DIAPHANE: Muon tomography applied to volcanoes, civil engineering, archeaology.

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

Thessaloniki, 21/12/2015

Muon tomography

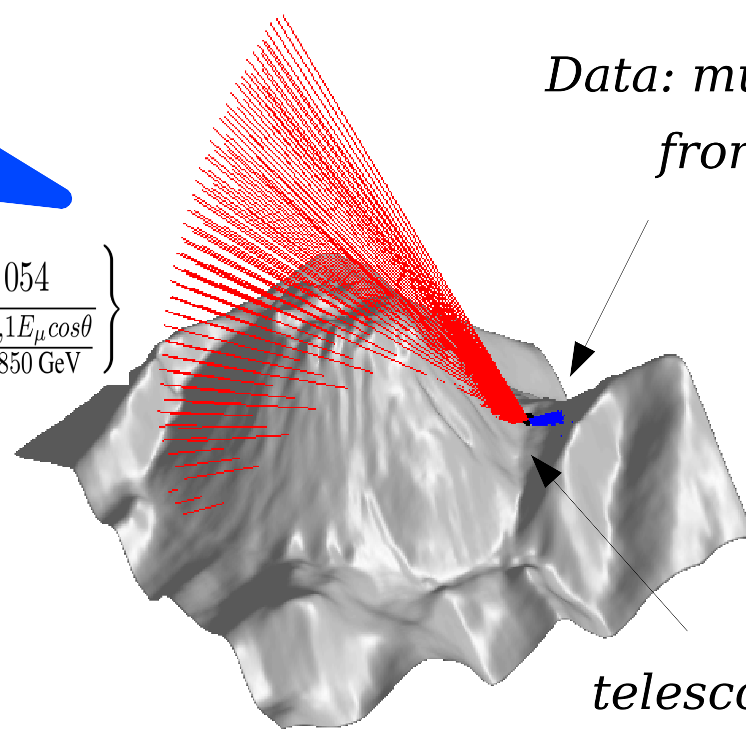
Measurement of the muon flux emerging from the volcano to determine its opacity (amount of matter):

$$\varrho(L) \equiv \int_L \rho(\xi)\mathrm{d}\xi$$

ϱ = opacity
ρ = density

incident muon flux

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

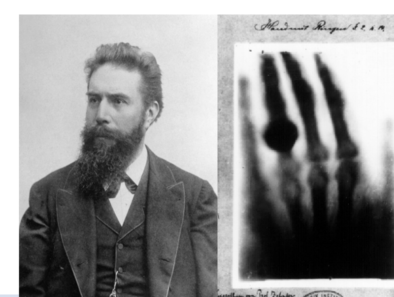


Data: muon flux emerging from the volcano

telescope

Alvarez, L.W. et al., 1970

Nagamine, K. et al., 1995



Röntgen, 22 déc. 1895.

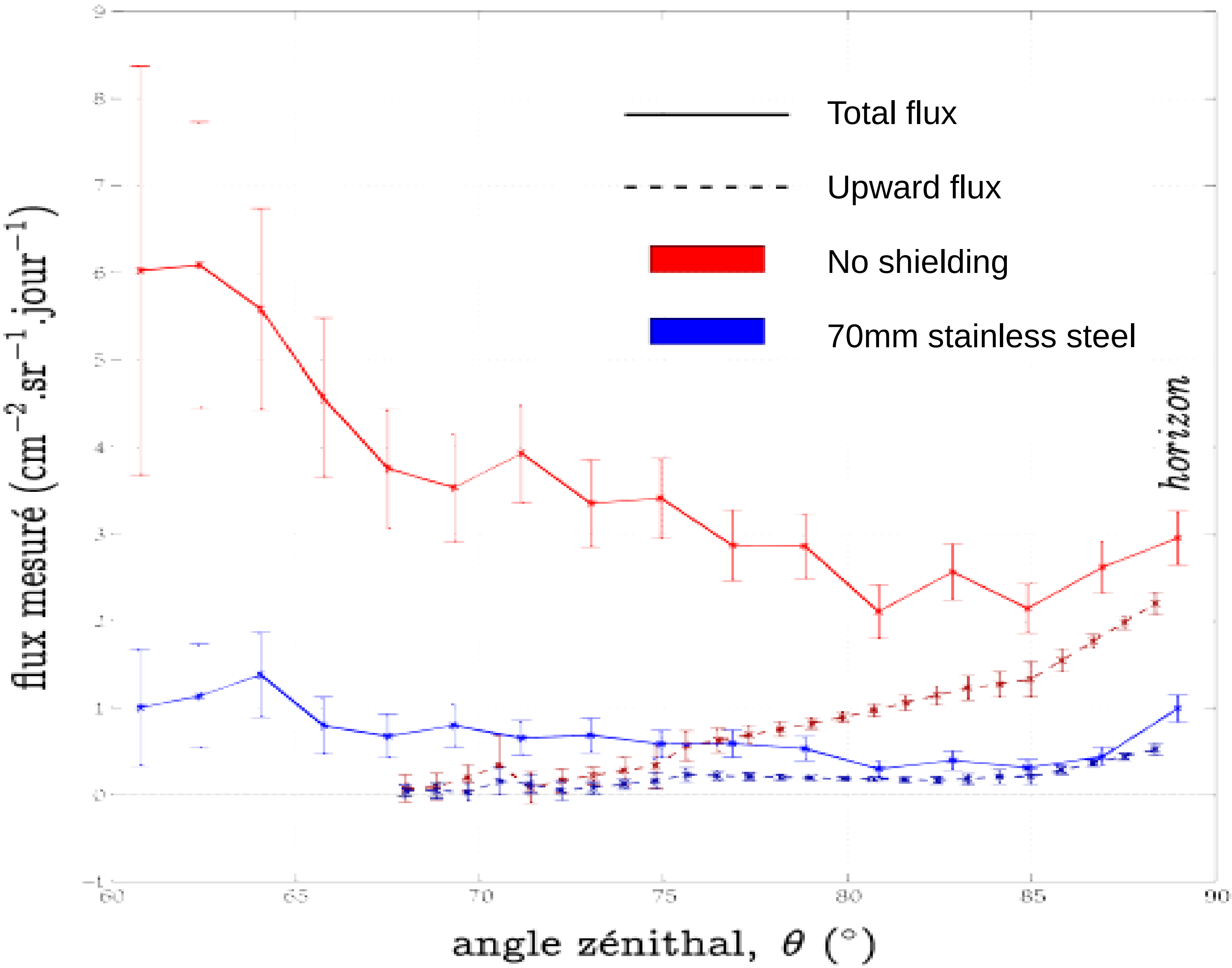
Muon tomography noise sources

We have various sources of uncertainties:

- Bad estimation of the open-sky differential muon flux (solution: simulation)
- Low energy particles diffusing near the telescope (solution: shielding and data treatment)
- Upward going particles coming from very inclines showers (solution: nanosecond clock to distinguish the particles direction (Jourde, K. et al. 2013))
- Noise coming from open-sky particles hitting

Muon tomography noise sources

Role of the shielding (5cm lead ~ 7cm stainless steel)



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)

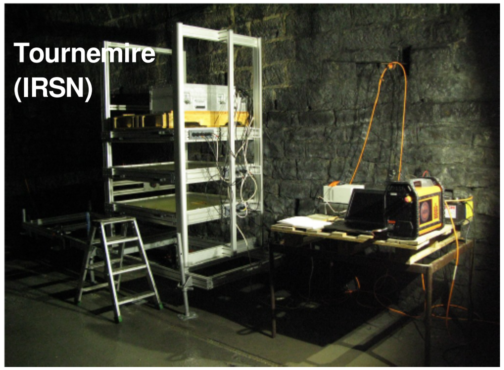
- 2009: first installation in Mont-Terri (funding: Swisstopo) for methodological developments in a known geology

- 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)



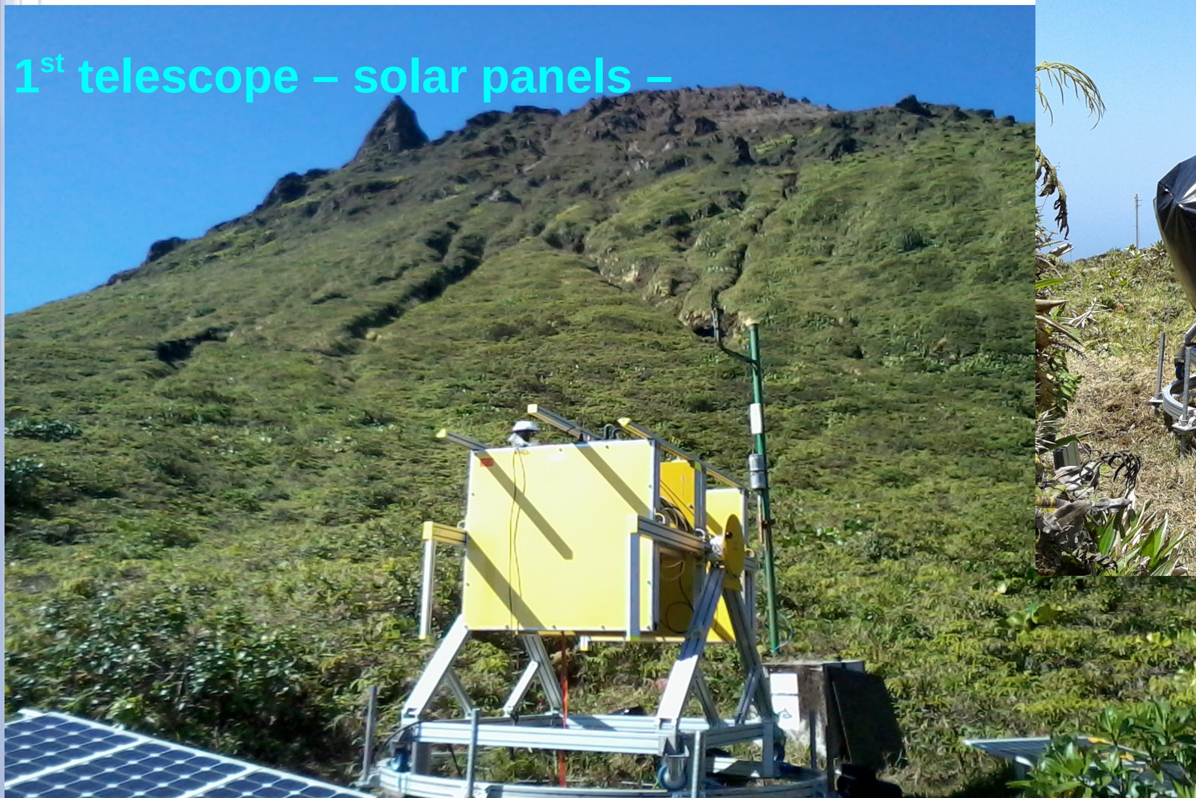
Diaphane '15: installation

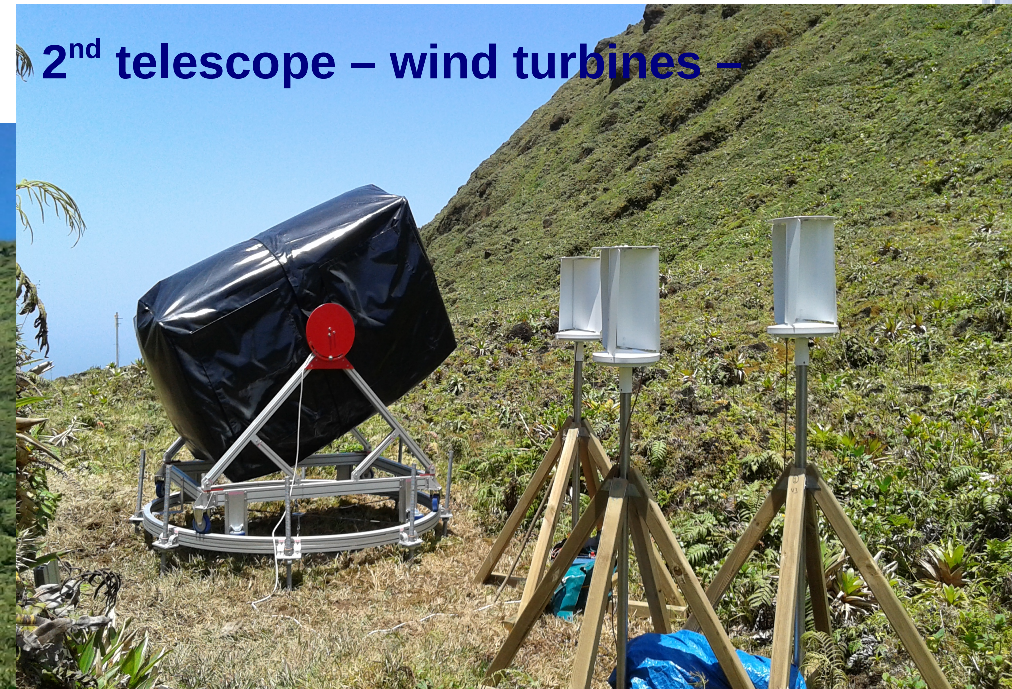
4 telescopes installed
and operated on site
in 2 weeks. 3 tons of
material including shielding

Helicopter transfer of a
premounted structure

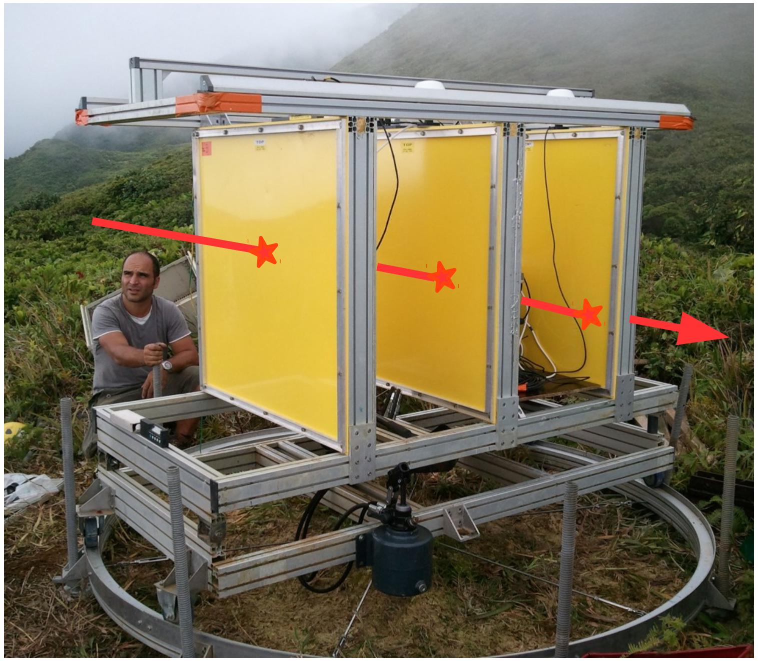
Mini-telescope in a fault
(faille du 30 août)

Diaphane '15: installation





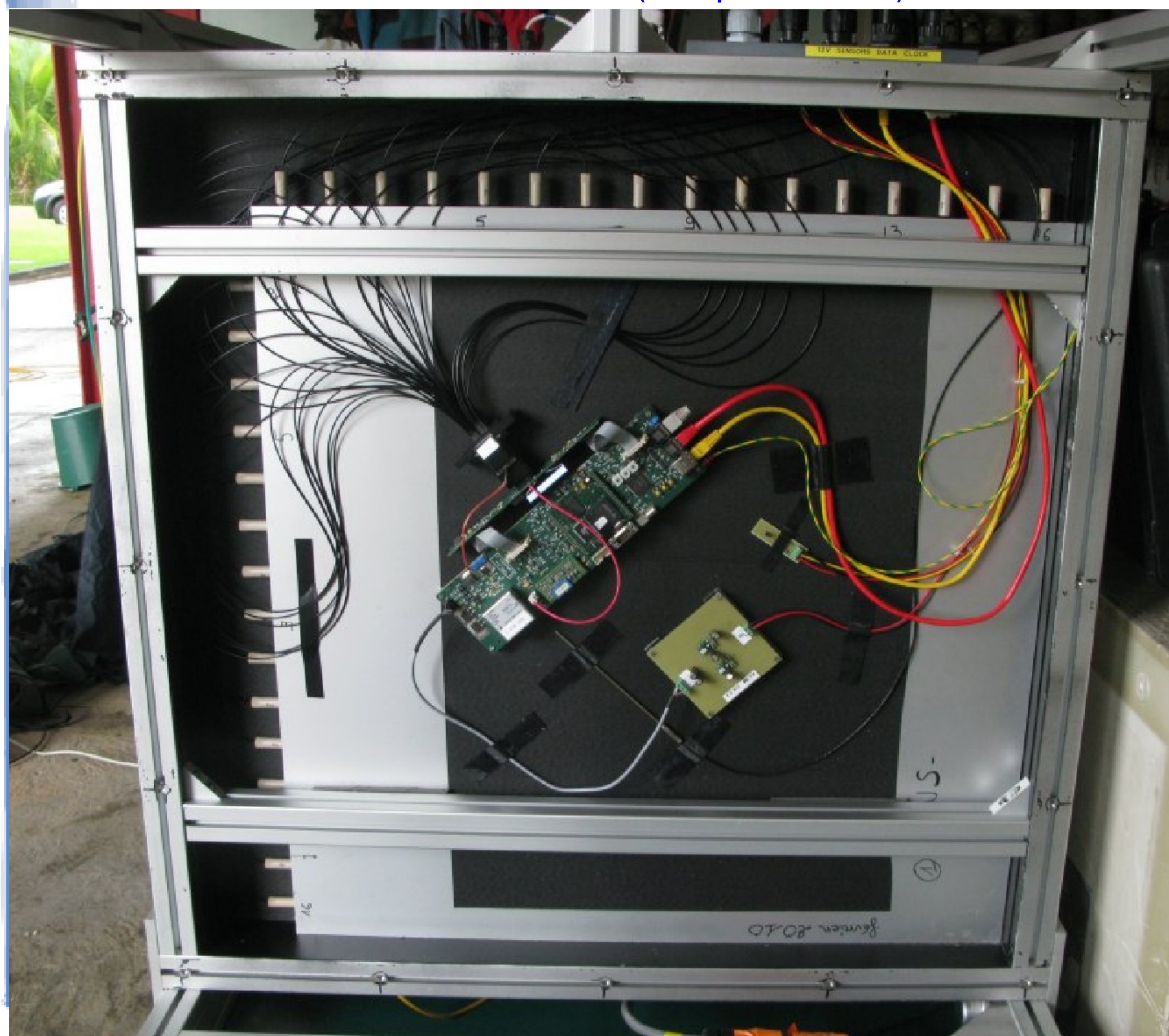
A field instrument

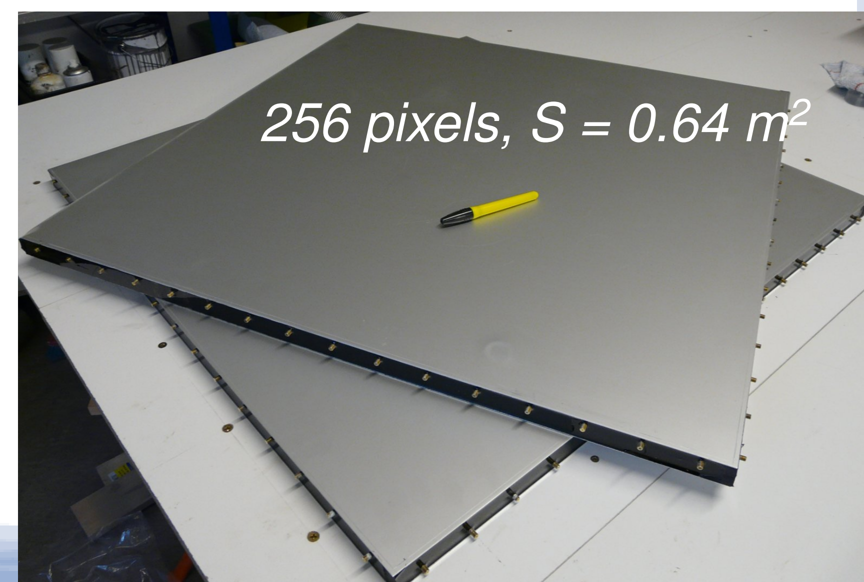


– Power: photovoltaic panels, wind turbine, fuel cells
– Total mass: 200 to 600 kg (lead/iron shielding)
– Angular aperture: 30° - 60°
– Angular resolution: 1° - 2°
– Consumption: ~50W
– Remote Ethernet control

Detection planes

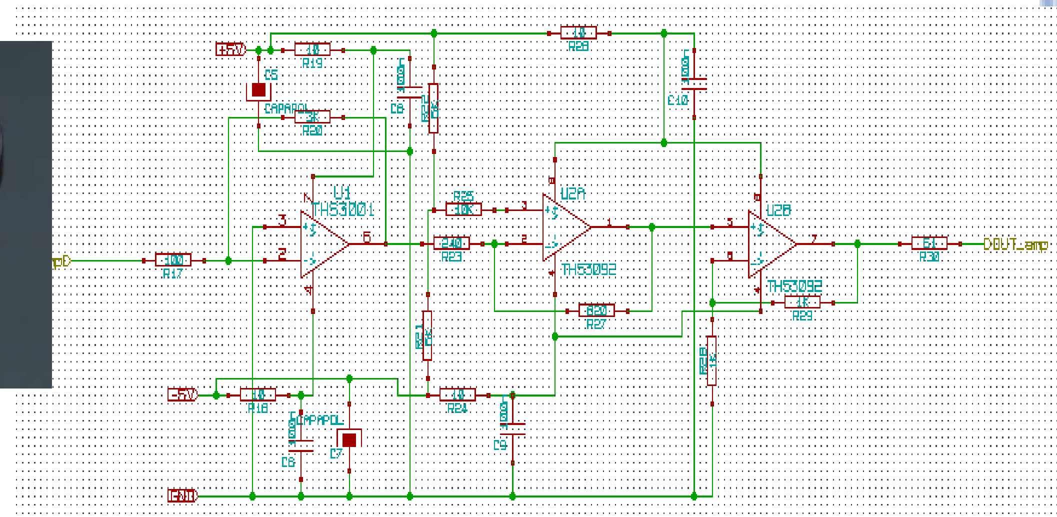
- 256 = 16 x 16 pixels. Scintillators + WLS + MaPMT/SiPM
- Same électronics for all types of matrices / photosensors
- Technology transfer from OPERA
- Common Clock locked on GPS (10ns timestamps)
- TDC embedded in the FPGA (100ps vernier) for t.o.f.





SiPM readout system

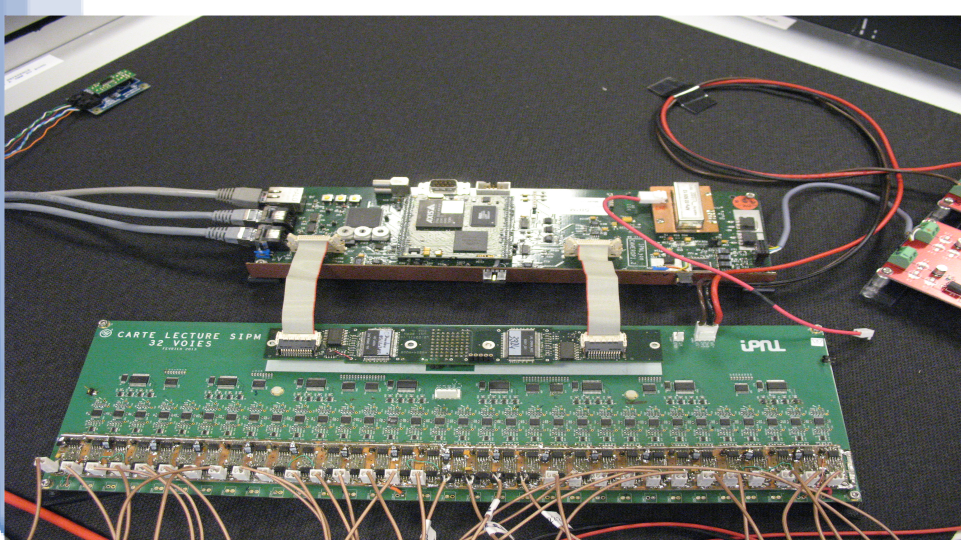
Front-end stage design based on a simplified chain (P.E. counter) with a robust, high gain amplifier.

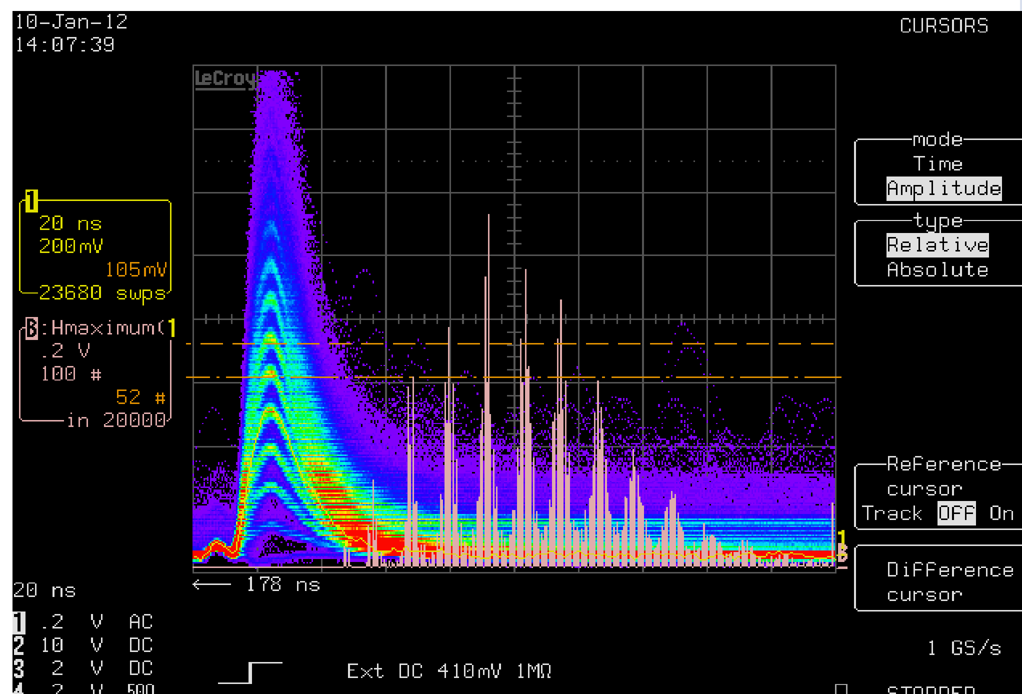


Successful operation in auto-trigger mode (full telescope running in Lyon)

Benefits from the excellent P.E. counting capabilities

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

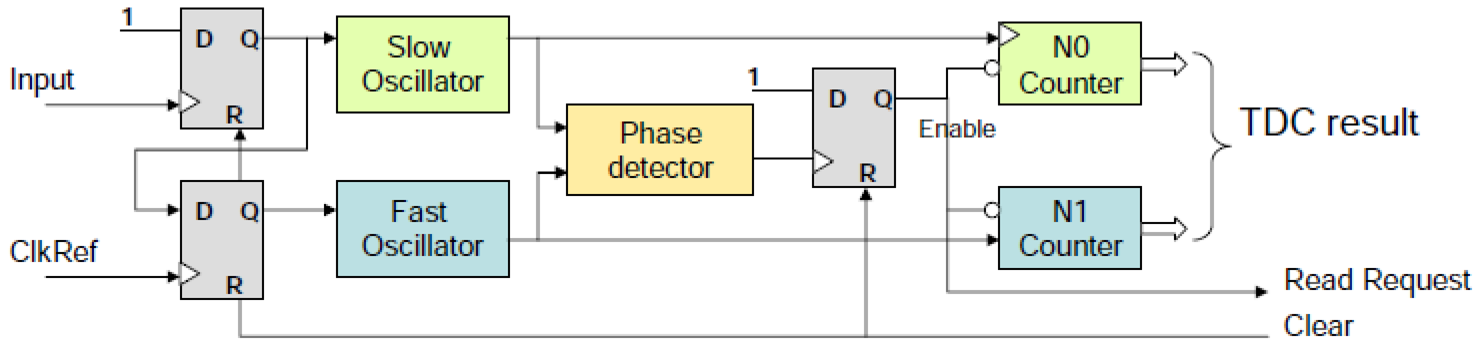




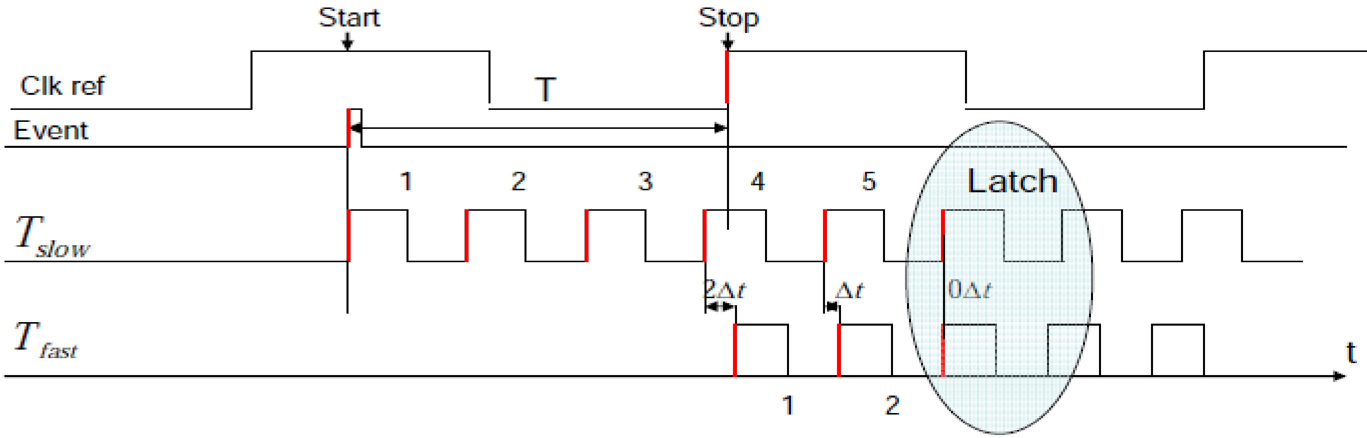
Upward flux monitoring : TDC techniques

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.



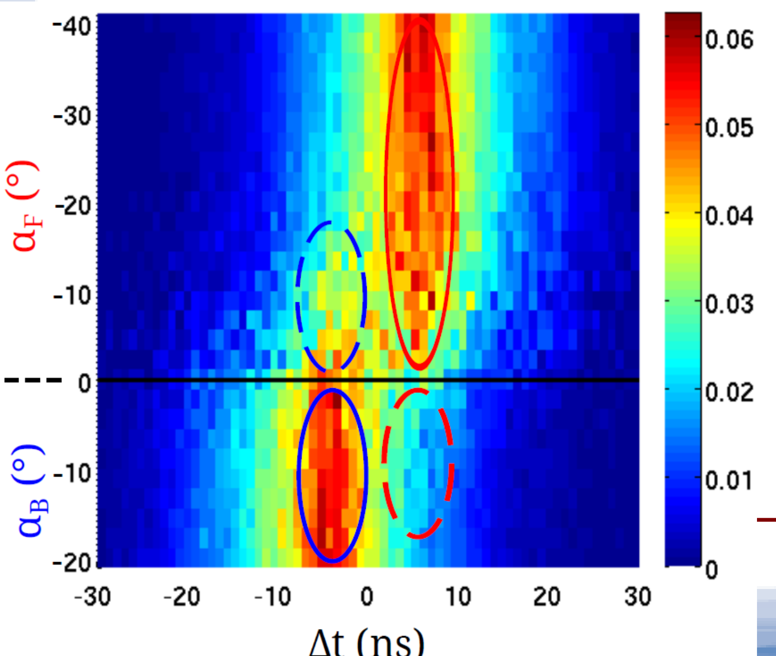
Low area, low power consumption, no extra fast clock.



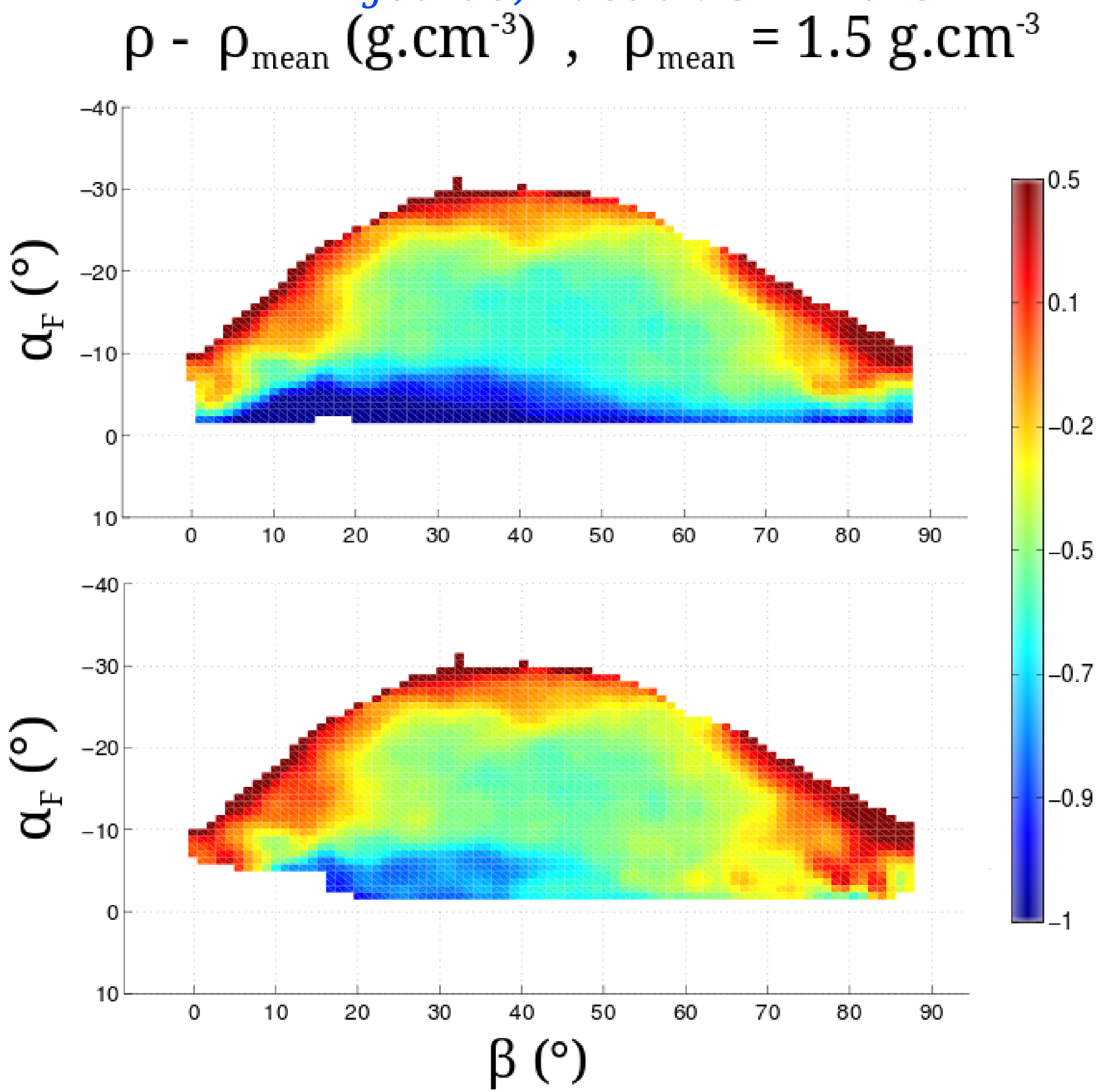
Direct implementation inside FPGA. Different design = optimal timing resolution

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.



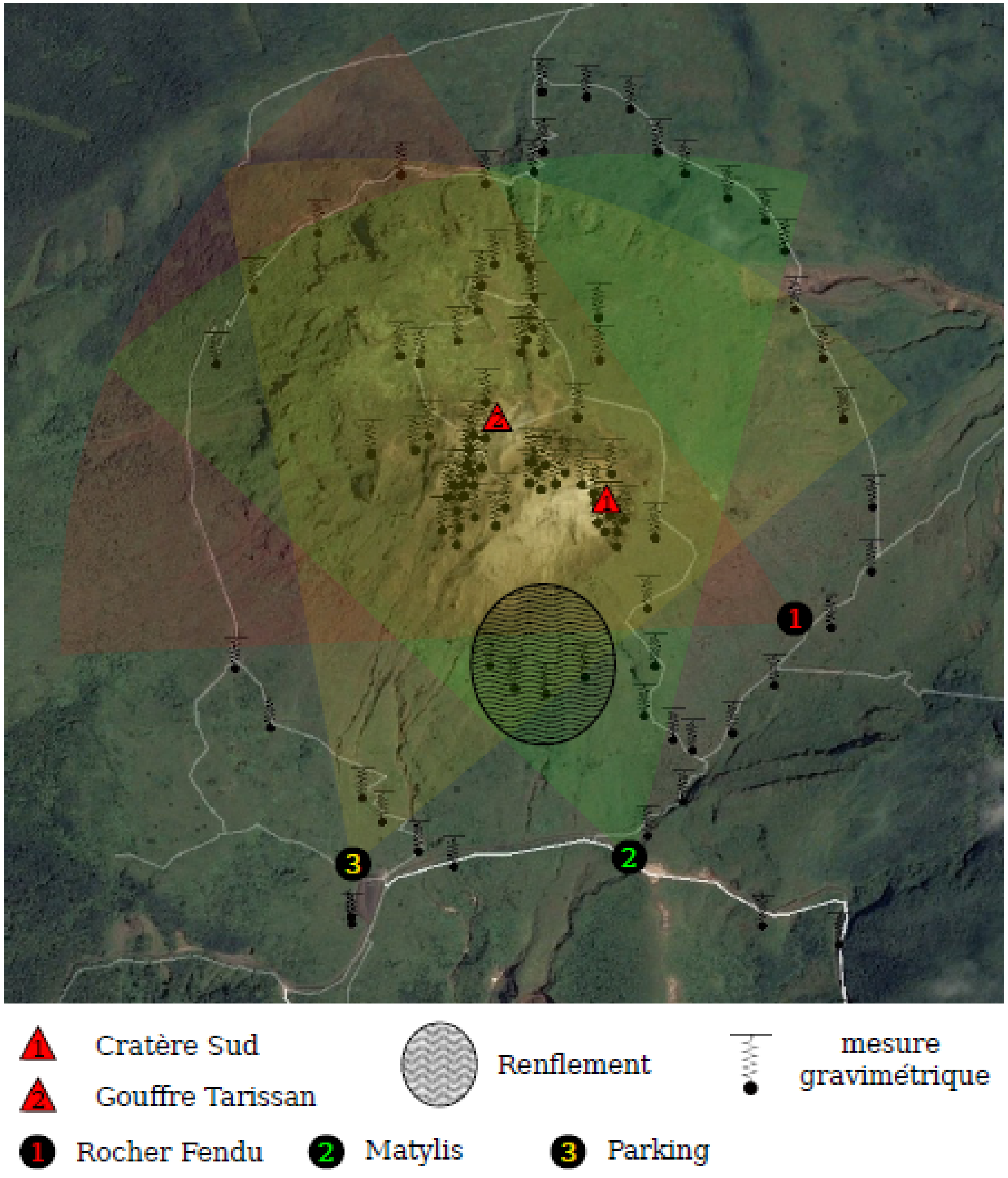
Jourde, K. et al. GRL 2013

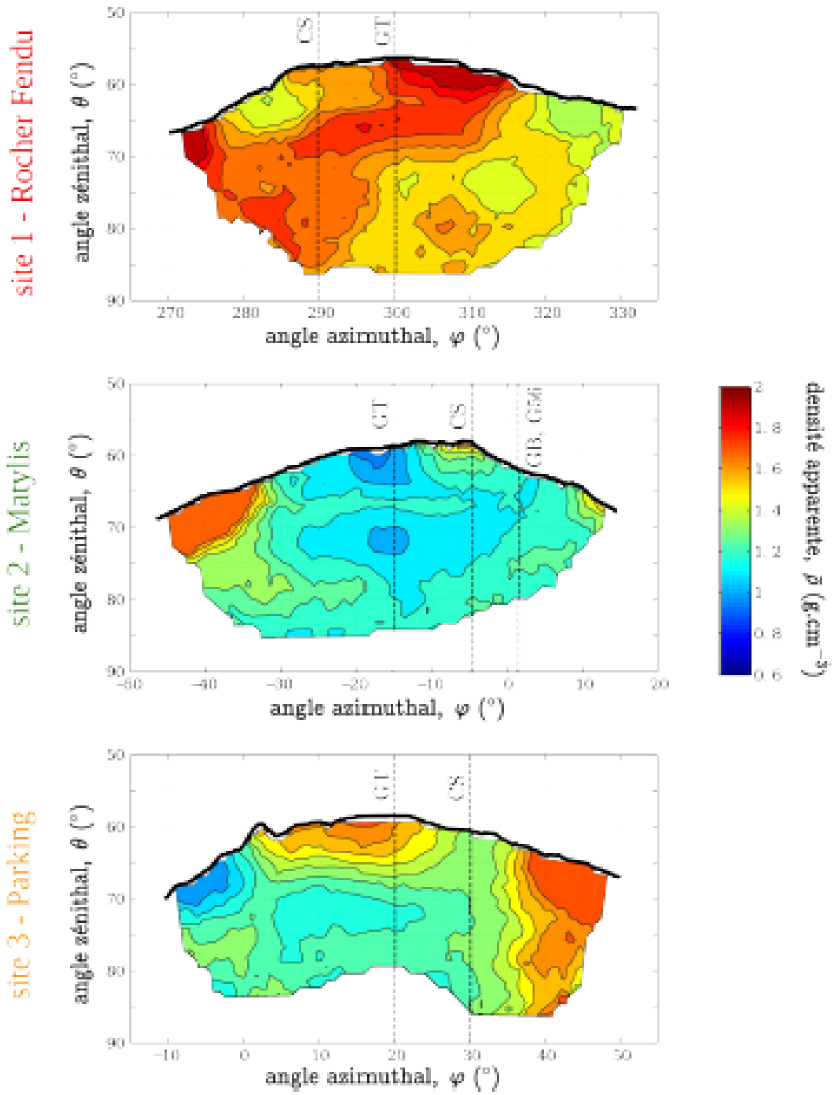


Tomographies from 2011-2014 campaigns

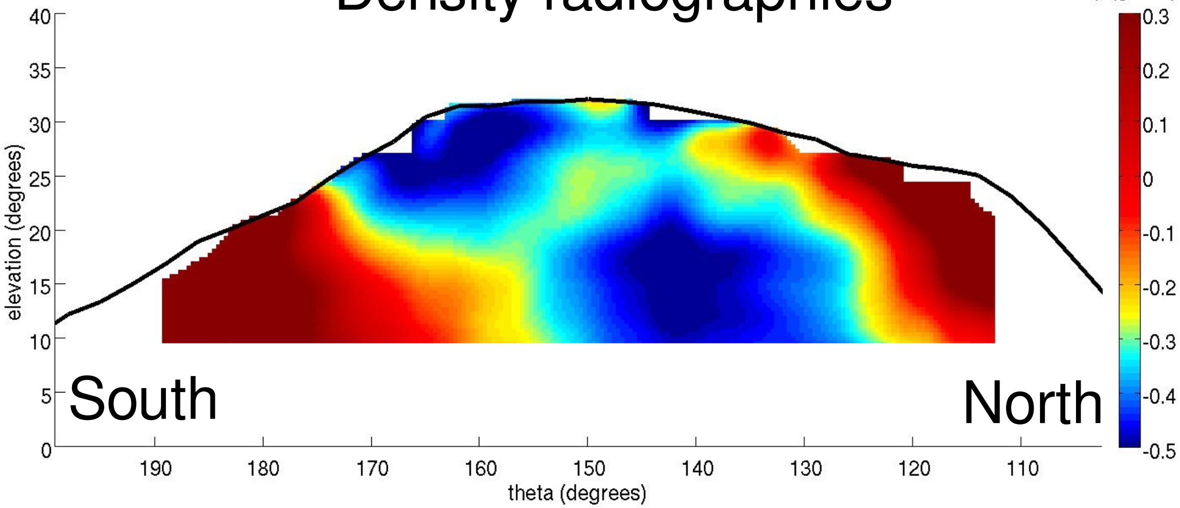
Lesparre, N. et al. 2012

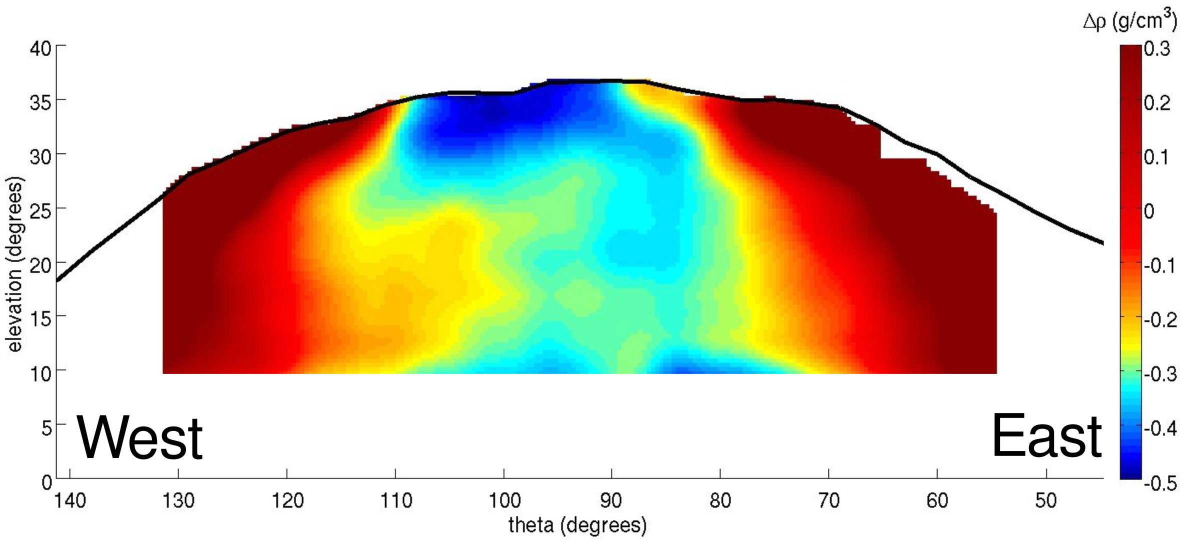
Jourde, K. et al. 2013





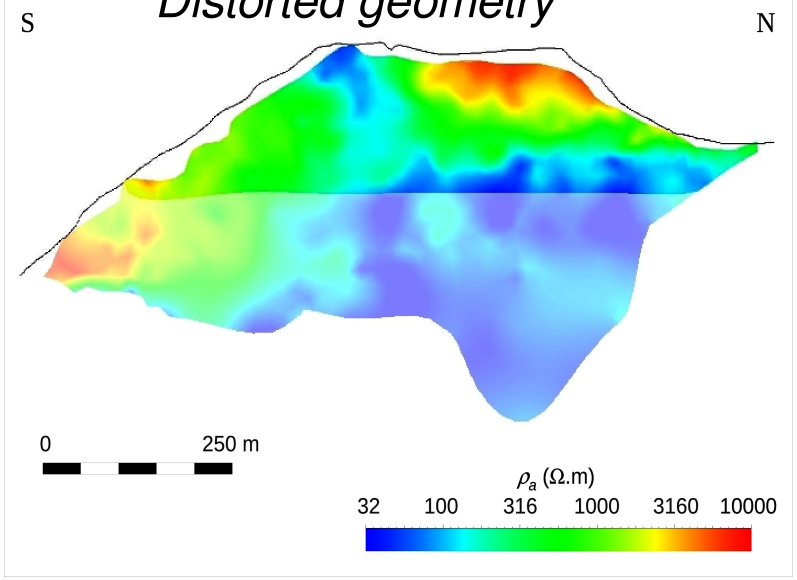
Density radiographies

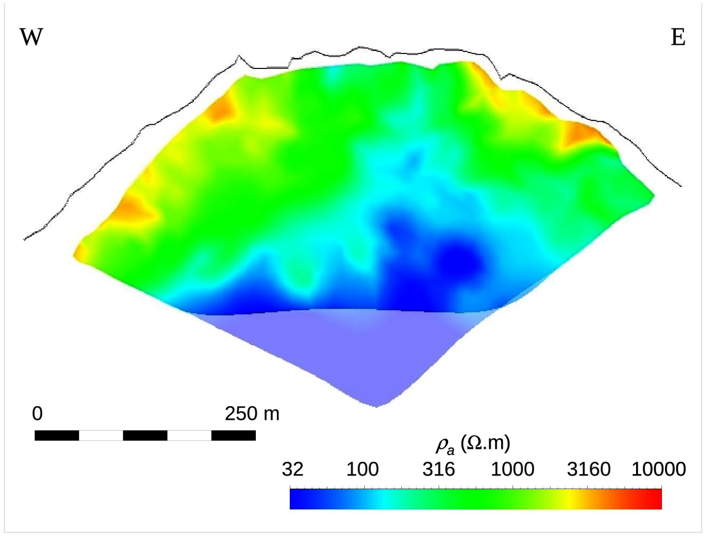




Electrical resistivity

Distorted geometry





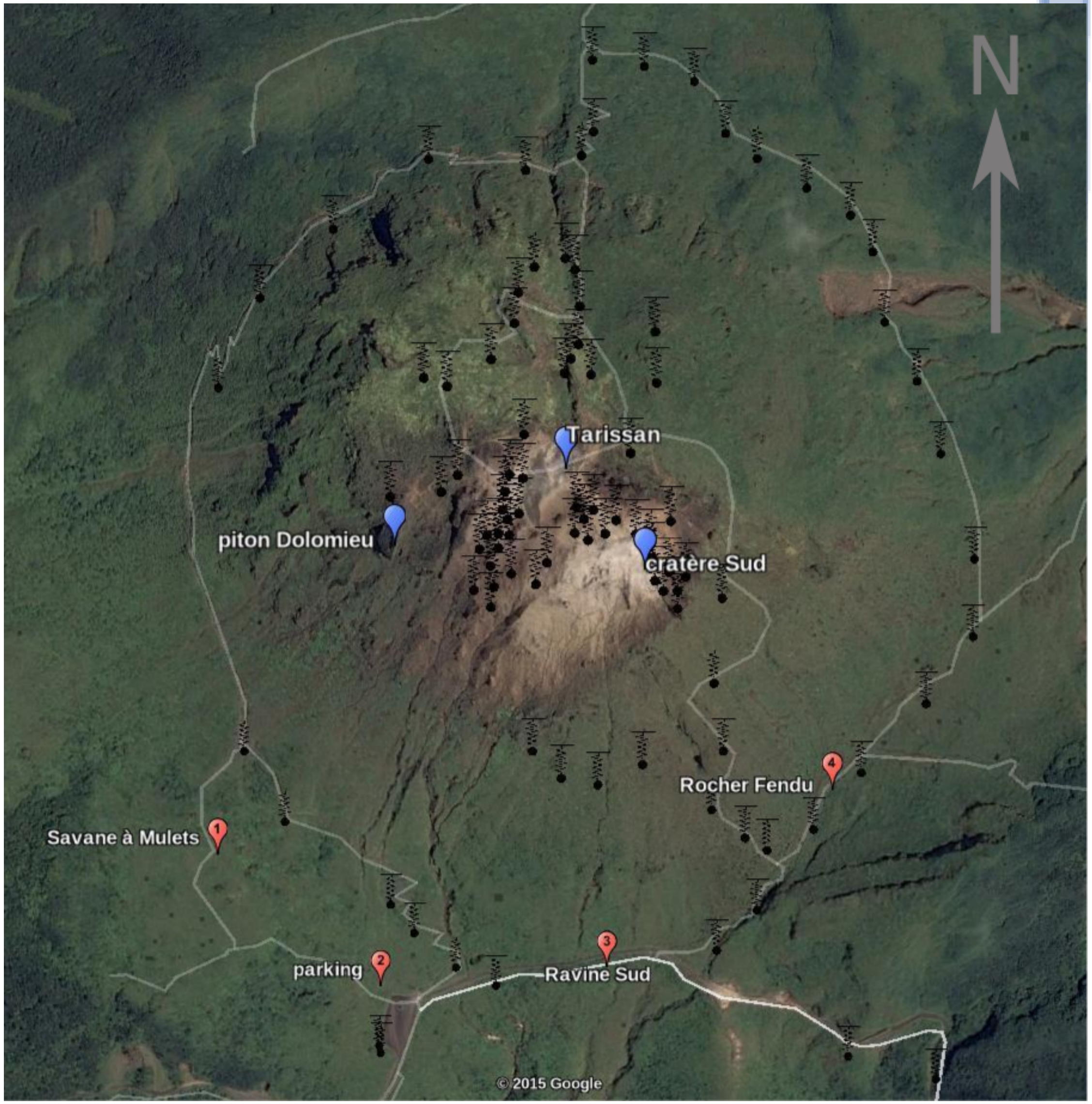
Muon-gravimetry coupling: a kernel approach

2014/2015 Soufrière gravimetry survey:

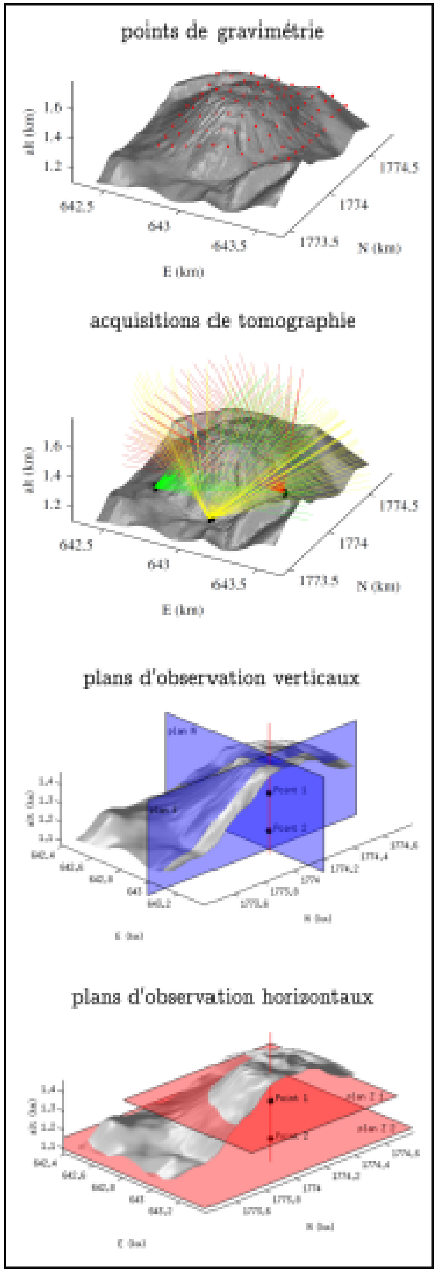
- 146 measurements
- 2 CG5 gravimeters during 1 year
- 1.5km large, 500m height difference survey
- on an island
- 40 µGal precision
- 1 absolute measurement

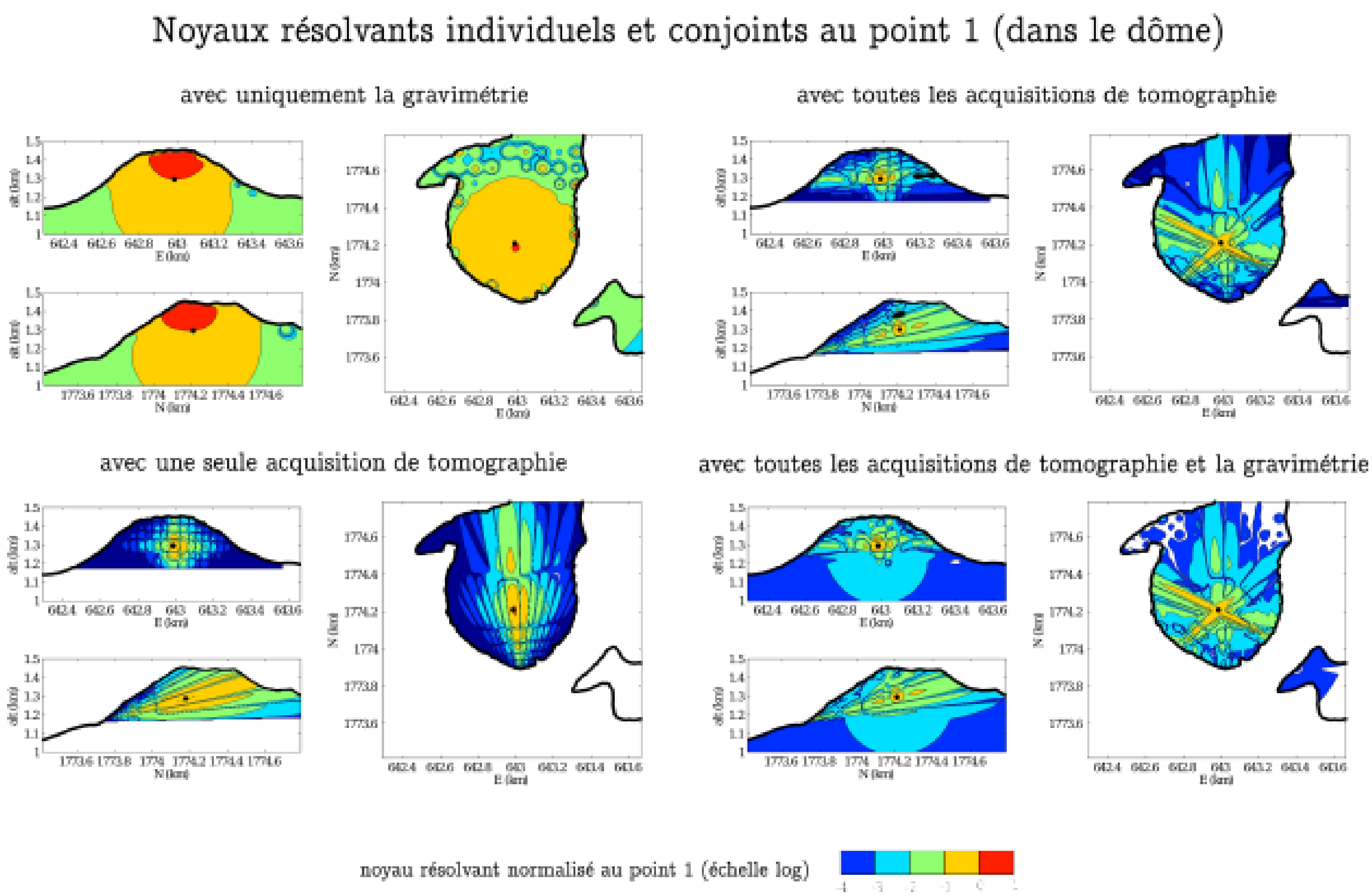
Imply complex corrections:

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

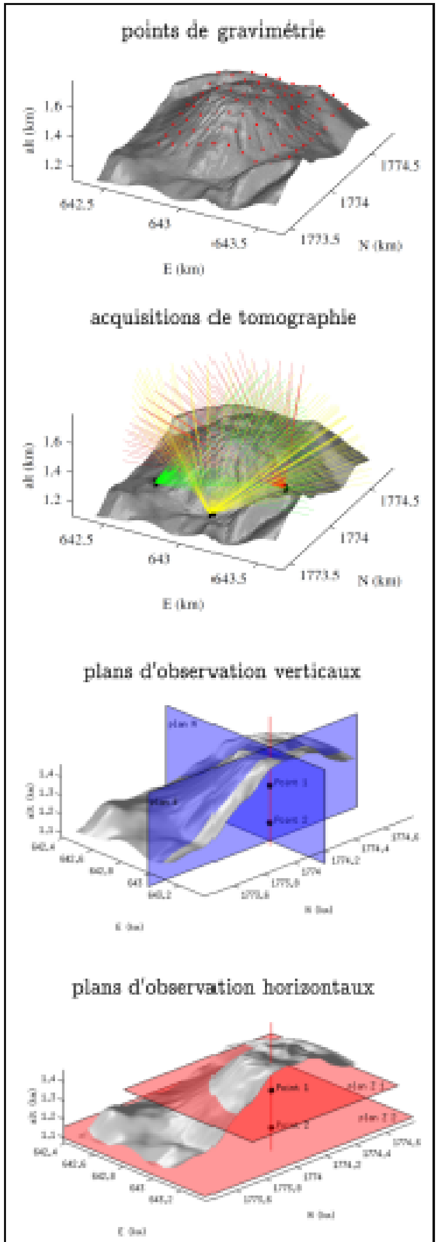


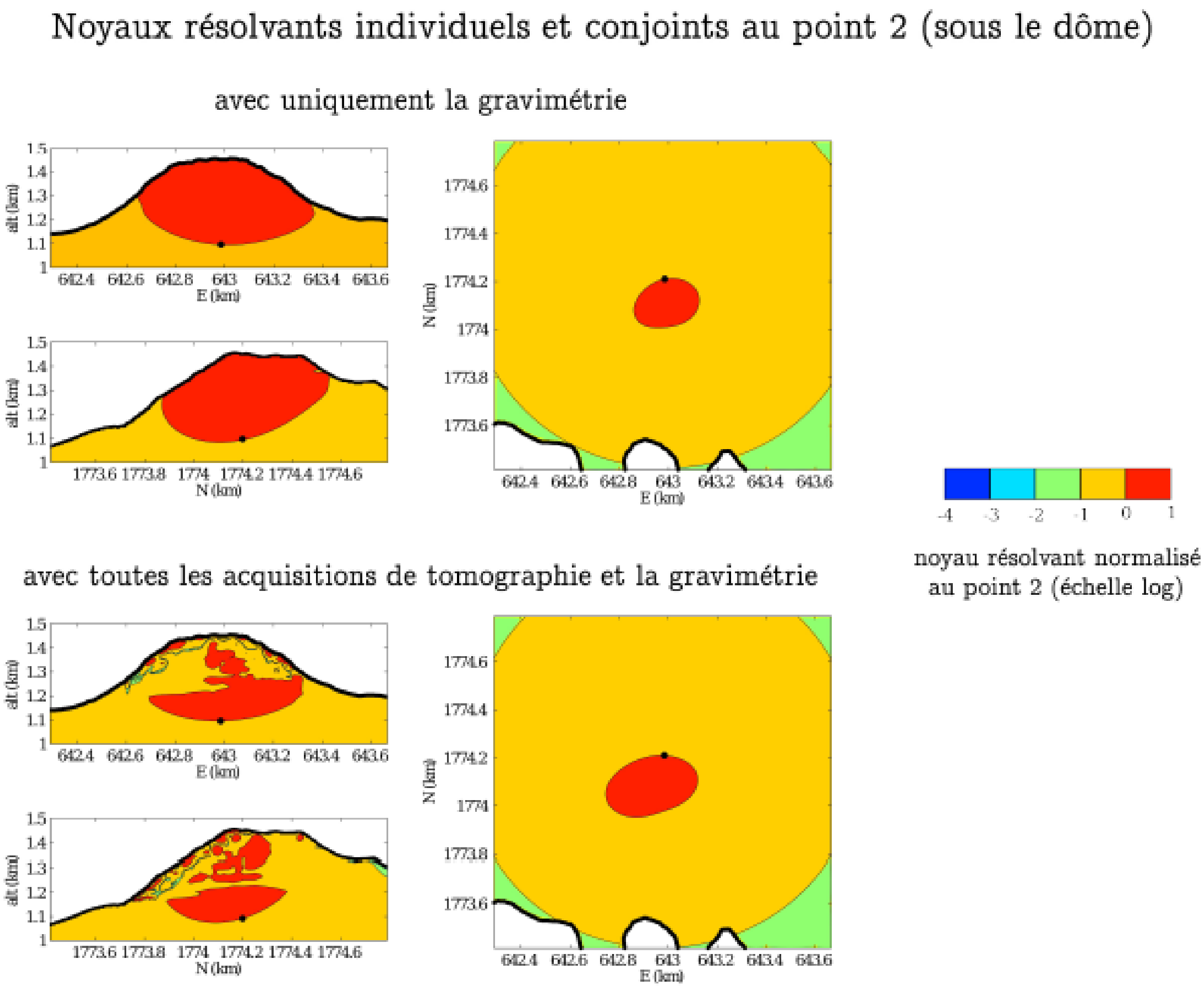
Muon-gravimetry coupling: a kernel approach



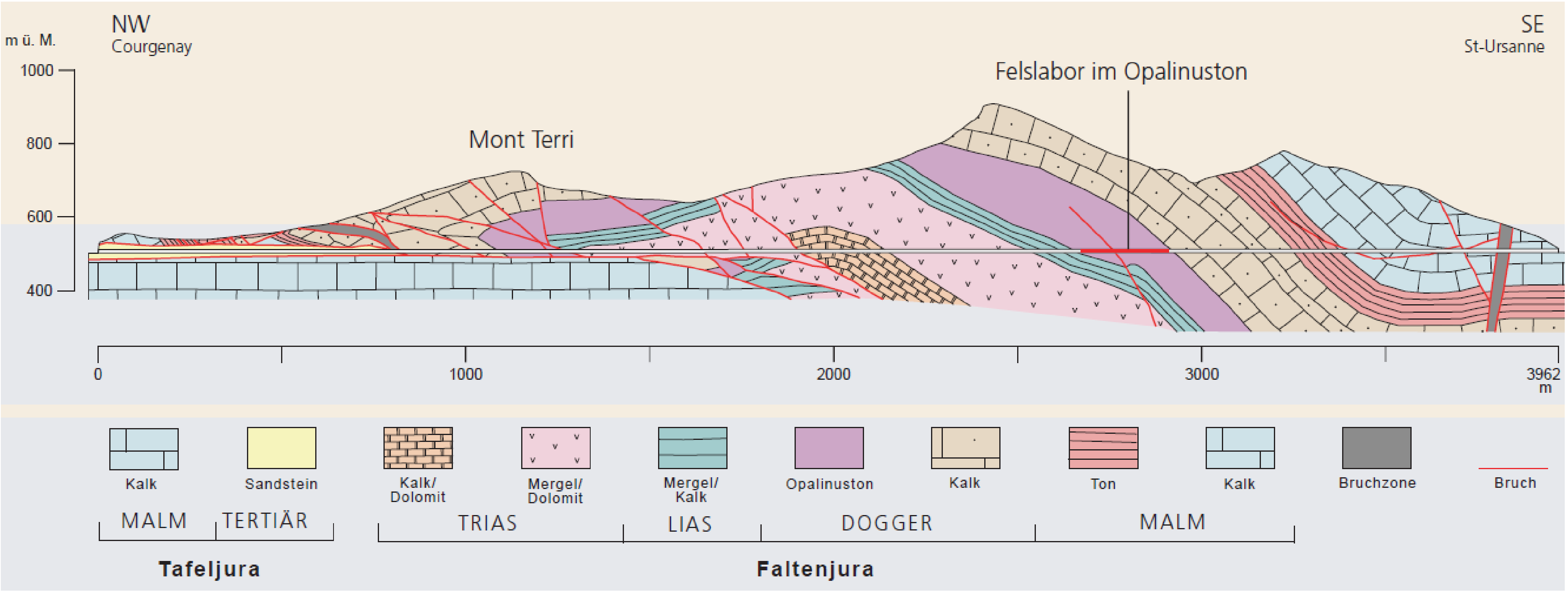


Muon-gravimetry coupling: a kernel approach



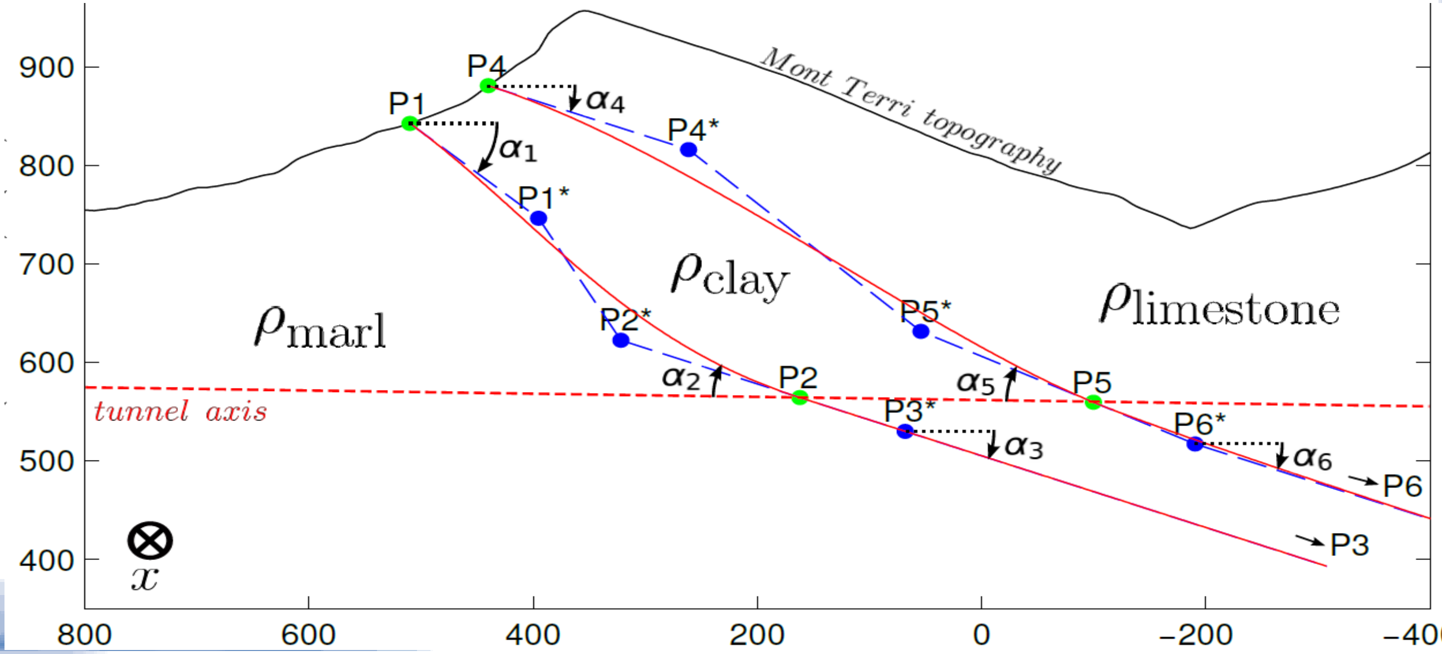


MT geology parametrization

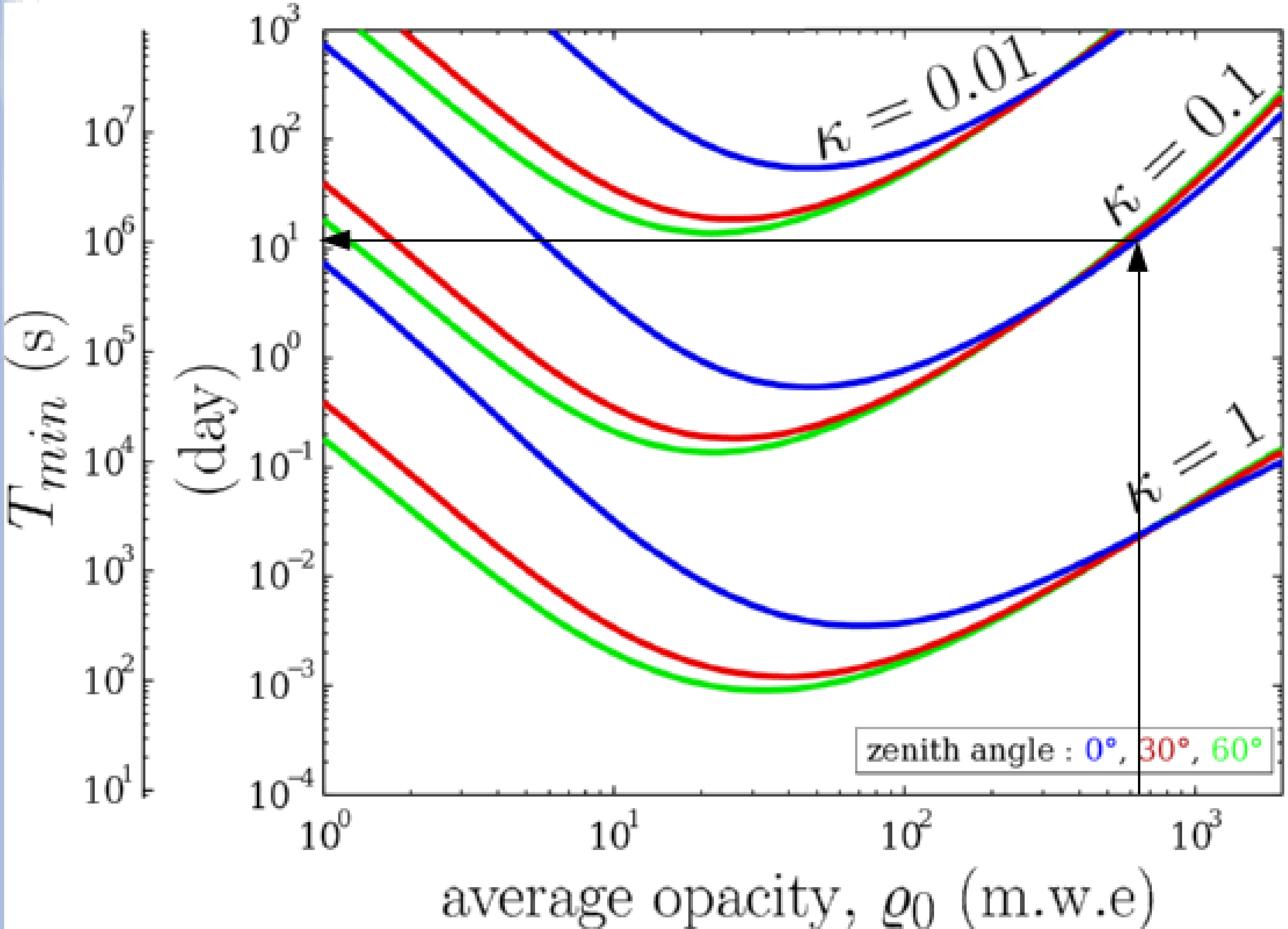


Analyzing **gravimetry & muon** direct problems

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



Feasibility curves (analytic pb)

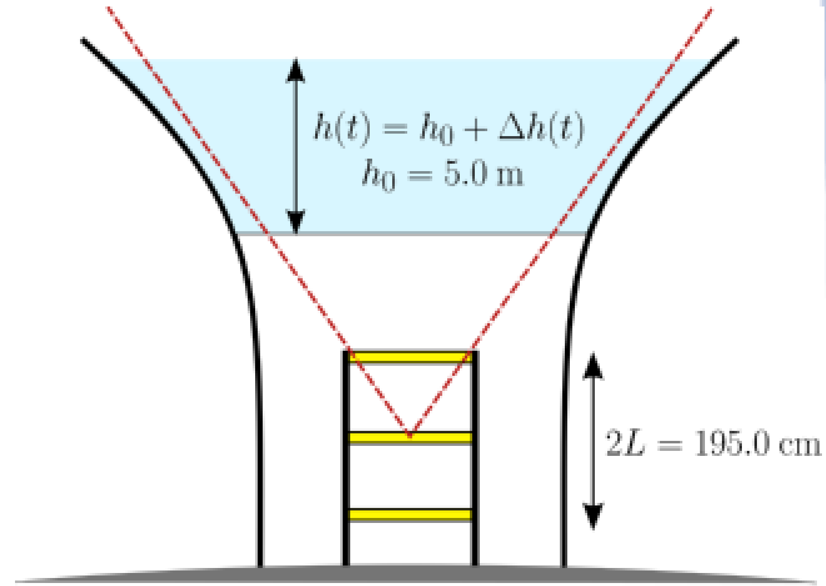


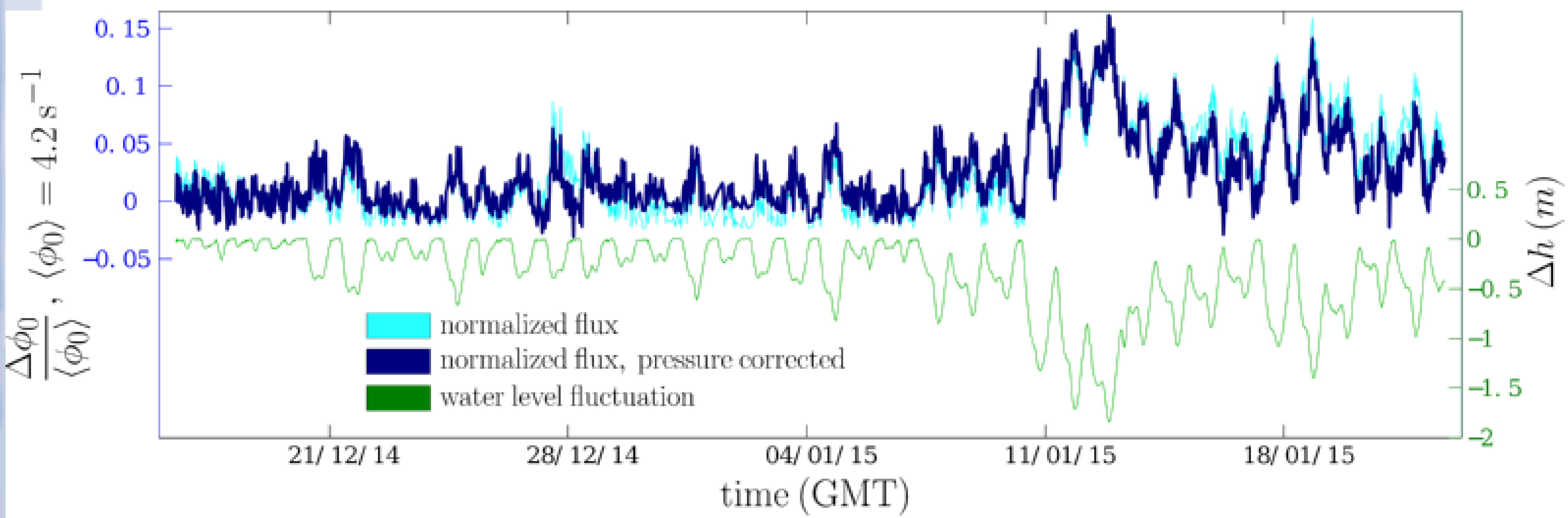
Computed with an acceptance of 10 cm^2.sr and using the modified Gaisser model from Tang et al. 2006.

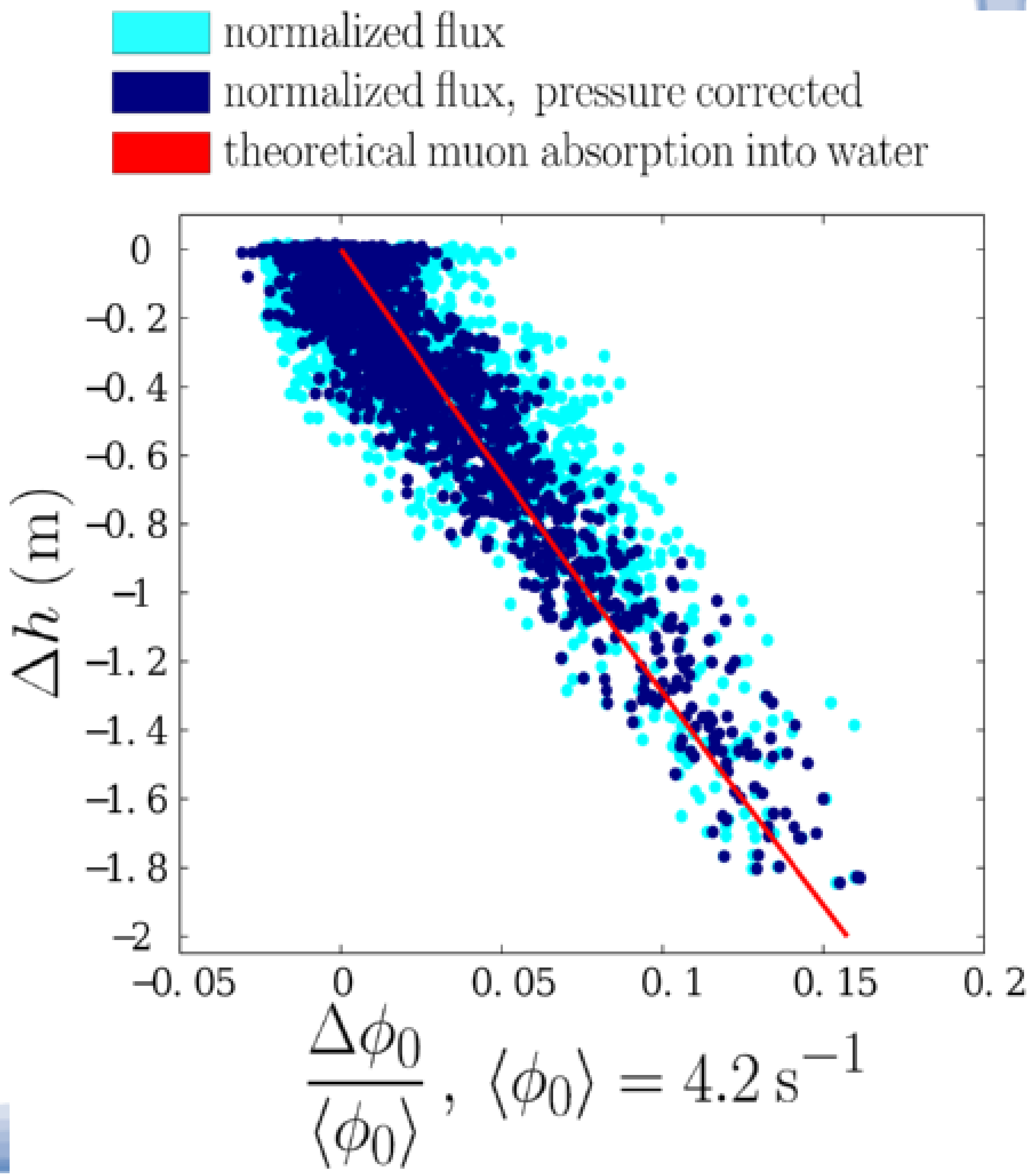
For example : at a zenith angle of **60°**, a **10%** opacity fluctuation around an average opacity of **600 mwe** needs about **10 days** to be detected.

The SHADOW experiment :

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






normalized flux
normalized flux, pressure corrected
theoretical muon absorption into water
Δh (m)
0
−0.2
−0.4
−0.6
−0.8
−1
−1.2
−1.4
−1.6
−1.8
−2
−0.05
0
0.05
0.1
0.15
0.2
$\frac{\Delta\phi_0}{\langle\phi_0\rangle}$, $\langle\phi_0\rangle = 4.2\,s^{-1}$

Conclusions

- 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**

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