Sulphur dioxide from ground-based Fourier transform infrared spectroscopy: application to volcanic emissions

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Motivation

- FTIR harmonised SO_2 retrieval within NDACC/IRWG
- Volcanic emissions, but it could be extended to other SO_2 sources

NDACC sites and Volcanoes

- **Arrival Heights** (AH, Antarctica) – **Erebus** (1972-ongoing)
- **Altzomoni** (ALT, Mexico) – **Popocatépetl** (1994-ongoing)
- **Mauna Loa** (MLO, USA) – **Kilauea** (May-Aug 2018)
- **Izaña** (IZO, Spain) – **Cumbre Vieja** (Sep-Dec 2021)
- **Reunion Island/Maido** (MAI, France) – **Piton de La Fournaise** (1999-ongoing)
    Hunga Tonga (Dic 2021-Jan 2022)
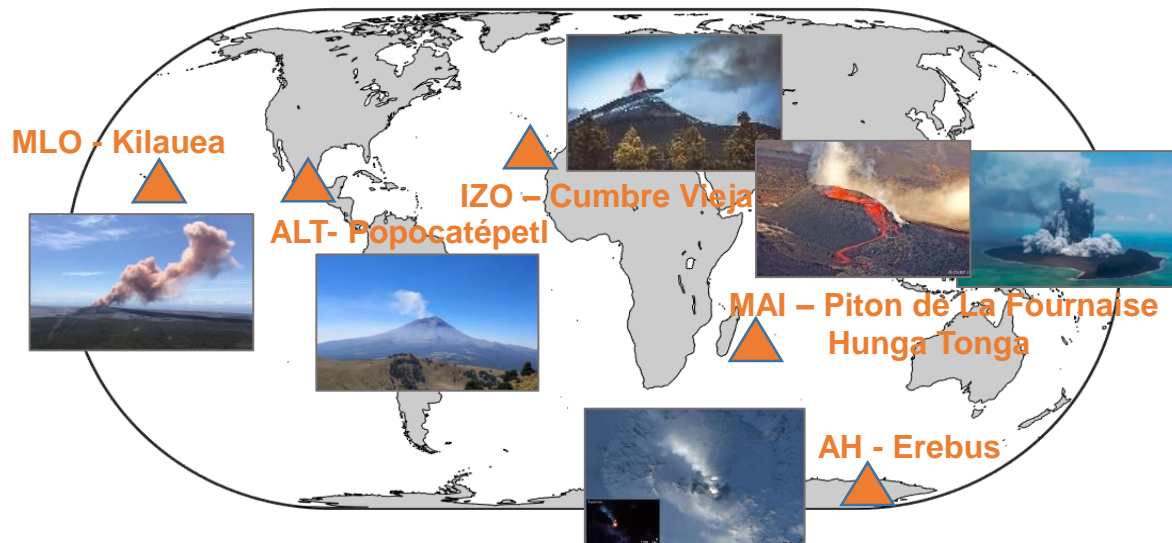
SO$_2$ Retrieval Strategies (1/2)

- Based on Taquet et al. (2019), but they have been optimized and applied consistently to all FTIR sites

Variability in the Gas Composition of the Popocatépetl Volcanic Plume

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MW (cm^{-1})	Filter/Detector	Interfering Gases	Fit
2480-2520	S3&S4, InSb	H$_2$O, CO$_2$, O$_3$, CH$_4$, N$_2$O, SO$_2$	Scale retrieval for all gases
1120-1180	S6, MCT	H$_2$O, HDO, CO$_2$, O$_3$, CH$_4$, N$_2$O, SO$_2$, CFC12	**Profile retrieval for SO$_2$**, H$_2$O, O$_3$ Scale retrieval for the remaining gases

- For 1100 cm^{-1} region the **positive constrain using a profile retrieval on a logarithmic scale** is **CRITICAL,** because it avoids SO$_2$ negative concentrations and provides more stable retrievals.

- Total **DOFS ≈ 1**
(SO$_2$ vertical information is not retrievable!).

- WACCM v6 for all a priori profiles, except for SO$_2$
(on-site information!).
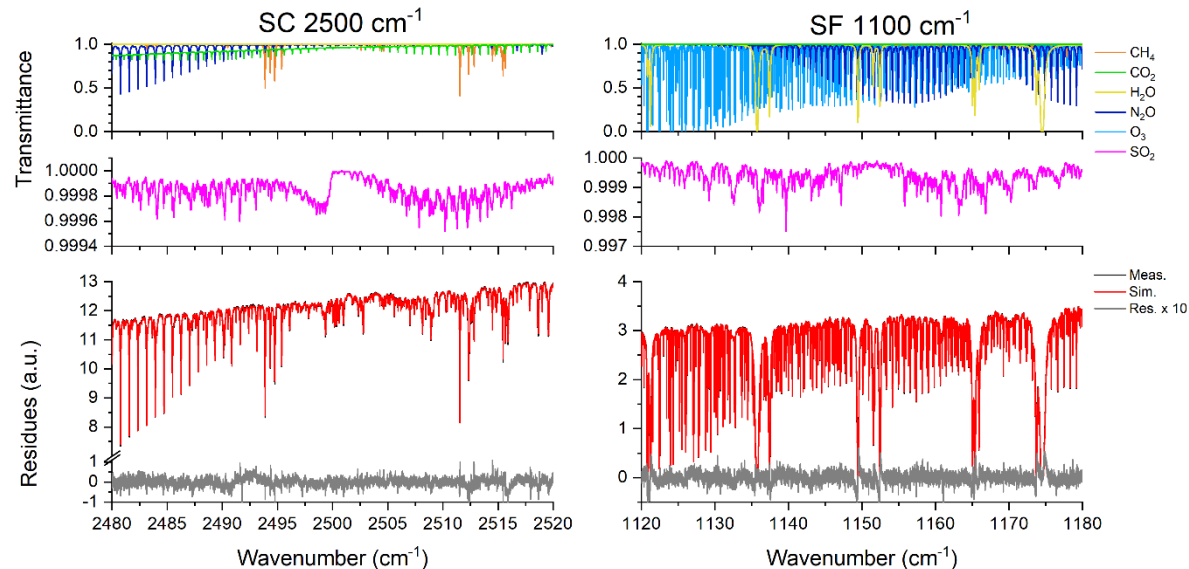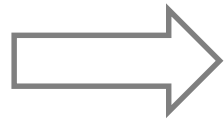
SO₂ Retrieval Strategies (2/2)

- HITRAN 2008/2020 Comparison

HIT2020 > HIT2008 by 1% for 2500 cm^{-1}

(fitting residuals&convergence&comparison wrt Brewer/Pandora are similar)

HIT2020 < HIT2008 by 3% for 1150 cm^{-1}

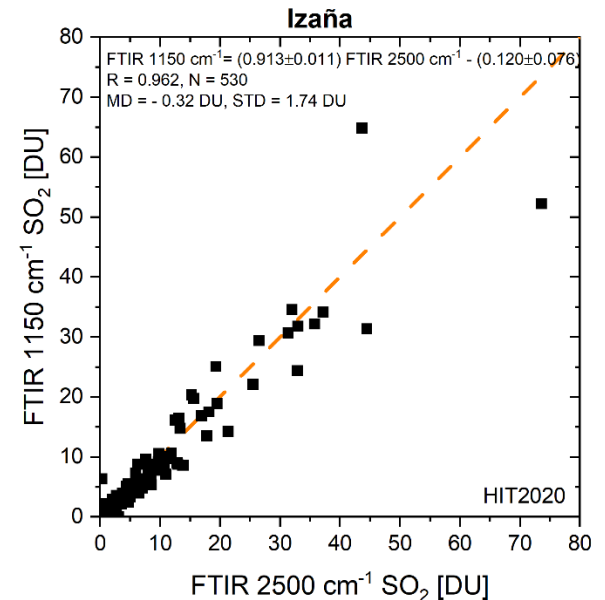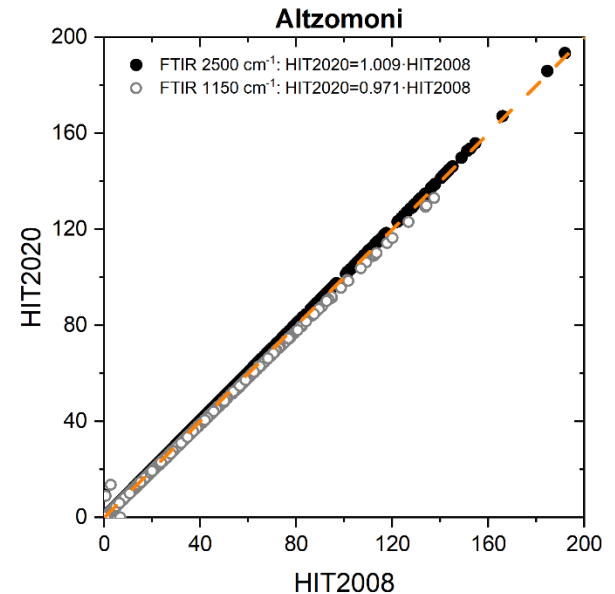(fitting residuals (4%)&convergence&comparison wrt Brewer/Pandora are better for HIT2020)

⟹ **HIT2020 for all gases**

- Consistency between 2500 cm^{-1} and 1150 cm^{-1}

Temporal Window: ± 10 min

Mean Difference (1150 cm^{-1} - 2500 cm^{-1}) = -0.32 DU

STD =1.74 DU, Greater variability for large SO₂ columns

Altzomoni

- FTIR 2500 cm^{-1}: HIT2020=1.009·HIT2008
○ FTIR 1150 cm^{-1}: HIT2020=0.971·HIT2008

Izaña

FTIR 1150 cm^{-1}= (0.913±0.011) FTIR 2500 cm^{-1} - (0.120±0.076)
R = 0.962, N = 530
MD = - 0.32 DU, STD = 1.74 DU

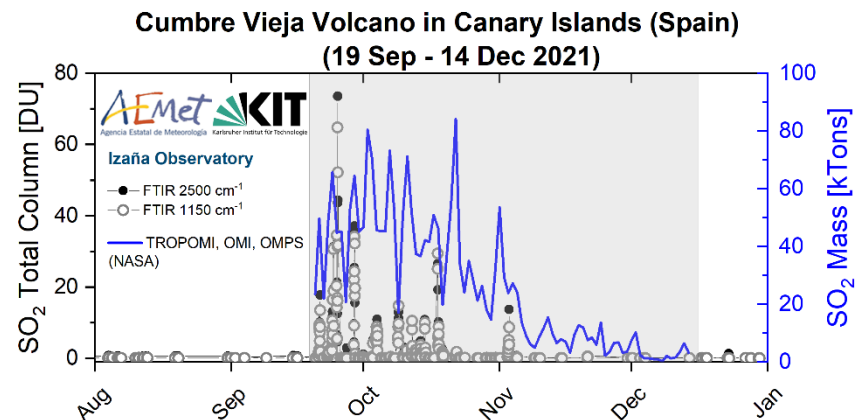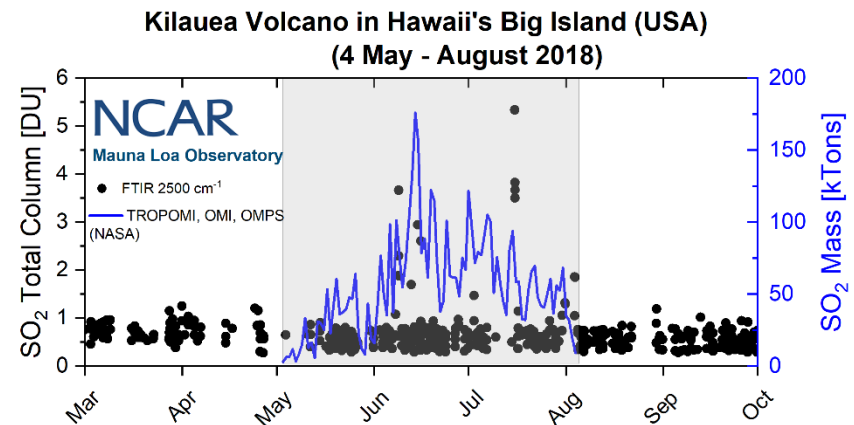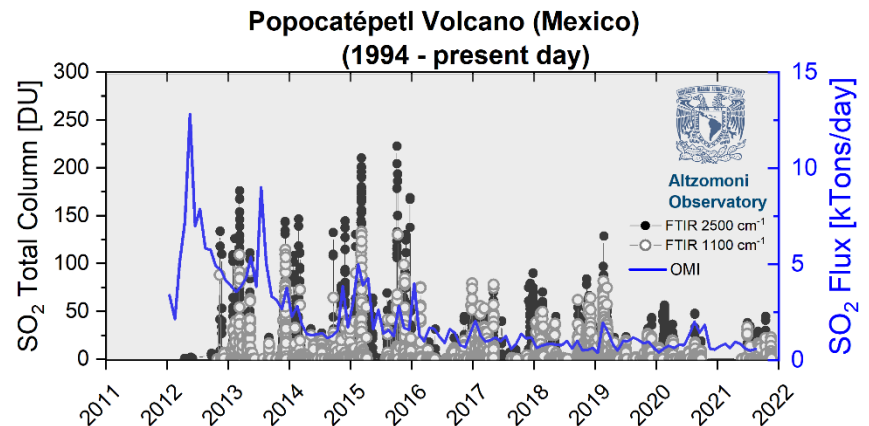HIT2020

SO$_2$ Time Series

ALT ~ 10 km from Popocatépetl=>
SO$_2$ enhancements as large as 250 DU
Great variability (very quick SO$_2$ changes)
Continuous SO$_2$ signal, pure plume

MLO ~ 33 km from Kilauea=>
Sparse and low SO$_2$ enhacements of 5 DU
SO$_2$ background < 1 DU

IZO ~ 140 km from Cumbre Vieja=>
Moderate SO$_2$ enhancements between 10-70 DU
SO$_2$ plume transport, pure plume
SO$_2$ background < 1 DU

Space-based SO$_2$ flux for Popocatépeti from Boulesteix et. al., Modulation of Popocatépetl's activity by regional and worldwide earthquakes, Bulletin of Volcanology, in press, 2022.

Space-based SO$_2$ mass for Kilauea and Cumbre Vieja from NASA (https://so2.gsfc.nasa.gov/)

Popocatépetl Volcano (Mexico)
(1994 - present day)

Kilauea Volcano in Hawaii's Big Island (USA)
(4 May - August 2018)

Cumbre Vieja Volcano in Canary Islands (Spain)
(19 Sep - 14 Dec 2021)

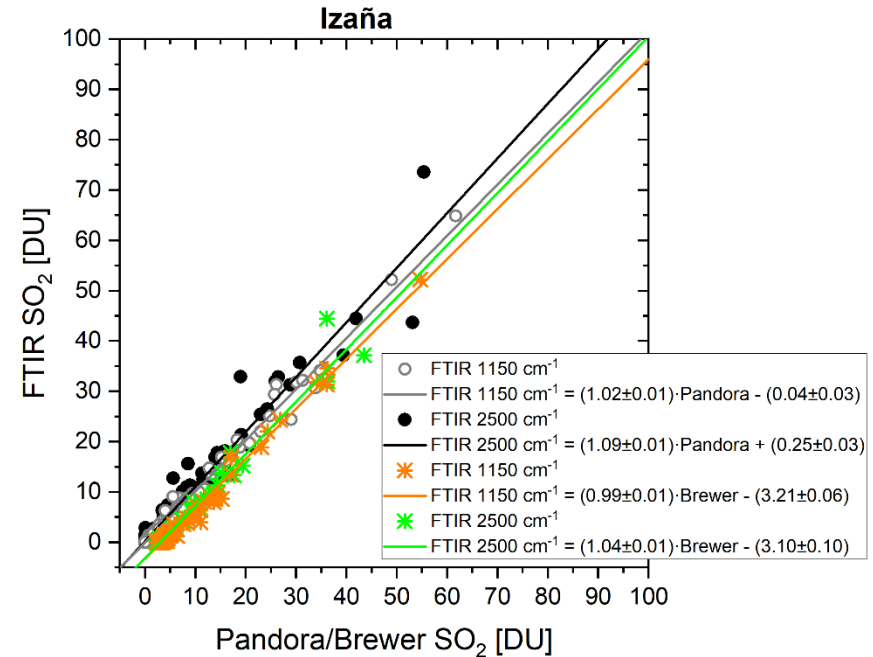# Comparison to Other Reference Observations: Izaña

Pandora/Brewer (Sep2021 - Feb2022)

Temporal Window: ± 10 min

Difference = FTIR - Pandora/Brewer

Izaña

Pandora (All SO2>0)	MD (DU)	STD (DU)	R
2500 cm^{-1} HIT2008	0.535	1.368	0.981
2500 cm^{-1} HIT2020	**0.463**	**1.368**	0.981
1150 cm^{-1} HIT2008	0.085	0.697	0.995
1150 cm^{-1} HIT2020	**-0.007**	**0.623**	0.995

Brewer	MD (DU)	STD (DU)	R
2500 cm^{-1} HIT2008	-2.836	0.975	0.984
2500 cm^{-1} HIT2020	**-2.897**	**0.978**	0.984
1150 cm^{-1} HIT2008	-3.160	0.698	0.995
1150 cm^{-1} HIT2020	**-3.248**	**0.670**	0.995

Excellent correlation for all SO$_2$ range

HITRAN 2020 provides the best agreement between techniques (1150 cm^{-1})

Brewer shows a positive bias of 3 DU (SO$_2$ cross section?)

Comparison to Other Reference Observations: Altzomoni

Pandora (2019 - Feb2022)

Temporal Window: ± 12 sec

Difference = FTIR - Pandora

Altzomoni

FTIR 1150 cm^{-1}
FTIR 1150 cm^{-1} = (1.13±0.01)·Pandora + (0.07±0.09)
FTIR 2500 cm^{-1}
FTIR 2500 cm^{-1} = (1.26±0.01)·Pandora + (0.07±0.07)

Pandora-ALT (All SO2>0)*	MD (DU)	STD (DU)	R
2500 cm^{-1} HIT2008	1.789	**4.023**	0.994
2500 cm^{-1} HIT2020	**1.752**	4.182	0.994
1150 cm^{-1} HIT2008	0.710	1.913	0.997
1150 cm^{-1} HIT2020	**0.549**	**1.635**	0.997

Pandora-IZO (All SO2>0)	MD (DU)	STD (DU)	R
2500 cm^{-1} HIT2008	0.535	1.368	0.981
2500 cm^{-1} HIT2020	**0.463**	**1.368**	0.981
1150 cm^{-1} HIT2008	0.085	0.697	0.995
1150 cm^{-1} HIT2020	**-0.007**	**0.623**	0.995

* Comparison ruling out plumes not detected by one of the techniques
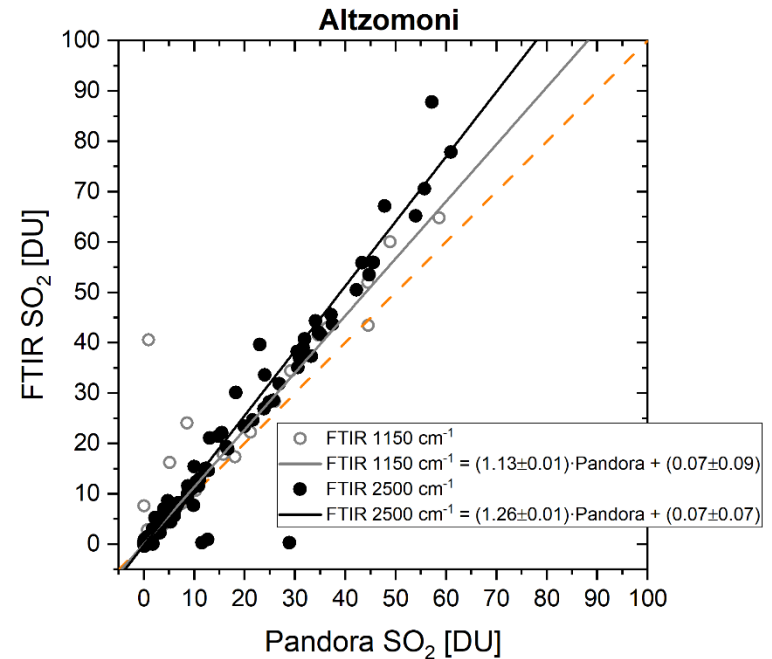
Altzomoni FTIR-Pandora comparison shows a bias wrt Izaña comparison

Altzomoni doubles the scatter observed at IZO (greater SO$_2$ variability)

Scatter between techniques is comparable to background signal!!

Summary and Outlook

- **Harmonised SO$_2$ retrieval strategy** valid for different volcanic events (high SO$_2$ amounts and quick SO$_2$ changes, low enhacements, …)

- **Consistent SO$_2$ retrievals from two spectral regions** (covered by MCT and InSb detectors), which allows ratios among different co-emitted volcanic gases to be assessed in order to understand the evolution of volcanic eruptions (i.e. HCl, HBr, SiF$_4$, CO).

- Different tests are still pending (HIT2008 vs HIT2020, WACCM V6 vs V7, TIKP vs OE, uncertainty assesment, …)**. However,**

- Excellent agreement with other reference observations: **reliable FTIR SO$_2$ retrieval**!!!

- Maido and Arrival Heights SO$_2$ retrievals are ongoing. **Other FTIR sites affected by volcanic emissions**?

- Retrieval strategy valid for **other SO$_2$ sources**? Other FTIR sites?

Many thanks!!!!