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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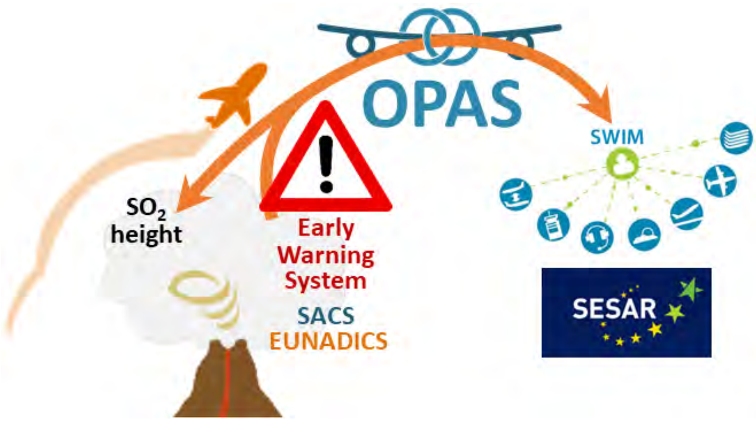
1. Abstract and executive summary

1.1 Abstract

Volcanic emission is a threat to ATM and the safety of flights. Early warnings are an essential source of information for the stakeholders. The OPAS project is the development of a SWIM Technical Infrastructure Yellow Profile service providing information (notification & data access) about volcanic SO_2 height. The OPAS service considers observations from three hyperspectral satellite sensors (TROPOMI, IASI-A and IASI-B), respectively operating in the ultraviolet and infrared ranges. These instruments represent the state of the art of satellite SO_2 measurements. The IASI sensor already provides well recognised estimations of SO_2 height, which is available through the SACS early warning system and contributes to the OPAS service. The outcome of the OPAS project is the new algorithmic development (iterative SO_2 optical depth fitting) of TROPOMI SO_2 height retrievals, the creation of alerts and the access to tailored information, i.e. SO_2 contamination of flight level and improved mass loading estimates.

1.2 Executive summary

Natural airborne hazard can affect the good proceedings of long-haul flights, being a possible threat to the health of the passengers, affecting Air Traffic Management (ATM) and causing potential damage to aircraft engines. For this reason, it is essential to give stakeholders access 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 warning and the delivery of tailored information to avoid the contamination of sulphur dioxide (SO_2) during long-haul flights.

The type of alert developed by the OPAS project is the plume height of SO_2 emitted by a volcanic eruption. The knowledge of the height of the volcanic plume is essential for the good proceedings of a flight. The SO_2 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 SO_2 exposure and the sulphur damage to engines has been diagnosed for several hundred flights. This highlights the critical interest for stakeholders to get information on the SO_2 plume height to avoid contamination.

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

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

These three hyperspectral instruments, operating respectively in the ultraviolet and infrared ranges, contribute significantly to the state of the art of SO_2 measurements from satellite.

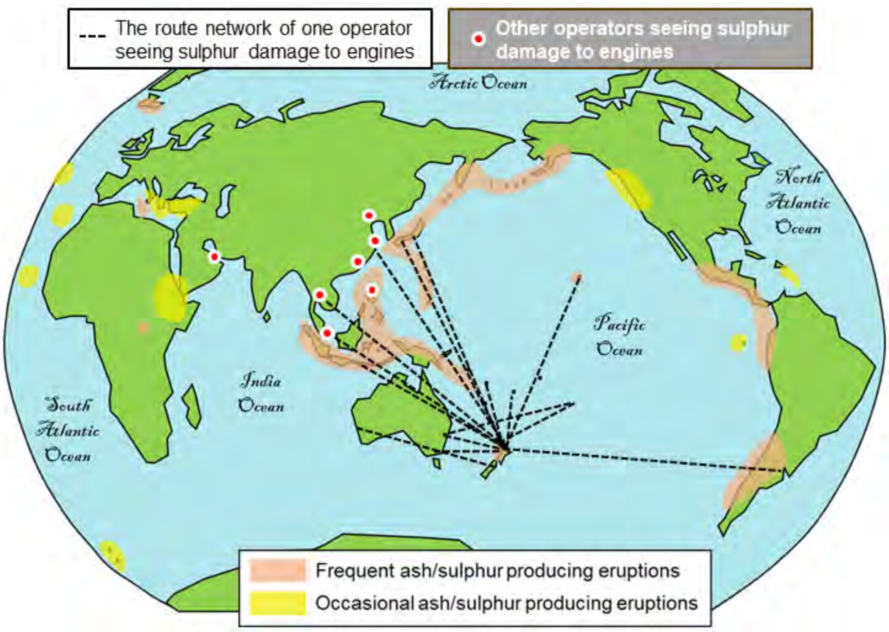
The outcome of the OPAS project is the new algorithmic development (iterative SO_2 optical depth fitting) of TROPOMI SO_2 layer height retrievals (SO_2 LH). This algorithm is operationally running at BIRA by using the spectral radiance provided by the ESA hub. In addition, the OPAS project developed a new type of warning, the SO_2 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 SO_2 LH and alerts, which are used by the SACS EWS. The outcome of the OPAS project is the improvements of the SO_2 LH alerts (TROPOMI and IASI) by providing tailored information, i.e. SO_2 contamination of flight level (FL) and improved SO_2 mass loading.

The OPAS Engage-KTN project has developed a SWIM Technical Infrastructure Yellow Profile service. The OPAS SO_2 LH notification SWIM service allows subscribers to receive warnings with information on the height of volcanic plume (emission of SO_2 from an erupting volcano) and the associated SO_2 contamination of FL. The subscriber receives an email notification that provides access to datasets of SO_2 LH from three satellite instruments (via https connection). These datasets are characterised based on metadata and provided in NetCDF format.

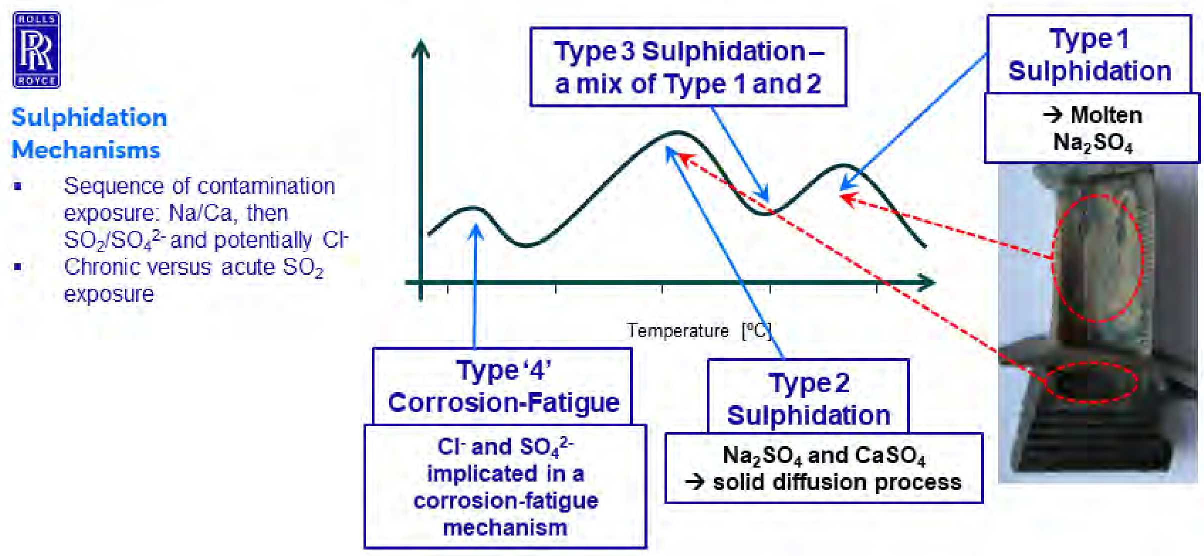
2. Overview of catalyst project

2.1 Operational/technical context

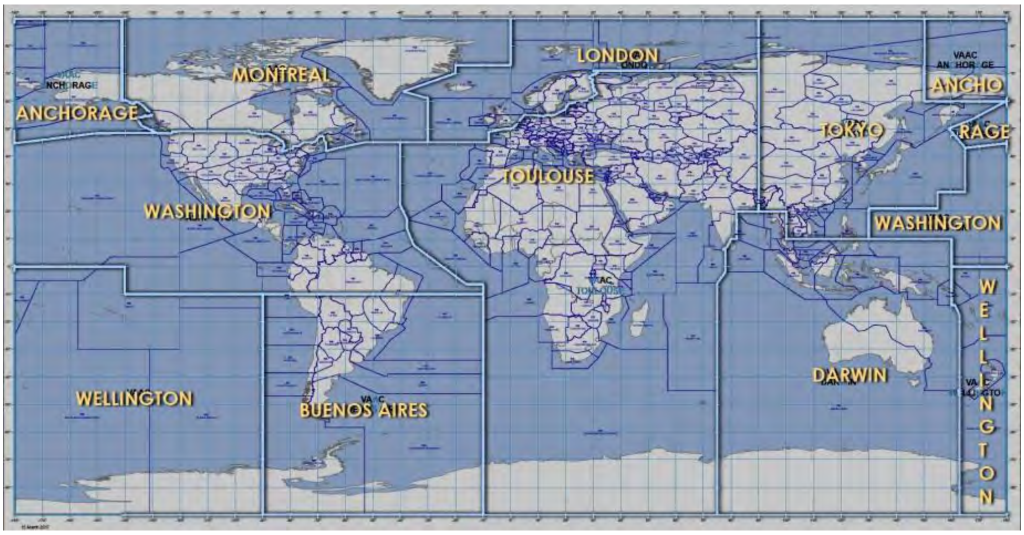
Volcanic emissions (gas and particles) can affect long-haul flights, being a possible threat to the health of the passengers, affecting the ATM and causing potential damage to aircraft engine. A recent study achieved by Rolls-Royce, shows that the impact of the SO_2 exposure and the sulphur damage to 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.



This figure illustrates four 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-haul 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).



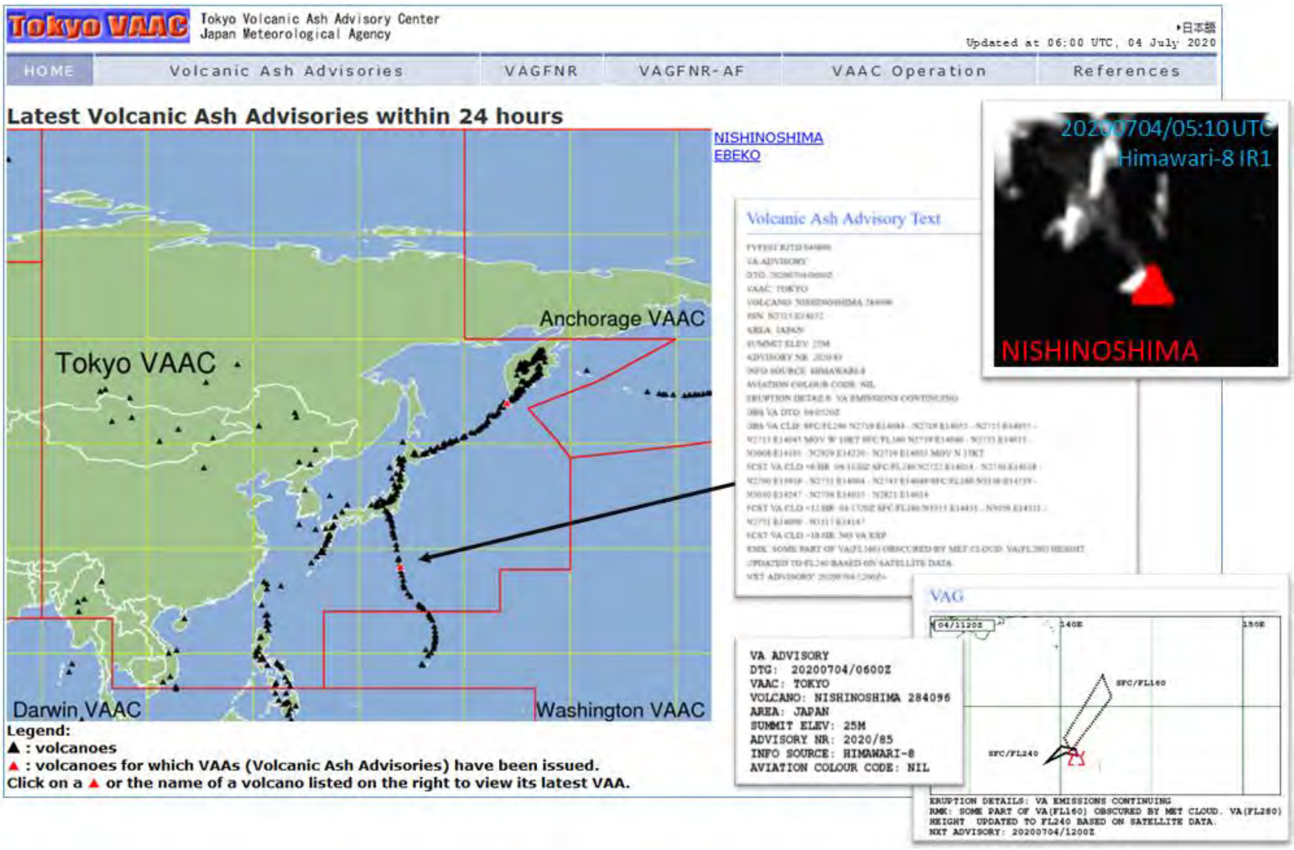
Region of responsibility of the 9 VAACs.

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 SO_2 plume is considered as an atmospheric phenomena in the IWXXM (ICAO Meteorological Information Exchange Model). A specific consideration of the SO_2 cloud may occur in the future within the ICAO. The exchange of information on the SO_2 cloud is not part of the task of the Volcanic Advisory, but the concern about SO_2 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 SO_2 product. The SO_2 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 SO_2 contamination during long-haul 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 ultraviolet (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.
The 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 SO_2 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 SO_2 LH images: the IASI SO_2 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 SO_2 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 SO_2 LH with clear scientific and societal added values. The motivation for developing an SO_2 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 SO_2 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 SO_2 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 SO_2 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 SO_2 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 SO_2 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.

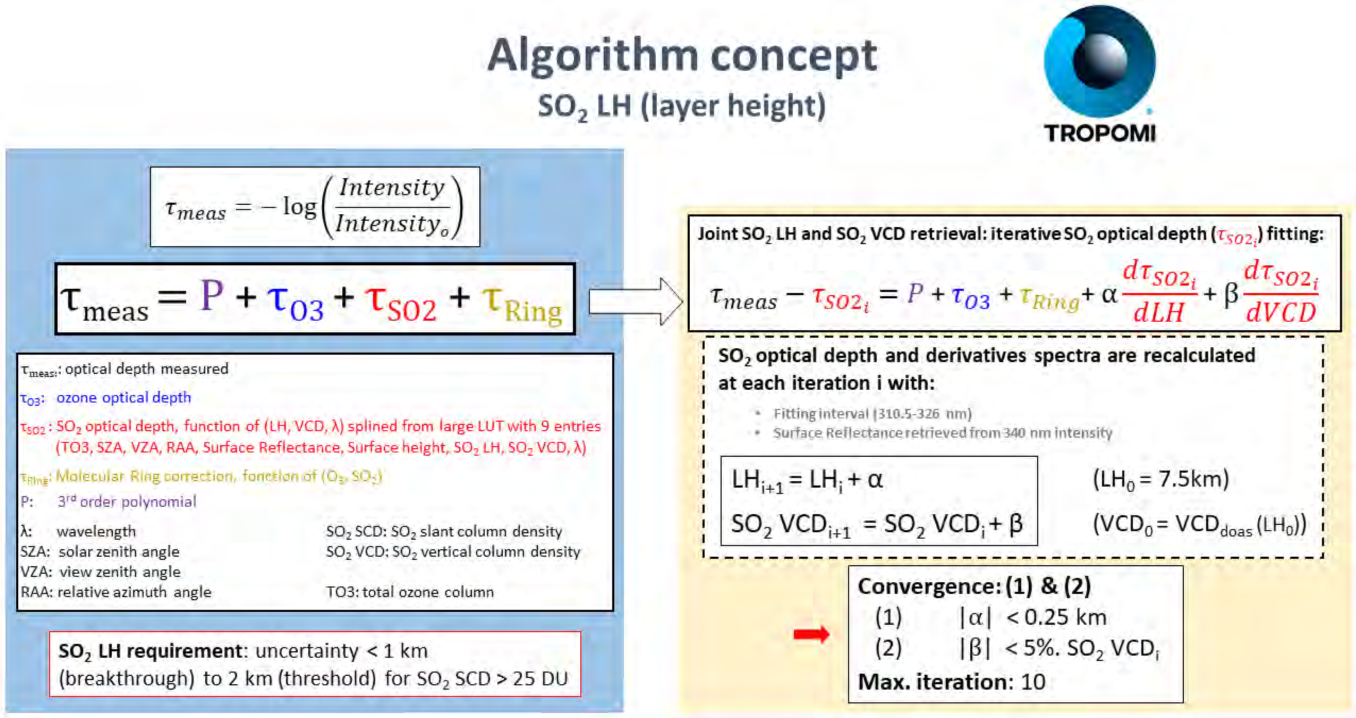
R6. The TROPOMI SO_2 LH dataset shall be consistent with other operational SO_2 LH product developments, notably from Sentinel-5.

R7. The TROPOMI SO_2 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 SO_2 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 SO_2-rich eruption, such as Raikoke, that could possibly solicit all the available hardware in a massive way.

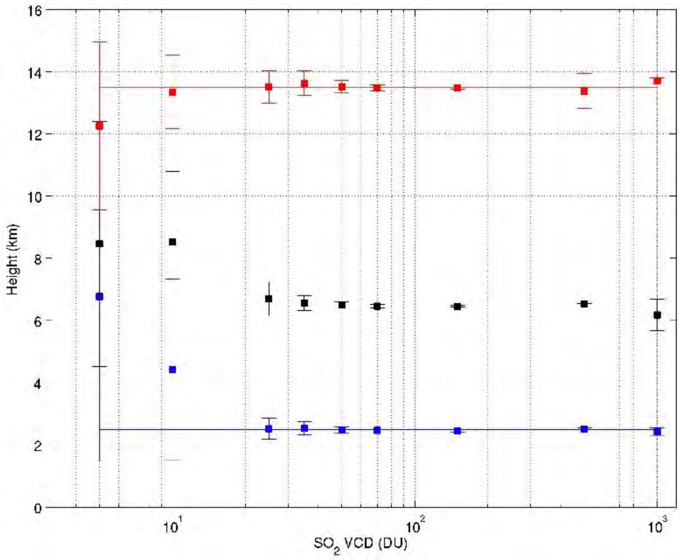
For this reason, we have developed in the frame of the Sentinel-5 L2 Prototype Processors ESA project (S5L2PP) and the OPAS project, a new SO_2 LH algorithm conceptually close to Extended Iterative Spectral Fitting (EISF) algorithm of Yang et al (2010). It make use of SO_2 slant optical depth (hereafter referred simply as OD) spectra look-up-table (LUT) generated as a function of many parameters (geometry, Lambertian equivalent reflector, ozone optical depth τ_{O3}, SO_2 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 SO_2 SCD above a threshold of 25 Dobson Units (DU), a sub-LUT is selected (splined) form the (large) SO_2 optical depth spectra LUT. Starting from an a-priori pair of SO_2 VCD (vertical column density) and height, an SO_2 optical depth spectra is calculated and subtracted from the total measured optical depth. SO_2 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 SO_2 height and VCD) are used to calculate new SO_2 spectra for the next calculation and few iterations are performed until convergence is reached (α < 0.25 km, β < 5% SO_2 VCD; see the illustration of the algorithm concept below).



At the final iteration, the retrieval points to the output SO_2 VCD and height. From the computational point of view, the SO_2 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 SO_2 LH with theoretical precision and accuracy of a few hundred meters for input SO_2 VCD typically larger than 25 DU, as show in the figure below.



Synthetic validation of our algorithm

Input
SO_2 VCD: 5 -1000 DU
SO_2 LH: 2.5, 6.5, 13.5 km

Results
Mean + std retrieved SO_2 LH
for 100 noisy spectra (SNR: 1000)

Findings
Good precision and accuracy (of a few hundred meters) for all conditions with SO_2 VCD > 25 DU, in line with previous study (Nowlan et al., 2011).

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 SO_2 height.

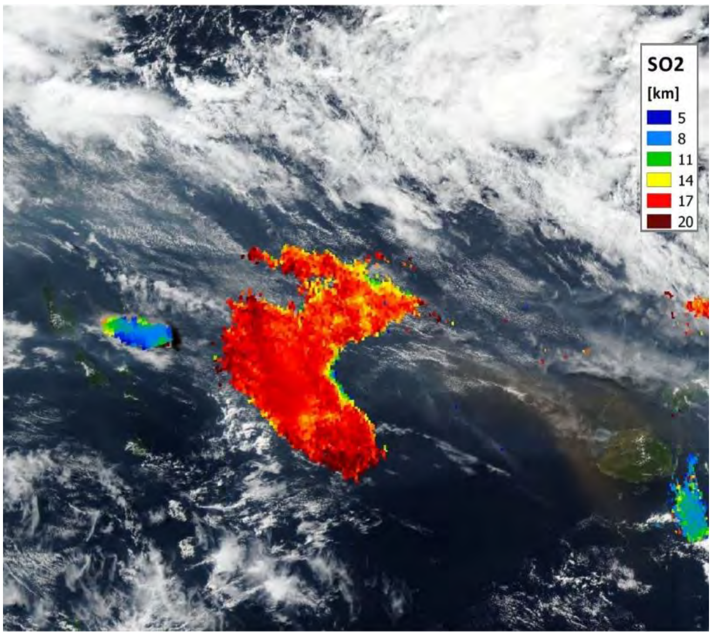
We find a solution to fix this potential problem (use of the cloud top as a proxy of the SO_2 height). If an explicit aerosols treatment cannot be found, the pixels affected are identified and the reduced quality of the data is reported through a flag, comprehensively documented. For these flagged pixels, there will be non-compliance of the accuracy requirement of 1-2 km on SO_2 LH. Note that for such scenes, a good estimate of SO_2 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 SO_2 LH product is the following:

Quality flag associated to SO_2 LH retrieval (activation for SO_2 SCD > 25DU).
VCD is the SO_2 vertical column established assuming SO_2 profile with a centre of mass altitude of 15 km.
AAI is the Absorbing Aerosol Index.

- flag = 0: SO_2 LH module not activated.
- flag = 1: SO_2 LH module activated but no convergence (number of iterations: max allowed).
- flag = 2: SO_2 LH module activated, low level of confidence due to absorbing aerosols (AAI > 4 or AAI missing).
- flag = 3: SO_2 LH module activated, medium level of confidence due to low signal (SO_2 improved for VCD >= 10 DU and VCD < 25 DU).
- flag = 4: SO_2 LH module activated, medium level of confidence due to absorbing aerosols (AAI>4) with the use of nearest cloud altitude.
- flag = 5: SO_2 LH module activated, high level of confidence, convergence with good data quality.

The operational implementation of SO_2 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 SO_2 LH products from TROPOMI should take place in 2021, which will definitely be of interest for the activity developed by the OPAS project (service).



Example of SO_2 LH results from TROPOMI for the eruption of Ambae (Vanuatu) on July 27, 2018. An extended SO_2 plume injected at tropopause level is observed.

We have reprocessed data archive from December 2018 of SO_2 LH from TROPOMI. This represents a consequent amount of spectral radiance data. The SO_2 LH data is produced only if there is a detection of SO_2 SCD > 25 DU. The numbers about our SO_2 LH archive are the following:

- 27.5 Tb of spectral radiance data analysed,
- currently 1830 files (granule of SO_2 LH products) have been produced,
- the size of a data file granule is 8 Mb,
- the current total size of SO_2 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 SO_2 LH,

2) the operational implementation of SO_2 LH from TROPOMI and IASI (A&B),

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 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 SO_2 LH retrievals.

The algorithmic development **1)** of TROPOMI SO_2 LH and its operational implementation **2)** is presented in previous section 2.3. Note that **the operational SO_2 LH from IASI-A & -B has been implemented in the EUNADICS project**, contributing to the OPAS project.

The table below 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**	Fire radiative power *(NASA/FIRMS)*	Selective	Smoke
Suomi-NPP / **OMPS**	Aerosol index	Triggered	Dust & Smoke
Terra & Aqua / **MODIS**	Aerosol optical depth	Triggered	Smoke

The SO_2 LH alert products **3)** from TROPOMI implemented in the OPAS project and the upgraded SO_2 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 SO_2 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 SO_2 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 SO_2 LH from IASI-A and IASI-B sensors.

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

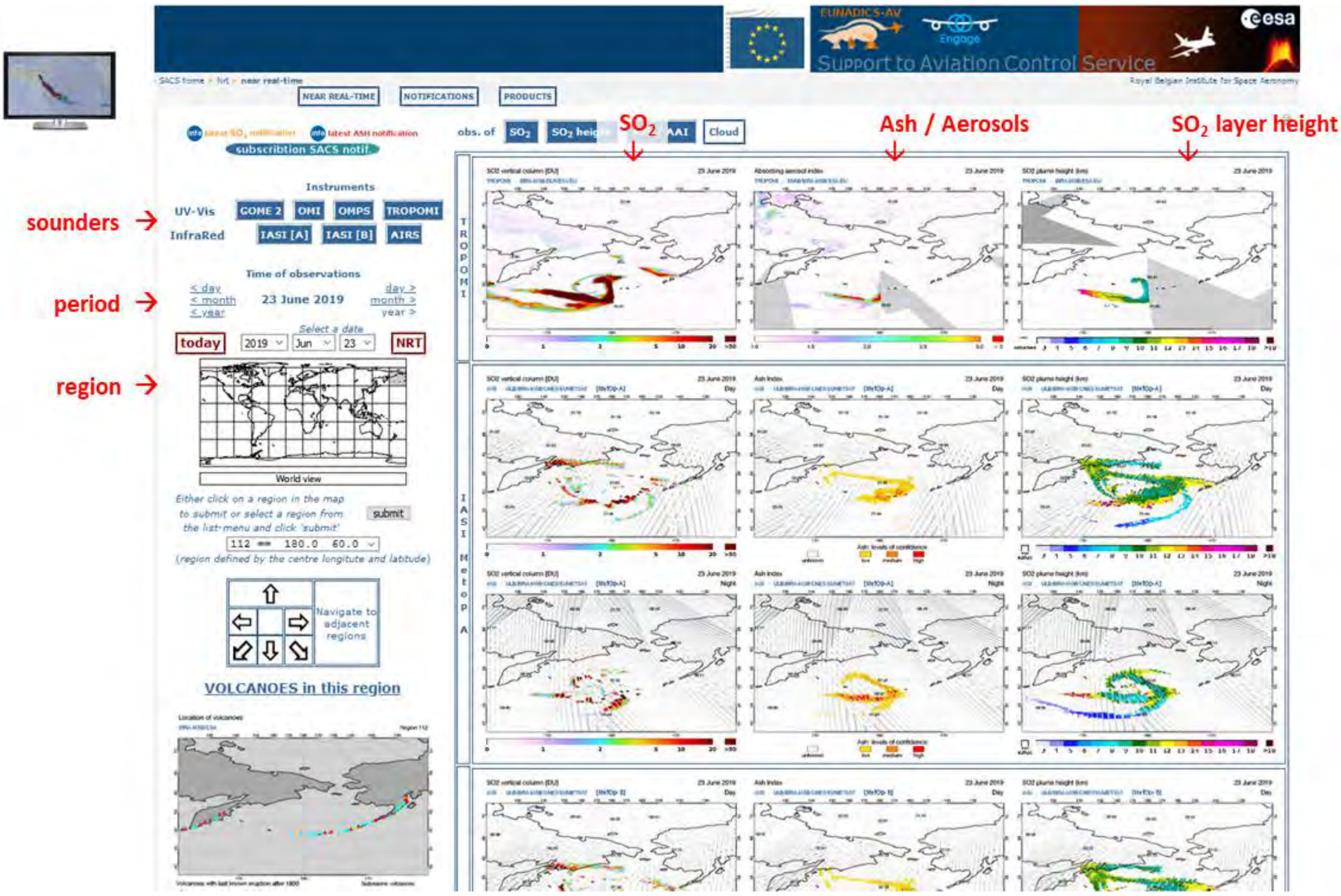
NRT imaging on a dedicated web interface

Email notifications (with key information and link to dedicated tailored images)

Creation of homogenised alert data products (SO_2 height information, improved SO_2 mass loading, SO_2 contamination of the FL, identification of source, and links to images)

To illustrate the achievement of the OPAS project, this report presents an example of each kind of SACS/OPAS SO_2 LH alert products.

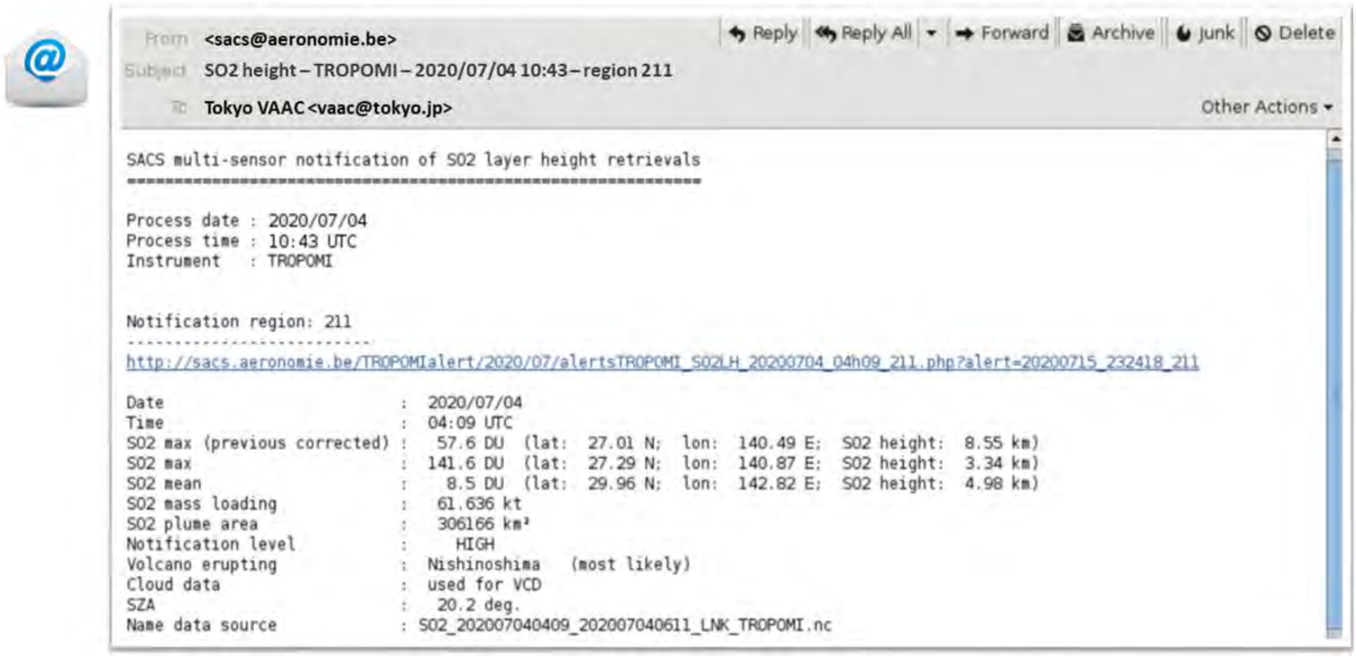
Here is a snapshot of SACS website (http://sacs.aeronomie.be) showing an example of images (archive) for the Raikoke eruption on 22 June 2019.



The text in red is here for giving you a quick overview of the functionality of SACS website (sounders, period, region, type of observations – SO_2, ash or SO_2 LH).

The SO_2 LH products is only shown for IASI-A, IASI-B and TROPOMI. There are five UV instruments (composite GOME-2A&-B, OMI, OMPS and TROPOMI) and three IR instruments shown on SACS.

In case a TROPOMI SO_2 slant column is over 25 DU, our algorithm is activated and SO_2 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.



From <sacs@aeronomie.be>
Subject SO2 height – TROPOMI – 2020/07/04 10:43 – region 211
To Tokyo VAAC <vaac@tokyo.jp>

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SACS multi-sensor notification of SO2 layer height retrievals
==============================================================

Process date  :  2020/07/04
Process time  :  10:43 UTC
Instrument    :  TROPOMI

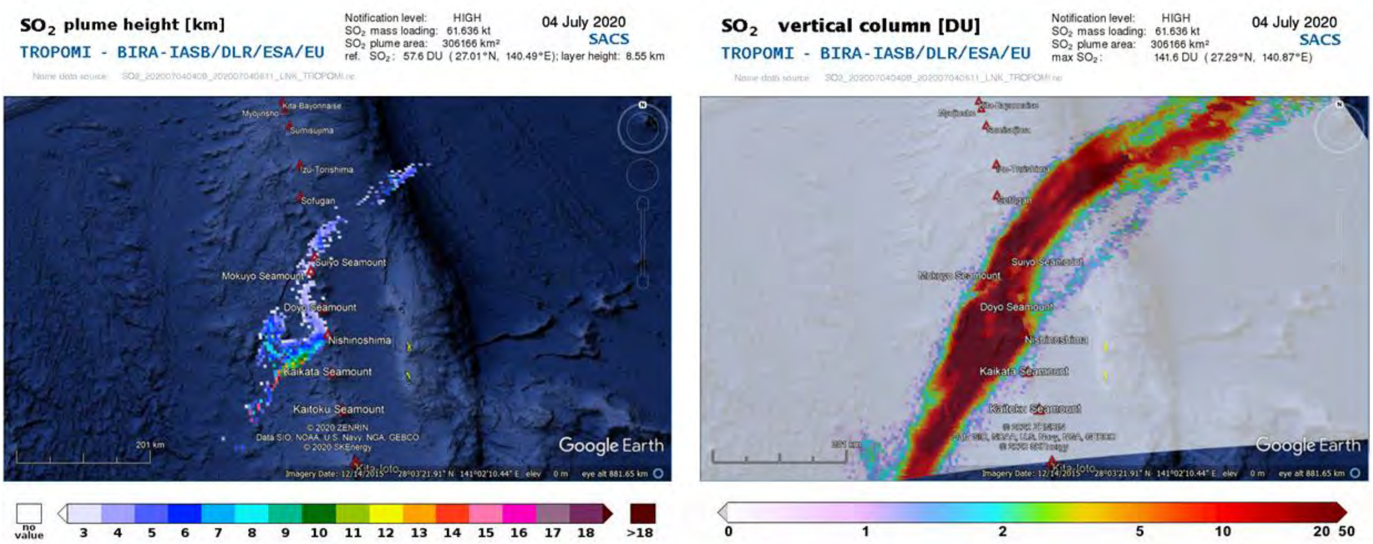
Notification region: 211
--------------------------
http://sacs.aeronomie.be/TROPOMIalert/2020/07/alertsTROPOMI_SO2LH_20200704_04h09_211.php?alert=20200715_232418_211

Date                          :  2020/07/04
Time                          :  04:09 UTC
SO2 max (previous corrected)  :   57.6 DU  (lat:  27.01 N;  lon:  140.49 E;  SO2 height:  8.55 km)
SO2 max                       :  141.6 DU  (lat:  27.29 N;  lon:  140.87 E;  SO2 height:  3.34 km)
SO2 mean                      :    8.5 DU  (lat:  29.96 N;  lon:  142.82 E;  SO2 height:  4.98 km)
SO2 mass loading              :   61.636 kt
SO2 plume area                :   306166 km²
Notification level            :     HIGH
Volcano erupting              :  Nishinoshima   (most likely)
Cloud data                    :  used for VCD
SZA                           :   20.2 deg.
Name data source              :  SO2_202007040409_202007040611_LNK_TROPOMI.nc
```


Illustration of the key information are received by subscribers in the SO_2 height email notification.

SO_2 heights and improved SO_2 vertical columns are simultaneously retrieved using our algorithm. We can eventually obtained a new SO_2 maximum (especially if the SO_2 height is smaller than 15 km, which is the assumed height considered in the SO_2 notification). An improved SO_2 mass loading is estimated using the new SO_2 vertical columns (quality flags 3, 4 and 5).

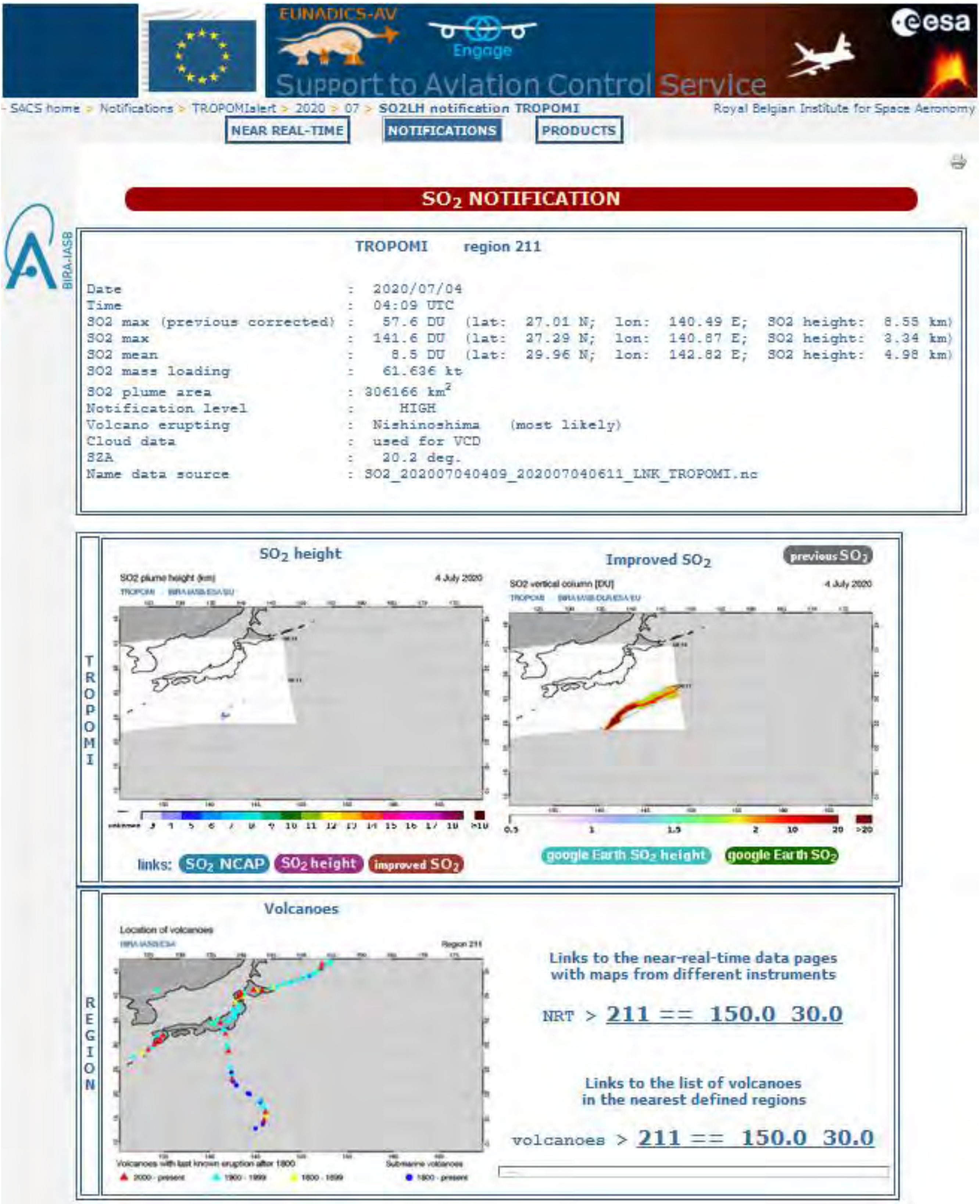
The notification level is based on the new SO_2 mass loading (if this mass is higher than 5 kt, the level is HIGH, otherwise it is LOW). The name of the erupting volcano is provided.



Tailored images (Google Earth) of the SO_2 LH and the improved SO_2 are provided in the notification.

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

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

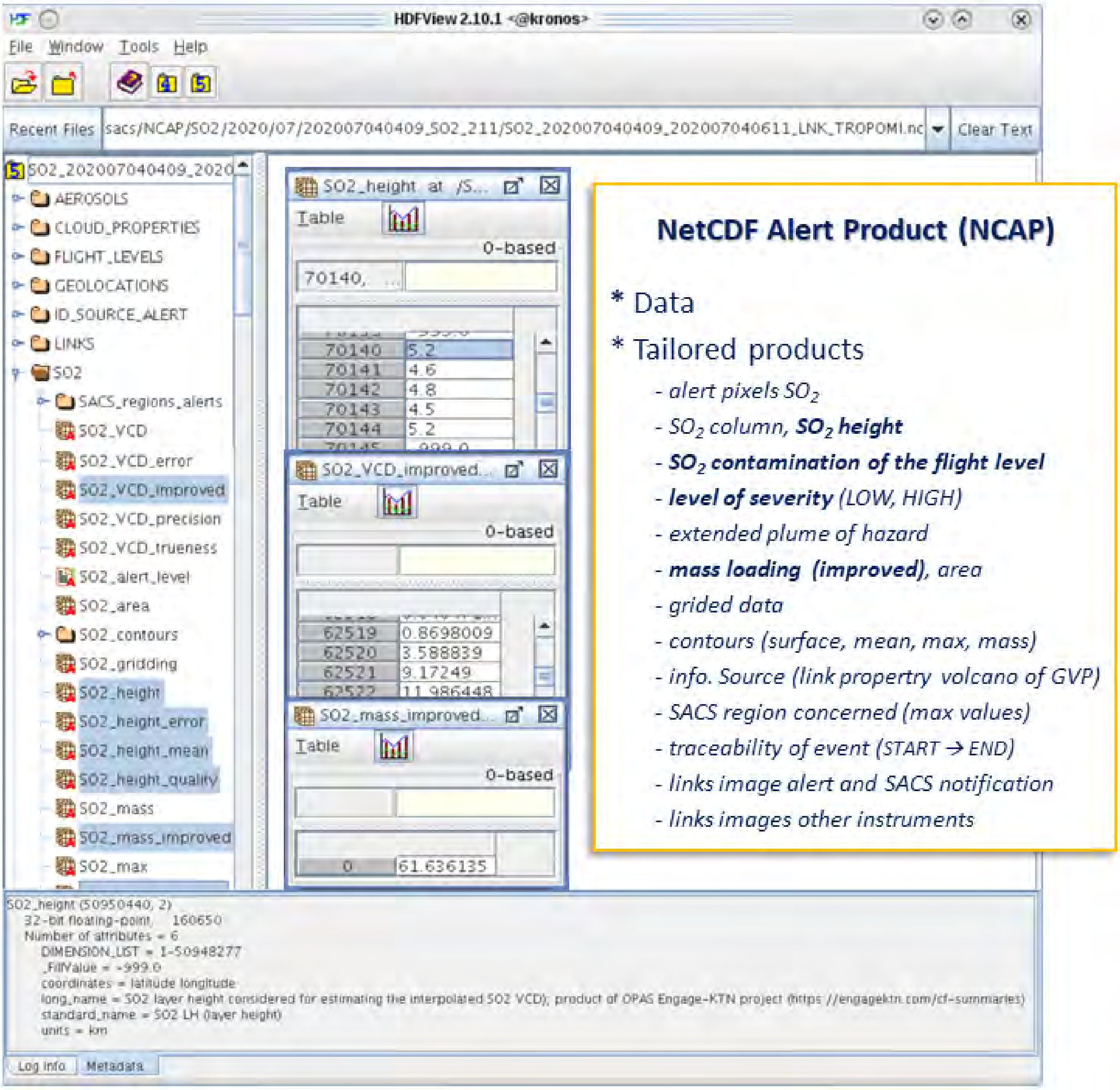


Information and images are shown with links to Google Earth images.

The third OPAS SO_2 LH alert product is the creation of a NetCDF data file. This file is an upgraded version of the existing SO_2 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

SO_2 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.



We can note that the NCAP data provides detailed information, with notably the SO_2 contamination of the flight level (FL).

Illustration of the SO_2 contamination for FL150, as retrieved by TROPOMI on 4 July 2020 at 04:00 UTC.

For the example of the SO_2 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 SO_2 contamination could be of great interest for the VAACs if they take the responsibility of producing advisory report related to volcanic SO_2 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 SO_2 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:

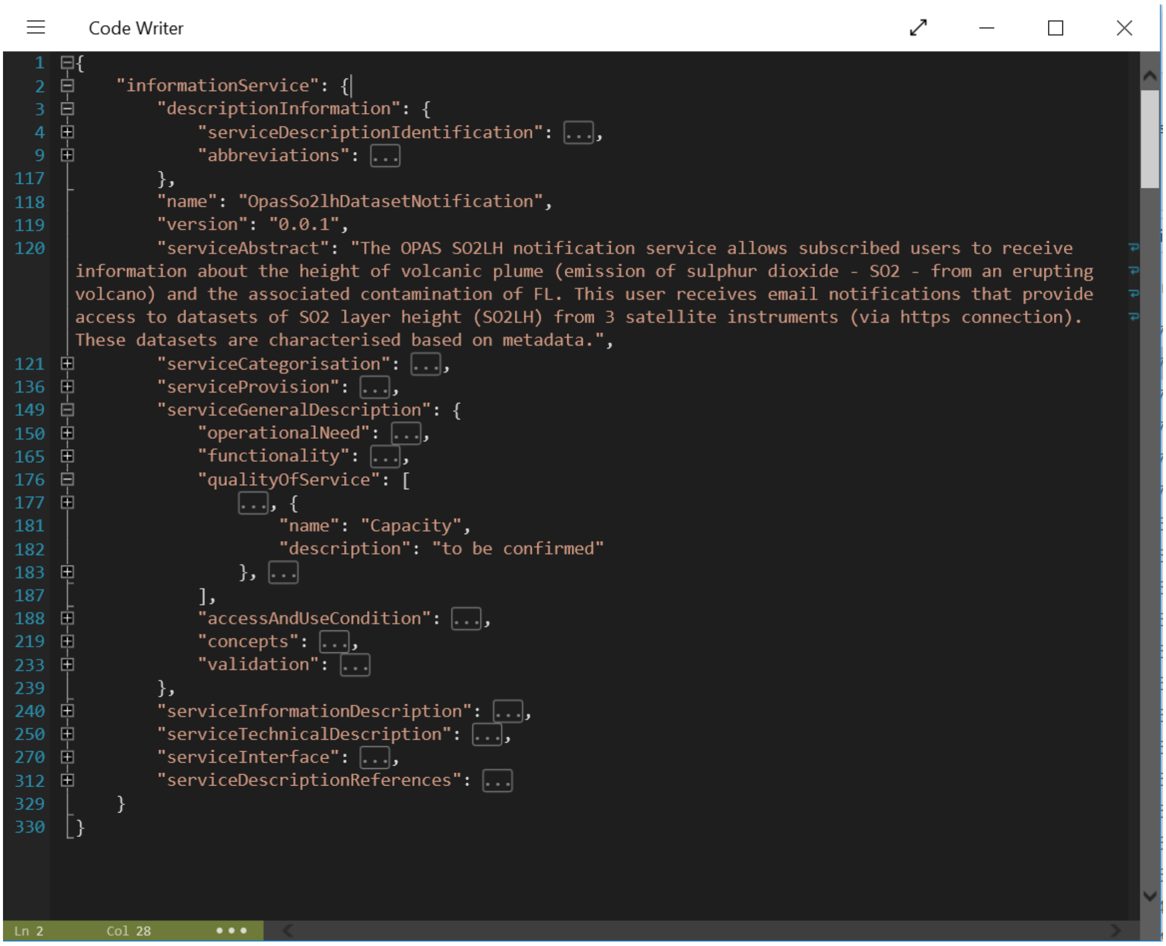
1. Ensure information exchanges are properly defined and understandable for the stakeholders.
2. Create information model ("information definition" in SWIM terms).
3. Design the service ensuring it uses options from the SWIM TI Yellow Profile.
4. Implement and deploy the service (creation of a "service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



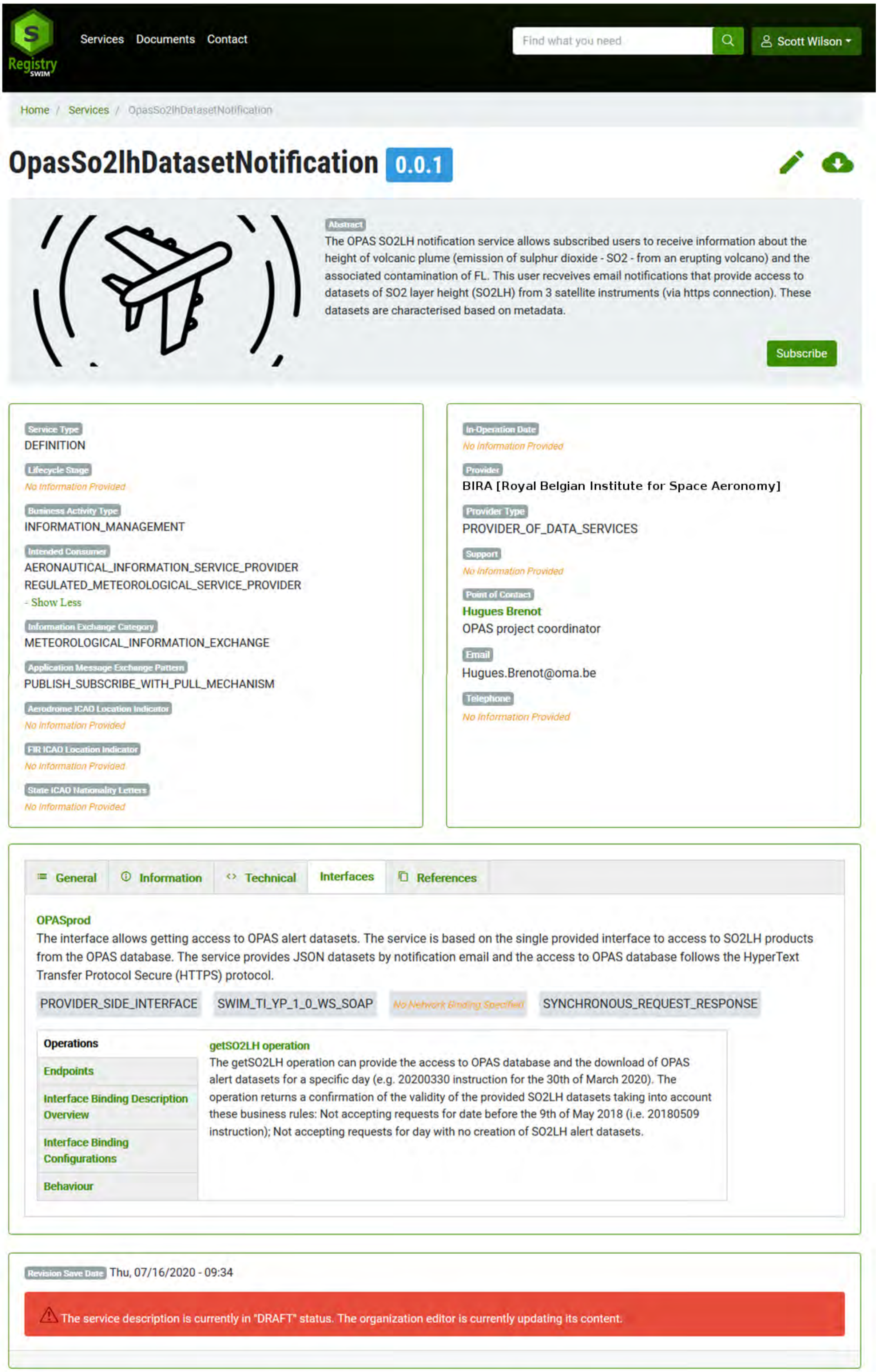
Overview of the edition of the definition of OPAS notification service in JSON format.

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

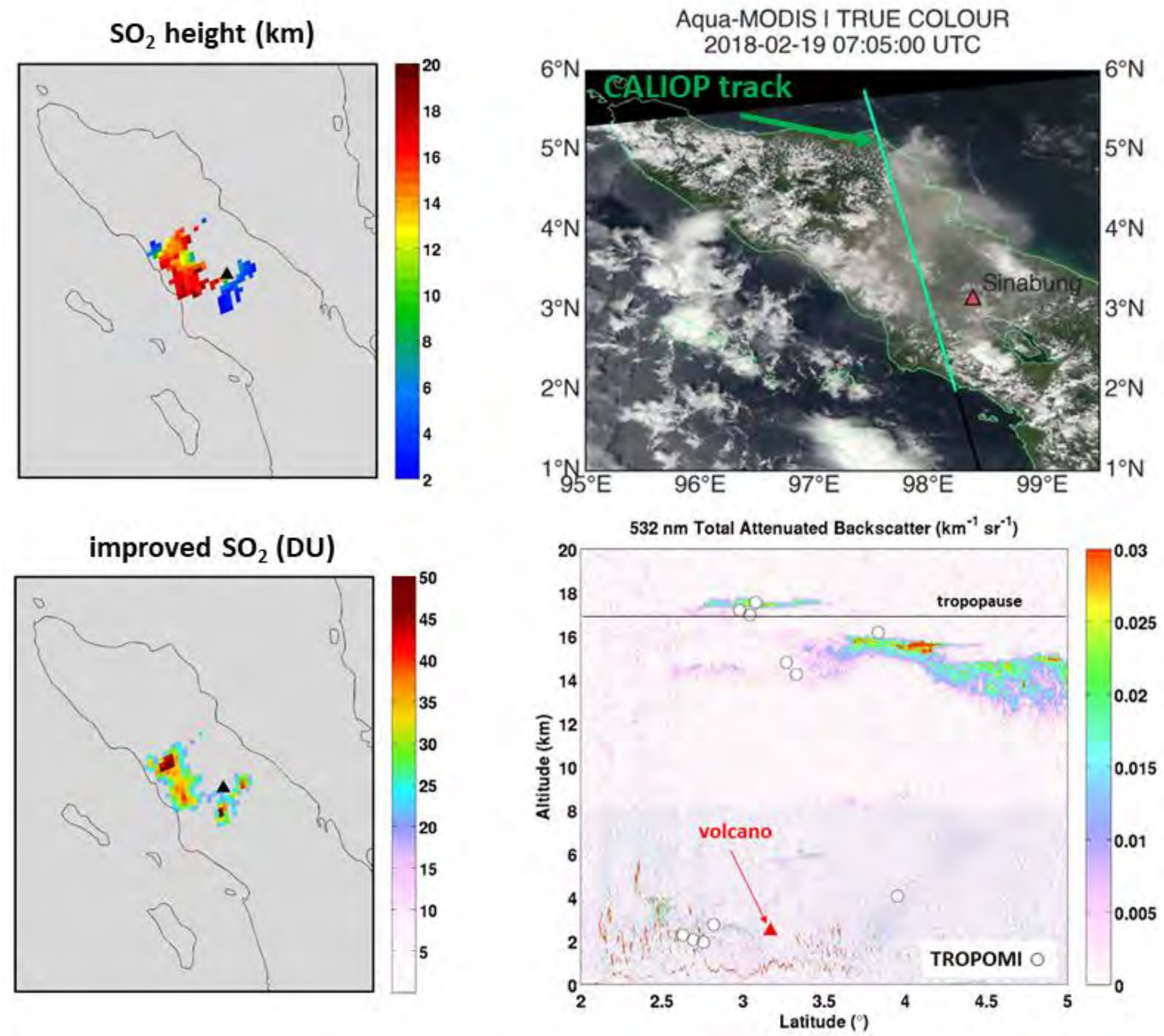
The service description of OPAS Yellow Profile captures the fact that:

- subscription is by email. Notifications of SO_2 alerts with SO_2 LH are sent to subscribers,
- an Internet Protocol (IP) address has to be provided, giving access right to BIRA *https* server.

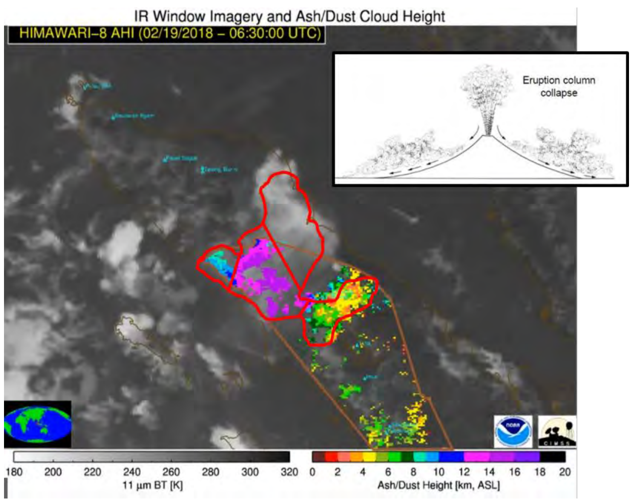
The registry of OPAS as a SWIM service is not yet completed (i.e. step 5; see next section 3.2), but a first draft of what it will look like has been created (see next illustration).


Registry SWIM
Services Documents Contact
Find what you need
Scott Wilson
Home / Services / OpasSo2lhDatasetNotification
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 recveives 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
Aerodrome ICAO Location Indicator
No Information Provided
FIR ICAO Location Indicator
No Information Provided
State ICAO Nationality Letters
No Information Provided
In-Operation Date
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_TI_YP_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 Save Date 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 SO_2 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.

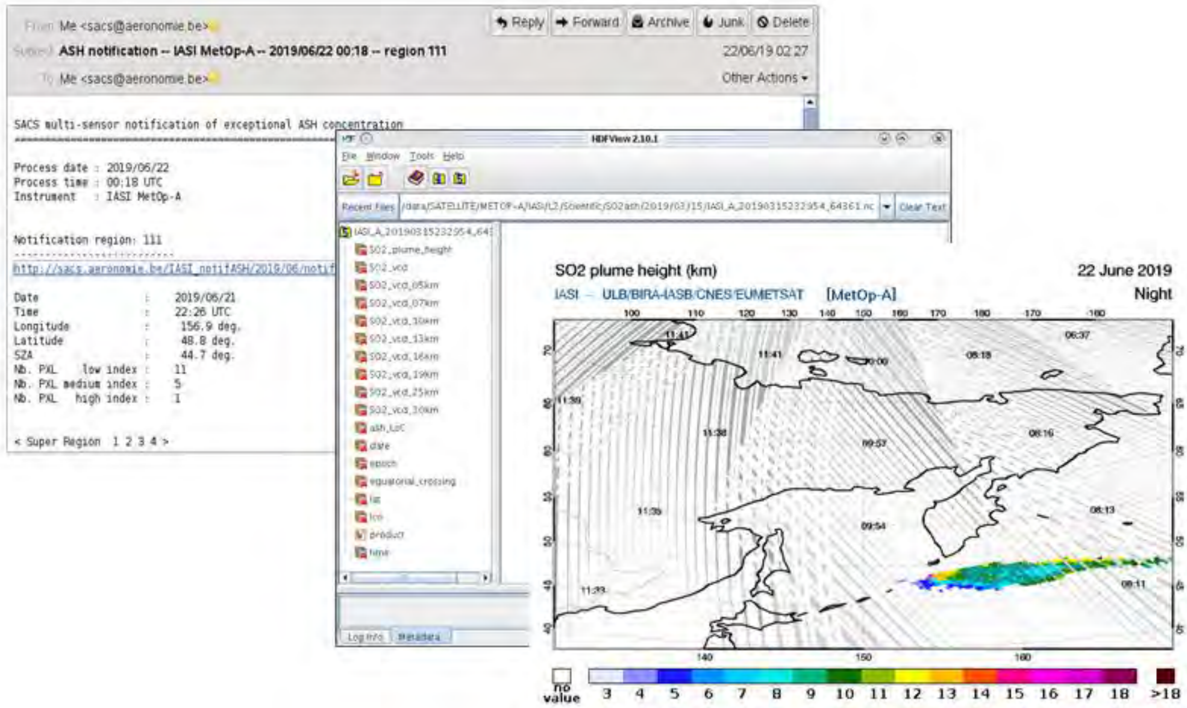


Mount Sinabung on the Indonesian island of Sumatra erupted violently on 19 February 2018 (see the true colour image from Aqua-MODIS), spewing violent blasts of gas and ash at least 12 to 16 km into the air (as confirmed by CALIOP total attenuated backscatter at 532 nm). The SO_2 height and improved SO_2 retrieved by OPAS algorithm shows a plume spreading westward of Sinabung for a height range of 14–18 km. It also shows an SO_2 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).

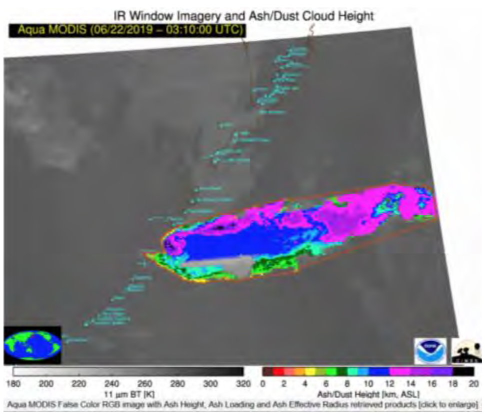


Credit: CIMSS / NOAA

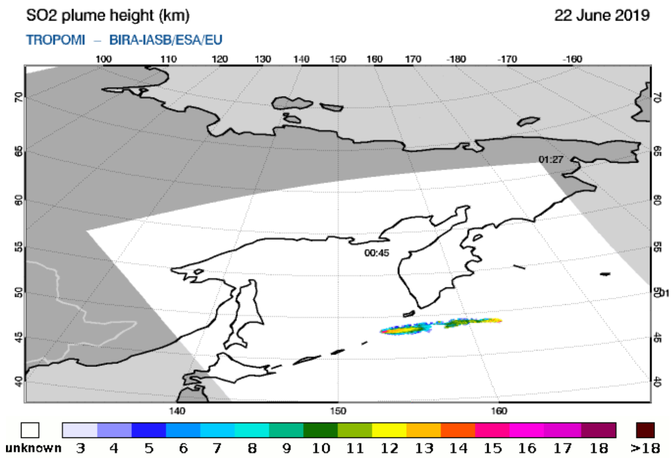
The second case study presented here is the explosive eruption of Raikoke volcano (Kurile Islands) on 21-23 June 2019. A powerful explosive eruption, possibly sub-plinian, started from the remote island volcano at 18:00 UTC on 21 June, emitting copious amounts of SO_2 (~ 1.4 Tg) and ash in the upper-troposphere lower stratosphere. SACS EWS sent ASH and SO_2 notification from IASI instruments, as illustrated below, and provided relevant information to users. Note that TROPOMI was not yet implemented in SACS system.



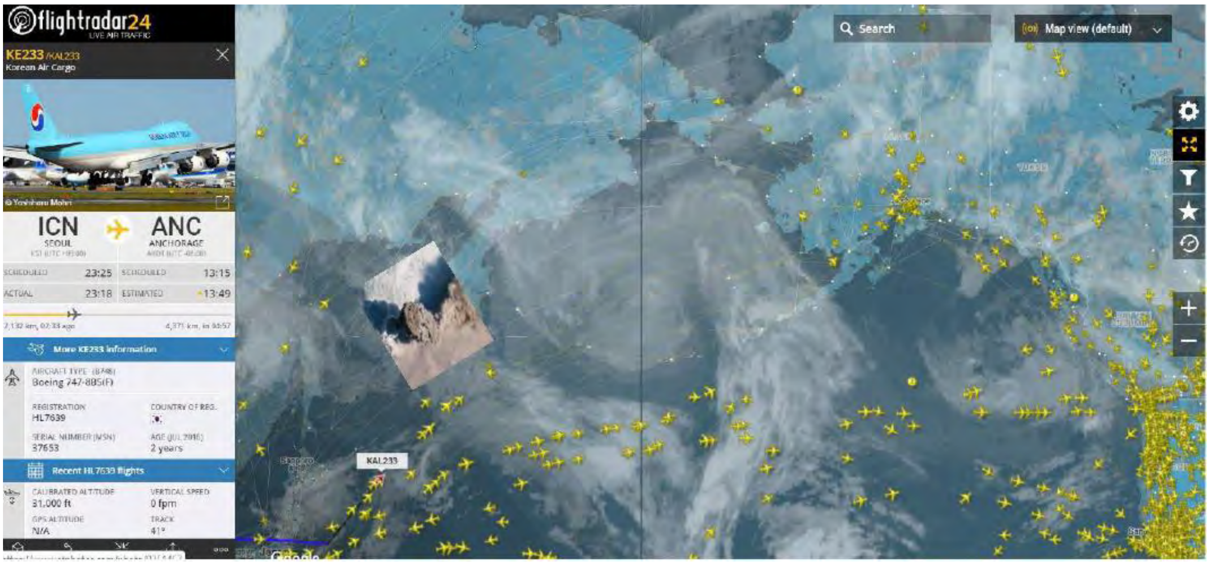
The SO_2 plume height information provided by IASI started to be provided at 00:18 UTC, about 4 hours after the start of the eruption. The SO_2 LH range was from 5 to 12 km. The first over path of TROPOMI provides the same range of altitude. This is also in agreement with the Volcanic Cloud height observed by Aqua-MODIS and provide by CIMSS / NOAA service.



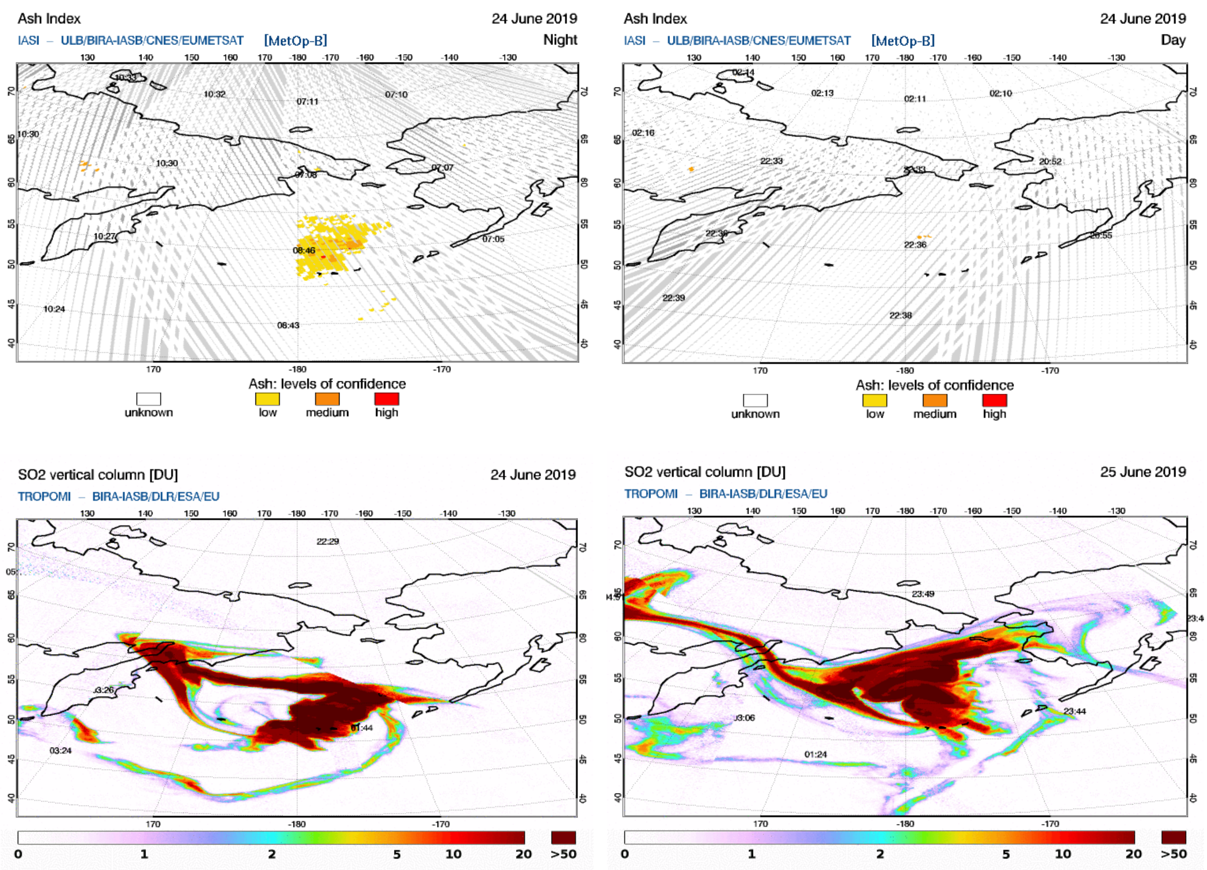
Credit: CIMSS / NOAA



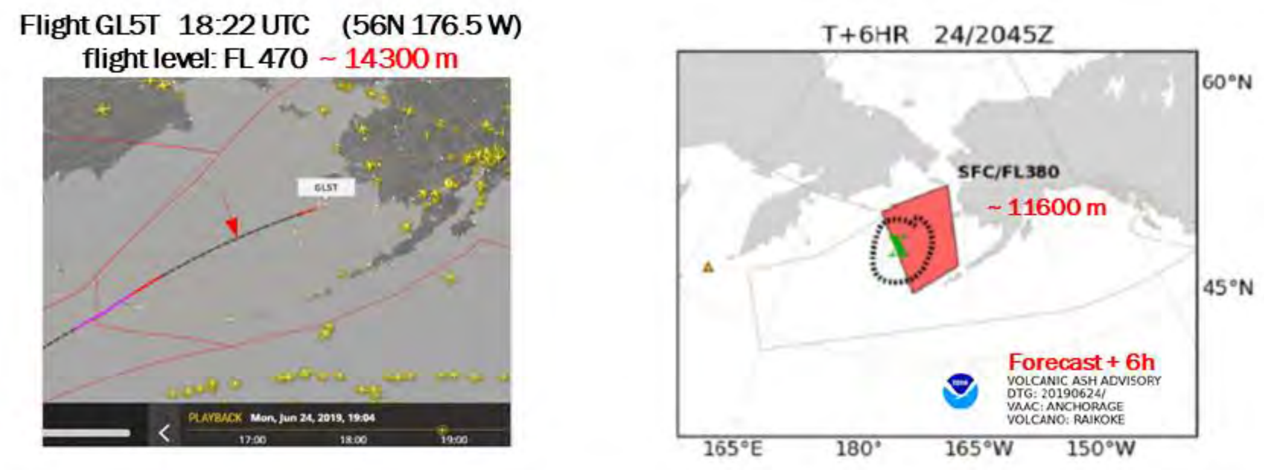
This eruption had a consequent impact on the air traffic as illustrated by the next flight-radar image, with a no-flight zone over the Bering sea, on 22 June 2019.



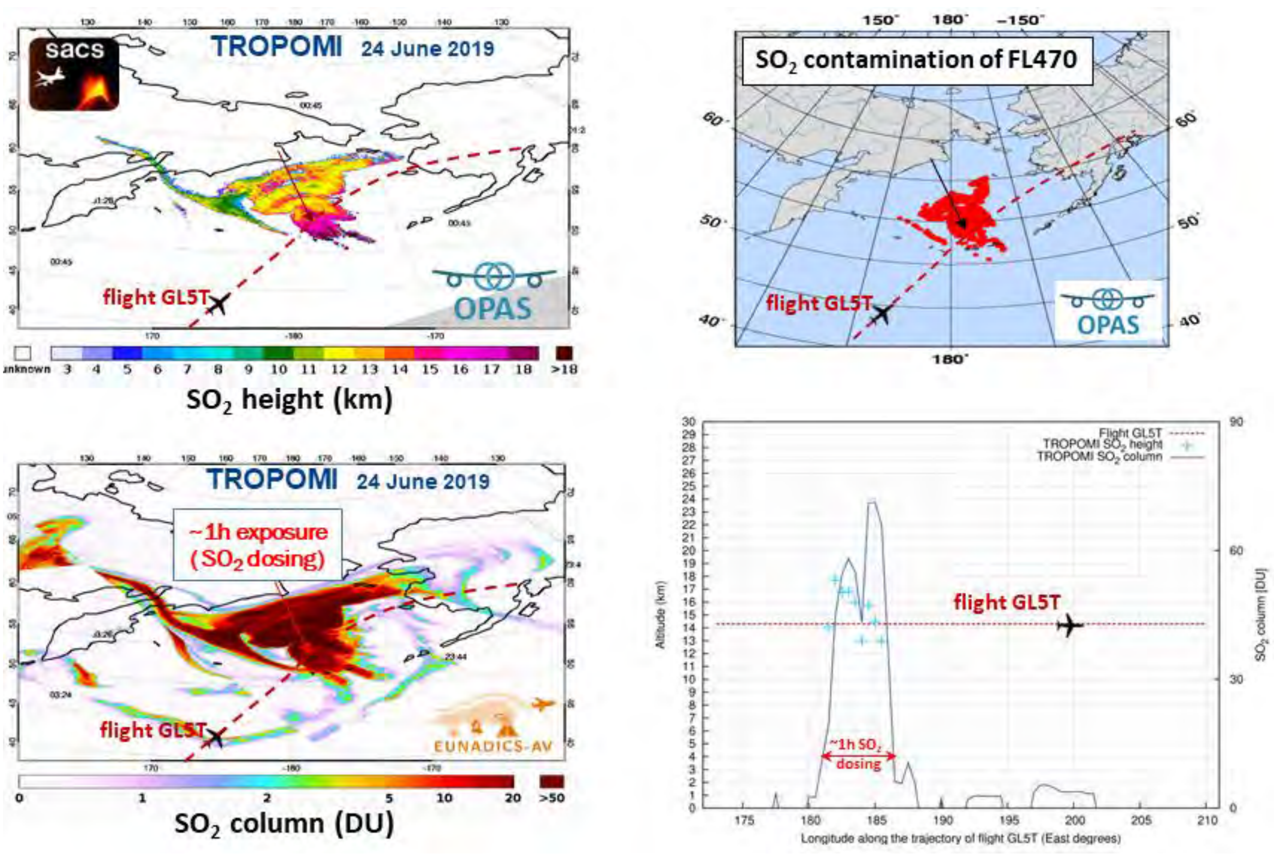
Raikoke 2019 was an SO_2-rich eruption. Its ash cloud (due to aggregation or dispersion) disappeared quite quickly from the satellite observation systems. No ash detection was observed by SACS after the 25th of June. The advisory sent by Anchorage and Tokyo VAACs only concerned the ash cloud, and no information about possible SO_2 contamination was provided.



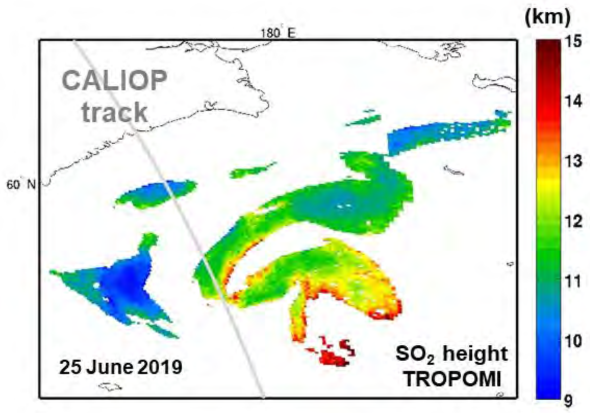
These ash and SO_2 images from IASI-B and TROPOMI, respectively, illustrates the character of this eruption, e.g. the copious amount of SO_2 emitted with respect to the ash.

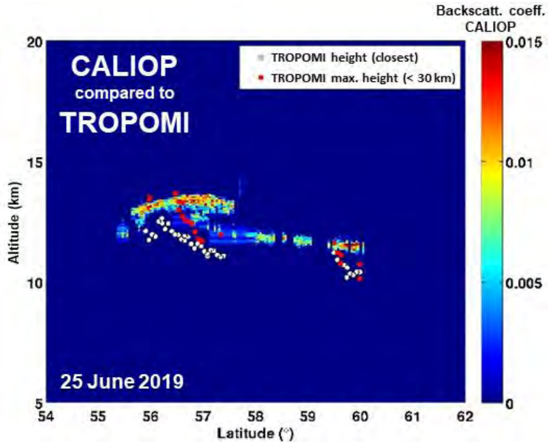


The flight GLT5 in direction of Anchorage airport was flying at FL470 (~ 14300 m). Following, the VAA from Anchorage VAAC, this flight was supposed to fly over the ash plume from Raikoke. However, the route of flight GL5T crossed Raikoke SO_2 volcanic cloud.



The TROPOMI SO_2 image shows about 1 hour of exposure to SO_2 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 SO_2 contamination. However, we can see that the tailored SO_2 products of FL contamination provided by OPAS represents useful information for building Volcanic SO_2 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 SO_2 height (at 01:30 UTC). The grey circles show the SO_2 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 SO_2 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 SO_2 LH product,
- the implementation of TROPOMI SO_2 LH alert product and the upgrade of IASI-A & -B SO_2 LH alert products, with information about the FL SO_2 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 SO_2 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-haul flight exposure.

The transfer of homogenised near real-time SO_2 height observation via a SESAR SWIM Yellow Profile service, providing unambiguous (i.e. with selective SO_2 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 SO_2 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 SO_2 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 (SO_2 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 SO_2 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 participating 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 Dimitropolou 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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Theys, N., Hedelt, P., De Smedt, I. et al. Global monitoring of volcanic SO2 degassing with unprecedented resolution from TROPOMI onboard Sentinel-5 Precursor. *Scientific Reports,* 9, 2643, doi:10.1038/s41598-019-39279-y, 2019.

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.