

Remote Monitoring of Volcanic Eruptions using IMS Infrasound Data

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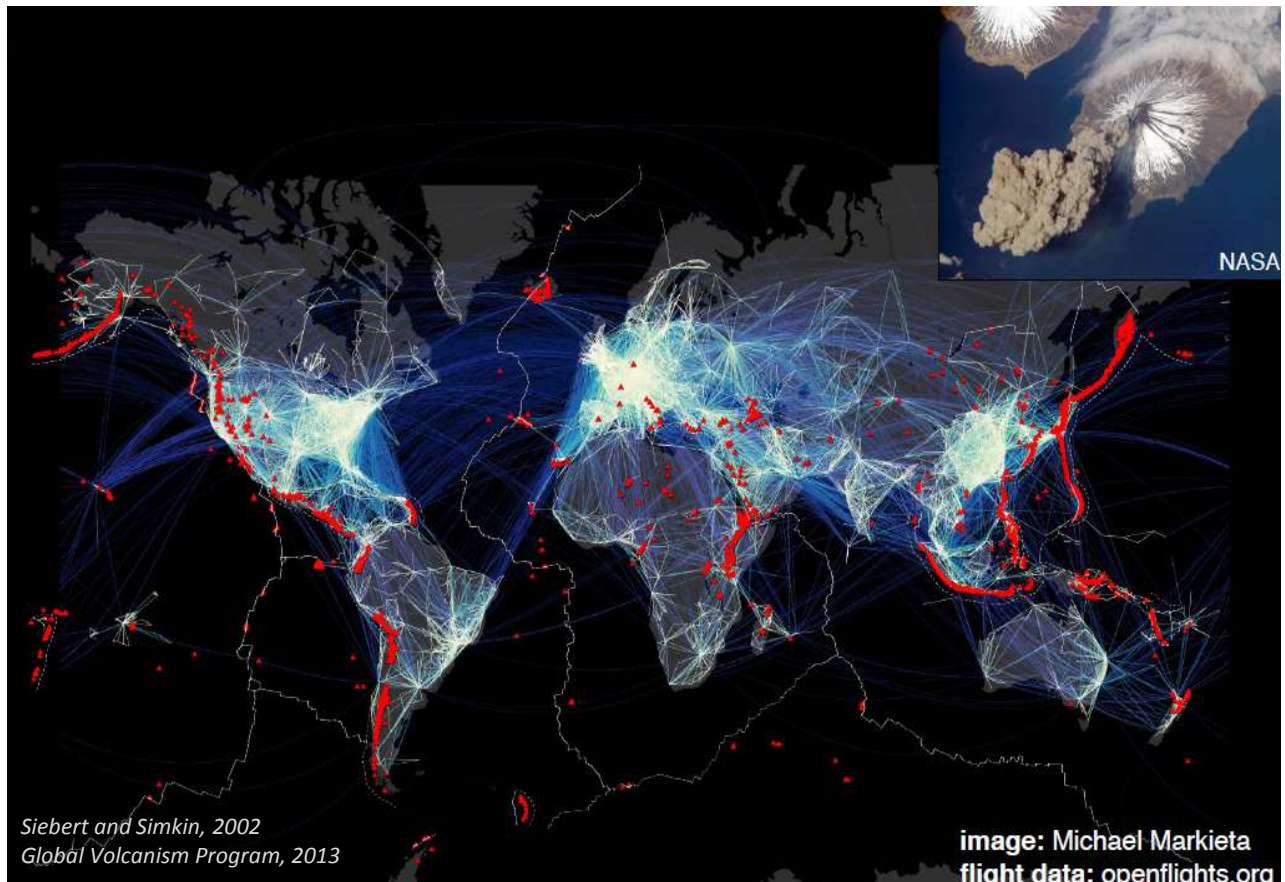
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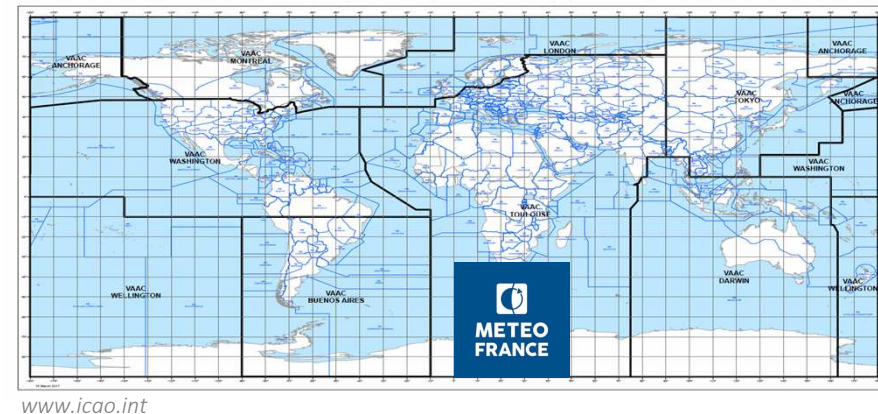
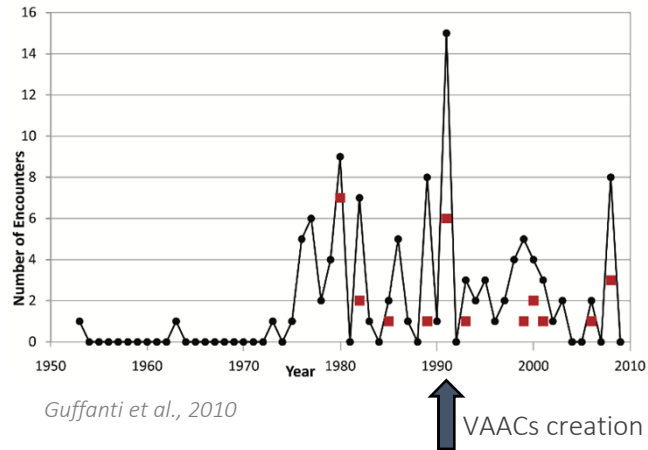
³ Comprehensive Nuclear-Test-Ban Treaty Organization (CTBTO/IDC, Austria)

⁴ VAAC Toulouse (Météo France, France)



- ~1500 active volcanoes worldwide over the past 10,000 years
- Serious hazards to aircraft in flight near to the ash plume
- Many of the world's volcanoes lack dedicated monitoring instruments





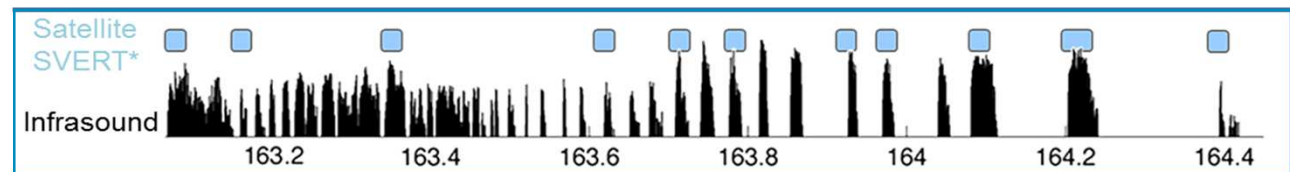
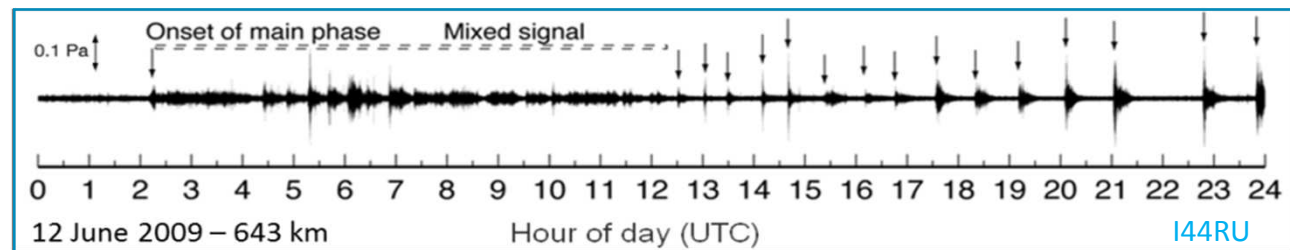
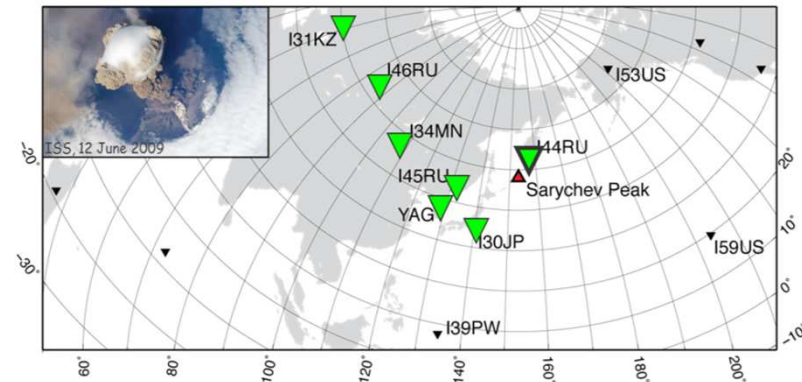
- **94** ash encounters of commercial flights between 1953 and 2009; whereas **9** encounters caused engine shutdown during flight
- On average, 2 damaging encounters per year since 1976, mostly occurring **within 24 hours** from the eruption and at **less than 1000 km** from the volcano

- Volcanic Ash Advisory Centers (VAACs) are mandated by the International Civil Aviation Organization (ICAO) to coordinate and disseminate information on volcanic ash clouds
- Global and continuous **infrasound** recordings **supplement other techniques** to remotely monitor volcano activity, which has already been expressed from ICAO to CTBTO in 2005; therefore IDC is in discussions with VAAC Toulouse since 2007

- Many research studies demonstrated the feasibility of detecting volcanic eruptions with infrasound*

Ex: large-scale eruptions of Sarychev Peak, Kuril Islands, June 2009

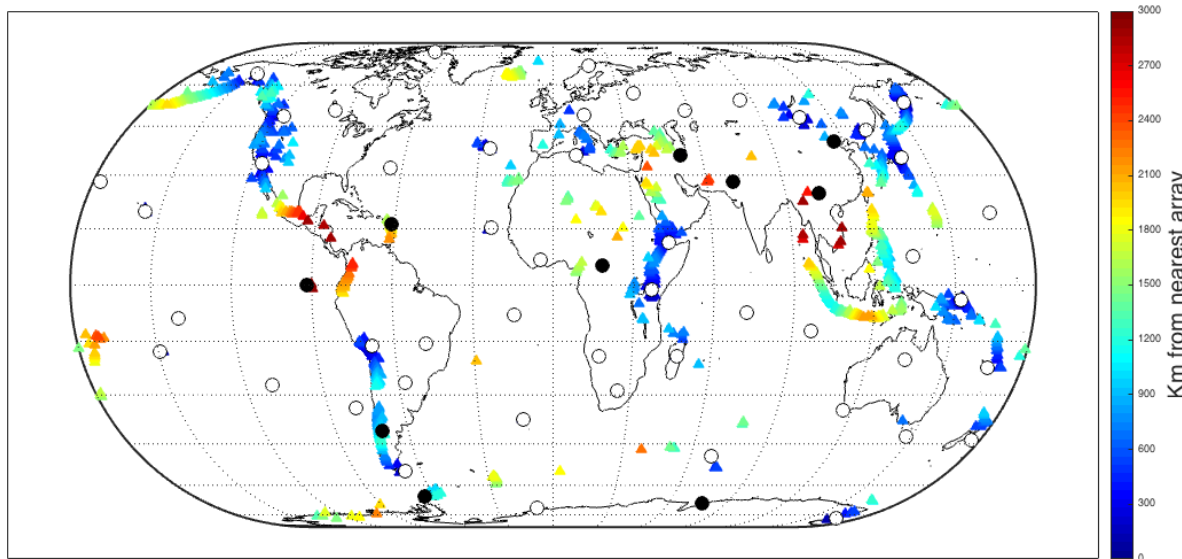
- 6 detecting IMS stations downwind (640-6400 km range)
- At 640 km (I44RU), eruption sequence detailed in high resolution
- Infrasound can complement satellite monitoring, especially in case of **dense cloud coverage**



* *McCornack et al, 2006*
Garcés et al, 2008
Dabrowa et al, 2011
Olivieri et al, 2013
Fee et al, 2013

Matoza et al., 2011

Distribution of IMS infrasound arrays and volcanoes (triangles) that had activity during the last 10,000 years. For each volcano, the distance to the nearest IMS infrasound station is colour-coded.

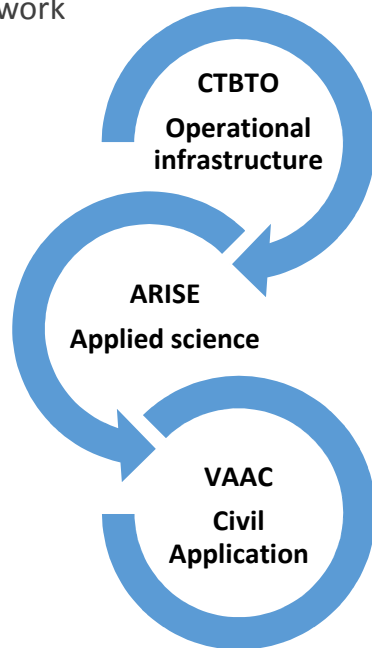


Ceranna et al, 2018

- Multi-year continuous quality recordings
- Global coverage : as of December 2016, median distance from any volcano to the nearest IMS infrasound array was ~980 km
 - ➔ mean travel time of ~55 min assuming an isotropic propagation with a celerity of 0.3 km/s

Development of a Volcanic Information System (VIS)

The synergy CTBTO / ARISE (Atmospheric dynamics Research InfraStructure in Europe, H2020 project funded by EU 2015-2018; arise-project.eu) offers a unique opportunity for the VIS establishment using infrasound data from a global station network

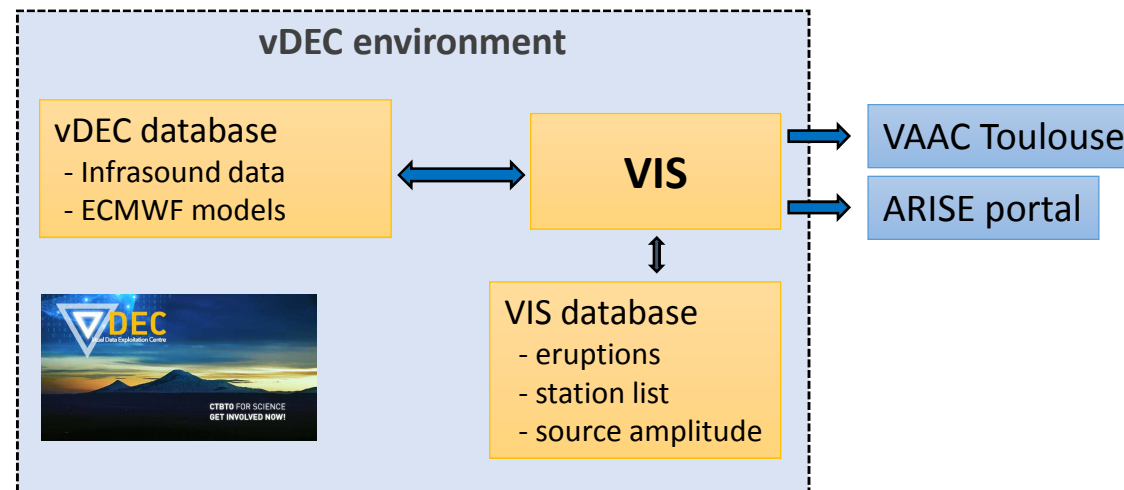


- ARISE advanced products provide valuable parametric inputs on the atmosphere dynamics that drives the infrasound wave propagation
- CTBTO brings its operational infrastructure to support dissemination of information to VAACs through the VIS
- The proposed approach is tested with **VAAC Toulouse**, mandated by the ICAO, to demonstrate the usefulness of infrasonic data to International Airways Volcano Watch

Prototype system has been developed within ARISE-2 project (2018)

Objectives:

- Detect a volcanic eruption as soon and as certainly as possible, accounting for long-range propagation effects
- Disseminate the information and provide updates to VAAC and ARISE data portal
- Estimate volcanic source term (origin time and amplitude), critical parameters to model ash dispersion
- Get a low false alerts rate through adequate parameterization



Search for infrasound detections matching with a known volcano

Select and filter data, search criteria: distance (<3000 km), azimuth (+/- 10°), frequency [*Brachet et al, 2010*]

Search for grouped detections: the origin time of the eruption corresponds to the period overlap $T_0 \pm DT$ for the detecting stations

Infer source amplitude from far field observations using semi-empirical frequency and wind-dependent attenuation relation [*Le Pichon et al., 2012*]; discard strongly attenuated signals (>110 dB)

Build eruption events from detections

Eruptive sequences triggered evaluating Infrasound Parameter (IP)

Sequencing: notification sent every **3 hours** when an eruption is detected; 1 notification with state "Ended" when no detection have been recorded for 6 h

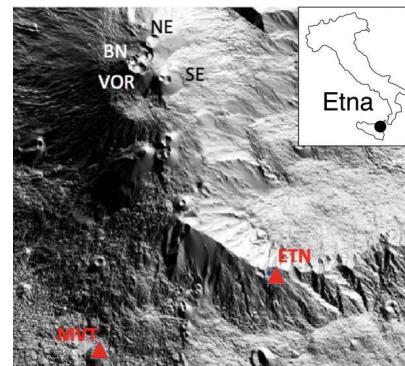
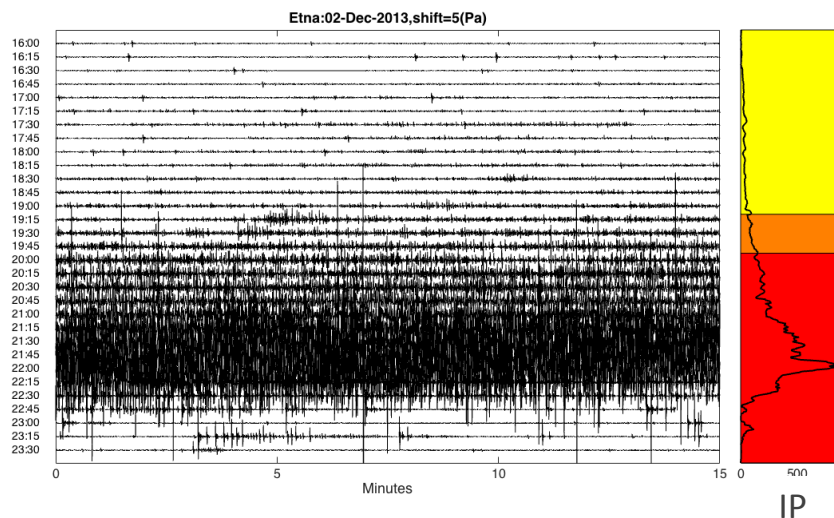
Adapting near-field results to improve far-field analysis

Infrasound Parameter (IP) used to characterize the eruption persistency and magnitude. It used to reduce false alarms:

$$IP = N_{det} \times A_m$$

N_{det} : number of detections per minute

A_m : average RMS pressure @1 km of the source



Marchetti et al., 2018

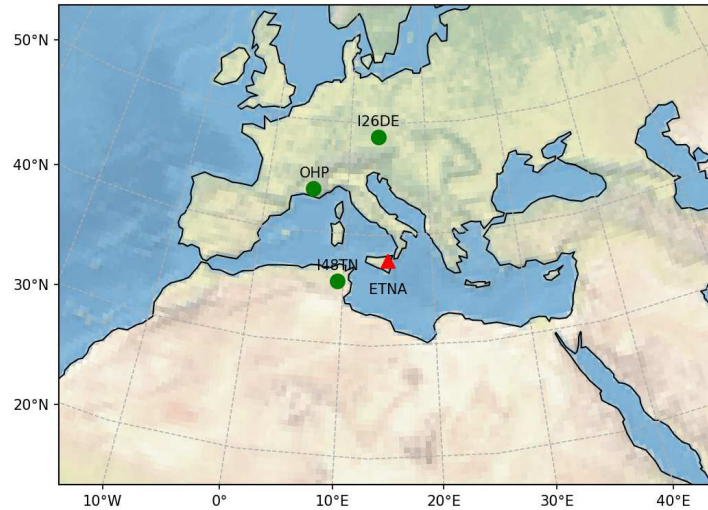
2 infrasound arrays

- ETN @ 5 km
- MVT @ 6 km

processed in real time to provide a single parameter describing activity (IP)



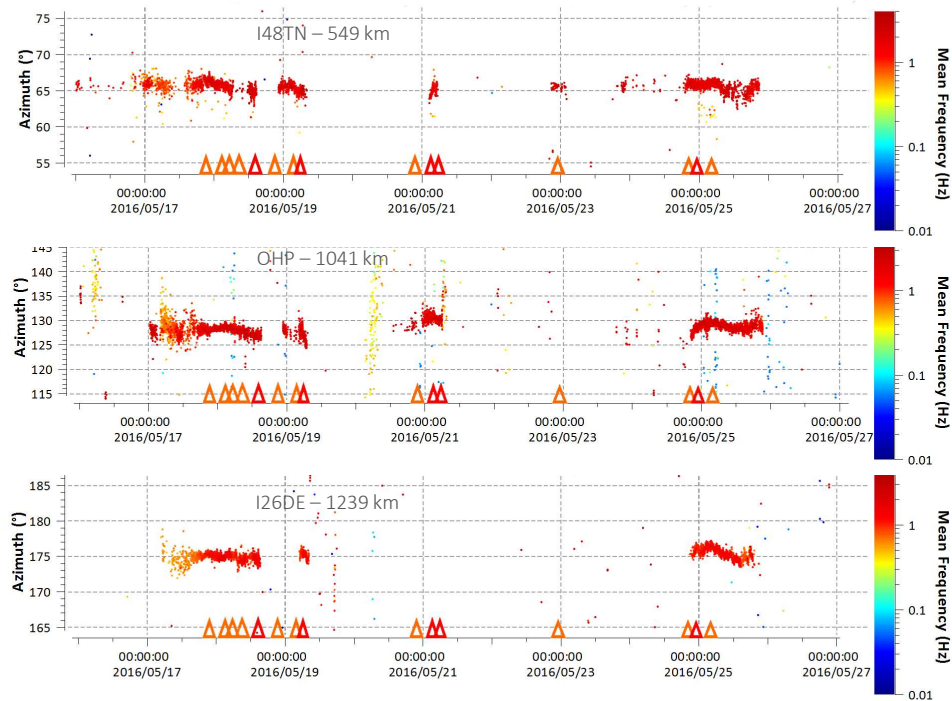
Marchetti et al, T5.2-05
Thursday 27th – 10am



Source: INGV

- Well monitored volcano by experimental nearfield infrasound arrays operated by Univ. of Firenze (UNIFI) since 2007. Good candidate to assess the detection capability of the European infrasound network.
- Downwind, there are clear detections from Etna eruptive episodes at I48TN (550 km), I26DE (1240 km) and other ARISE experimental arrays (e.g. OHP, France – 1040 km)

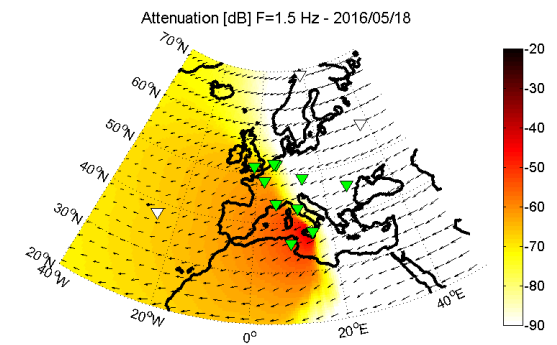
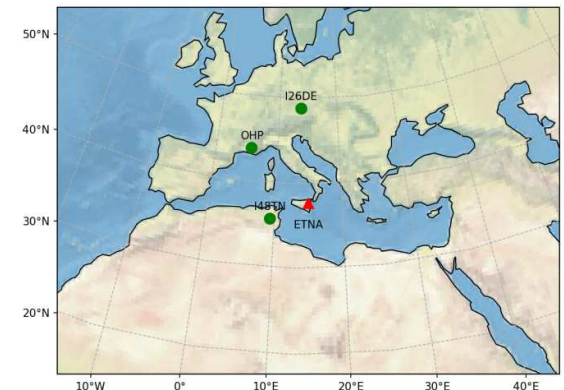
Comparison between infrasound detections from regional arrays and VAAC advisories



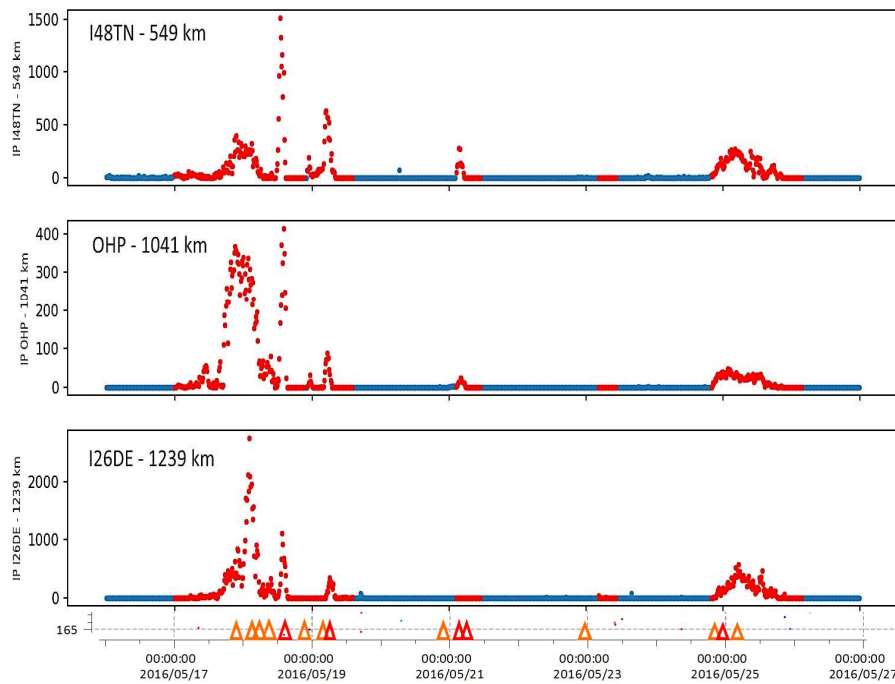
Aviation color code

- Orange: volcanic eruption is underway with no or minor ash emission
- Red: eruption is underway with significant emission of ash into the atmosphere

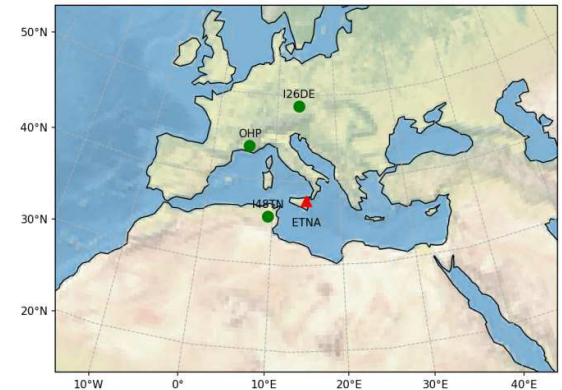
Source: Météo France, VAAC Toulouse



Comparison between IP calculated for regional arrays and VAAC advisories



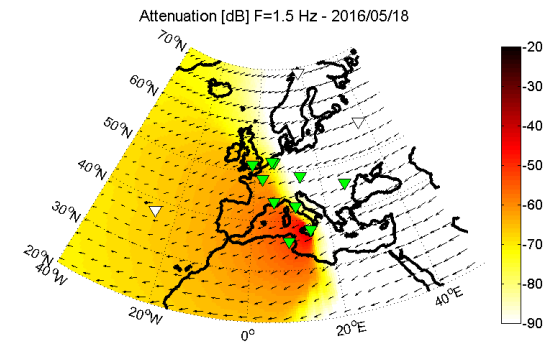
- IP every 15 min
- Threshold : $IP \geq 10$
- Attenuation < 110 dB




Aviation color code

- ▲ Orange: volcanic eruption is underway with no or minor ash emission
- ▲ Red: eruption is underway with significant emission of ash into the atmosphere

Source: Météo France, VAAC Toulouse



- The 3 major eruptive sequences are well observed stations and match the emitted VAAs
- The IP indicator timely account for the dynamic of the eruption



VOLCANO NOTIFICATION TO VAAC
Volcanic Information System v2018.2

Notification

ID : ETNA2016144
ISSUED : 2018/08/15 12:55:00 UTC
REVISION : 17
ISSUED BY : CEA (ARISE)
RECIPIENT : VAAC TOULOUSE (METEO FRANCE)

Volcano

NAME : ETNA
ID : 211060
LATITUDE : 37.73
LONGITUDE : 15.0
ELEVATION : 3350 m

Summary

START TIME : 2016/05/23 20:35:06 UTC
END TIME : 2016/05/25 20:29:58 UTC
STATUS : ENDED

STATION	DISTANCE (km)	NB DETECTIONS	MAX AMPLITUDE (Pa)	EST. AMPLITUDE (Pa)
I48TN	549	1339	0.05566	260
OHP	1041	2179	0.04394	46
I26DE	1239	1039	0.01154	510

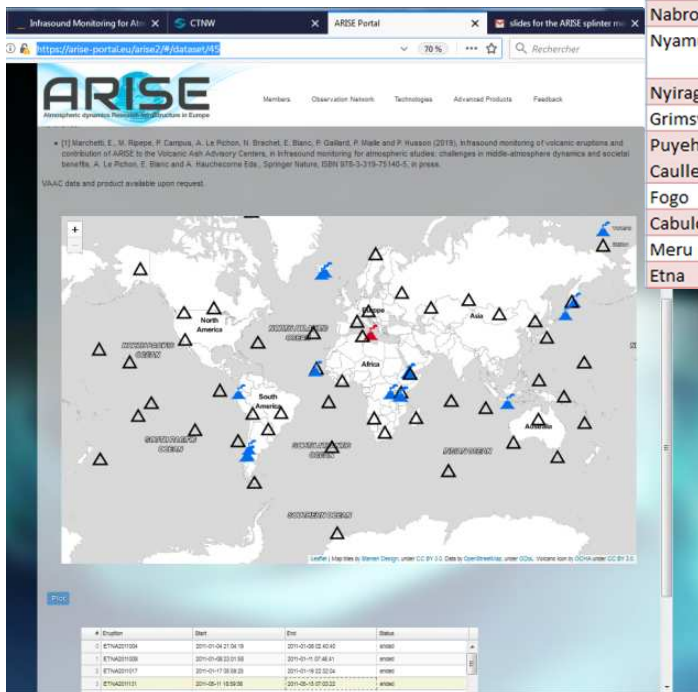
SOURCE AMPLITUDE : 510 Pa

Application

VIS evaluation of historic data

Sources: VAAC Toulouse, London, Buenos Aires and Global Volcanism Program

Volcano name	Country	Year	VAA emitted by	Start Date (VIS)	End Date (VIS)	Stations detecting
Eyjafjallajokull	Iceland	2010	VAAC London	30/04/2010	11/05/2010	I18DK, I26DE
Dubbi	Eritrea	2011	VAAC Toulouse	12/06/2011*	*	A notification is triggered for Dubbi in the same time with Nabro because I32KE (1700km) cannot differentiate the two volcanoes. I19DJ(260km) provides data only since Sept. 2011
Nabro	Eritrea	2011	VAAC Toulouse	12/06/2011	11/07/2011	I32KE, several eruptions over this period
Nyamuragira	RD Congo	2011	VAAC Toulouse	07/11/2011	27/11/2011	I32KE, impossible to differentiate with Nyiragongo. Volcanoes are too close.
Nyiragongo	RD Congo	2011	VAAC Toulouse	11/03/2011	04/04/2011	I32KE, several eruptions over this period
Grimsvotn	Iceland	2011	VAAC London	22/05/2011	22/05/2011	I18DK
Puyehue-Cordon Caulle	Chile	2011	VAAC Buenos Aires	04/06/2011	10/06/2011	I02AR, I41PY, I08BO
Fogo	Cape Verde	2014	VAAC Toulouse	27/11/2014	04/12/2014	I11CV
Cabulco	Chile	2015	VAAC Buenos Aires	22/04/2015	23/04/2015	I14CL, I02AR, I08BO, I09BR
Meru	Tanzania	2015	VAAC Toulouse			No detection and no confirmed eruption
Etna	Italy	2016	VAAC Toulouse	16/05/2016	25/05/2016	I48TN, (OHP), I26DE



ARISE data portal

Science and Technology Conference, Vienna, Austria, 24 – 28 June 2019

- VIS was able to **detect all the major eruptions (VEI 3-4)** associated with the VAA we tested
 - Systematic comparison with UNIFI Early Warning results (2008-2016)
- > The most significant episodes of lava fountaining and ash eruptions are well identified
- > For smaller events, **system performances highly depend on favorable propagation conditions**

- Scientific collaboration on VIS is an asset for ARISE (research), CTBTO (operations) and ICAO/WMO (civil application, safety) communities
- VIS prototype has been developed and tested in ARISE-2 Design Study with the operational support of CTBTO
- First results are promising, especially in the case of major eruptions

Future work:

- Improve the reliability of the notification results, reduce the false alarms rate. Further evaluation required, using volcanic eruption database (GVP, REB...)
- Calculate the source amplitude from long range infrasound measurements to estimate the acoustic energy (in relation with the flux of ash injection in the atmosphere)
- Integrate data from regional infrasound array to lower response time and improve reliability
- **Implement VIS in a near real-time environment**