

Active volcanoes muon tomography

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Collaboration DIAPHANE (ANR, 2014):

IPNL Lyon: Jacques Marteau (co-PI), Alain Benoît, Bruno Carlus, Claude Girerd, Jean-Christophe Ianigro, Jean-Luc Montorio, [Maryté Costa, Sandra Goncalves, Franck Mounier, Alexis Eynard, Alain Benoît, George Verdier, Titi Alliaume]

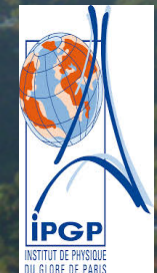
IPG Paris: Sébastien Deroussi, Michel Diamant, Kevin Jourde, Jean-Christophe Komorowski, Pierre Agrinier, Céline Dessert, Vincent Robert, Steve Tait, Jean-Jacques Sibilla,

Géosciences Rennes: Dominique Gibert (co-PI), Jean de Bremond d'Ars, Bruno Kergosien, Florence Nicollin, Pascal Rolland, Yves Le Gonidec, Christian LeCarlier

Labex UnivEarthS (IPGP-APC)

Observatoires: OVSG (Guadeloupe), EOS (Singapour), Phivolcs (Philippines), Laboratoire du Mont-Terri (Swisstopo), Laboratoire de Tournemire (IRSN)

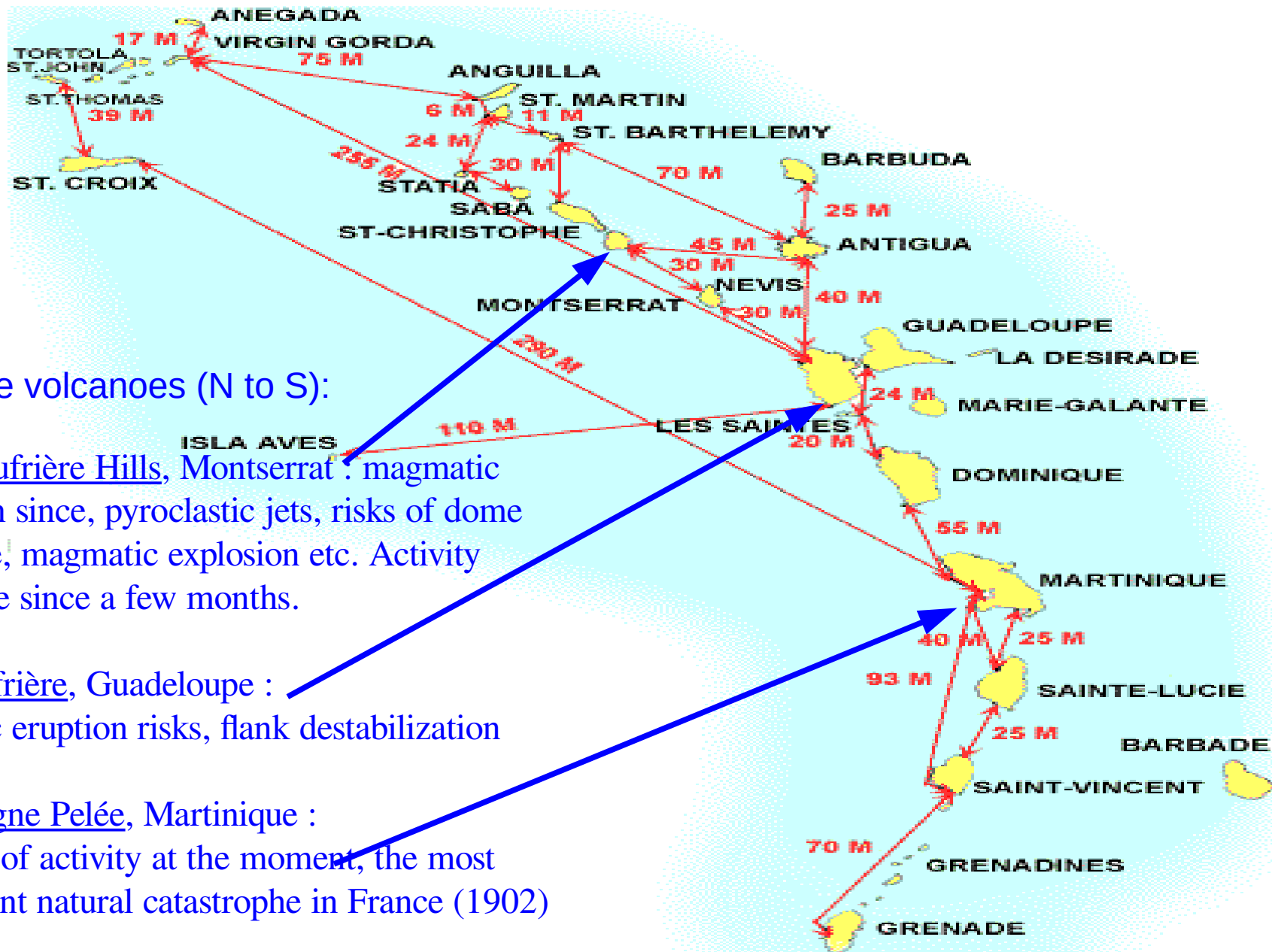
Autres collaborateurs : Daniele Carbone (INVG Catane), Fabrice Dufour, Quentin Gibert, Benoît Taisne (EOS Singapour), Nolwenn Lesparre (IRSN)



- 1 -

Physics case & methodology

Extended monitoring: the Lesser Antilles



3 active volcanoes (N to S):

The Soufrière Hills, Montserrat : magmatic eruption since, pyroclastic jets, risks of dome collapse, magmatic explosion etc. Activity decrease since a few months.

La Soufrière, Guadeloupe : phreatic eruption risks, flank destabilization

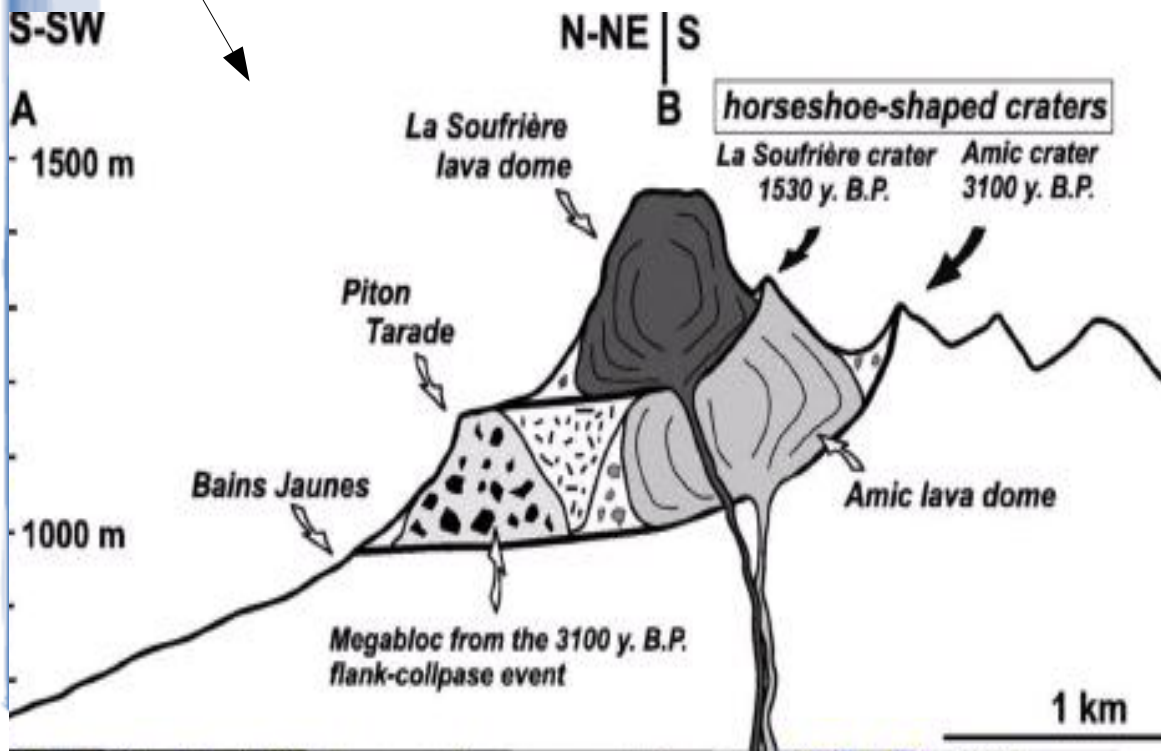
Montagne Pelée, Martinique : no sign of activity at the moment, the most important natural catastrophe in France (1902)

La Soufrière de Guadeloupe

Active vent during 1976 eruption

The Soufrière of Guadeloupe is an **active volcano** which last important manifestation was a **phreatic eruption in 1976-1977**.

A **new phreatic eruption or a flank collapse** are the most likely hazards for la Soufrière today.



... the same in 2010



La Soufrière de Guadeloupe

The volcano is under cautious surveillance as a **regain of activity** has been noticed in the vents (Allard et al. 2014) and in the sources (Villemant et al. 2014).



New vents between South crater and
Tarissan pit (April 2015)

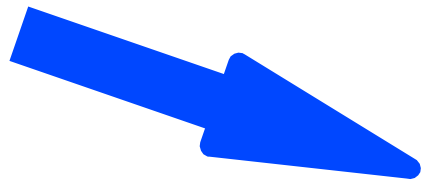
Muon tomography

Measurement of the muon flux emerging from the volcano to determine its opacity (amount of matter):

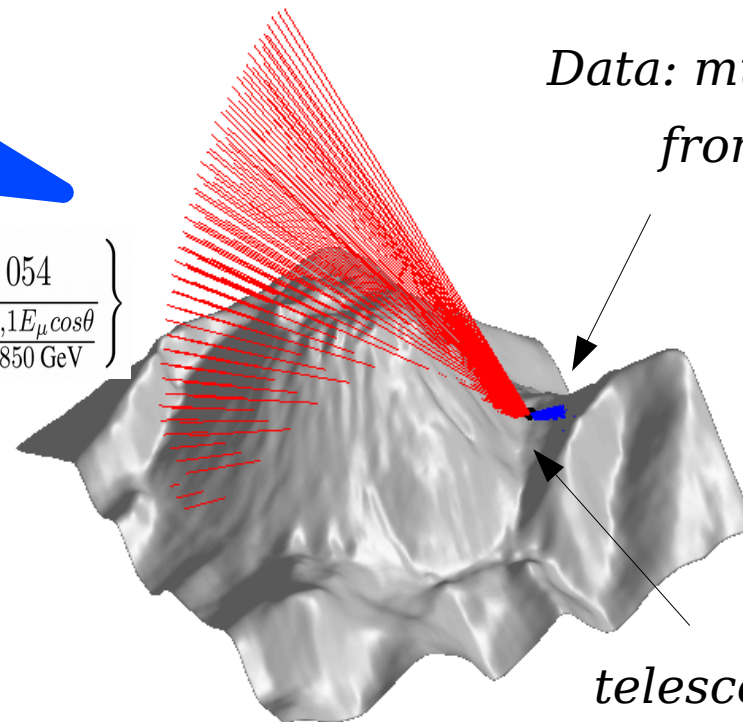
$$\varrho(L) \equiv \int_L \rho(\xi) d\xi$$

ϱ = opacity
 ρ = density

incident muon flux



Data: muon flux emerging from the volcano



$$\frac{dN_\mu}{dE_\mu d\Omega} \approx \frac{0,14 E_\mu^{-2,7}}{\text{cm}^2 \text{ s sr GeV}} \times \left\{ \frac{1}{1 + \frac{1,1 E_\mu \cos\theta}{115 \text{ GeV}}} + \frac{0,054}{1 + \frac{1,1 E_\mu \cos\theta}{850 \text{ GeV}}} \right\}$$

Alvarez, L.W. et al., 1970

Nagamine, K. et al., 1995



Röntgen, 22 déc. 1895.

- 2 -

**Methodological and
Instrumental developments**

(2008-2014)

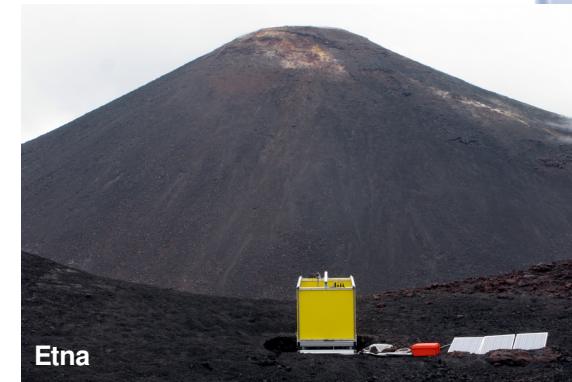
Diaphane 2008-2014



- 2007: BQR D.Gibert (Université Paris / IPGP) to start a technical evaluation

- 2008 : ANR Domoscan (INSU) including a small muon tomography part

- 2008 : collaboration started between IPNL-IPGP-GR (IN2P3/INSU) on technical aspects (Opera opto-electronics chain recycled)



- 2009: first installation in Mont-Terri (funding: Swisstopo) for methodological developments in a known geology

- 2010 (and 2012): exploration of Etna South crater (funding: INSU & IN2P3 A.A.P. – P & U, Instrumentation aux limites)

- 2010: first installation on the Soufrière de Guadeloupe

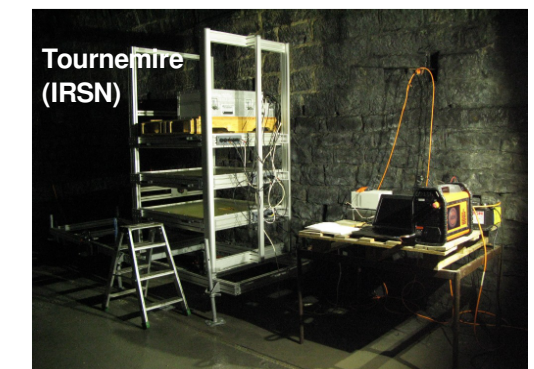


- 2011-2014: upgrades of the local telescope on the Soufrière and other sites explored (RS, Roche Fendue, Savane à Mulets)

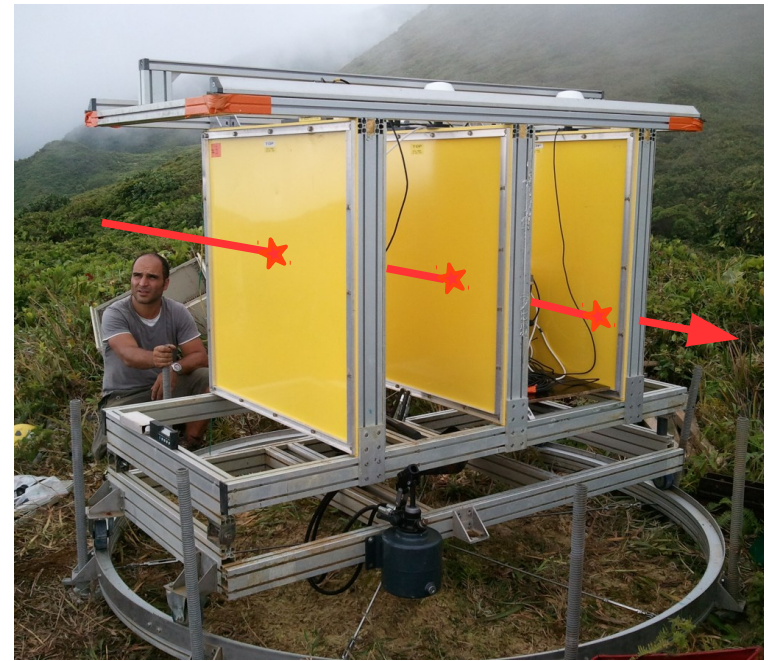
- 2013: collaboration started with IRSN for methodological developments in Tournemire (funding: IRSN)

- 2014: installation of a detector on the Mayon volcano (funding: E.O.Singapore, PHIVOLCS)

- 2014: installation of a SiPM telescope in Lyon (funding: fédération de physique FRAMA)



A field instrument

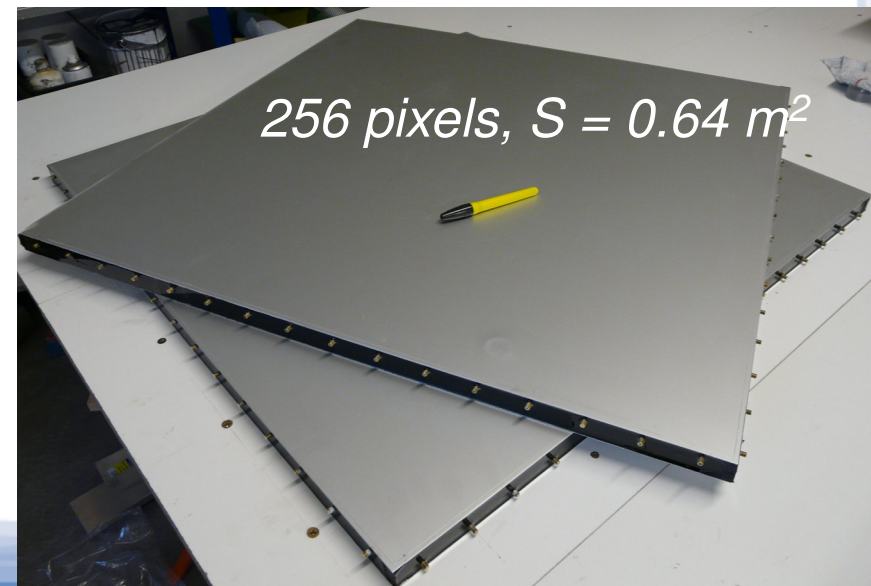
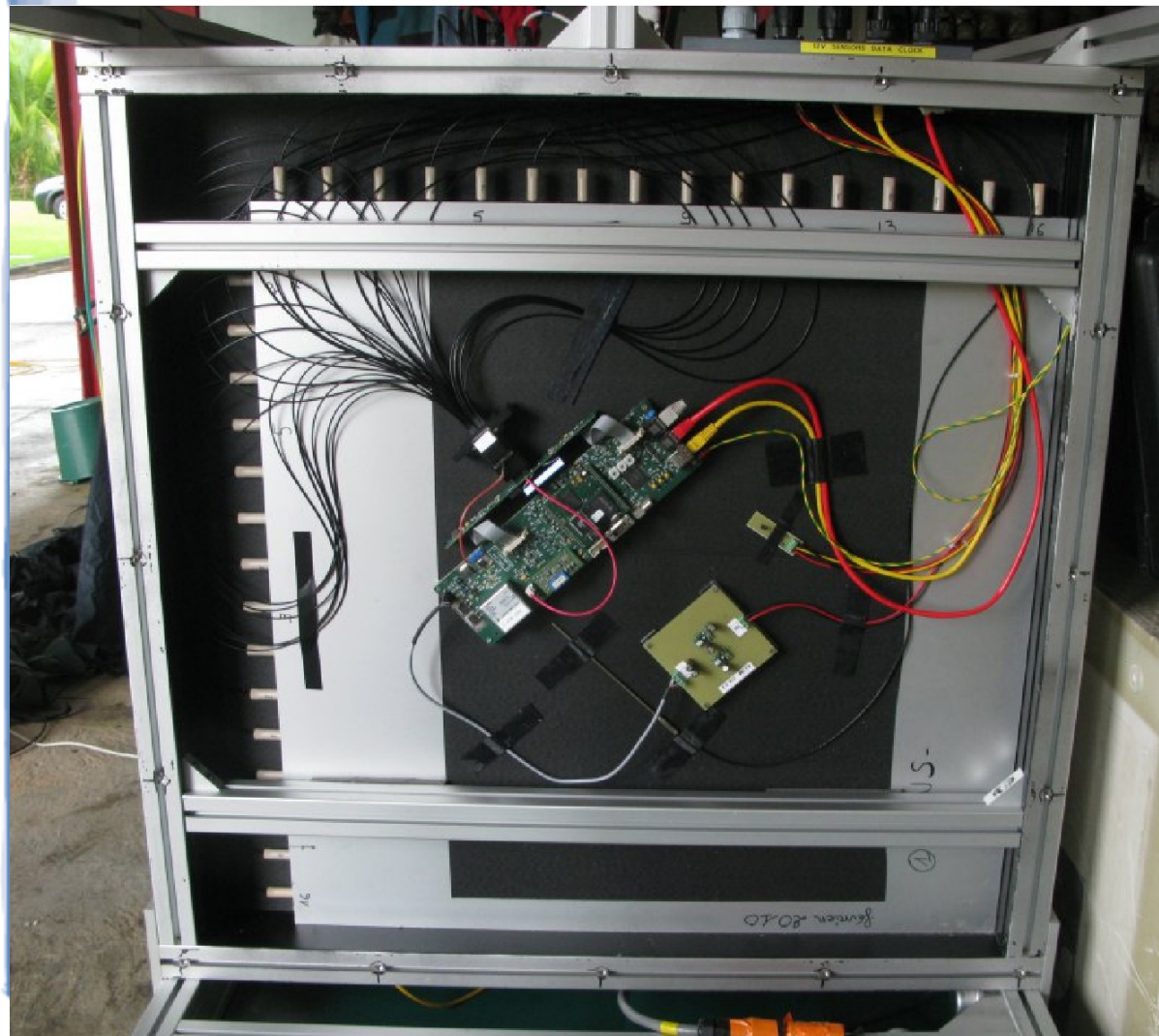


- Power: photovoltaic panels, wind turbine, fuel cells
- Total mass: 200 to 600 kg (lead/iron shielding)
- Angular aperture: 30° - 60°
- Angular resolution: 1° - 2°
- Consumption: $\sim 50\text{W}$
- Remote Ethernet control



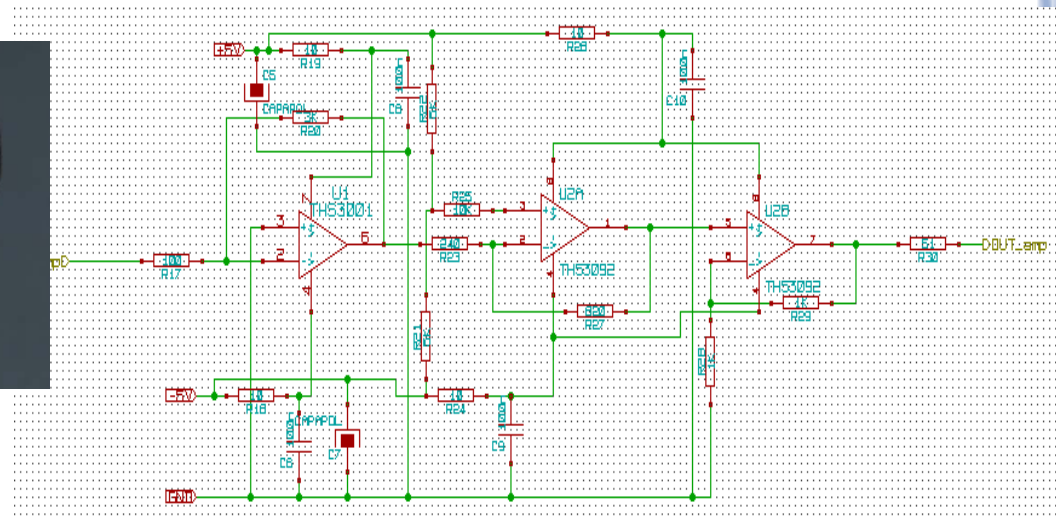
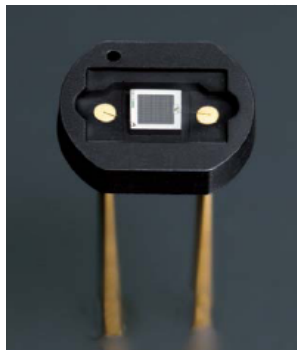
Detection planes

- 256 = 16 x 16 pixels. Scintillators + WLS + MaPMT/SiPM
- Same electronics for all types of matrices / photosensors
- Technology transfer from OPERA
- Common Clock locked on GPS (10ns timestamps)
- TDC embedded in the FPGA (100ps vernier) for t.o.f.



SiPM readout system

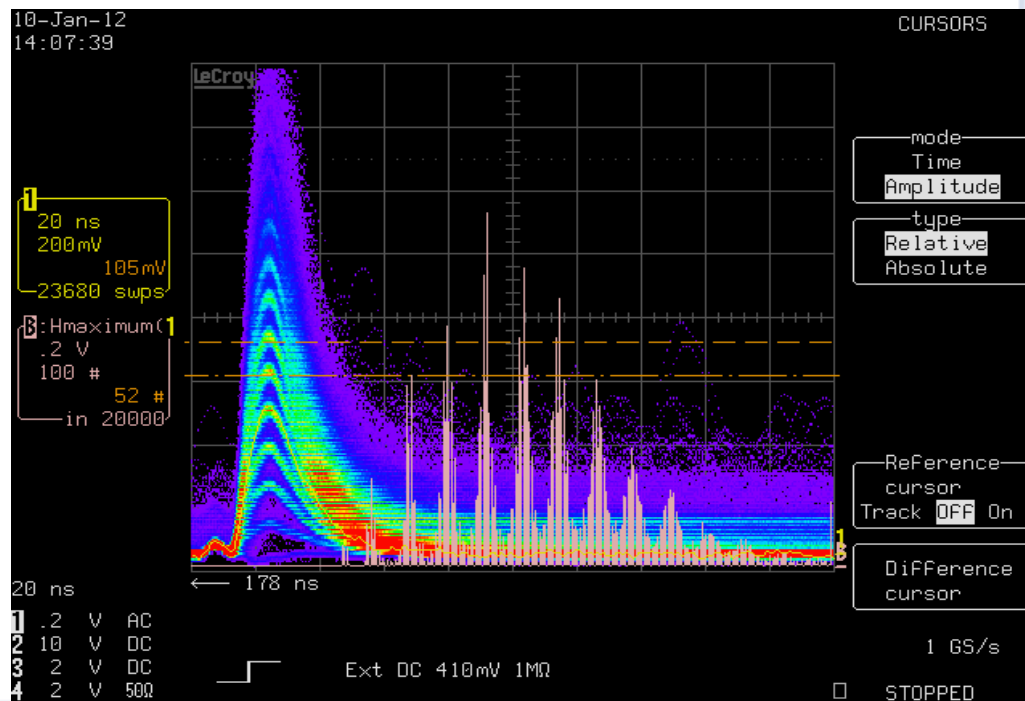
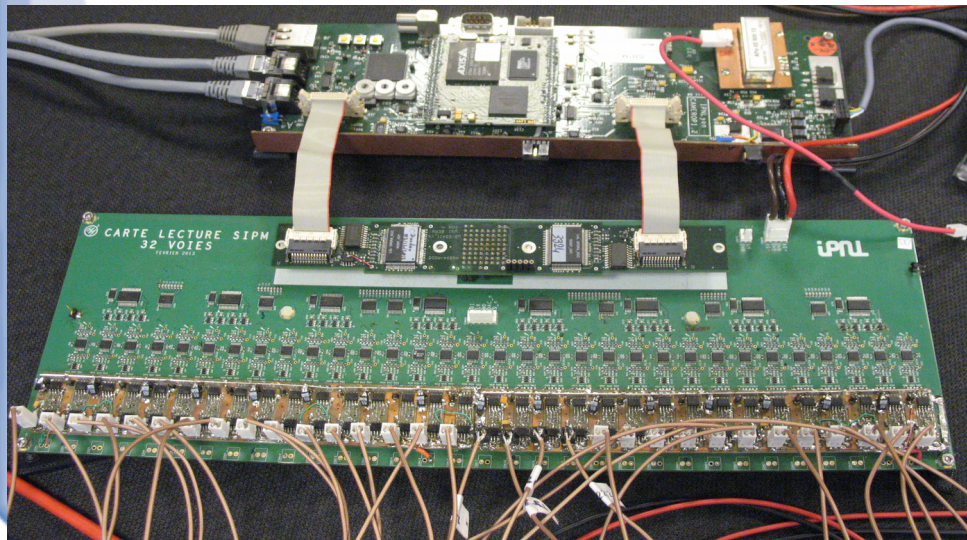
Front-end stage design based on a simplified chain (P.E. counter) with a robust, high gain amplifier.



Successful operation in auto-trigger mode (full telescope running in Lyon)

Benefits from the excellent P.E. counting capabilities

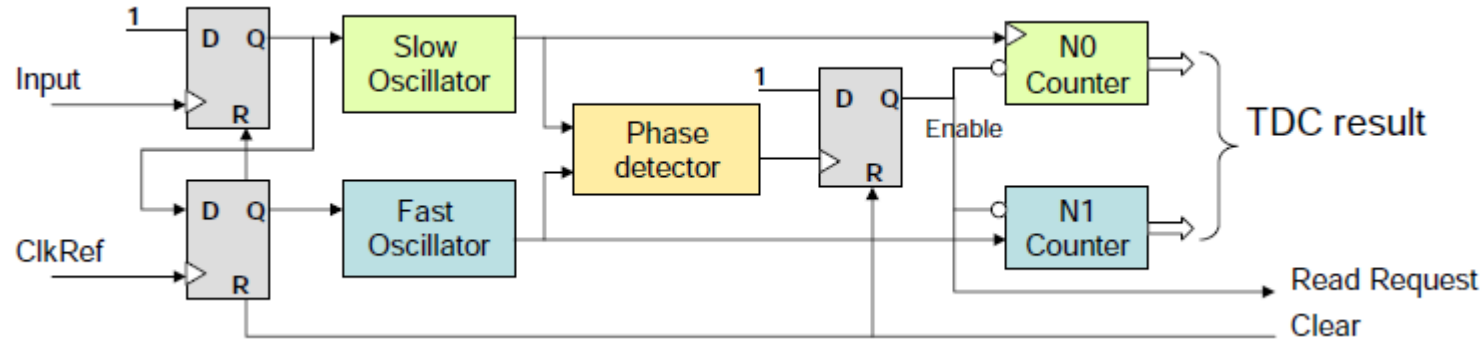
Integrated in the same DAQ chain as for the PMT's option



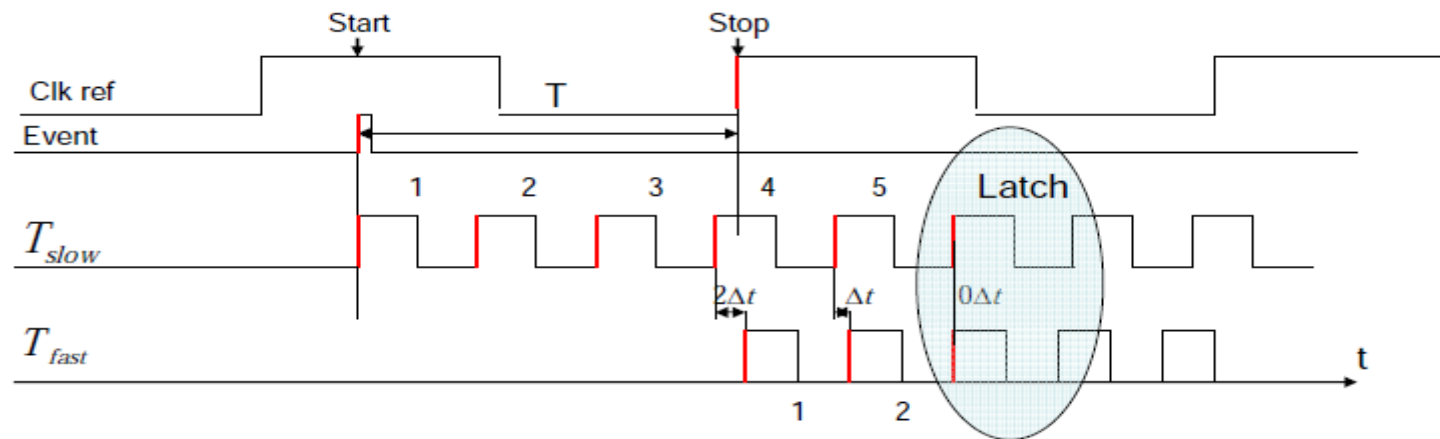
Upward flux monitoring : TDC techniques

Marteau, J. et al. MST 2013

Ring-oscillator TDC technique implemented in FPGA allowed, without any extra hardware, to improve the timing resolution of the electronics down to a few tens of picoseconds.



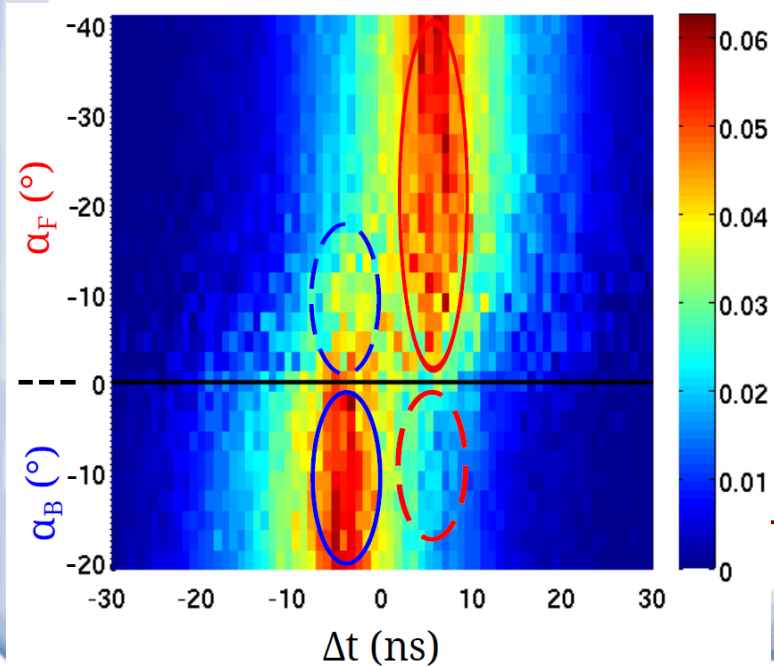
Low area, low power consumption, no extra fast clock.



Direct implementation inside FPGA. Different design = optimal timing resolution

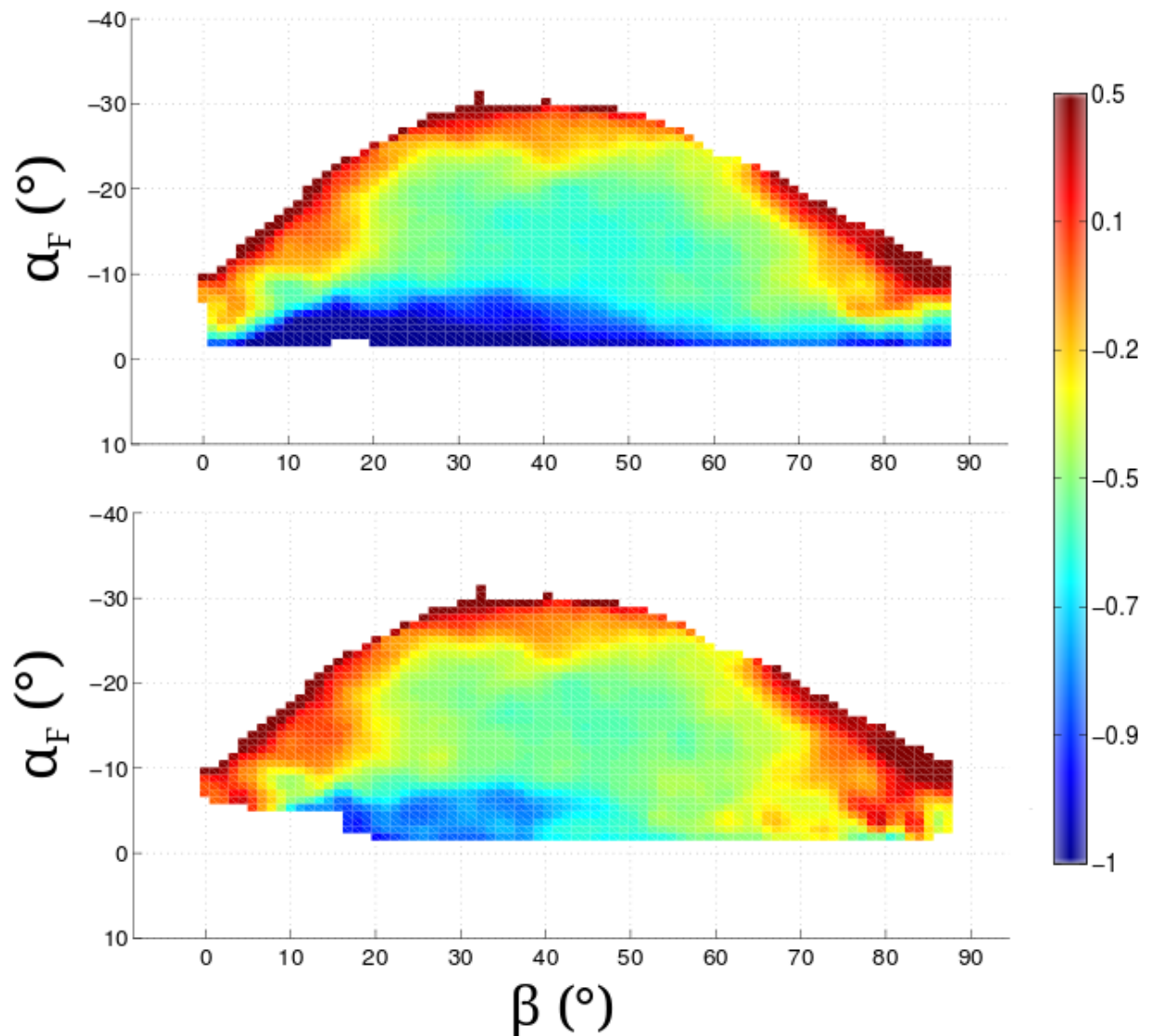
Upward flux monitoring : TDC techniques

The **high precision clock** allows a TOF analysis to disentangle particles coming either from **the front or the rear** of the telescope. A particle upward-flux was enhanced on the Savane à Mulets (Soufrière de Guadeloupe) site permitting to **correct the low density region** above the horizon.



Jourde, K. et al. GRL 2013

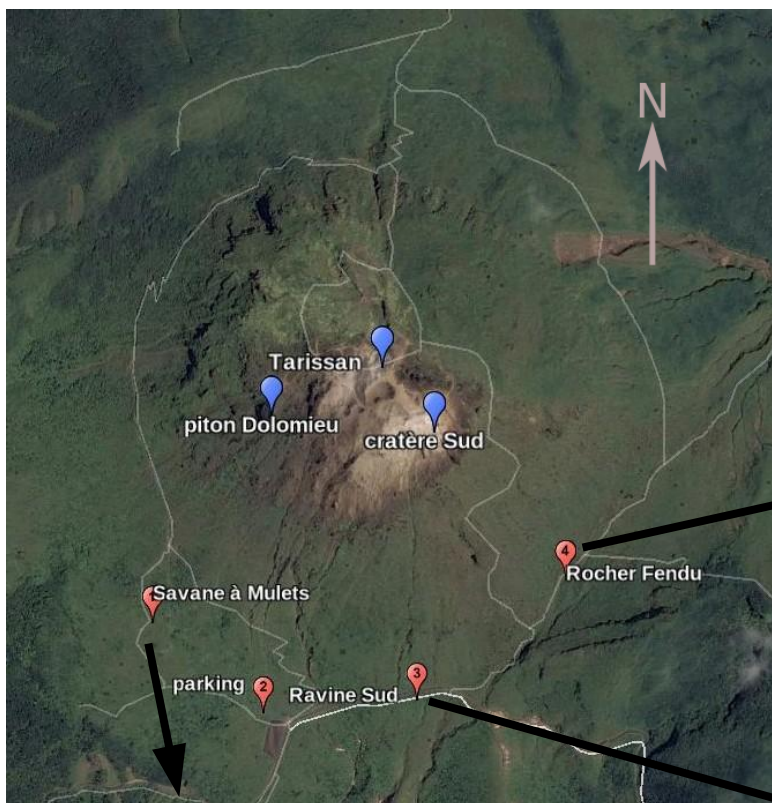
$$\rho - \rho_{\text{mean}} \text{ (g.cm}^{-3}\text{)}, \quad \rho_{\text{mean}} = 1.5 \text{ g.cm}^{-3}$$



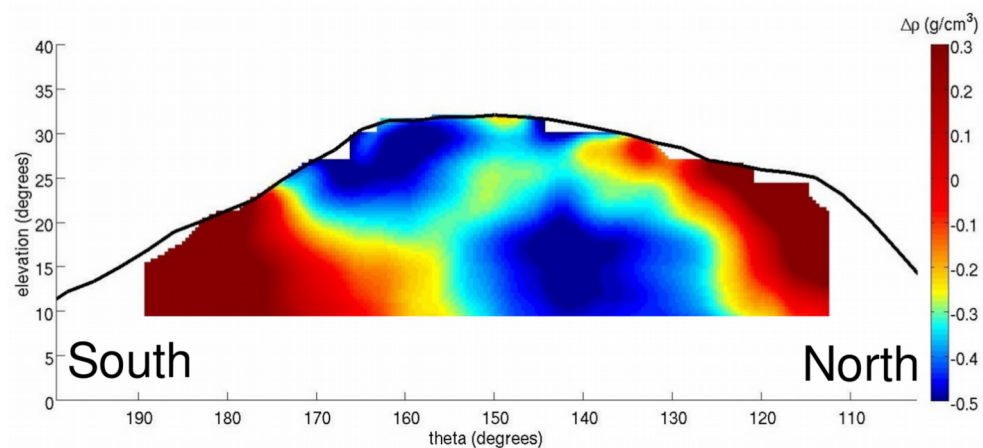
Tomographies from 2011-2014 campaigns

Lesparre, N. et al. 2012

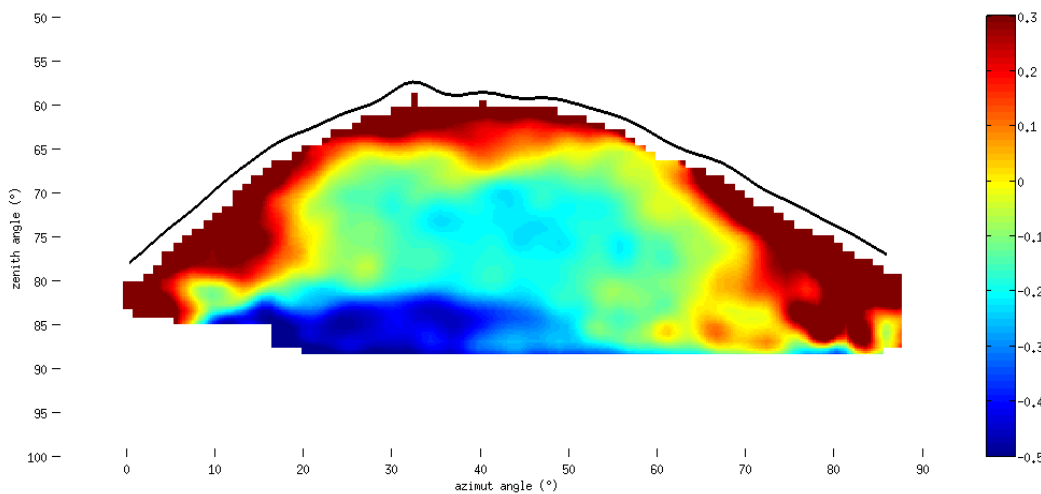
Jourde, K. et al. 2013



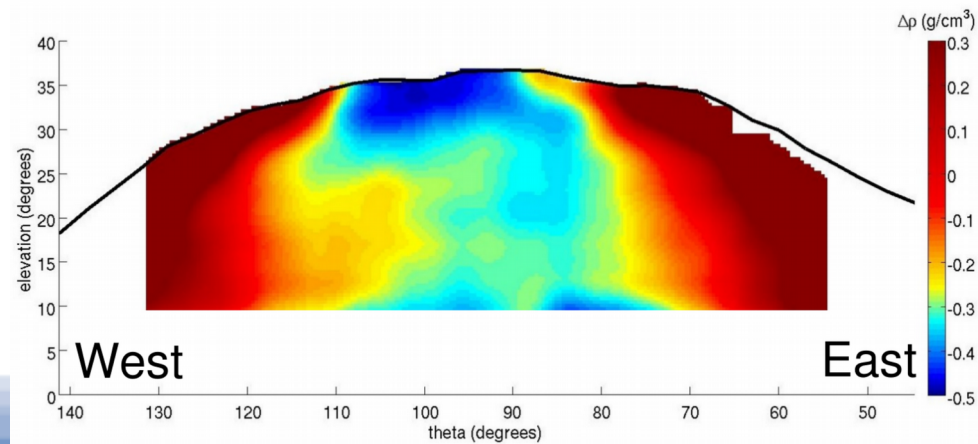
Rocher Fendu



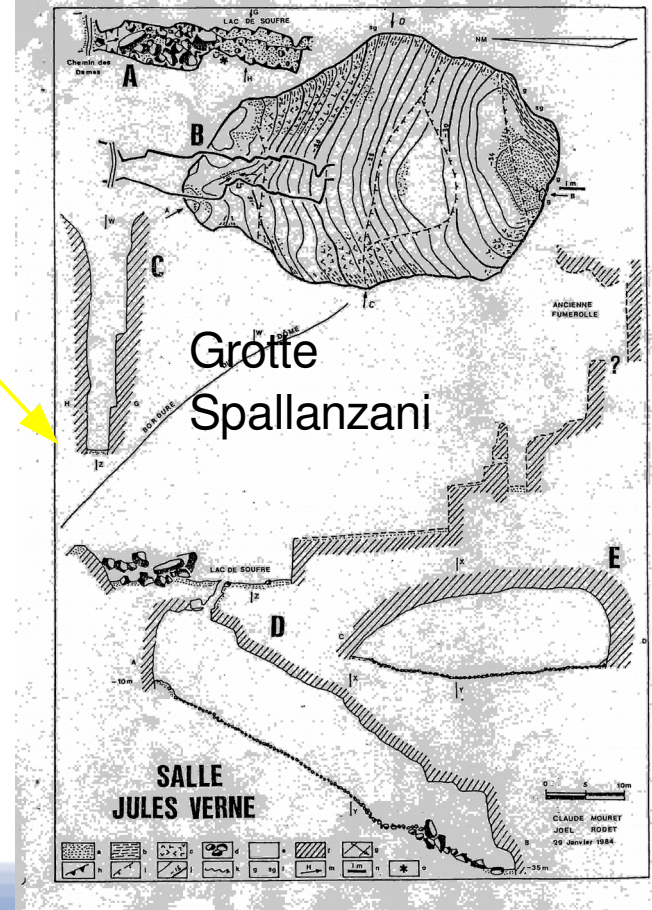
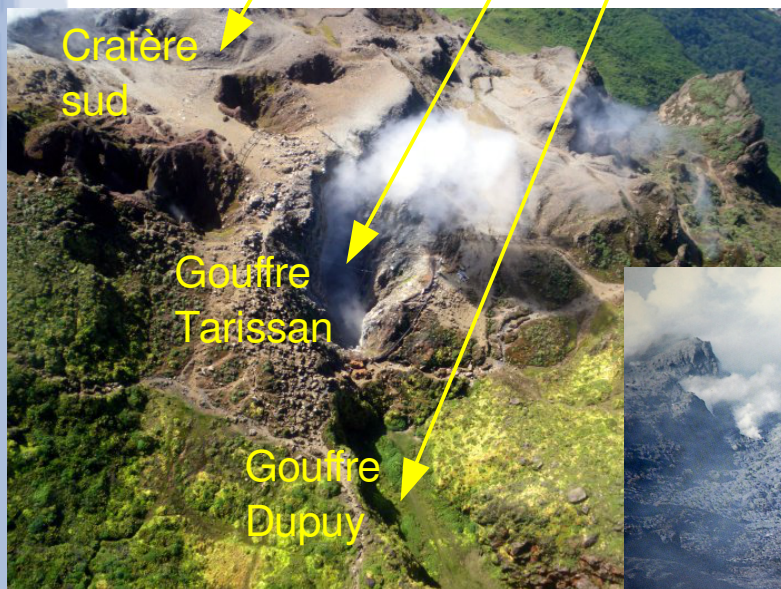
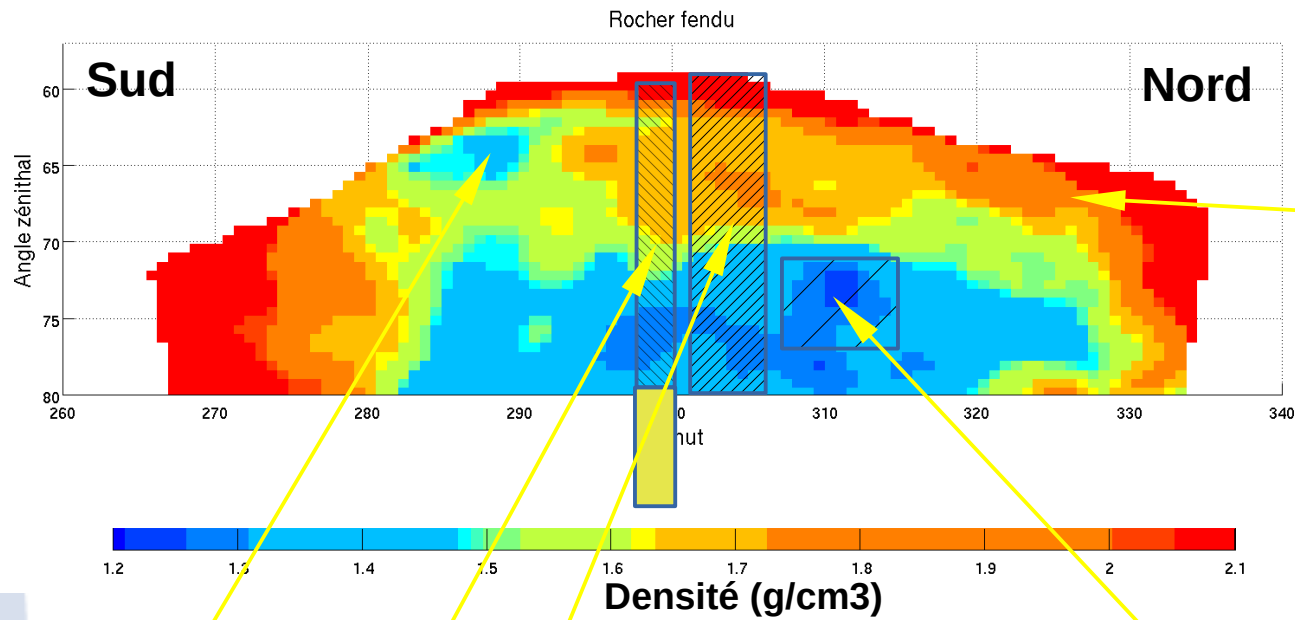
Savane à Mulets



Ravine Sud

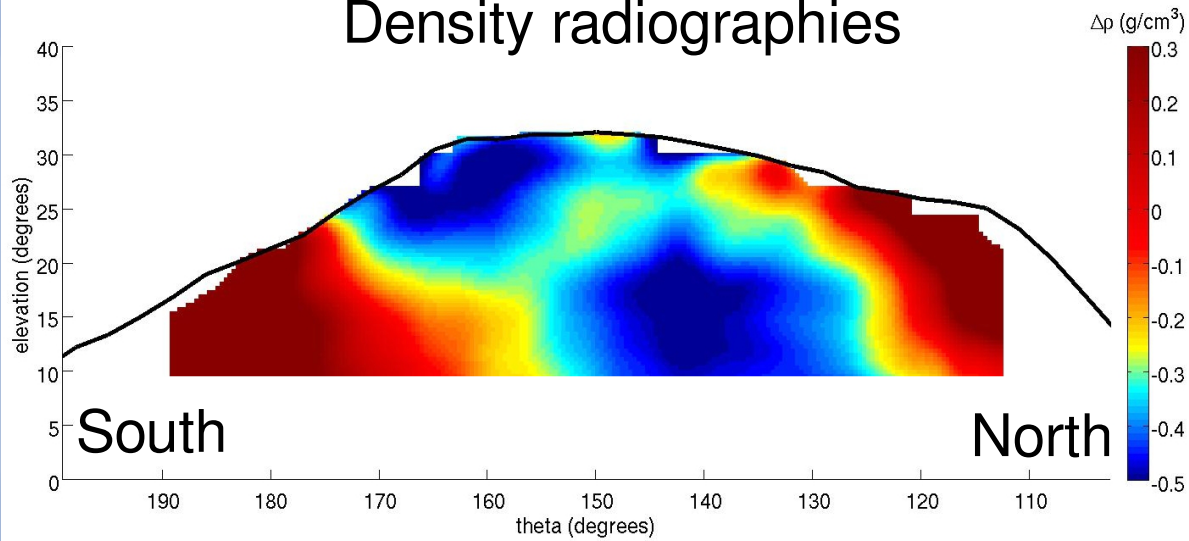


Tomographies from 2011-2014 campaigns

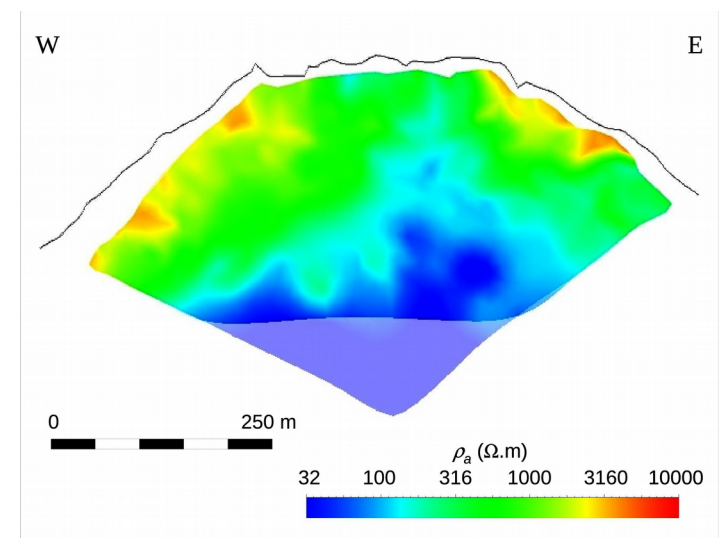
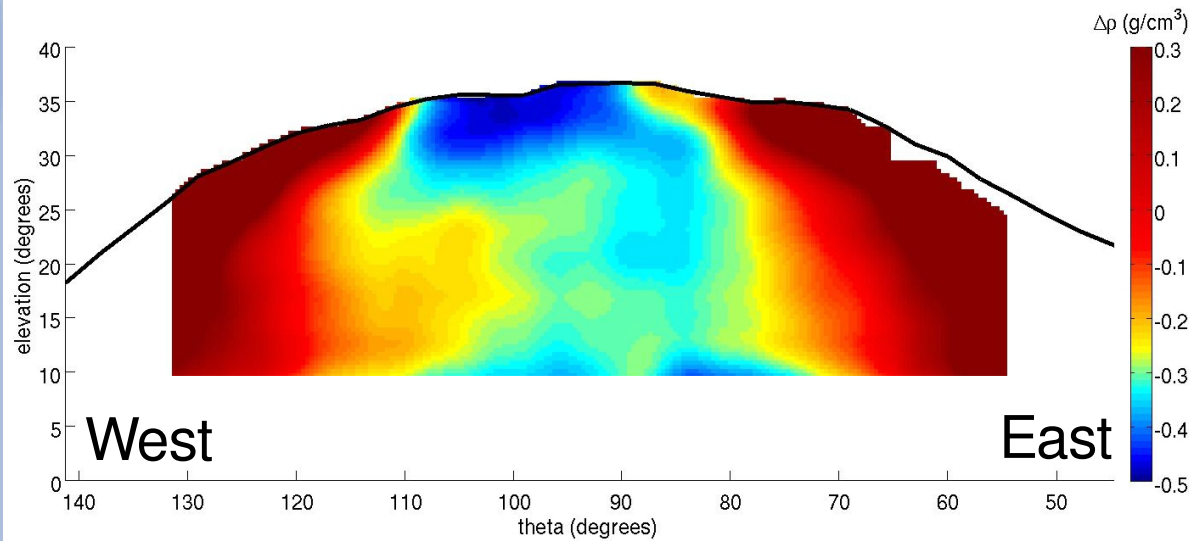
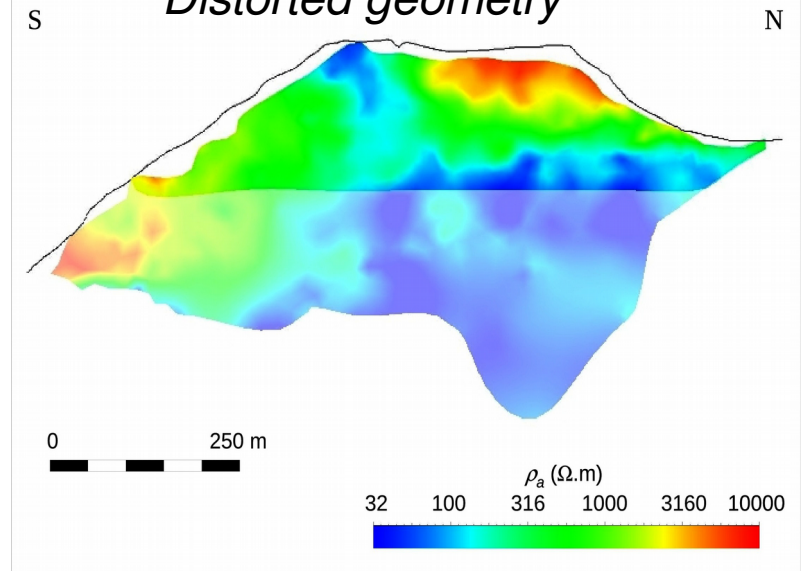


La Soufrière structural imaging

Density radiographies

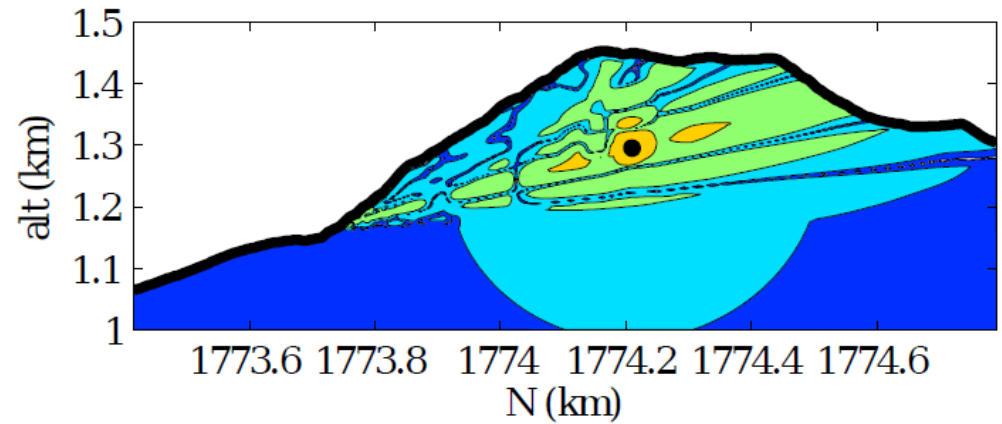
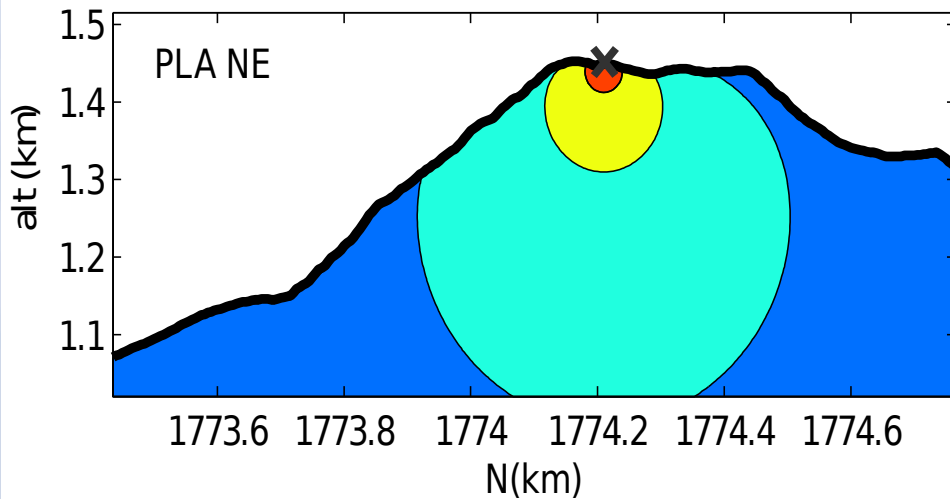


Electrical resistivity *Distorted geometry*

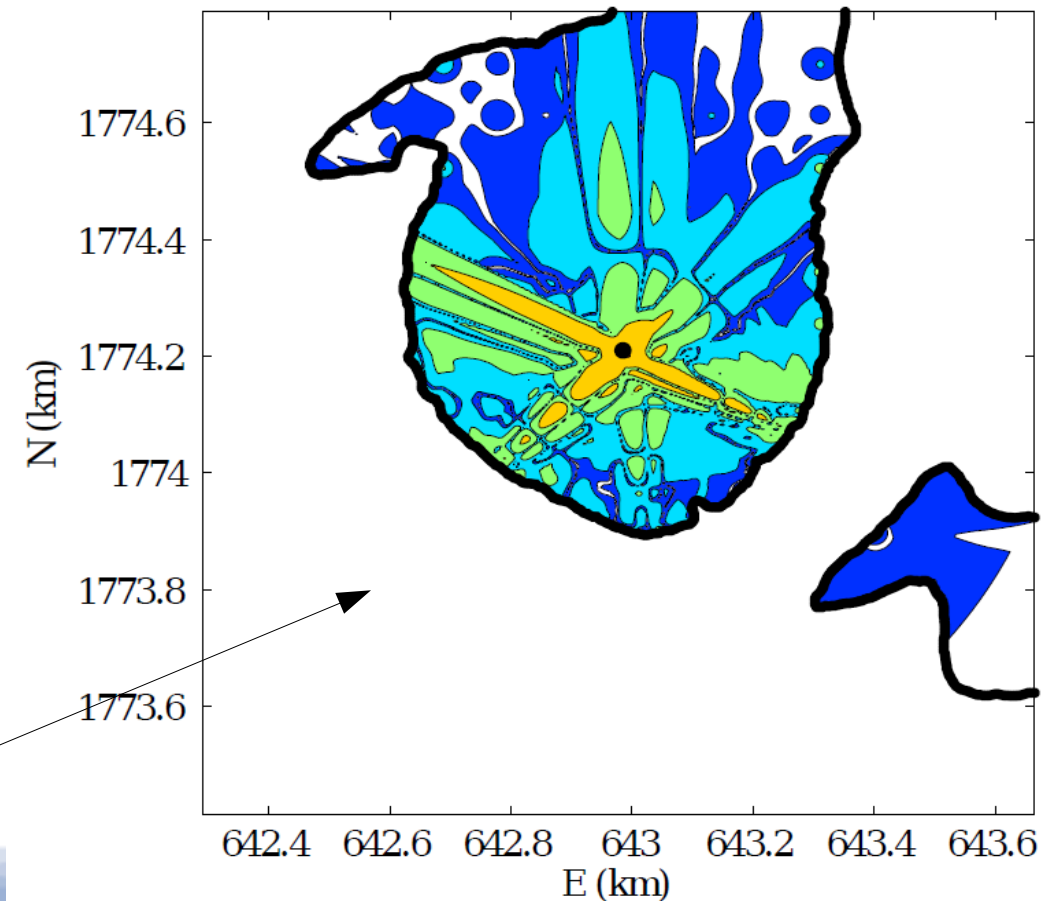
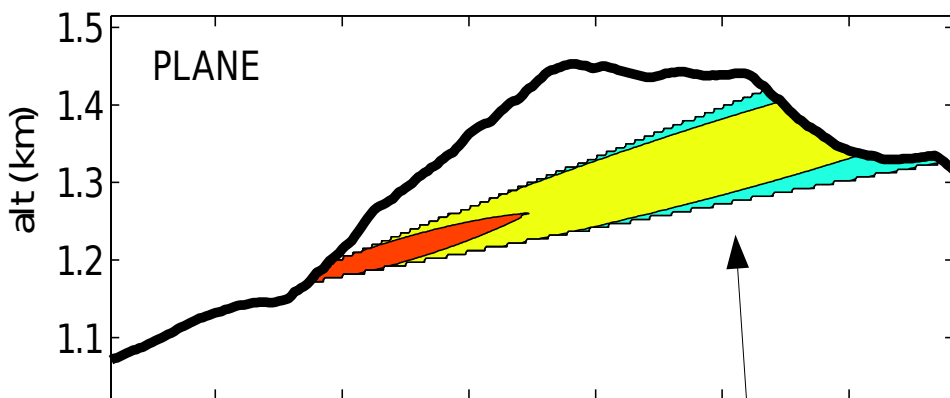


Muon-gravimetry coupling: a kernel approach

gravimetry acquisition kernel, \mathcal{G}



tomography acquisition kernel, \mathcal{M}



*The acquisition kernels
& resolution achieved*

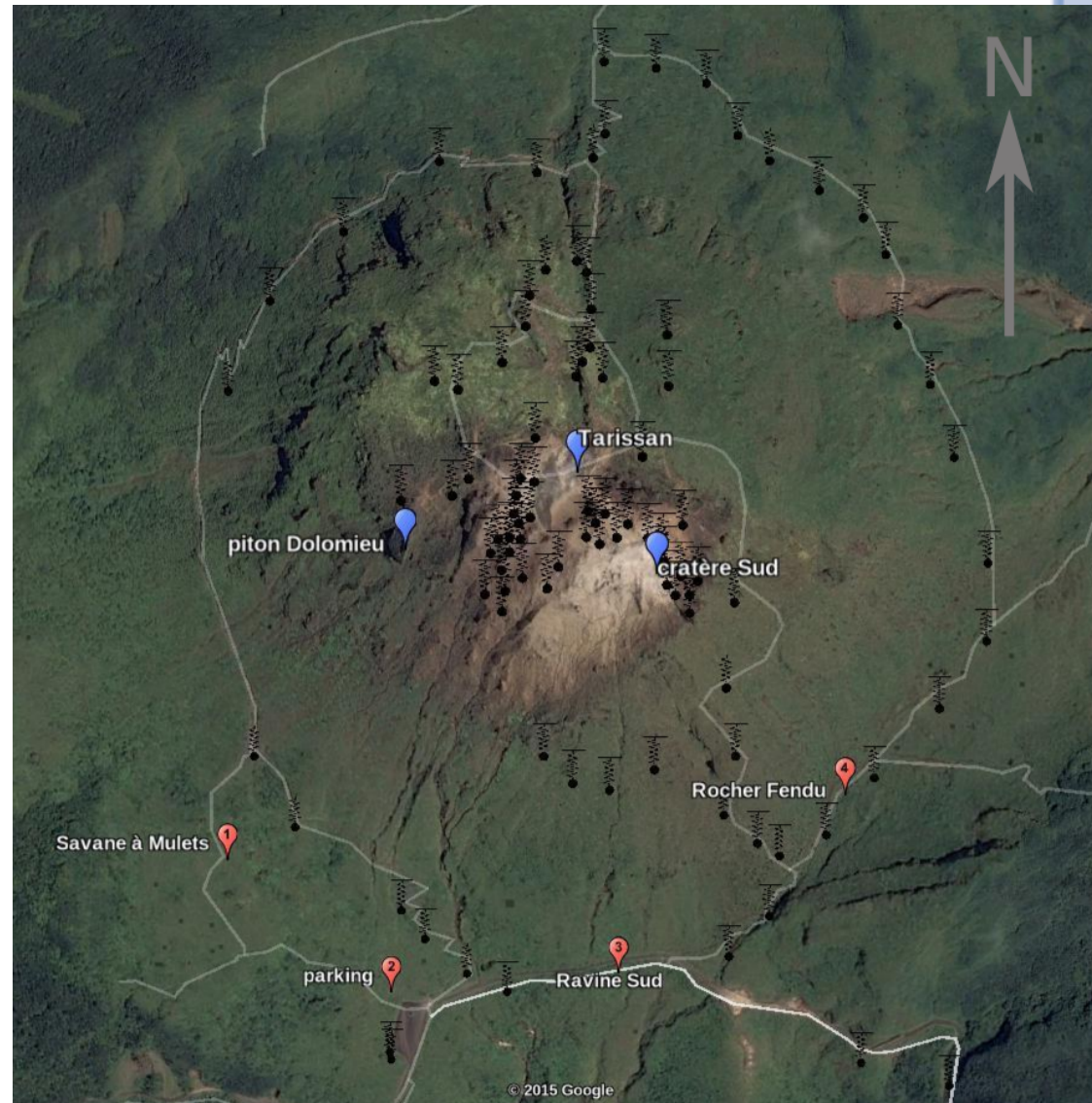
Muon-gravimetry coupling: a kernel approach

2014/2015 Soufrière gravimetry survey:

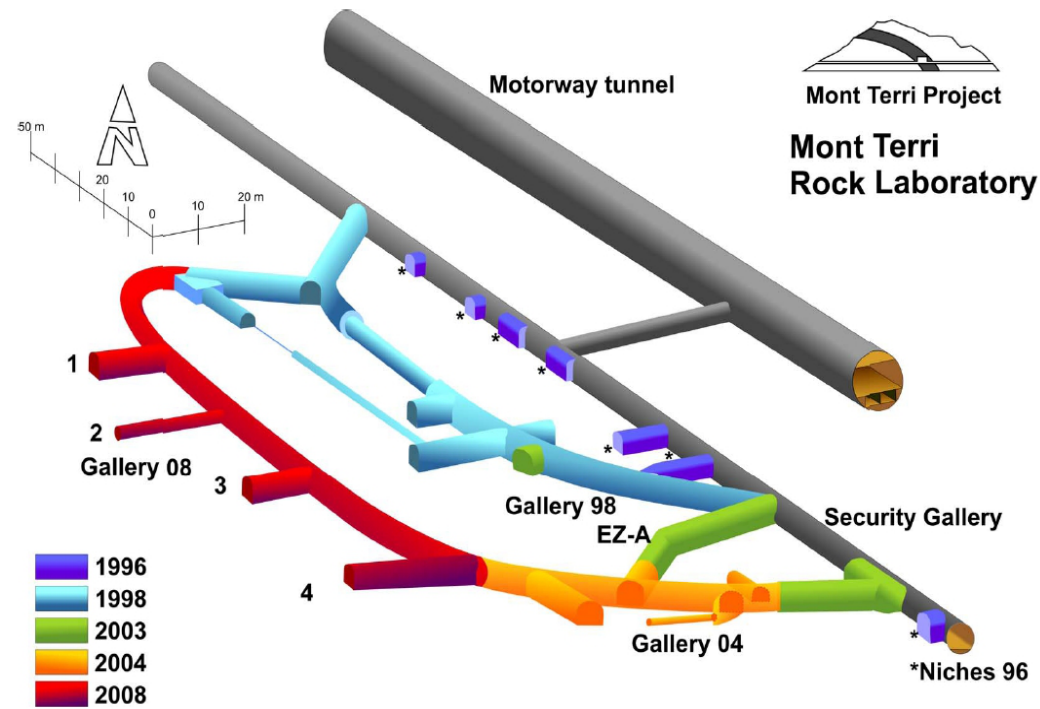
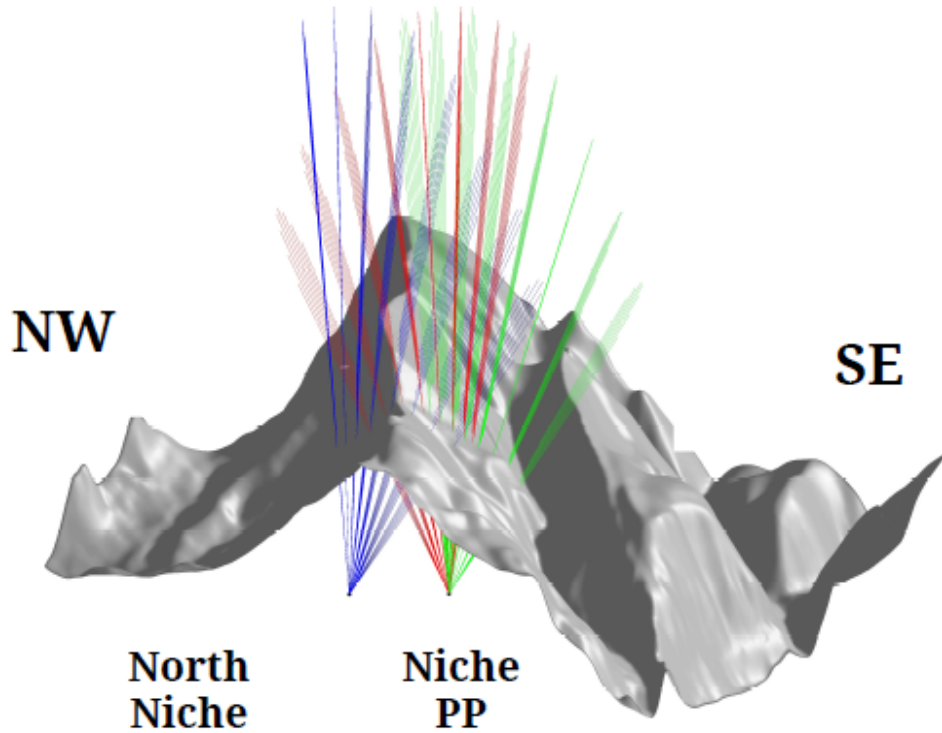
- 146 measurements
- 2 CG5 gravimeters during 1 year
- 1.5km large, 500m height difference survey
- on an island
- 40 μGal precision
- 1 absolute measurement

Imply complex corrections:

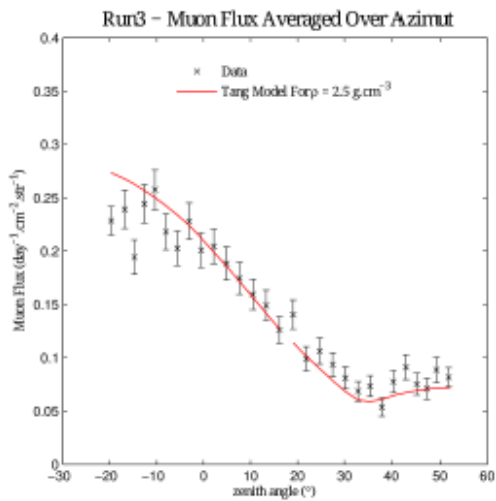
- geoid oscillations
- earth and sea tides
- atmosphere weight
- earth curvature
- precise Bouguer correction



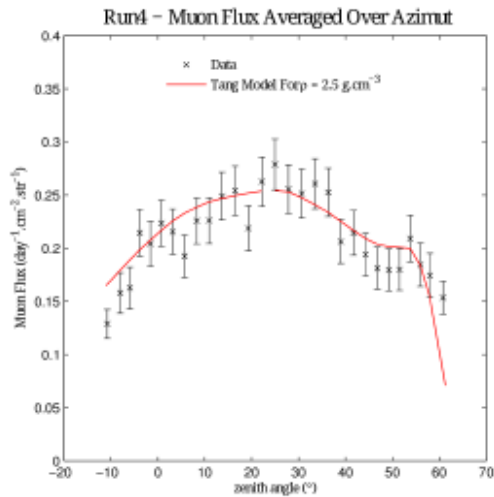
Mont-Terri underground lab



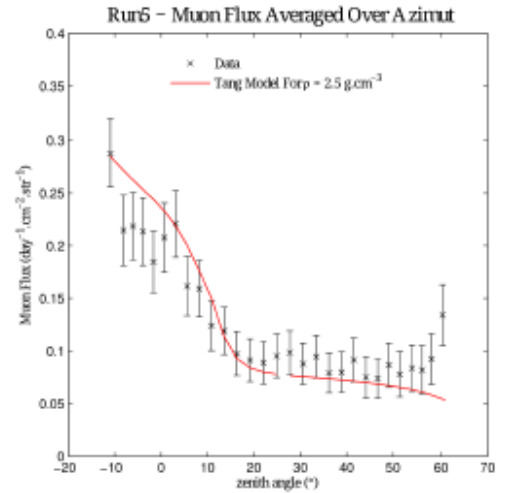
RUN 3



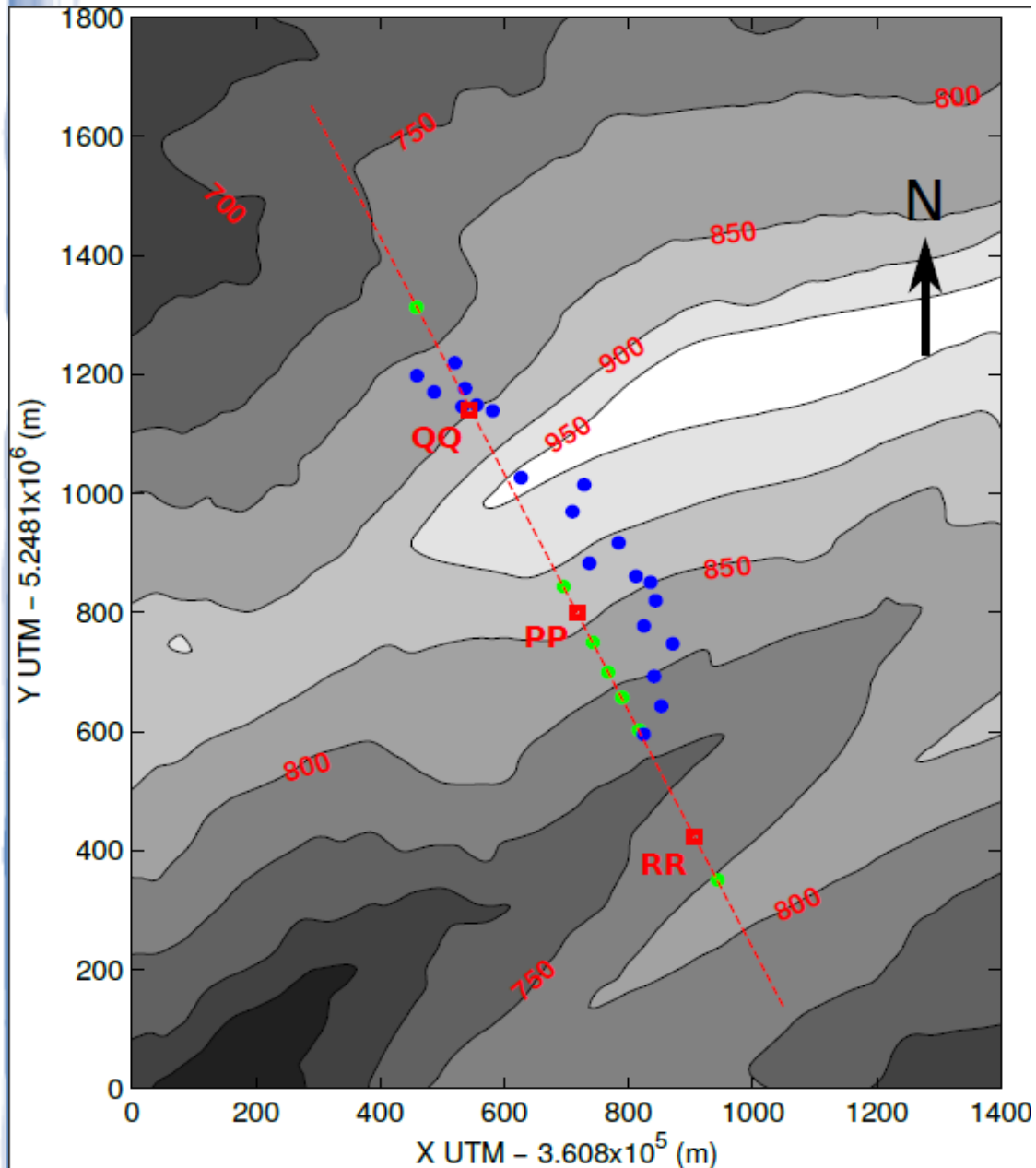
RUN 4



RUN 5



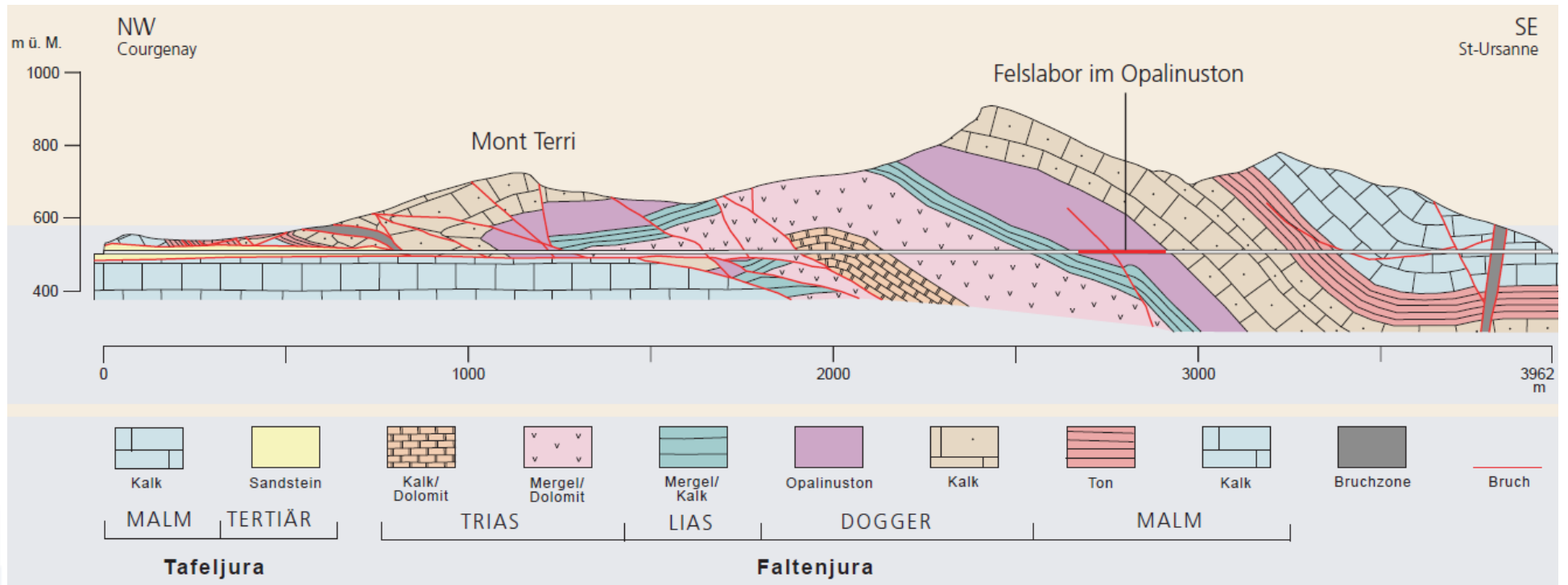
Mont-Terri underground lab



- tunnel axis
- telescope niche
- underground gravimetry measurement
- open-sky gravimetry measurement

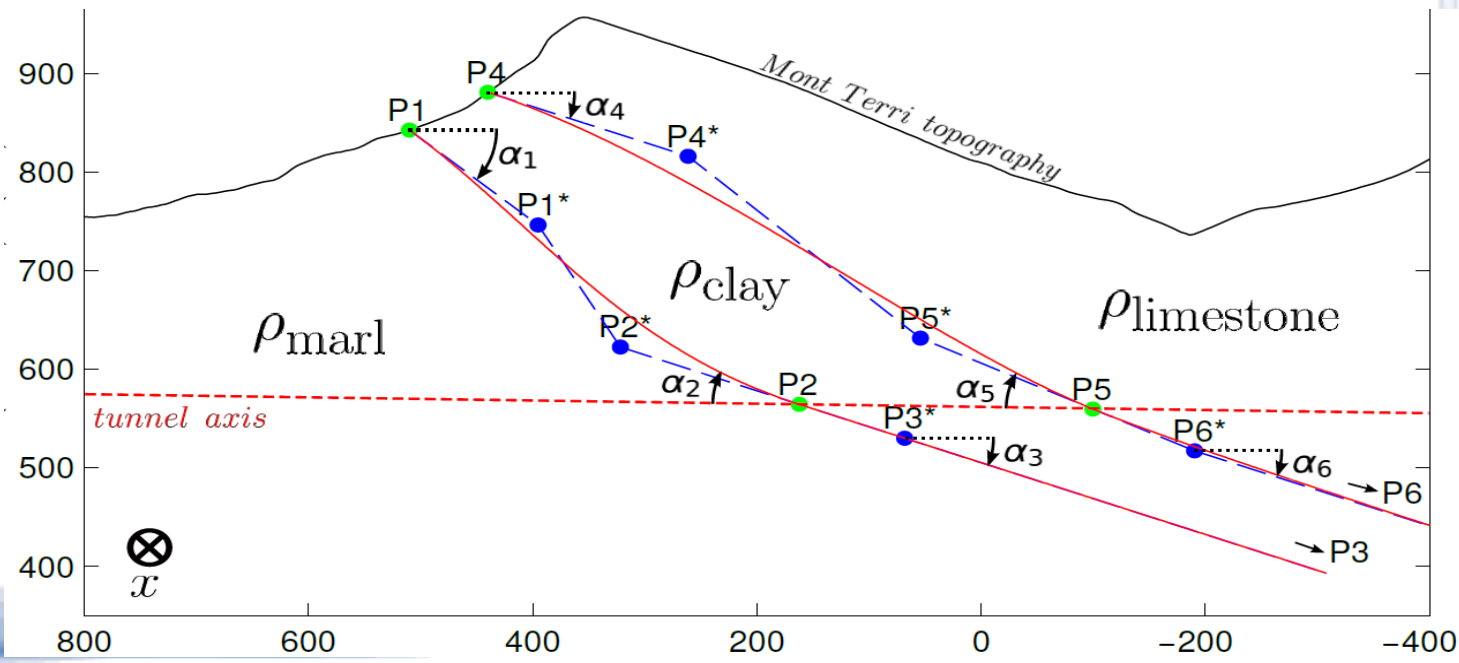


MT geology parametrization



Analyzing **gravimetry & muon** direct problems

Inverting to find the parameters of the **Bézier curves**

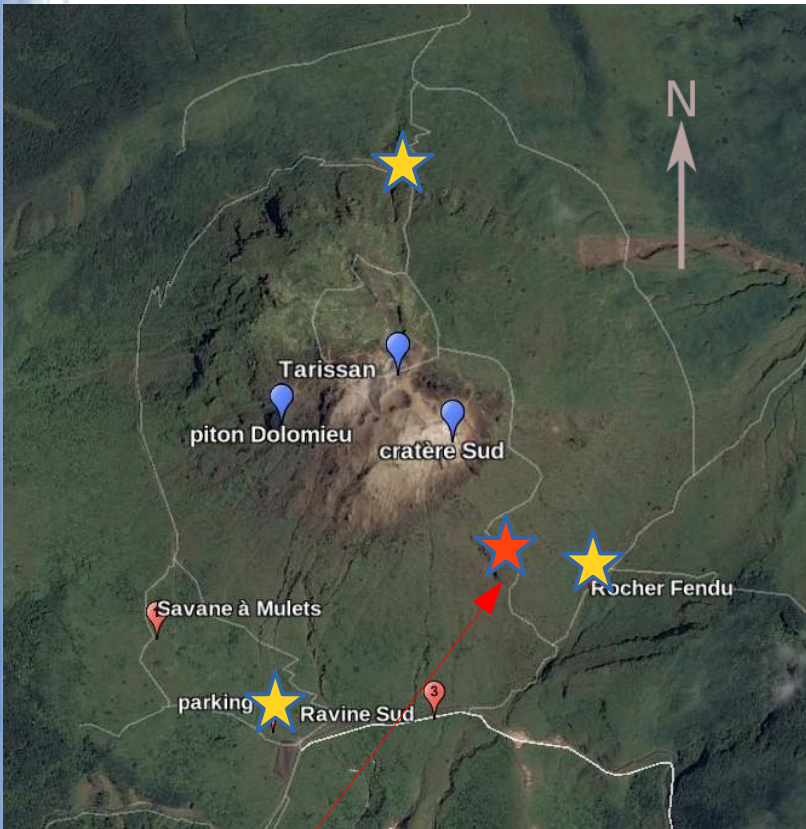


- 3 -

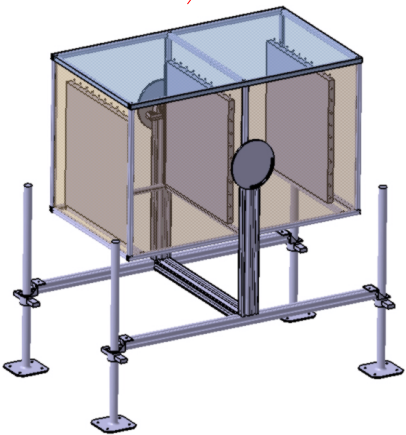
**ANR Diaphane
Present & Future**

(2014-20xx)

Diaphane 2014-2018



- ANR Diaphane retained in 2014
- Solved: technical choices (opto-electronics: MaPMT, computing, power supply: solar-wind, network) and adaptation to harsh field conditions (transportation: helicopter, dust, rains, acids, hurricanes, large T variations etc)
- From the R&D phase (static radiography) to the active volcano monitoring (integration as a standard geophysical instrument)
- Just done: installation of 4 telescopes around Soufrière (April-May 2015) : RS, RF, SAM, FD30A.
- One reduced telescope in a fault to monitor the activity of the South crater (FD30A)
- Muons-gravimetry coupling to improve the overall resolution
- In parallel R&D in Lyon Croix-Rousse (in collaboration with PdS/CETU)



Diaphane '15: installation

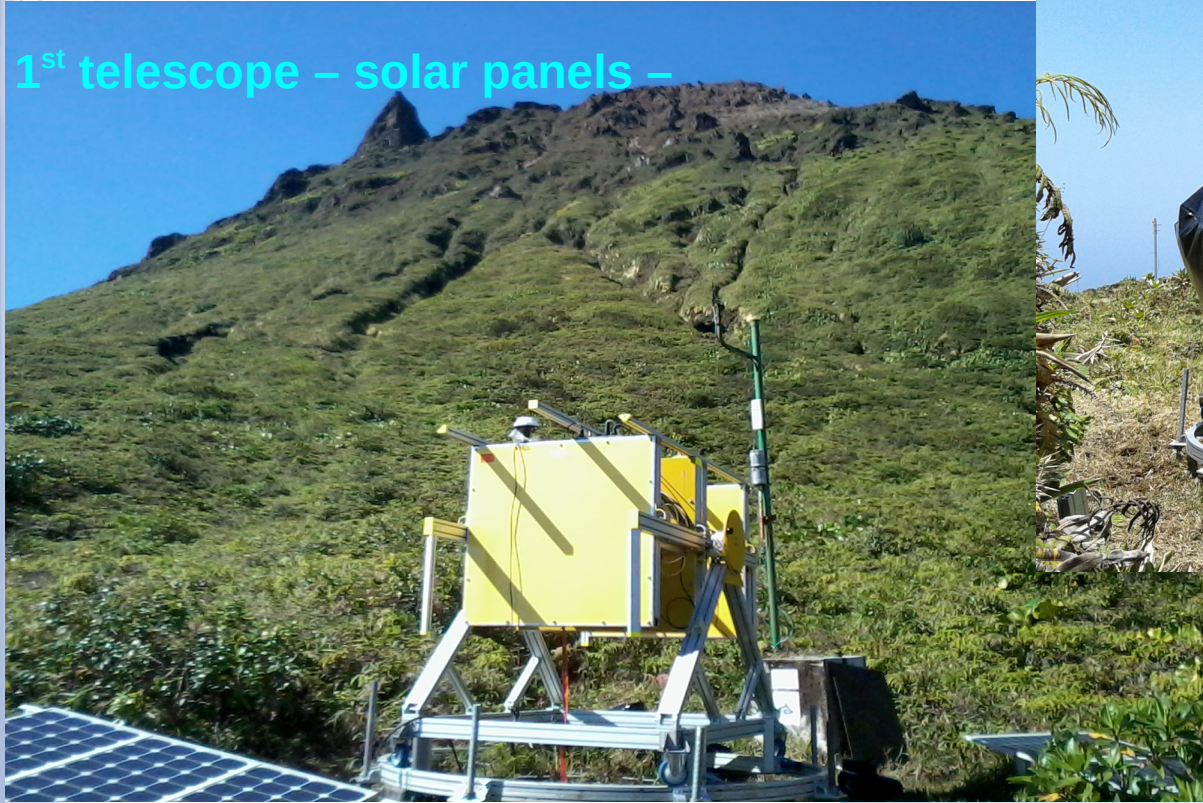
4 telescopes installed and operated on site in 2 weeks. 3 tons of material including shielding

Mini-telescope in a fault (faïlle du 30 août)

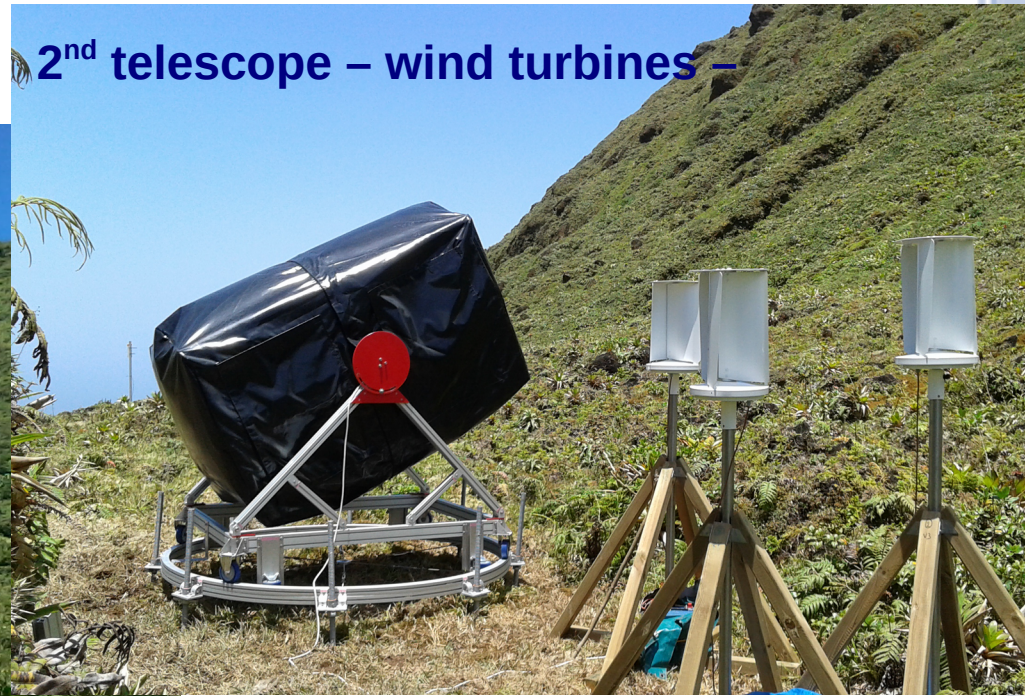


Diaphane '15: installation

1st telescope – solar panels –



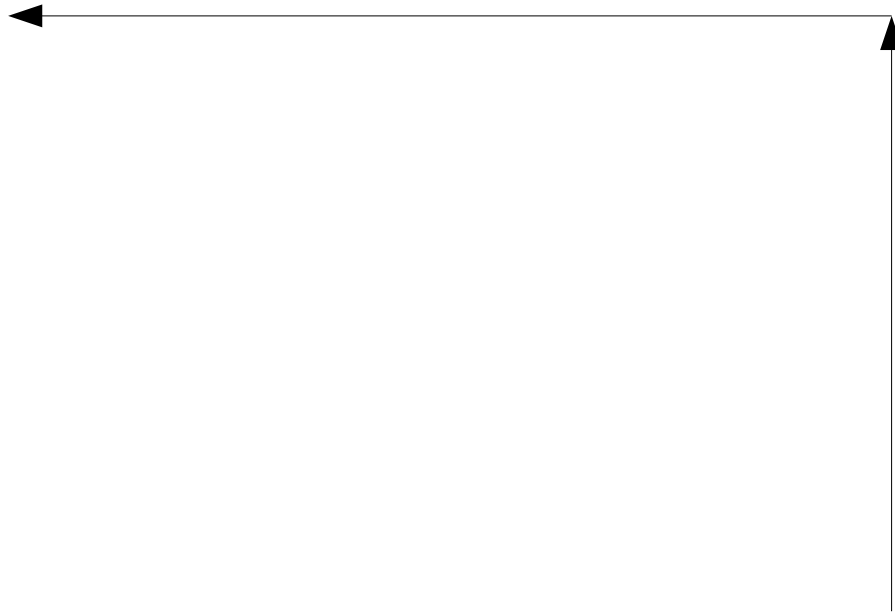
2nd telescope – wind turbines –



3rd telescope – wind turbines –



Feasibility curves (analytic pb)



Computed with an acceptance of $10 \text{ cm}^2 \cdot \text{sr}$ and using the modified Gaisser model from Tang et al. 2006.

For example : at a zenith angle of **60°** , a **10%** opacity fluctuation around an average opacity of **600 mwe** needs about **10 days** to be detected.

The SHADOW experiment :

A simple experiment to get a better understanding of the **perturbing phenomena** and the **resolution** of a muon tomography temporal monitoring.

SHADOW



Application to the hydrothermal system monitoring

- DIAPHANE group is operating detectors on active volcanoes and underground labs.
- DIAPHANE detectors successfully faced harsh environments since many years.
- Muon tomography provides not only structural imaging for geophysical structures but also relevant monitoring informations.
- Present measurements are focused on la Soufrière de Guadeloupe and the Lesser Antilles.
- At this moment we are monitoring the regain of activity of la Soufrière, confirmed by complementary measurements (acoustics, seismic etc).
- The analysis is complicated but will be improved by the new set of instruments.

Publications: www.ipgp.fr/~gibert/Publications.html

Blog (Ulisse): <https://ulisse.exposure.co/ulisse-au-service-de-la-riadiographie-dun-volcan?slow=1>

Mails: jourde@ipgp.fr gibert@univ-rennes1.fr marteau@ipnl.in2p3.fr

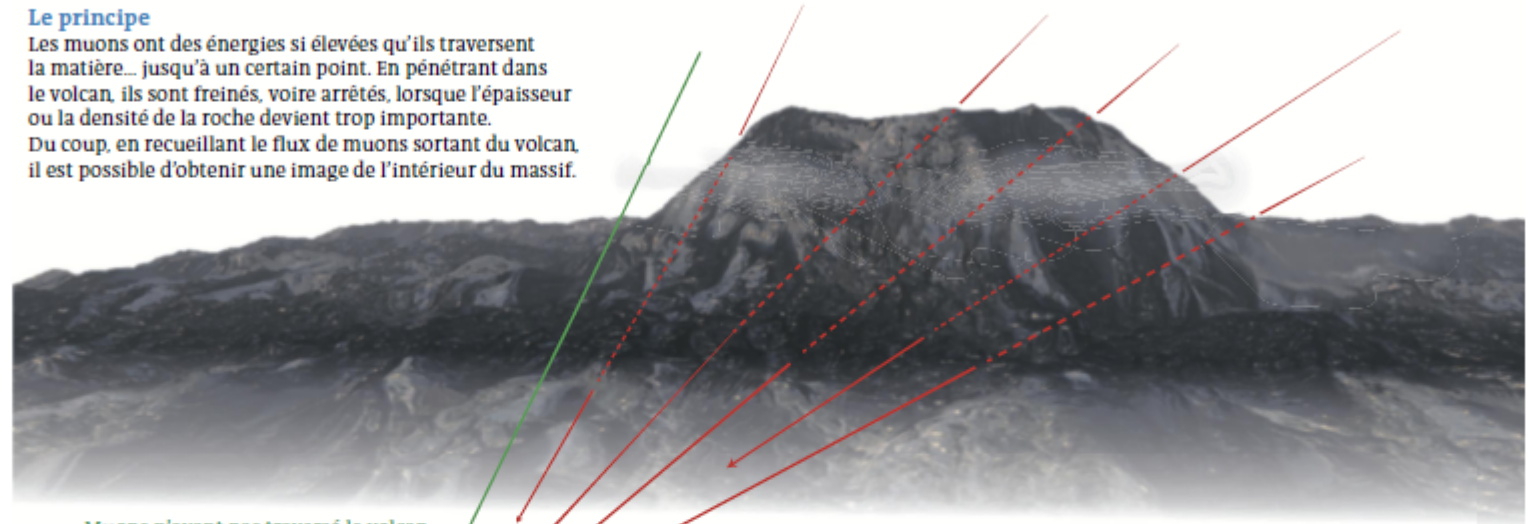
Les muons, explorateurs des entrailles de la Soufrière

En avril, quatre télescopes d'un genre particulier vont être installés en Guadeloupe, autour de la Soufrière. Ils n'auront d'yeux que pour le « petit » volcan et pour des particules qui se forment dans la haute atmosphère, les muons. « Depuis 2008, nous développons une méthode utilisant ce flux de muons pour radiographier les entrailles des volcans », explique Dominique Gibert, de l'Observatoire des sciences de l'université de Rennes. Les muons peuvent tout à la fois traverser la matière et être absorbés quand cette dernière devient trop dense ou trop épaisse. Ils peuvent donc être utilisés pour visualiser les variations de densité au cœur d'un volcan et ce de façon très directe : les muons parcourent la matière en ligne droite là où les ondes sismiques, signaux très souvent utilisés pour surveiller les entrailles des volcans, sont déviées chaque fois que le milieu change de nature. « Nous testons les performances de notre méthode lorsque, en 2012, de nouvelles fumerolles sont apparues au sommet de la Soufrière. Or, peu avant cette nouvelle activité, notre télescope a détecté ce qui semble être de petites poches de vapeur en formation. » Ce qu'aucune autre méthode n'aurait pu déceler. C'est la raison pour laquelle les chercheurs ont décidé d'installer des télescopes tout autour du volcan en vue d'effectuer un suivi en temps réel des humeurs du volcan. Une première. ■

VIVIANE THIVENT

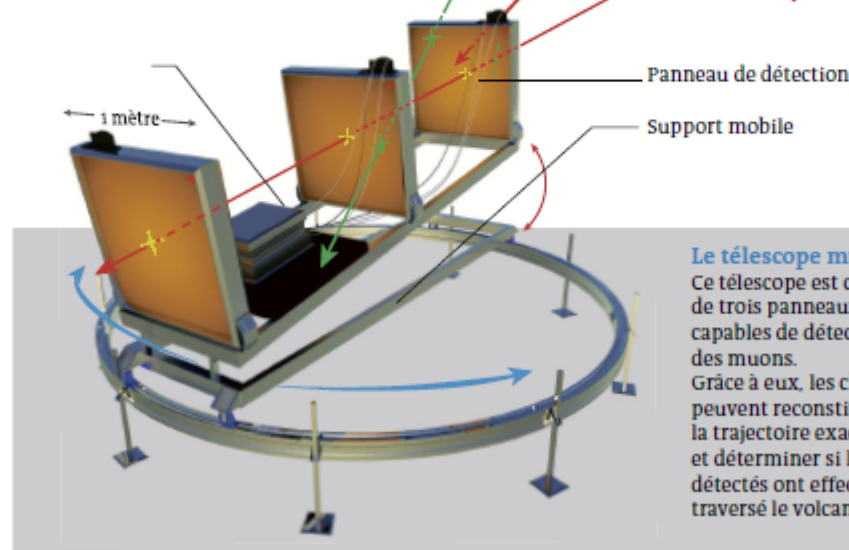
Le principe

Les muons ont des énergies si élevées qu'ils traversent la matière... jusqu'à un certain point. En pénétrant dans le volcan, ils sont freinés, voire arrêtés, lorsque l'épaisseur ou la densité de la roche devient trop importante. Du coup, en recueillant le flux de muons sortant du volcan, il est possible d'obtenir une image de l'intérieur du massif.



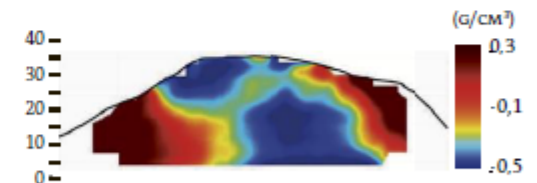
Muons n'ayant pas traversé le volcan, éliminés dans l'analyse de l'image

Muons utilisés pour l'imagerie du volcan



Le télescope muonique

Ce télescope est composé de trois panneaux parallèles capables de détecter le passage des muons. Grâce à eux, les chercheurs peuvent reconstituer la trajectoire exacte des muons et déterminer si les muons détectés ont effectivement traversé le volcan.



L'image

En analysant le flux muonique, on obtient une image dont la résolution dépend du temps de mesure. Ce cliché montre des variations de densité parfois difficiles à interpréter. En radiographiant le volcan en temps réel, sous quatre angles différents, les chercheurs espèrent mieux comprendre le sens des données récoltées.