advisory, but the concern about SO₂ is growing for the ICAO and the VAACs. Indeed, during the conjoint session of the 7th WMO VAAC Best Practice Workshop and the 9th WMO/IUGG VASAG Meeting (21-22 Nov. 2019, Washington DC), London VAAC accepted to be in charge of the development of a future SO₂ product. The SO₂ advisory is on a good way to become soon part of the task of the VAACs.

The OPAS project aims for giving a support to the VAACs and the stakeholders with respect to the SO₂ contamination during long-line flights.

2.2 Project scope and objectives

The access to near real-time (NRT) data, with a time delivery of only few hours, is essential for the VAACs, to complete their task and deliver the volcanic advisory (see section 2.1). A volcanic plume is composed, among others, by sulphur dioxide gas (SO_2). The layer height of an SO_2 plume, in addition to the selective detection of the vertical amounts of SO_2 , can be retrieved using ultra-violet (UV) and infrared (IR) hyperspectral sensors. The scope of the OPAS project is to provide NRT information on the height of a volcanic plume (i.e. SO_2 height) and the associated SO_2 mass loading, which is relevant to the VAACs as it can substantially improve the forecast and the advisory created during a crisis. Information on the SO_2 height is also critical for the stakeholders (airlines, pilots and aircraft manufacturers) to avoid health problem for passengers, unpleasant flights and especially to avoid SO_2 contamination of the engines, which represents consequent maintenance costs.

The objective of the OPAS project are:

- 1) the algorithmic development of TROPOMI SO_2 LH,
- 2) the operational implementation of SO_2 LH,
- 3) the creation of tailored alert products of SO_2 LH from TROPOMI and IASI (A&B),
- 4) the implementation of SO_2 LH early warnings inside SACS EWS,
- 5) the SWIM registry of OPAS as a notification service (Yellow Profile).

The algorithm development and the operational implementation are presented in section 2.3.

The SO_2 LH alert products and early warnings are illustrated in section 2.4.

The advance for the SWIM registry are presented in sections 2.4 and 3.2.

In addition to the objective of the OPAS project, the research questions approached are:

- the requirements, the confidence and the quality of the SO_2 height retrievals,
- the reliability of the OPAS service,
- the validation of the SO_2 height retrievals.

The requirements and quality are presented as part of the algorithm development in the section 2.3.

These reliability of OPAS inside SACS EWS is part of section 2.4.

The first results of validation are shown in the section 2.4.

The consolidated results of validation are mentioned in section 3.2.

2.3 Research carried out

From satellite SO_2 measurements, mostly from UV and IR sensors on board low Earth, polar orbiting satellites, information on SO_2 height can be inferred essentially using two methods: the model approach, which uses inverse modelling, or the measurement approach, which needs algorithm development. This is the second approach we have considered in the OPAS project.

The algorithmic developments to retrieve SO_2 plume height from space nadir hyperspectral measurements directly have been undertaken over the last 10 years. Based on the dependence of the spectral response to different altitude of the SO_2 , the retrieved value is an SO_2 LH, i.e. an effective quantity over the averaged photon path in the SO_2 vertical layer. In the UV spectral range, the first studies were presented by Yang et al. (2010) and Nowlan et al. (2011), based on OMI and GOME-2 instruments. More recently, SO_2 LH retrievals in the thermal IR have been reported by Carboni et al. (2012) and Clarisse et al. (2014), both for the IASI sensor.

As a matter of fact, and in spite of its importance, there is currently no official operational algorithm available to retrieve SO₂ LH from any of the space nadir sensors on orbit. To our knowledge, there is only one scientific algorithm running in near-real time and providing SO₂ LH images: the IASI SO₂ height algorithm of Clarisse et al. (2014), operated by the Free University of Brussels (ULB), recently implemented in SACS/EUNADICS EWS, and part of the SO₂ LH alerts considered by the OPAS project.

With the advent of UV sounders with high spatial resolution like TROPOMI (3.5 × 5.5 km²), new possibilities are offered to retrieve SO₂ LH with clear scientific and societal added-values. The motivation for developing an SO₂ layer height retrieval algorithm for TROPOMI is driven by scientific and operational needs. The potential scientific users are from different communities (volcanologists, atmospheric researchers and climate modellers), while operational users are linked to the aviation sector (VAACs and other ATM stakeholders – airlines, pilots, aircraft manufacturers) or atmospheric modelling community (potentially the Copernicus Atmosphere Monitoring Service – CAMS).

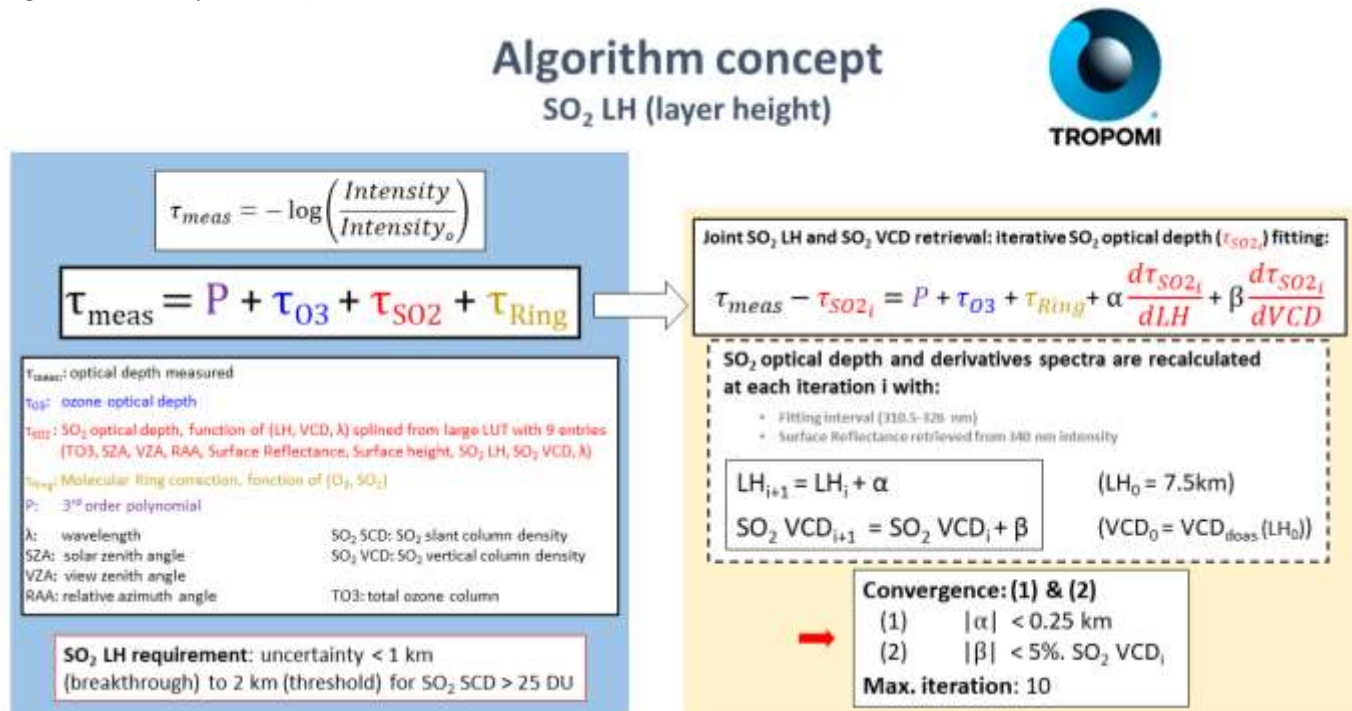
To maximise the return from the development of a TROPOMI SO₂ LH product, the proposed algorithm (and related OPAS activities), will need to fulfil certain high-level requirements. Based on our expertise and from a critical review of the ESA statement of work, these requirements are:

- R1.** The uncertainty on retrieved SO₂ height shall be smaller than 1-2 km, whenever possible and in most atmospheric conditions.
- R2.** A rigorous scientific basis shall be developed to assess the applicability of TROPOMI SO₂ LH. The conditions for which **R1** can be reached shall be clearly delineated. For more difficult conditions (especially in the presence of aerosols), research shall be pursued to improve the retrievals and if no satisfactory solution can be found, a flag needs to be available to identify those cases. An error module shall be developed, so that each TROPOMI pixel reports an SO₂ LH uncertainty (when applicable).
- R3.** The algorithm shall be demonstrated on several volcanic eruptions in varying conditions. Dedicated and comprehensive validation and cross-comparison activities shall be performed.
- R4.** The new SO₂ LH algorithm shall be described and traceable information on input data, performances and validation results shall be made available.
- R5.** The developed methodology shall be portable in a relatively easy way to operational processing and should fulfil operational requirements in terms of computational time.
- R6.** The TROPOMI SO₂ LH dataset shall be consistent with other operational SO₂ LH product developments, notably from Sentinel-5.
- R7.** The TROPOMI SO₂ LH algorithm related activities shall directly include scientific users as a step towards better integration between the geological community and the satellite community.

The pioneering studies on SO₂ plume height retrievals from space UV measurements of Yang et al. (2010) and Nowlan et al. (2011) are based on retrieval schemes making use of demanding online radiative transfer modelling. Thus, such algorithms are difficult to apply for TROPOMI NRT processing especially in the scenario of an extreme eruption, such as Pinatubo, or an SO₂-rich eruption, such as Raikoke, that could possibly solicit all the available hardware in a massive way.

For this reason, we have developed in the frame of the Sentinel-5 L2 Prototype Processors ESA project (S5L2PP) and the OPAS project, a new SO₂ LH algorithm conceptually close to Extended Iterative Spectral Fitting (EISF) algorithm of Yang et al (2010). It make use of SO₂ slant optical depth (hereafter referred simply as OD) spectra look-up-table (LUT) generated as a function of many parameters (geometry, Lambertian equivalent reflector, ozone optical depth τ_{O_3} , SO₂ VCD and height).

In brief, the slant column density (SCD) results from the spectral fitting of the DOAS technique (Differential Optical Absorption Spectroscopy) are first considered. For each of the measurements with a SO₂ SCD above a threshold of 25 Dobson Units (DU), a sub-LUT is selected (splined) from the (large) SO₂ optical depth spectra LUT. Starting from an a-priori pair of SO₂ VCD (vertical column density) and height, an SO₂ optical depth spectra is calculated and subtracted from the total measured optical depth. SO₂ OD height and VCD derivatives are also determined from the sub-LUT (by finite differences) and used in the forward model matrix. Then the results of the fit (updates on SO₂ height and VCD) are used to calculate new SO₂ spectra for the next calculation and few iterations are performed until convergence is reached ($\alpha < 0.25$ km, $\beta < 5\%$ SO₂ VCD; see the illustration of the algorithm concept below).



At the final iteration, the retrieval points to the output SO₂ VCD and height. From the computational point of view, the SO₂ LH retrieval takes less than 0.1 s/spectrum which is fast enough knowing that only a small part of the pixels will need to be processed.

Application of the algorithm to synthetic spectra (closed-loop retrievals) demonstrated the capability of the scheme to retrieve SO₂ LH with theoretical precision and accuracy of a few hundred meters for input SO₂ VCD typically larger than 25 DU, as show in the figure below.

The application of our algorithm on real spectra from TROPOMI shows that the accuracy requirement of 1-2 km is fulfilled in most cases, except in the presence of high aerosol loadings (notably volcanic ash), conditions for which the algorithm dramatically underestimate the SO₂ height.

We find a solution to fix this potential problem (use of the cloud top as a proxy of the SO₂ height). If an explicit aerosols treatment cannot be found, the pixels affected are identified and the reduced quality of the data is reported through a flag, comprehensively documented. For these flagged pixels, there will be non-compliance of the accuracy requirement of 1-2 km on SO₂ LH. Note that for such scenes, a good estimate of SO₂ LH could still be obtained for the surrounding pixels of a dense ash cloud, where lower Aerosol Optical Depth (AOD) will take place (so called umbrella cloud effect).

The description of the quality flag of our SO₂ LH product is the following:

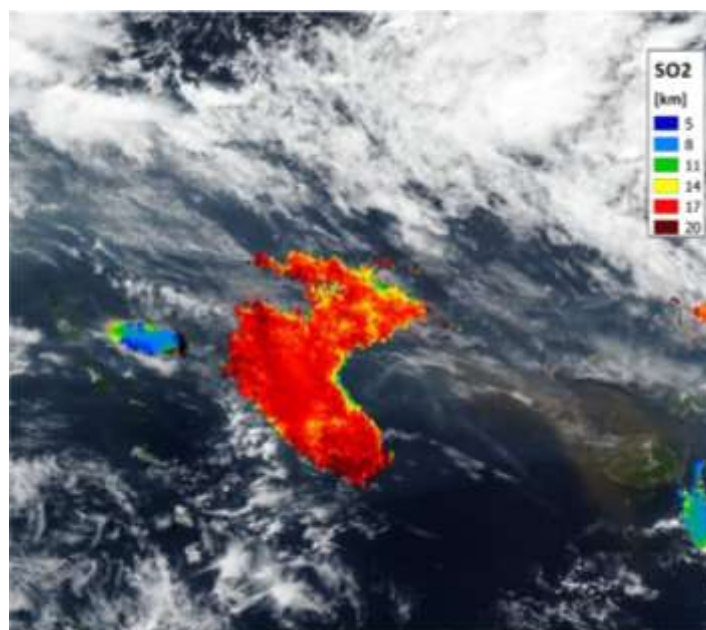
Quality flag associated to SO₂ LH retrieval (activation for SO₂ SCD > 25DU).

VCD is the SO₂ vertical column established assuming SO₂ profile with a centre of mass altitude of 15 km.

AAI is the Absorbing Aerosol Index.

- flag = 0: SO₂ LH module not activated.
- flag = 1: SO₂ LH module activated but no convergence (number of iterations: max allowed).
- flag = 2: SO₂ LH module activated, low level of confidence due to absorbing aerosols (AAI > 4 or AAI missing).
- flag = 3: SO₂ LH module activated, medium level of confidence due to low signal (SO₂ improved for VCD ≥ 10 DU and VCD < 25 DU).
- flag = 4: SO₂ LH module activated, high level of confidence, convergence with good data quality.
- flag = 5: SO₂ LH module activated, medium level of confidence due to absorbing aerosols (AAI>4) with the use of nearest cloud altitude.

The operational implementation of SO₂ LH products from TROPOMI is running since April 2020 (use of spectral radiances from ESA hub). The current time delivery (~ 6 hours) for the TROPOMI data (spectral radiances), is not optimal. This could decrease to few hours in the near future. The official delivery of the SO₂ LH products from TROPOMI should take place in 2021, which will definitely be of interest for the activity developed by the OPAS project (service).



We have reprocessed data archive from December 2018 of SO₂ LH from TROPOMI. This represents a consequent amount of spectral radiance data. The SO₂ LH data is produced only if there is a detection of SO₂ SCD > 25 DU. The numbers about our SO₂ LH archive are the following:

- 27.5 Tb of spectral radiance data analysed,
- currently 1830 files (granule of SO₂ LH products) has been produced,
- the size of a data file granule is 8 Mb,
- the current total size of SO₂ LH data is 14.5 Gb.

2.4 Results

The overview of the results obtained in the OPAS project is:

- 1) the algorithmic development of TROPOMI SO₂ LH,
- 2) the operational implementation of SO₂ LH from TROPOMI and IASI (A&B),
- 3) the creation of tailored alert products of SO₂ LH from TROPOMI and IASI (A&B),
- 4) the implementation of SO₂ LH early warnings inside SACS EWS,
- 5) the definition of OPAS notification service (creation of information model, design of the service, service description in SWIM terms),
- 6) the first results of validation of TROPOMI SO₂ LH retrievals.

The algorithmic development **1)** of TROPOMI SO₂ LH and its operational implementation **2)** is presented in previous section 2.3. Note that **the operational SO₂ LH from IASI-A & -B has been implemented in the EUNADICS project**, contributing to the OPAS project.

The table bellow presents the 14 operational alert products developed in this project.

Sat. platform / Instrument	Observation	Type of detection	Source alert
MetOp-A & -B / IASI	SO ₂ / SO ₂ height / Ash index	Selective	Volcano
AQUA / AIRS	SO ₂ / Ash index	Selective	Volcano
MetOp-A & B / GOME-2	SO ₂	Selective	Volcano
AURA / OMI	SO ₂	Selective	Volcano
Suomi-NPP / OMPs	SO ₂	Selective	Volcano
Sentinel 5p / TROPOMI	SO ₂ / SO ₂ height	Selective	Volcano
Sentinel 3-A & -B / SLSTR	Aerosol index / Aerosol height	Selective	Volcano & Dust
MSG-10 / SEVIRI (geostationary)	Ash / Ash height (over EU only)	Selective	Volcano
MetOp-A & -B / IASI	Aerosol optical depth	Selective	Dust
Terra & Aqua / MODIS Suomi-NPP / VIIRS Suomi-NPP / OMPs	Fire radiative power (NASA/FIRMS)	Selective	Smoke
Terra & Aqua / MODIS		Triggered	Dust & Smoke
	Aerosol index	Triggered	Smoke
	Aerosol optical depth	Triggered	Smoke

The SO₂ LH alert products **3)** from TROPOMI implemented in the OPAS project and the upgraded SO₂ LH alert products from IASI-A&B appear in red and blue in this table, respectively.

The **alert products developed in the OPAS project 3)** and the **implementation of SO₂ LH early warnings 4)** are built on an existing EWS, so called SACS (Brenot et al., 2014). This system is dedicated to aviation and ATM, and was upgraded in the frame of the EUNADICS project (Deliverables D28, D29, D30) with a total of 14 alert products of airborne hazards, based on the detection of volcanic SO₂ and 3 aerosols (volcanic ash, desert dust and smoke from wildfire).

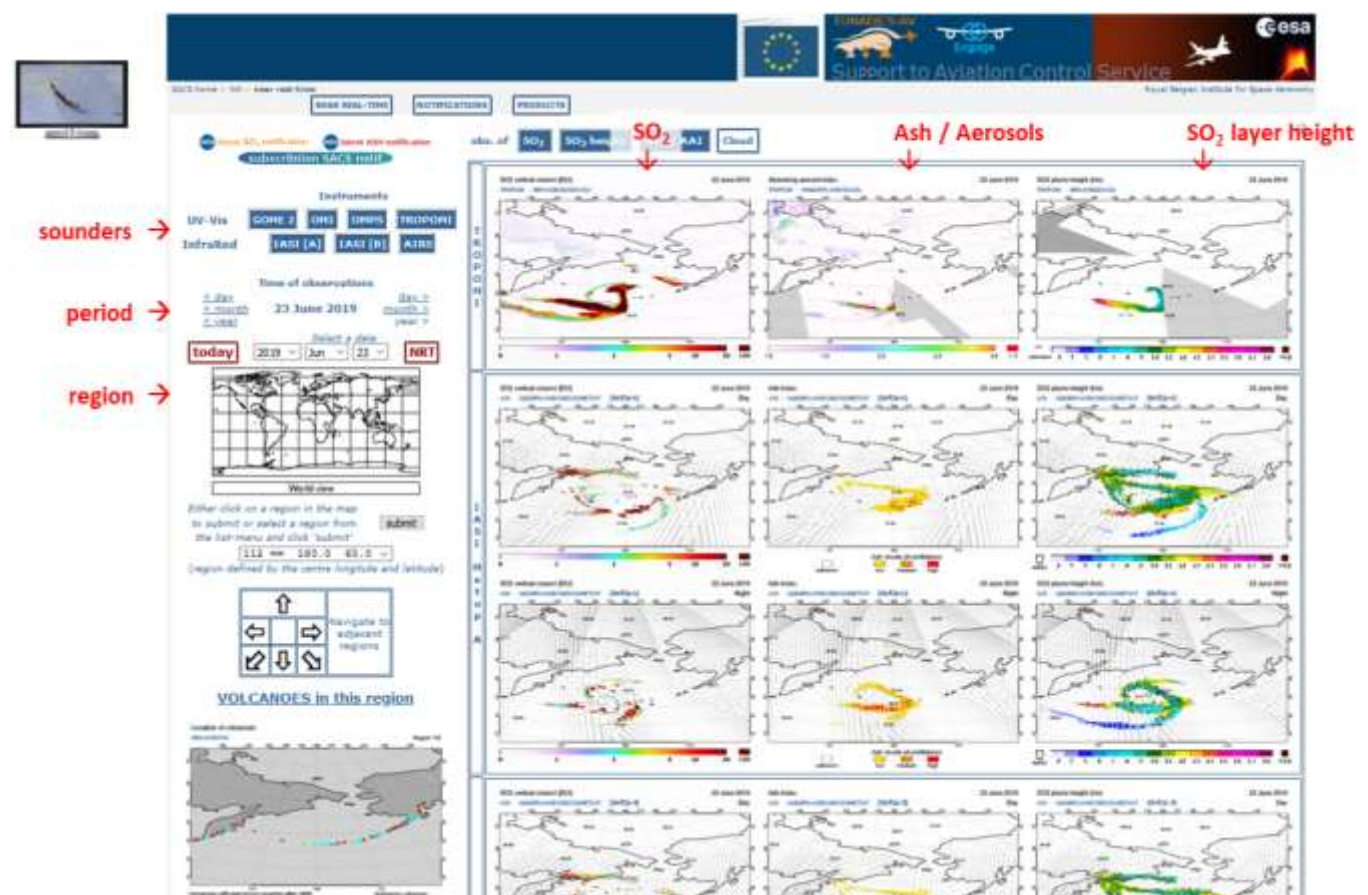
SACS provides alert products in near real-time (images, email notifications and homogenised alert data products, so called **NCAP – NetCDF Alert Products**). The two alert products from SACS/EUNADICS directly linked to the OPAS project are the SO₂ LH from IASI-A and IASI-B sensors.

The definition of the three types of alert products delivered by SACS is:



To illustrate the achievement of the OPAS project, this report presents an example of each kind of SACS/OPAS SO₂ LH alert products.

Here is a snapshot of SACS website (<http://sacs.aeronomie.be>) showing an example of images (archive) for the Raikoke eruption on 22 June 2019.



The text in red is here for giving you a quick overview of the functionality of SACS website (sounders, period, region, type of observations – SO₂, ash or SO₂ LH).

The SO₂ LH products is only shown for IASI-A, IASI-B and TROPOMI. There is 5 UV instruments (composite GOME-2A&-B, OMI, OMPS and TROPOMI) and 3 IR instruments shown on SACS.

In case a TROPOMI SO₂ slant column is over 25 DU, our algorithm is activated and SO₂ LH observations are retrieved. If the quality flag of at least one of the TROPOMI pixel reaches the value 5 (i.e. a high level of confidence; convergence with good data quality), an email notification is sent to subscribers.

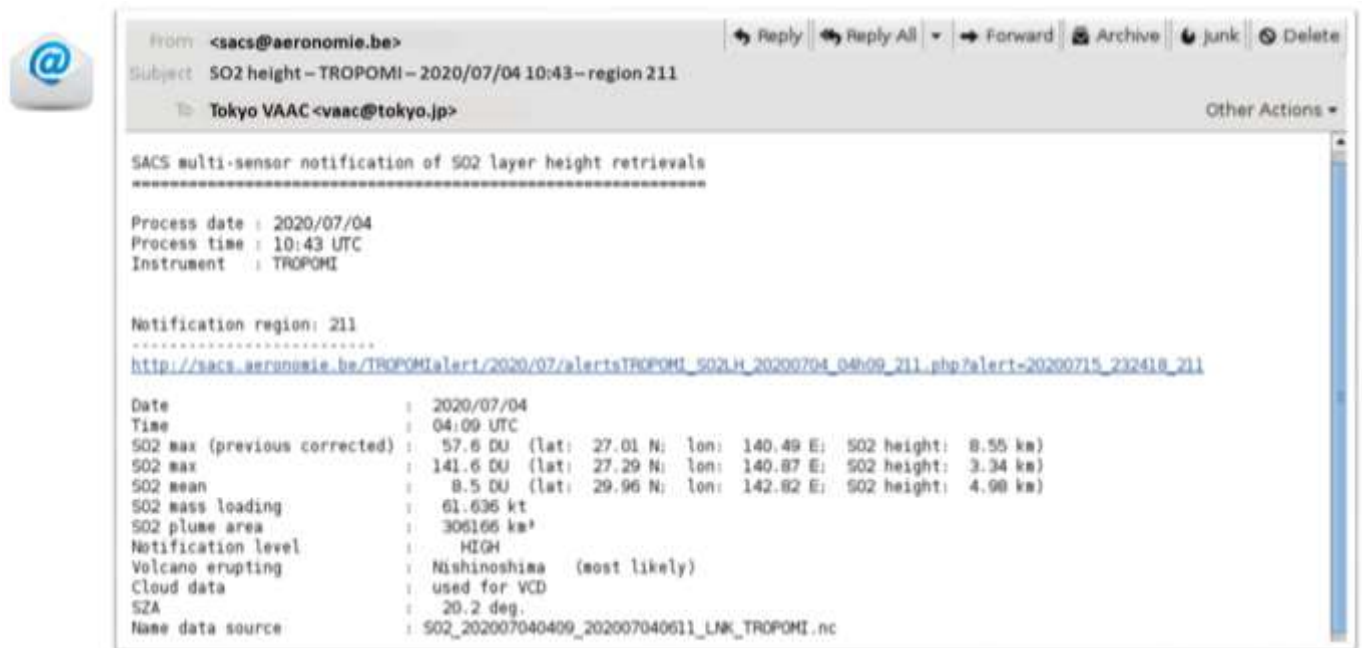
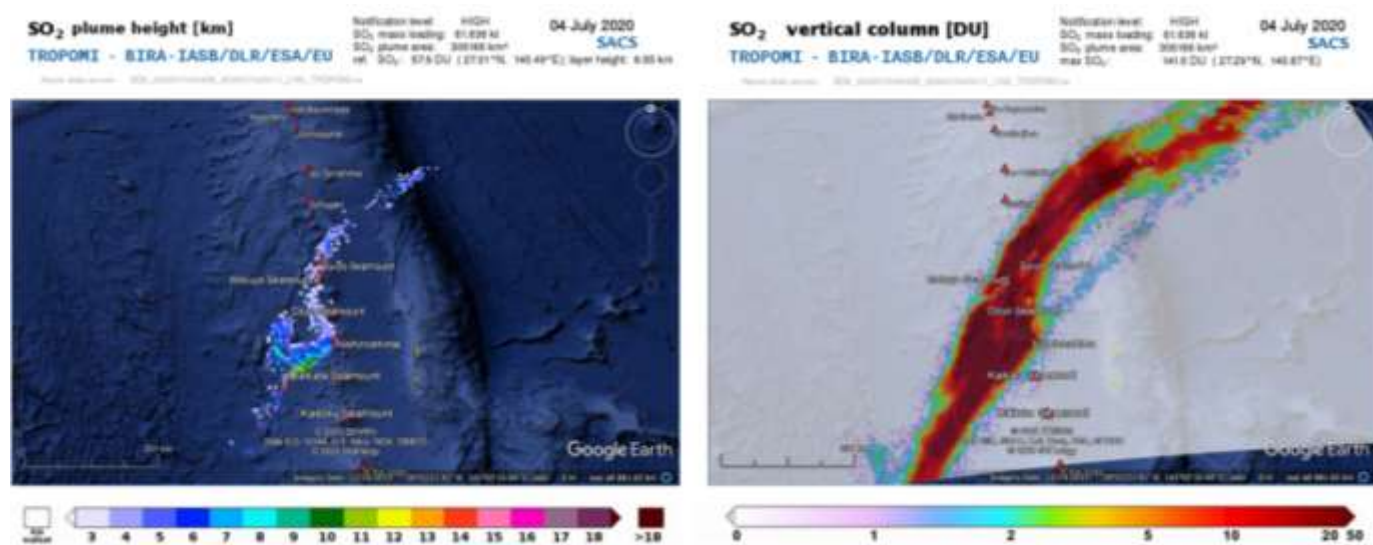


Illustration of the key information are received by subscribers in the SO₂ height email notification.

SO₂ heights and improved SO₂ vertical columns are simultaneously retrieved using our algorithm. We can eventually obtained a new SO₂ maximum (especially if the SO₂ height is smaller than 15 km, which is the assumed height considered in the SO₂ notification). An improved SO₂ mass loading is estimated using the new SO₂ vertical columns (quality flags 3, 4 and 5).

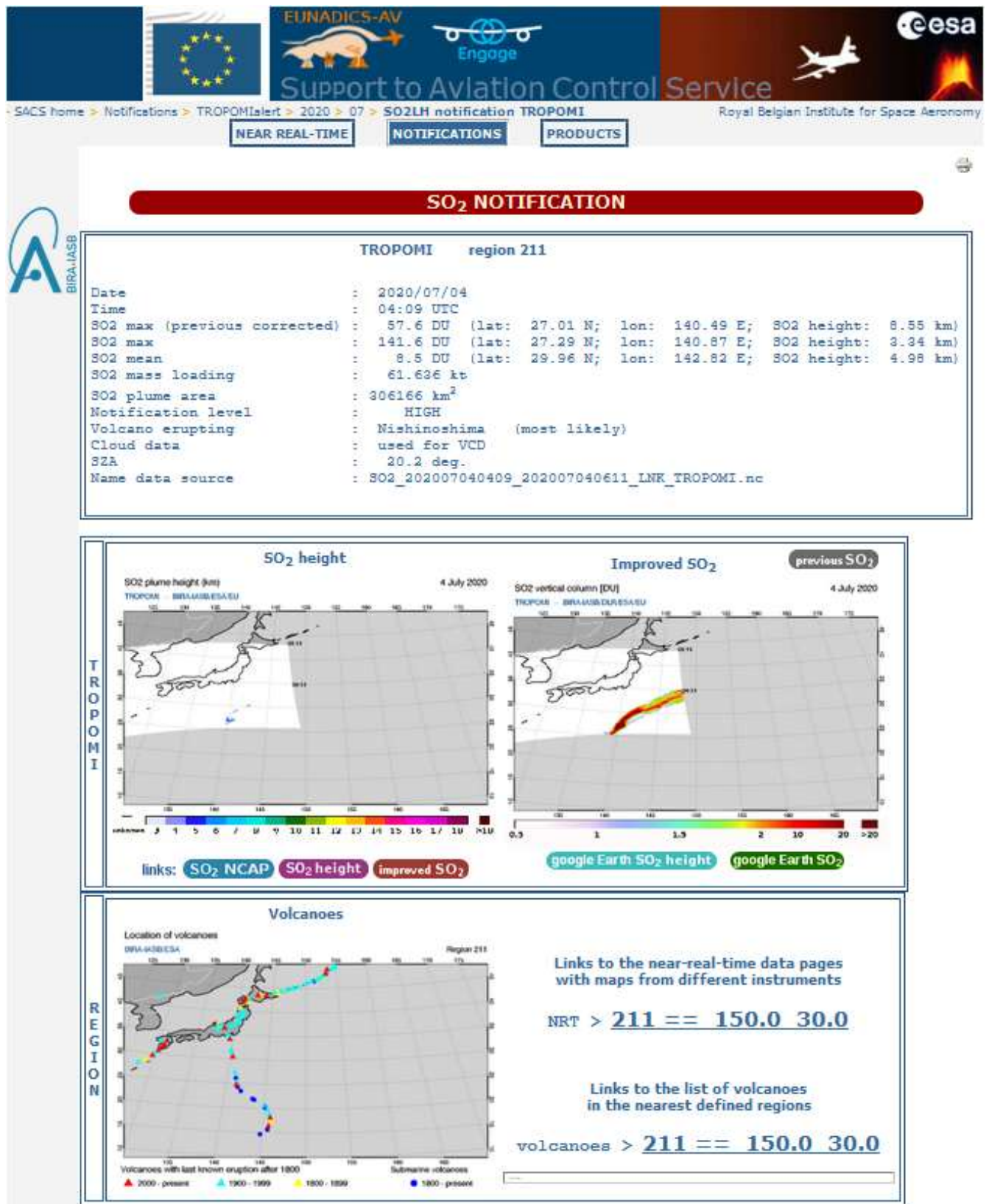
The notification level is based on the new SO₂ mass loading (if this mass is higher than 5 kt, the level is HIGH, otherwise it is LOW). The name of the erupting volcano is provided.



Tailored images (Google Earth) of the SO₂ LH and the improved SO₂ are provided in the notification.

The **SO2 height notification** provides a link to a webpage created by SACS EWS (snapshot bellow):

http://sacs.aeronomie.be/TROPOMIalert/2020/07/alertsTROPOMI_SO2LH_20200704_04h09_211.php



Information and images are shown with links to Google Earth images.

The third OPAS SO₂ LH alert product is the creation of a NetCDF data file. This file is an upgraded version of the existing SO₂ alert product developed in EUNADICS–AV project. This existing data file (called **NCAP – NetCDF Alert Product**), is already created in NRT by SACS EWS in case of an exceptional SO₂ detection. Simultaneously with the email notification and following the same criteria, SACS EWS proceeds the upgrade of the TROPOMI SO₂ NCAP file.

The following illustration shows you what the NCAP data looks like using the visualisation tool called *HDFview*. This gives you an overview of the field and variable accessible in the upgraded SO₂ NCAP file. The right yellow panel gives you an overview of all the information available.

The screenshot shows the HDFView 2.10.1 interface. The left pane displays a tree structure of the data file, with the 'SO2' group expanded. The right pane shows three data tables: 'SO2_height at /S...', 'SO2_VCD_improved...', and 'SO2_mass_improved...'. The bottom pane shows the metadata for the 'SO2_height' variable.

NetCDF Alert Product (NCAP)

- * Data
- * Tailored products
 - alert pixels SO₂
 - SO₂ column, **SO₂ height**
 - **SO₂ contamination of the flight level**
 - **level of severity** (LOW, HIGH)
 - extended plume of hazard
 - **mass loading (improved)**, area
 - grided data
 - contours (surface, mean, max, mass)
 - info. Source (link property volcano of GVP)
 - SACS region concerned (max values)
 - traceability of event (START → END)
 - links image alert and SACS notification
 - links images other instruments

SO2_height (50950440, 2)
 32-bit floating-point, 160650
 Number of attributes = 6
 DIMENSION_LIST = 1-50948277
 _FillValue = -999.0
 coordinates = latitude longitude
 long_name = SO2 layer height considered for estimating the interpolated SO2 VCD; product of OPAS Engage-KTN project (<https://engagektn.com/cf-summaries>)
 standard_name = SO2 LH (layer height)
 units = km

We can notice that the NCAP data provides detailed information, with notably the SO₂ contamination of the flight level (FL).



Illustration of the SO₂ contamination for FL150, as retrieved by TROPOMI on 4 July 2020 at 04:00 UTC.

For the example of the SO₂ height notification related to the eruption of Nishinoshima volcano, on 4 July 2020, the NCAP tailored products indicates that the most contaminated FL are FL090 to FL170 (between a range of altitude of about 2750 to 5200 m). This illustration of the SO₂ contamination could be of great interest for the VAACs if they take the responsibility of producing advisory report related to volcanic SO₂ plume.

In relation with the SWIM registry, one of the last results of the OPAS project is the definition of the OPAS notification service (creation of information model, design of the service, service description in SWIM terms). These achievements was required to complete the SWIM Yellow Profile service specifications by implementing the **OPAS SO2LH Dataset Service Definition**.

The first transfer of information to SWIM Technical Infrastructure proposed by OPAS is the volcanic SO₂ LH alert product. This kind of transfer of information related to atmospheric volcanic emission, is considered, in the AIRM semantic, as a '*Meteorological Information Exchange*'.

The specification of the requirements and the Technical Infrastructure (TI) of a SWIM Yellow Profile is now completed (*EUROCONTROL-SPEC 170, 5 July 2020*). The steps in transitioning to SWIM Yellow Profile are the following:

1. Ensure information exchanges are properly defined and understandable for the stakeholders.
2. Create information model ("information definition" in SWIM terms).
3. Design the service ensuring it uses options from the SWIM TI Yellow Profile.
4. Implement and deploy the service (creation of a "service description").
5. Register the service in the SWIM Registry.

The OPAS project has achieved steps 1–4.

A definition of OPAS notification service has been written in JSON and includes the following section:

- description information (service description identification, abbreviations)
- name ('*OpasSo2lhDatasetNotification*')
- version ('*0.0.1*')

- service abstract
- service categorisation (service type, business activity type, information category, intended consumer, application message exchange pattern)
- service provision (provider, provider type, point of contact)
- service general description (operational need, functionality, quality of service, access and use condition, concepts, validation)
- service information description (information definition)
- service technical description (technical constraint, security mechanism, service monitoring)
- service interface (name, description, interface message exchange pattern, TI primitive message exchange pattern, end point, service interface binding, network interface binding, interface binding description, operation, behaviour)
- service description references (service document)

```

1 {
2   "informationService": {
3     "descriptionInformation": {
4       "serviceDescriptionIdentification": "...",
5       "abbreviations": "...",
117     },
118     "name": "OpasSo2LhDatasetNotification",
119     "version": "0.0.1",
120     "serviceAbstract": "The OPAS SO2LH notification service allows subscribed users to receive
Information about the height of volcanic plume (emission of sulphur dioxide - SO2 - from an erupting
volcano) and the associated contamination of FL. This user receives email notifications that provide
access to datasets of SO2 layer height (SO2LH) from 3 satellite instruments (via https connection).
These datasets are characterised based on metadata.",
121     "serviceCategorisation": "...",
136     "serviceProvision": "...",
149     "serviceGeneralDescription": {
150       "operationalNeed": "...",
165       "functionality": "...",
176       "qualityOfService": [
177         {
181           "name": "Capacity",
182           "description": "to be confirmed"
183         },
184       ],
187     },
188     "accessAndUseCondition": "...",
219     "concepts": "...",
233     "validation": "...",
239   },
240   "serviceInformationDescription": "...",
250   "serviceTechnicalDescription": "...",
270   "serviceInterface": "...",
312   "serviceDescriptionReferences": "...",
329 }
330 }

```

Overview of the edition of the definition of OPAS notification service in JSON format.

In addition, OPAS information definition (xlsx file) has been written to provide Concept Definition and conformance to AIRM.

The service description of OPAS Yellow Profile captures the fact that

- subscription is by email. Notifications of SO₂ alerts with SO₂ LH are sent to subscribers.
- an Internet Protocol (IP) address has to be provided, giving access right to BIRA *https* server.

The registry of OPAS as a SWIM service is not yet completed (i.e. step 5; see next section 3.2), but a first draft of what it will look like has been created (see next illustration).

OpasSo2lhDatasetNotification 0.0.1



Abstract

The OPAS SO2LH notification service allows subscribed users to receive information about the height of volcanic plume (emission of sulphur dioxide - SO₂ - from an erupting volcano) and the associated contamination of FL. This user receives email notifications that provide access to datasets of SO₂ layer height (SO₂LH) from 3 satellite instruments (via https connection). These datasets are characterised based on metadata.

[Subscribe](#)

Service Type

DEFINITION

Lifecycle Stage

No Information Provided

Business Activity Type

INFORMATION_MANAGEMENT

Intended Consumer

AERONAUTICAL_INFORMATION_SERVICE_PROVIDER
REGULATED_METEOROLOGICAL_SERVICE_PROVIDER
[Show Less](#)

Information Exchange Category

METEOROLOGICAL_INFORMATION_EXCHANGE

Application Message Exchange Pattern

PUBLISH_SUBSCRIBE_WITH_PULL_MECHANISM

Responsible ICAD Location Indicator

No Information Provided

EMI ICAD Location Indicator

No Information Provided

State ICAD Nationality Letters

No Information Provided

Is Operation Data

No Information Provided

Provider

BIRA (Royal Belgian Institute for Space Aeronomy)

Provider Type

PROVIDER_OF_DATA_SERVICES

Support

No Information Provided

Point of Contact

Hugues Brenot
OPAS project coordinator

Email

Hugues.Brenot@oma.be

Telephone

No Information Provided

General Information Technical Interfaces References

OPASprod

The interface allows getting access to OPAS alert datasets. The service is based on the single provided interface to access to SO₂LH products from the OPAS database. The service provides JSON datasets by notification email and the access to OPAS database follows the HyperText Transfer Protocol Secure (HTTPS) protocol.

PROVIDER_SIDE_INTERFACE

SWIM_TL_VP_1_0_WS_SOAP

No Network Binding Specified

SYNCHRONOUS_REQUEST_RESPONSE

Operations

Endpoints

Interface Binding Description Overview

Interface Binding Configurations

Behaviour

getSO2LH operation

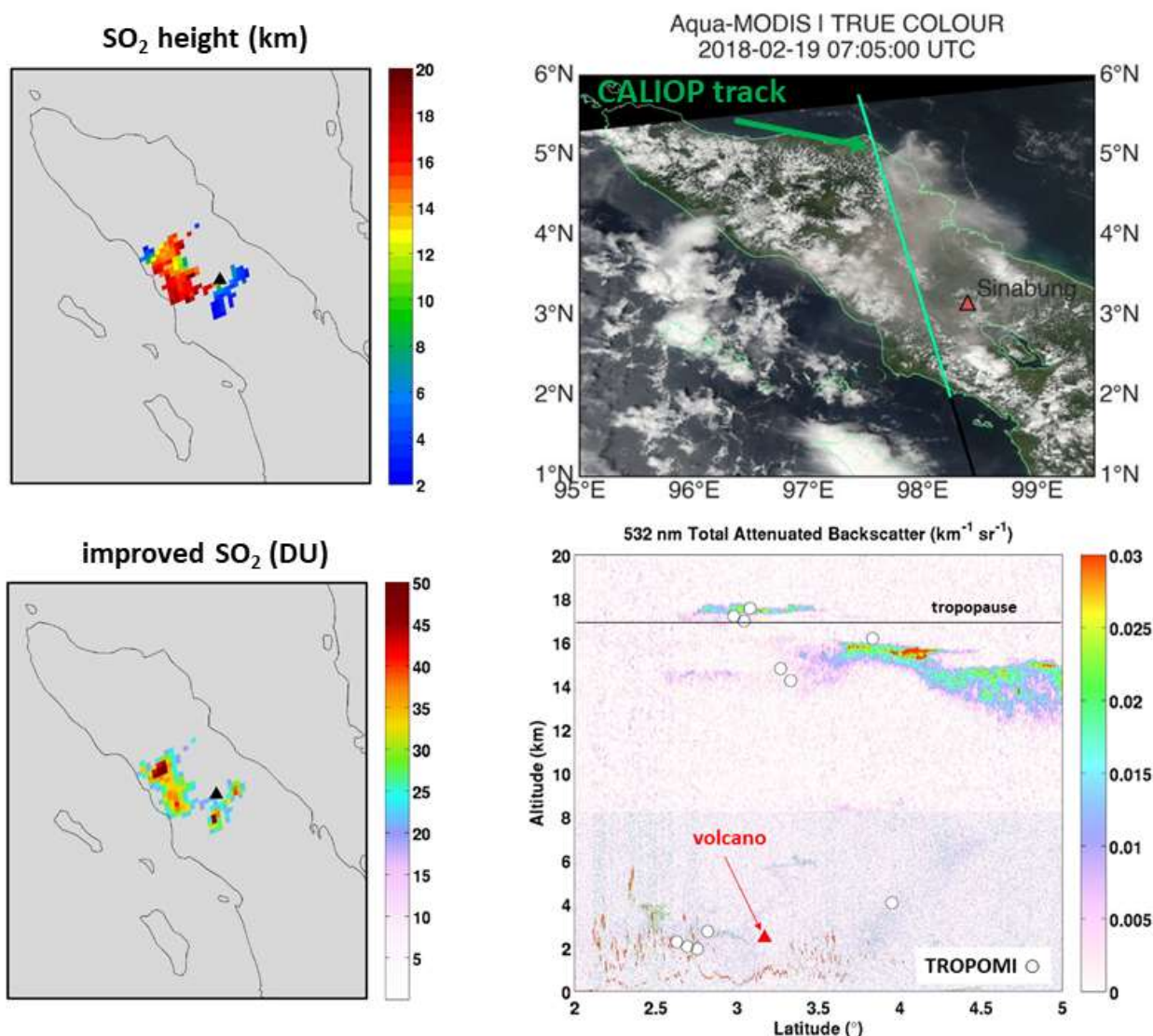
The getSO₂LH operation can provide the access to OPAS database and the download of OPAS alert datasets for a specific day (e.g. 20200330 instruction for the 30th of March 2020). The operation returns a confirmation of the validity of the provided SO₂LH datasets taking into account these business rules: Not accepting requests for date before the 9th of May 2018 (i.e. 20180509 instruction); Not accepting requests for day with no creation of SO₂LH alert datasets.

Revision: Same State Thu, 07/16/2020 - 09:34



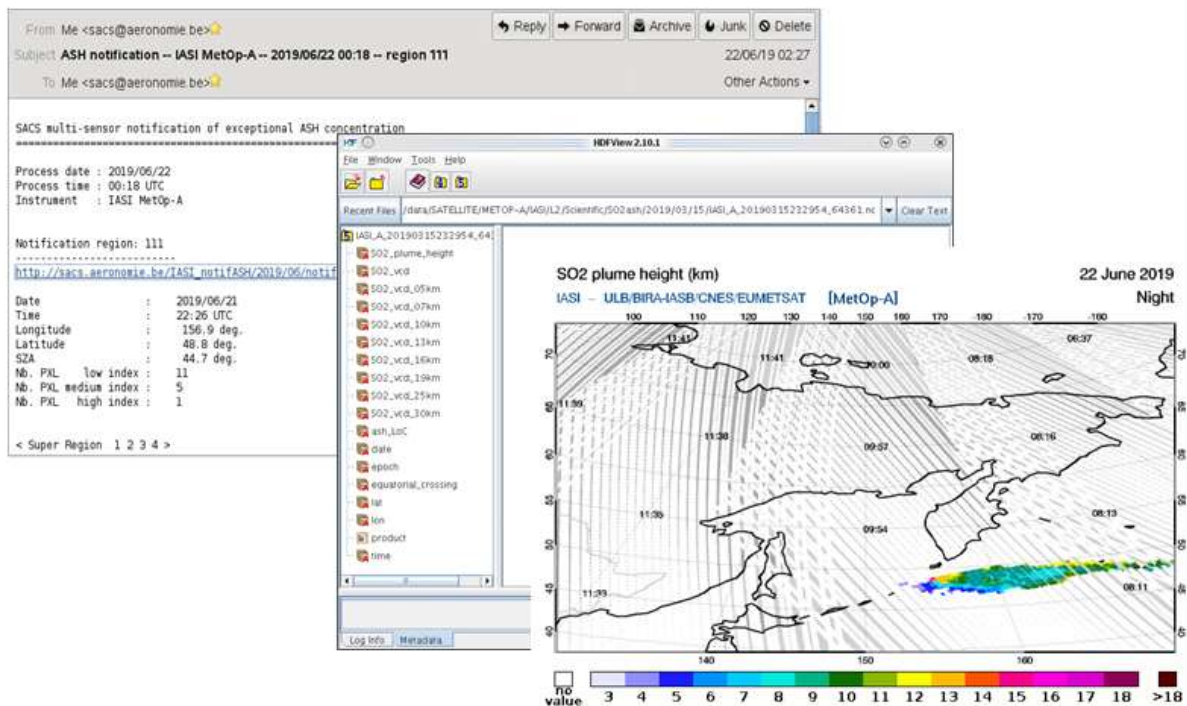
The service description is currently in "DRAFT" status. The organization editor is currently updating its content.

A last achievement of the OPAS project is the **first results of validation of TROPOMI SO₂ LH retrievals**. This goal was initially not planned in the OPAS proposal. After a fruitful IM meeting at SATAVIA, this is now considered as part of the OPAS activities. A validation process is essential for a such service.

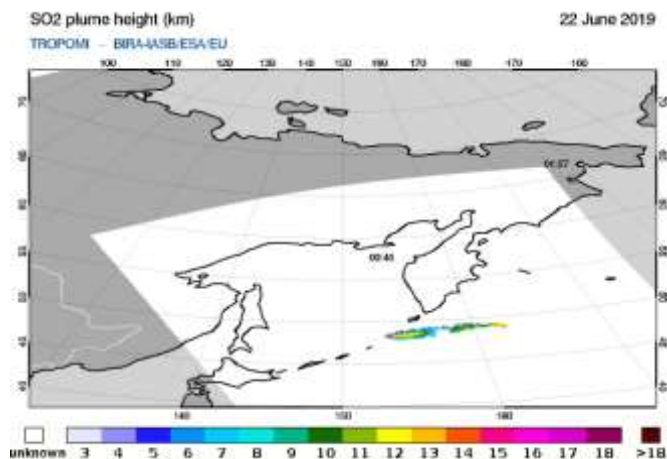


Mount Sinabung on the Indonesian island of Sumatra erupted violently on 19 February 2018 (see the true colour image from Aqua-MODIS), spewing violent blasts of gas and ash at least 12 to 16 km into the air (as confirmed by CALIOP total attenuated backscatter at 532 nm). The SO₂ height and improved SO₂ retrieved by OPAS algorithm shows a plume spreading westward of Sinabung for a height range of 14–18 km. It also shows an SO₂ cloud spreading to a lower altitude (2–3 km) on the south-east side of the mount. These 2 ranges of altitudes in two directions are confirmed by CALIOP track and the plume height retrieved from the IR channel of Himawari-8 (Eruption column collapse; c.f. CIMSS images).

The second case study presented here is the explosive eruption of Raikoke volcano (Kurile Islands) on 21–23 June 2019. A powerful explosive eruption, possibly sub-plinian, started from the remote island volcano at 18:00 UTC on 21 June, emitting copious amounts of SO₂ (~ 1.4 Tg) and ash in the upper-troposphere lower stratosphere. SACS EWS sent ASH and SO₂ notification from IASI instruments, as illustrated below, and provided relevant information to users. Note that TROPOMI was not yet implemented in SACS system.



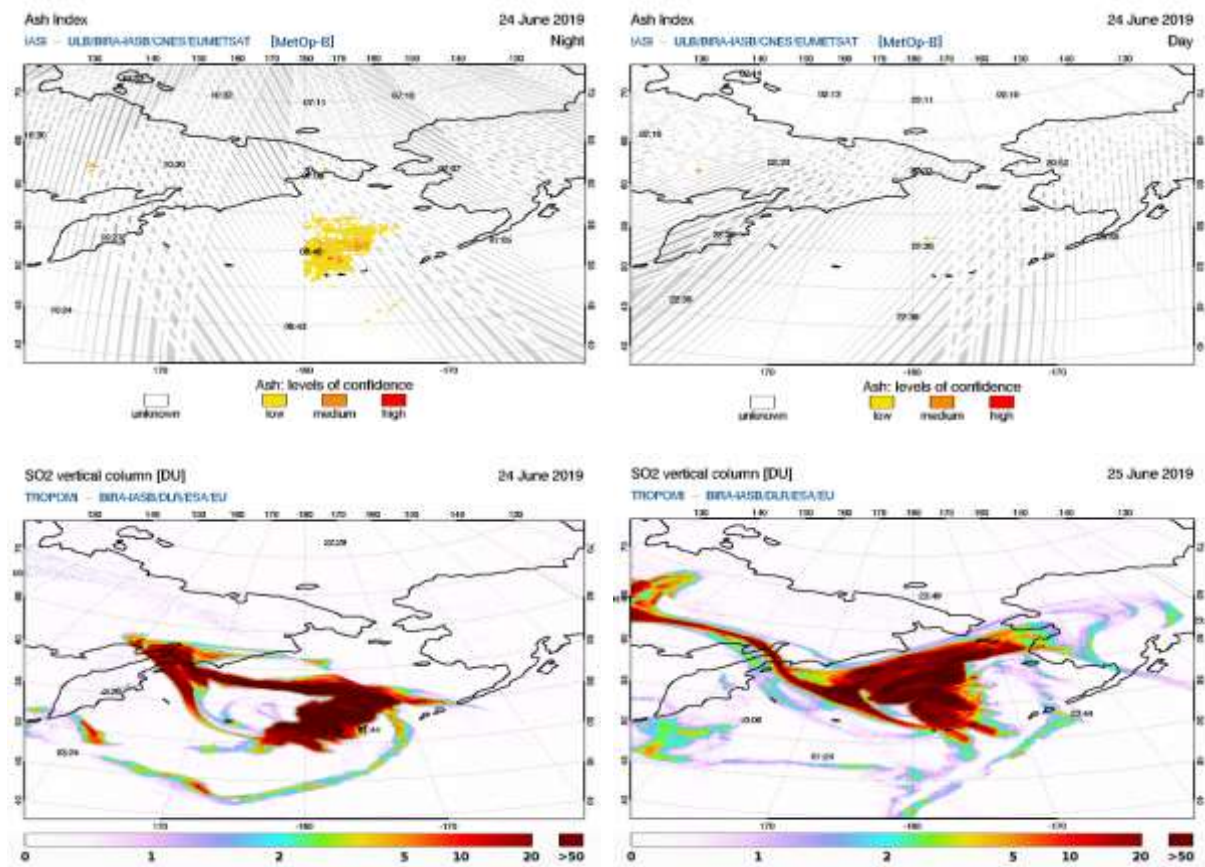
The SO₂ plume height information provided by IASI started to be provided at 00:18 UTC, about 4 hours after the start of the eruption. The SO₂ LH range was from 5 to 12 km. The first over path of TROPOMI provides the same range of altitude. This is also in agreement with the Volcanic Cloud height observed by Aqua-MODIS and provide by CIMSS / NOAA service.



This eruption had a consequent impact on the air traffic as illustrated by the next flight-radar image, with a no-flight zone over the Bering sea, on 22 June 2019.

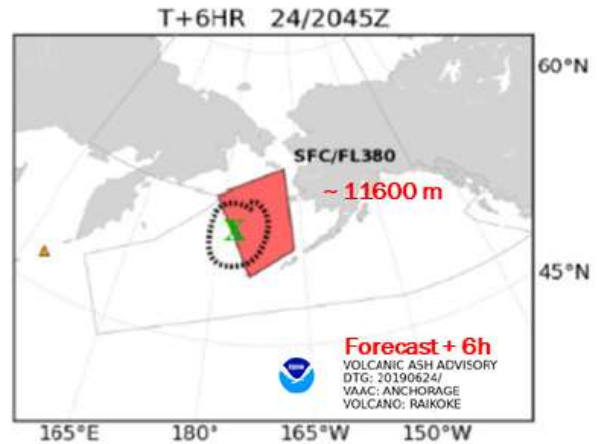


Raikoke 2019 was an SO₂-rich eruption. Its ash cloud (due to aggregation or dispersion) disappeared quite quickly from the satellite observation systems. No ash detection was observed by SACS after the 25th of June. The advisory sent by Anchorage and Tokyo VAACs only concerned the ash cloud, and no information about possible SO₂ contamination was provided.

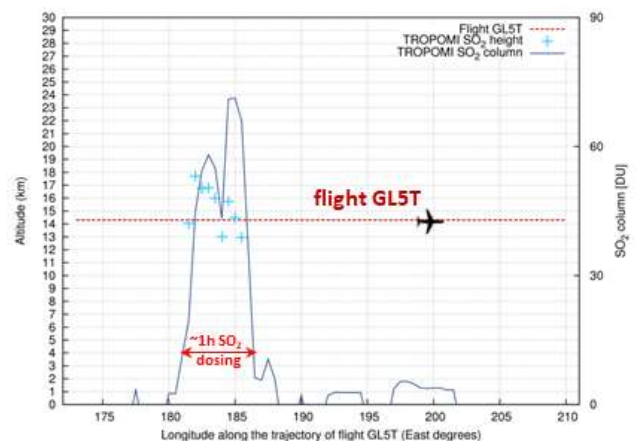
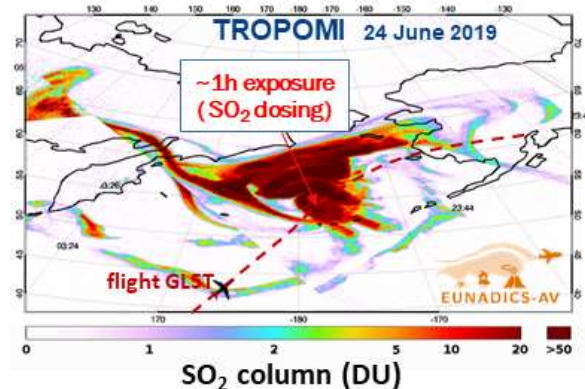
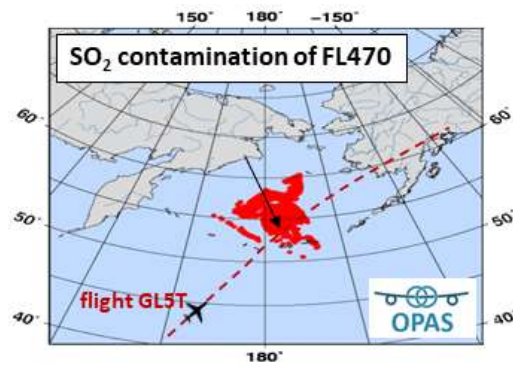
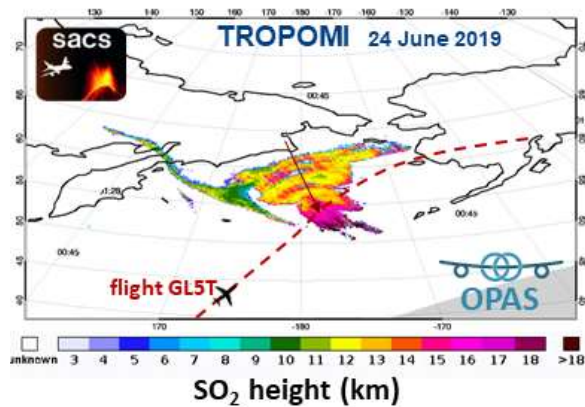


These ash and SO₂ images from IASI-B and TROPOMI, respectively, illustrates the character of this eruption, e.g the copious amount of SO₂ emitted with respect to the ash.

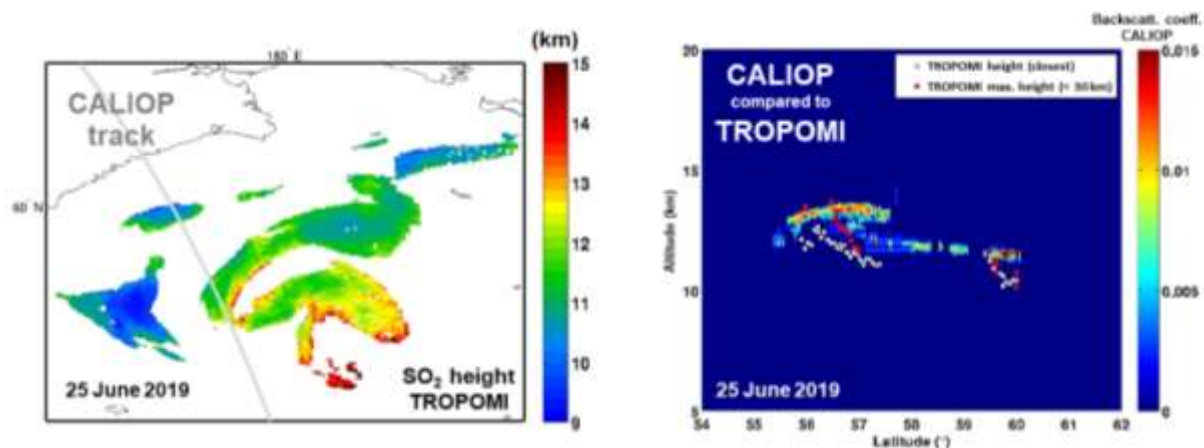
Flight GL5T 18:22 UTC (56N 176.5 W)
flight level: FL 470 ~ 14300 m



The flight GL5T in direction of Anchorage airport was flying at FL470 (~ 14300 m). Following, the VAA from Anchorage VAAC, this flight was supposed to fly over the ash plume from Raikoke. However, the route of flight GL5T crossed Raikoke SO₂ volcanic cloud.



The TROPOMI SO₂ image shows about 1 hour of exposure to SO₂ with column density over 50 DU (see the time-series). The scope of this report is not to quantify to risk of sulphidation that can occur with respect to SO₂ contamination. However, we can see that the tailored SO₂ products of FL contamination provided by OPAS represents useful information for building Volcanic SO₂ Advisory.



Few hour after the flight GL5T, a track from CALIOP crossed Raikoke plume on 25 June 2019. This figure shows a comparison of the height of the volcanic plume, as seen by CALIOP with the Backscattered coefficient (at 01:15 UTC), and TROPOMI SO₂ height (at 01:30 UTC). The grey circles show the SO₂ height of the closest TROPOMI pixels to this CALIOP track. The red circles show the maximum height measured by TROPOMI in the 30 km-surroundings pixels. A good agreement is fine.

These results of inter-comparison of TROPOMI SO₂ LH products with other observations, is the first step of the validation process (see section 3.2).

3. Conclusions, next steps and lessons learned

3.1 Conclusions

The OPAS project was a chance to create a bridge between SACS/EUNADICS EWS and SESAR SWIM. The transfer of EUNADICS alert products to SWIM could not be reached in the timeframe of this H2020 project but the OPAS project was the opportunity for achieving:

- the algorithm development and the operational run of TROPOMI SO₂ LH product,
- the implementation of TROPOMI SO₂ LH alert product and the upgrade of IASI-A & -B SO₂ LH alert products, with information about the FL SO₂ contamination,
- the writing of the definition of the OPAS notification service, with the creation of an information model, the design of the service and the service description in SWIM terms.

Such an achievement is promising for the next step, i.e. the creation of a first SWIM Yellow Profile service dedicated to the notification of early warnings of natural airborne hazard.

The OPAS Engage-KTN project was also an opportunity to consider some recent communications from the industry (Rolls-Royce) and to convincingly highlight the consequent risk of the SO₂ contamination in term of maintenance costs (contract for the stakeholders and turbine maintenance for the aircraft manufacturers), on the top of the safety and the problem of health for the passengers during a long-line flight exposure.

The transfer of homogenised near real-time SO₂ height observation via a SESAR SWIM Yellow Profile service, providing unambiguous (i.e. with selective SO₂ detection) and easy to interpret information, may benefit to all the operational ATM users for supporting aviation safety. The development of NRT information about the FL SO₂ contamination can be a real interest for the stakeholders, especially the airlines and aircraft manufacturers. The next step presented in the following section will help increasing the maturity towards of such activity.

3.2 Next steps

The next steps of the OPAS project are the following:

- The SWIM registry of OPAS as a Yellow Profile service.
- The achievement of consolidated results of validation of TROPOMI SO₂ LH by using several external sensors (CALIOP, IR hyperspectral sensors, broadband imagers, GNSS radio-occultation, ground-based data from FLAME network at Etna).

For this task, BIRA started a collaboration with international partners (CIMSS/NOAA, Vereinigung Cockpit – the German pilot association, the University of Padova, INGV and ULB). First results of validation (using CALIOP and CIMSS/NOAA products) has already been obtained. But additional comparison with data from IASI (Clarisse et al. 2014), CrIS (Hyman and Pavalonis, 2020), GNSS radio-occultation (Biondi et al., 2017), and SEVIRI and ground-based data for the Christmas 2018 Etna eruption (Corradini et al., 2020) will be investigated. Klaus Sievers, member of the German Pilot Association (Vereinigung Cockpit), is also involved in the validation process by showing the impact on air traffic of recent volcanic eruptions and highlighting the interest of OPAS new development (SO₂ LH) to mitigate the risk for ATM.

The output planned relating to the OPAS project is:

- To achieve these next steps for SIDs 2020, with a presentation and hopefully a proceedings.
- The publication of the algorithmic development of the TROPOMI SO₂ LH retrievals with consolidated results of validation.
- A video presentation at the IGAARS 2020, virtual symposium, 26 Sept.–2 Oct. 2020.

Note that the activity of SACS/OPAS EWS will keep developing as a part of the ALARM project, recently awarded by H2020 – SESAR. The use of geostationary satellites combined with polar orbiting sensors is a promising future achievement, with extension of OPAS service to other natural airborne hazard (i.e. dust from sand storms and smoke from wild forest fires).

The OPAS/ALARM team should certainly involves the VAACs (in priority London and Toulouse) in its activity. SATAVIA and SYMOPT partners of the ALARM project will help developing outcomes from OPAS/SACS EWS activities for the ATM stakeholders.

3.3 Lessons learned

- As the OPAS Engage-KTN project involved only BIRA and EUROCONTROL, it was really simple and fruitful for coordinating the management and the progress.
- The time duration of the OPAS Engage-KTN project (1 year) was probably just enough to reach all the goals (i.e. one extra PM was needed to proceed the SWIM Registry and another PM for the additional validation task)
- The implementation of operational process always takes more time than expected, especially due to maintenance task / IT structure / computing environment required for such a service.
- Finding regular incoming (at least 1 PM per year) is primordial to maintain such a service.

4. References

4.1 Project outputs

BIRA has participated to 5 workshops / conferences / events relating the activity of the OPAS project:

- Presentation at the 5th Training School on Convective and Volcanic Clouds (CVC) – 2nd Etna Edition, at INGV centre, in Nicolosi, Italy.
→ on 4 October 2019, Hugues Brenot presented two lectures related to Volcanic Clouds
The first lecture was about “Early Warning System for Natural Airborne Hazard”.
He presented SACS/EUNADICS EWS products related to volcanic eruption and OPAS project.

Link presentation: http://sacs.aeronomie.be/OPAS/20191004_CVC_EWS_part1.pptx

- Presentation at the Engage TC3 2nd workshop, in Brussels, at SESAR-JU
→ on 5 November 2019, Hugues Brenot presented a talk about OPAS project

Link presentation: http://sacs.aeronomie.be/OPAS/Engage_TC3_20191105_OPAS.pptx

- Participation to the 9th SESAR Innovation Days (SIDs) 2019, in Athens, at the National Centre of Scientific Research (NCSR) "Demokritos"
→ from 2 to 5 December 2019, Ermione Dimitropoulou presented OPAS teaser and poster, on behalf of Hugues Brenot

Link abstract (2 pages): http://sacs.aeronomie.be/OPAS/2019_SIDs_OPAS_abstract.pdf

Link teaser: http://sacs.aeronomie.be/OPAS/2019_SIDs_OPAS_teaser.pptx

Link poster: http://sacs.aeronomie.be/OPAS/2019_SIDs_OPAS_poster.pdf

- Presentation of Hugues Brenot at the EGU General Assembly 2020, Online, 4–8 May 2020

Link web: <https://meetingorganizer.copernicus.org/EGU2020/EGU2020-15249.html>

Link abstract: <https://meetingorganizer.copernicus.org/EGU2020/EGU2020-15249.html?pdf>

Link poster: https://presentations.copernicus.org/EGU2020/EGU2020-15249_presentation.pdf

- Presentation of Hugues Brenot at the 9th DOAS Workshop, virtual meeting, 13-15 July 2020

Link abstract: http://sacs.aeronomie.be/OPAS/20200713_DOASws_abstract_Brenot_OPAS.pdf

Link pitch: http://sacs.aeronomie.be/OPAS/20200713_DOASws_pitch-poster-6_Brenot_OPAS.pdf

Link poster: http://sacs.aeronomie.be/OPAS/20200713_DOASws_poster-6_Brenot_OPAS.pdf

- BIRA will participate to another workshop/conference/event relating the OPAS project:

- Presentation of Jeroen Van Gent at the IGAARS 2020, virtual symposium, 26 Sept.–2 Oct. 2020

Link proceedings: http://sacs.aeronomie.be/OPAS/20200930_IGARSS_proceedings_vanGent_OPAS.pdf

Link video: http://sacs.aeronomie.be/OPAS/20200930_IGARSS_video_vanGent_OPAS.mp4

- Other outputs/presentations/publications:

- The logo of Engage KTN is on the homepage and header of all pages of SACS website.

Link website: <http://sacs.aeronomie.be>

4.2 Other

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Yang, K., Liu, X., Krotkov, N. A., Krueger, A. J., and Carn, S. A. (2009), Estimating the altitude of volcanic sulfur dioxide plumes from space borne hyper-spectral UV measurements, *Geophys. Res. Lett.*, 36, L10803, doi:10.1029/2009GL038025.