Volcanic SO2 height retrieval from UV satellite measurements

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Abstract

Determining the height of a volcanic SO2 cloud after a volcanic eruption is a challenging task in UV satellite retrievals. The height is nevertheless the most important yet uncertain parameter required to forecast the movement of the volcanic cloud and to determine the total SO2 column and ejected SO2 mass, especially for local authorities and aviation safety applications. Retrieval algorithms developed so far use direct fitting and optimal estimation techniques to determine the height information, which is hidden in the spectral signature. They are computationally very expensive and time consuming and therefore are not practical in near-real time operational retrievals, especially for current and future satellite UV instruments with high resolution and related high data amount. We have therefore developed the 'Full-Physics Inverse Learning Machine' (FP_ILM) retrieval algorithm that combines principle component analysis and neural network , which performs an extremely fast (3 ms per TROPOMI pixel) yet accurate (<2km average accuracy) SO2 LH retrieval based on UV satellite measurements. The algorithm was first applied to GOME-2 and introduced by Efremenko et al. (2017) . Hedelt et al. (2019) further improved the algorithm and applied it to Sentinel-5p/TROPOMI data. The algorithm was optimized and validated in the framework of ESA's Sentinel-5p Innovations project (S5P+I) and is already performing SO2 LH retrievals in a semi-operational near-real time environment. Recently, Fedkin et al. (2021) applied the FP_ILM algorithm to OMI and OMPS data. Application to future UV LEO (Sentinel-5) and GEO (Sentinel-4, GEMS, TEMPO) satellite missions will follow. We present here SO2 LH results based on GOME-2, OMI/OMPS, and TROPOMI measurements of the Raikoke (Kuril Islands) volcanic eruption in June-July 2019 and La Soufriere St. Vincent volcanic eruption in April 2021 and make intercomparisons between the UV sensors as well as other (IR) independent measurements.

Volcanic SO_2 Height Retrieval From UV Satellite Measurements

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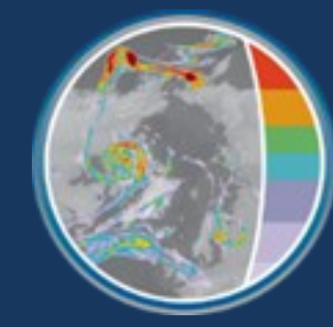

Background

Accurate determination of the location, height and loading of SO_2 plumes emitted by volcanic eruptions is essential for aviation safety. The SO_2 layer height (LH) is furthermore one of the most critical parameters that determine the impact on the climate.
Retrieving the SO_2 slant column from satellite UV measurements is simple, however for the determination of the total vertical column, the vertical SO_2 distribution is required and so far not known at measurement time since the retrieval was very time-consuming.

We have developed a **versatile, extremely fast yet accurate** SO_2 LH retrieval algorithm using the Full-Physics Inverse Learning Machine (**FP_ILM**) algorithm:

- Mapping between spectral radiance and SO_2 LH using supervised learning methods:
- Combination of **PCA** and **Neural Network** regression.
- **Extremely fast** application of inversion operator to real measurements **(<3ms per pixel)**
- **Accuracy**: <2km (for SO_2 VCD > 20 DU)
- Successfully applied to GOME-2 [1], TROPOMI [2] and OMI [3]
- Optimized in framework of ESA S5P+I: SO2LH project
- Validated against IASI SO_2 LH, CALIPSO ash LH [4]
- **Semi-operational quasi-NRT S5p SO_2 LH retrieval in DLR INPULS project**

Results & Outreach

We present here the results of the FP_ILM SO_2 LH algorithm that has been developed and applied to current UV satellite instruments:

- Extremely fast and accurate UV SO_2 layer height retrieval algorithm for UV satellite data
- The S5p SO_2LH algorithm has been improved and a prototype L2 product has been developed in the framework of the **ESA S5P+I: SO2LH** project, see https://atmos.eoc.dlr.de/so2-lh
- S5p SO_2LH product has been **successfully validated against IASI, OMI, CALIPSO**
  - Very good agreement for most volcanic cases considered, see [4]
- Already, **quasi-NRT SO_2 LH products are generated** in DLR INPULS project
- The S5p SO_2 LH product is **actively assimilated by ECMWF/CAMS**
  - Significant improvement in SO2 forecast, see [5]
- Application to Sentinel-4, Sentinel-5, GEMS, etc. is foreseen
- NRT S5p/TROPOMI data is automatically analyzed for ongoing volcanic eruptions on an hourly basis. Information about the eruption are published on **Twitter**: https://twitter.com/DlrSo2:
  - Name of volcano erupted, SO2 VCD, SO2 LH, SO2 mass

Raikoke eruption Jun-Sep 2019

The explosive eruption of Raikoke in June 2019 injected a strong ash and SO_2 cloud into the stratosphere. SO_2 was transported over the entire northern hemisphere and was detected even 2 months after the eruption. OMI and TROPOMI SO_2 LHs (Fig. 1) show a high altitude plume ranging from about 10 to 20km, which is in very good agreement (~0.5km) with the IASI Univ. Oxford AOPP and the official ULB LATMOS SO_2 LH products, see Fig. 2. For details, see [4]

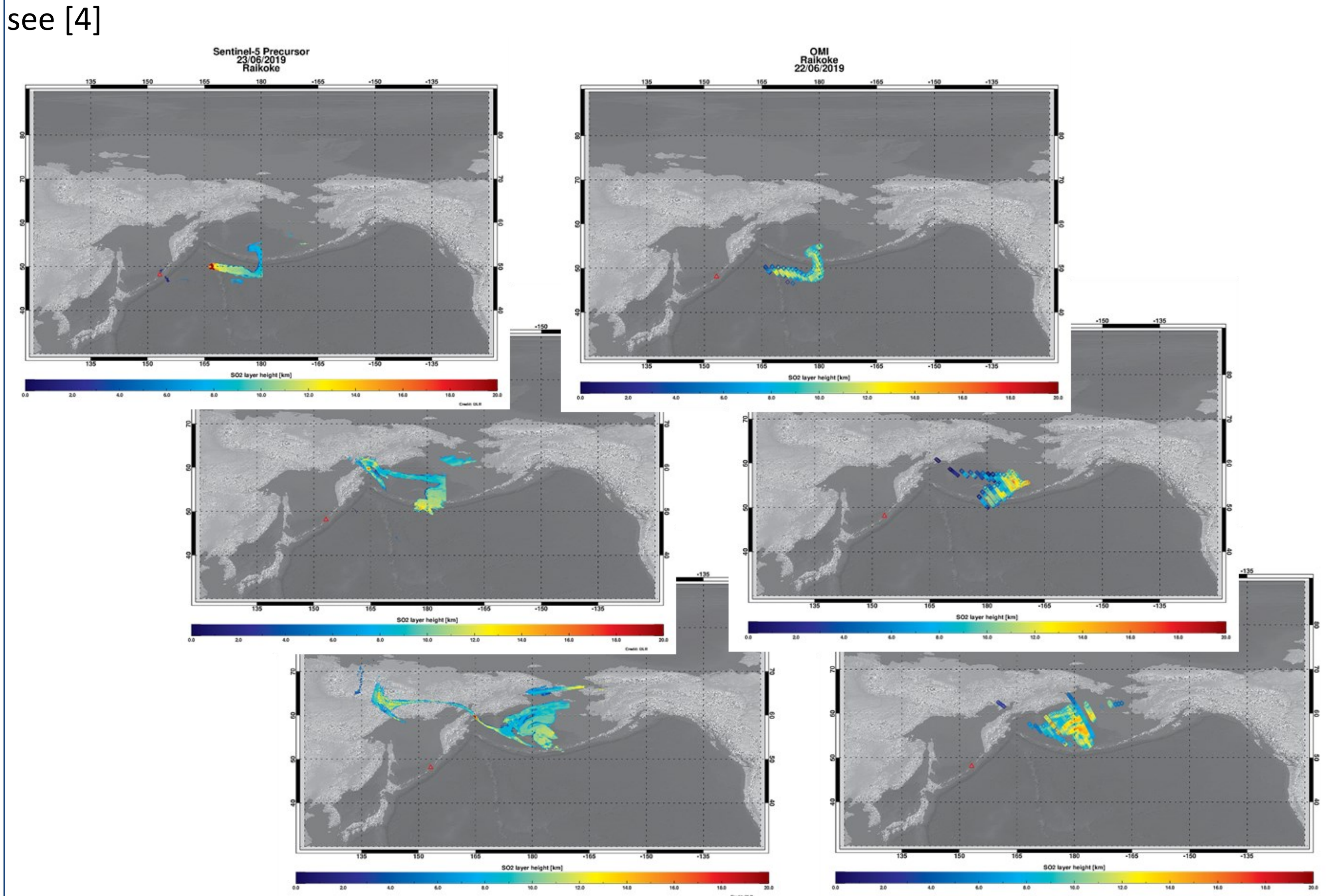

Fig. 1: TROPOMI SO_2 LH (left) and OMI SO_2 LH (right) retrieved by FP_ILM for the first days of the Raikoke eruption 2019 . Credit: DLR/ESA and NASA/DLR

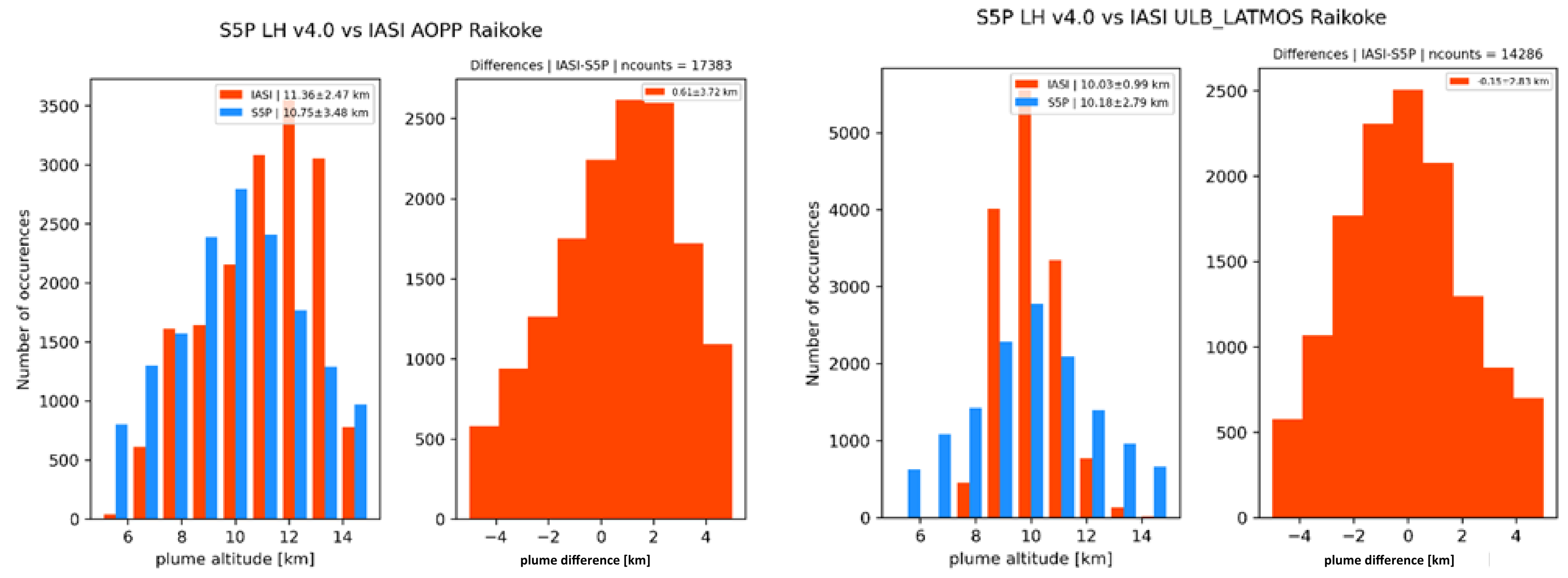

Fig 2: Histogram difference between TROPOMI and IASI SO_2 LH for all collocations of the Raikoke eruption.
The validation against the Univ. Oxford AOPP LH product is shown in the left panel whereas the right panel shows the validation against the ULB LATMOS LH product .

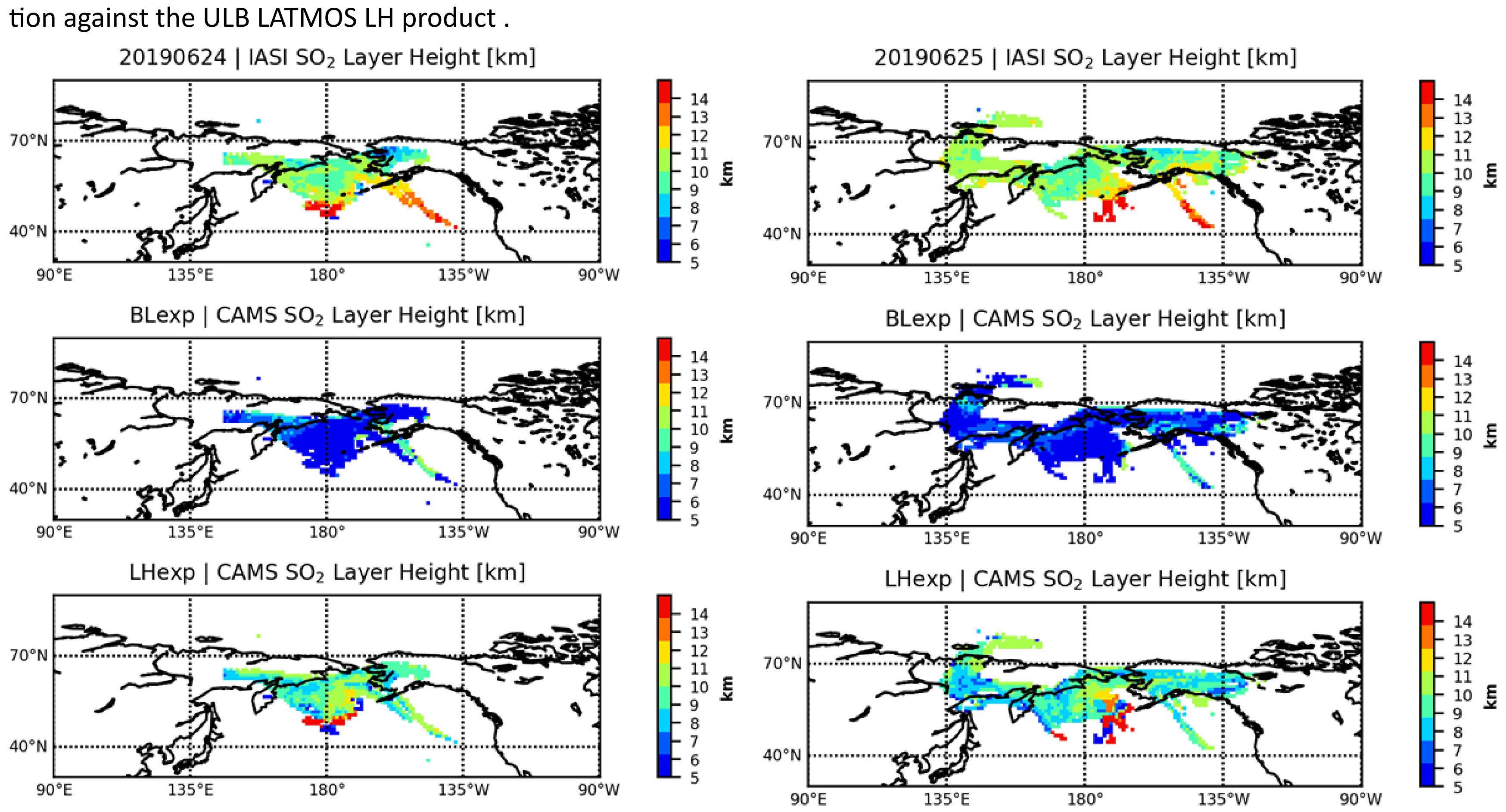

Fig.3: ECMWW/CAMS SO_2 forecast using different products.
Top row: IASI SO_2 LH of the Raikoke eruption on 24 (left) and 25 June (right).
Center row: Baseline ECMWF/CAMS SO_2 forecast using fixed LH as prior.
Bottom row: LH forecast after assimilating TROPOMI SO_2 LH product

In order to forecast the SO_2 plume movement, ECMWF/CAMS is assimilating the GOME2 and TROPOMI SO_2 VCD. Due to the lack of vertical information, in the baseline experiment BLexp the plume is positioned around 5km altitude, which works good for most moderate eruptions. However, for strong, high altitude eruption, this assumption no longer holds and the forecast in completely off (see Fig. 3, center row). When assimiliating the TROPOMI SO_2 LH product (LHexp), the forecast is significantly improved (Fig. 3, bottom row) and the resulting forecast field is in agreement with the IASI SO_2 LH (Fig. 3, top row). For details, see [4,5]

La Soufriere eruption April 2021

On 8 April 2021, the La Soufriere volcano erupted on the Caribbean Island of St. Vincent with a strong ash and SO_2 cloud, which could be detected by S5p/TROPOMI and OMI, showing SO_2 LH up to 20km, see Fig. 4. Clearly, a difference between the OMI (Fig. 4, right) and TROPOMI SO_2 LH (Fig. 4, left) is visible, which is currently under investigation. Most likely this is an effect of ash, which is currently not considered in the SO_2 LH retrievals.

The comparison with the two IASI SO_2 products in Fig. 5 shows a good agreement with a mean LH difference between the sensors of about ±0.6±3.6km (see [4] for details).

During the La Soufriere eruption an CALIPSO overpass enabled the comparison against the ash LH (not shown), showing a height difference between the CALIPSO ash LH and the TROPOMI SO_2 LH of about 1km (see [4] for details).

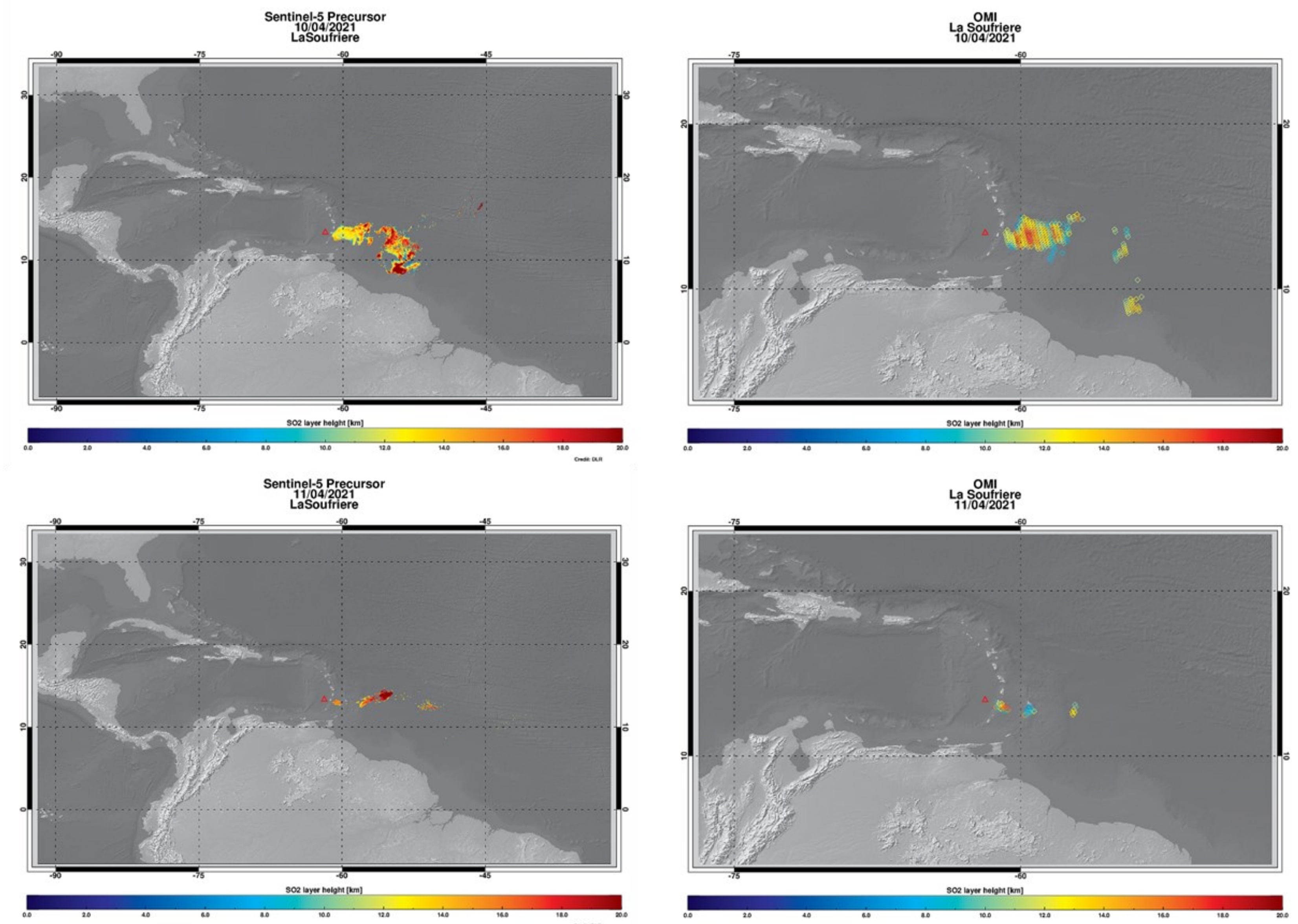

Fig. 4: TROPOMI SO_2 LH (left) and OMI SO_2 LH (right) retrieved by FP_ILM for the first days of the La Soufriere eruption 2021. Credit: DLR/ESA and NASA/DLR

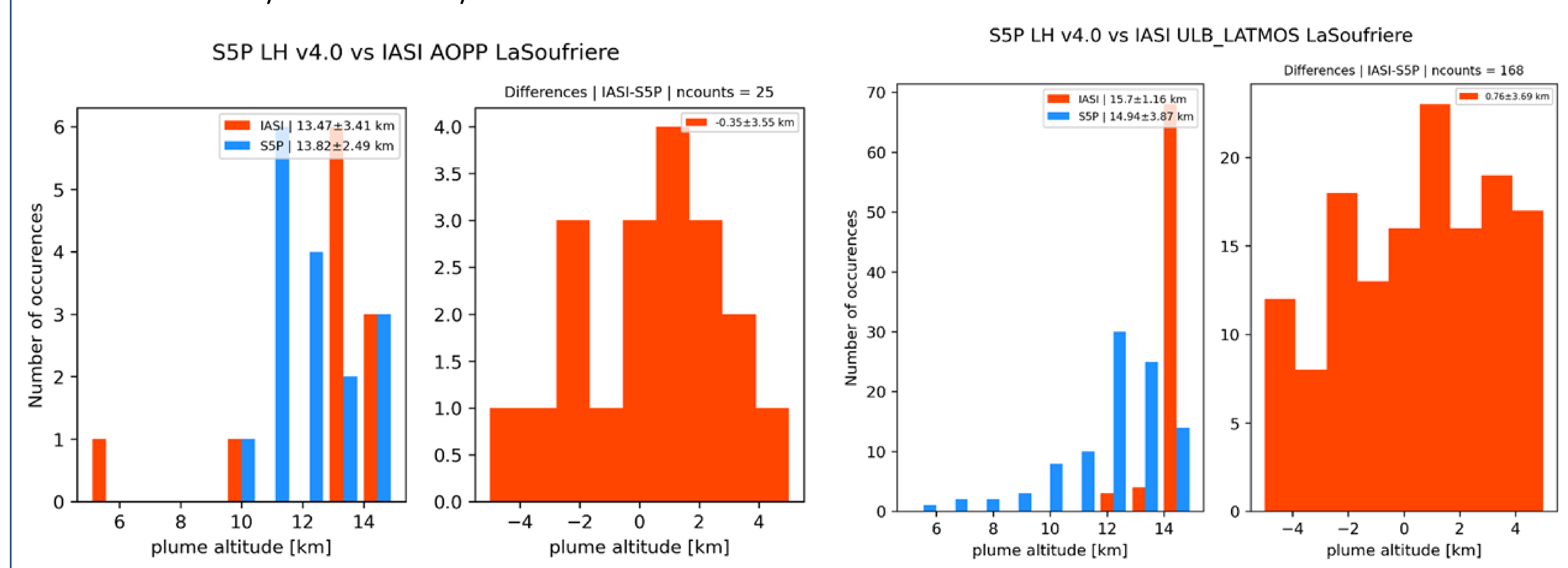

Fig 5: Histogram comparison of TROPOMI and IASI SO_2 LH for all collocations of the La Soufriere eruption.
The validation against the Univ. Oxford AOPP LH product is shown in the left panel whereas the right panel shows the validation against the ULB LATMOS LH product .

References

[1] D. Efremenko, et al. (2017): Volcanic SO2 plume height retrieval from UV sensors using inverse learning machines IJRS, Vol 38
[2] P. Hedelt, et al. (2019): SO2 Layer Height retrieval from Sentinel-5 Precursor/TROPOMI using FP_ILM, AMT-2019-13, Vol. 12, No. 10
[3] N. M. Fedkin, et al. (2020): Volcanic SO2 Effective Layer Height Retrieval for OMI Using a Machine Learning Approach, AMT, Vol14
[4] M.E. Koukouli, et al. (2021): Volcanic SO2 Layer Height by TROPOMI/S5P; validation against IASI/MetOp and CALIOP/CALIPSO observations, submitted to ACP , under review
[5] A. Inness, et al. (2021) The CAMS volcanic forecasting system utilizing near-real time data assimilation of S5P/TROPOMI SO2 retrievals, submitted to GMD, under review