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Single station Monitoring of Volcanoes Using Seismic ambient noise

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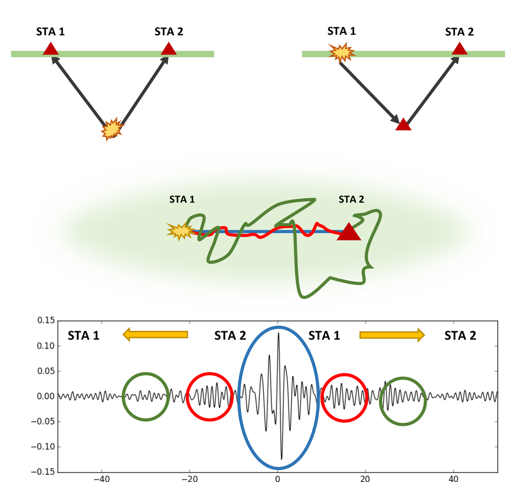
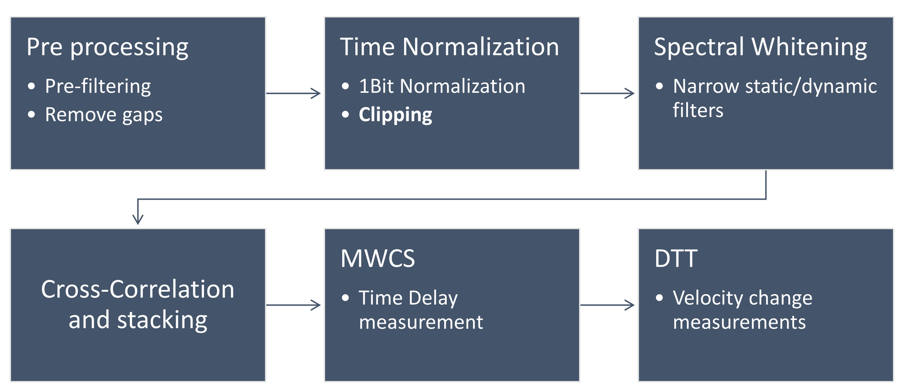
OVERVIEW

During volcanic eruptions, magma transport causes gas release, pressure perturbations and fracturing in the plumbing system. The potential subsequent surface deformation that can be detected using geodetic techniques and deep mechanical processes associated with magma pressurization and/or migration and their spatial-temporal evolution can be monitored with volcanic seismicity. However, these techniques respectively suffer from limited sensitivity to deep changes and a too short-term temporal distribution to expose early aseismic processes such as magma pressurisation.

Seismic ambient noise cross correlation uses the multiple scattering of seismic vibrations by heterogeneities in the crust to retrieves the Green's function for surface waves between two stations by cross-correlating these diffuse wavefields. Seismic velocity changes are then typically measured from the cross correlation functions (CCF) with applications for volcanoes, large magnitude earthquakes in the far field and smaller magnitude earthquakes at smaller distances. This technique is increasingly used as a non-destructive way to continuously monitor small seismic velocity changes (~0.1%) associated with volcanic activity, although it is usually limited to volcanoes equipped with large and dense networks of broadband stations.

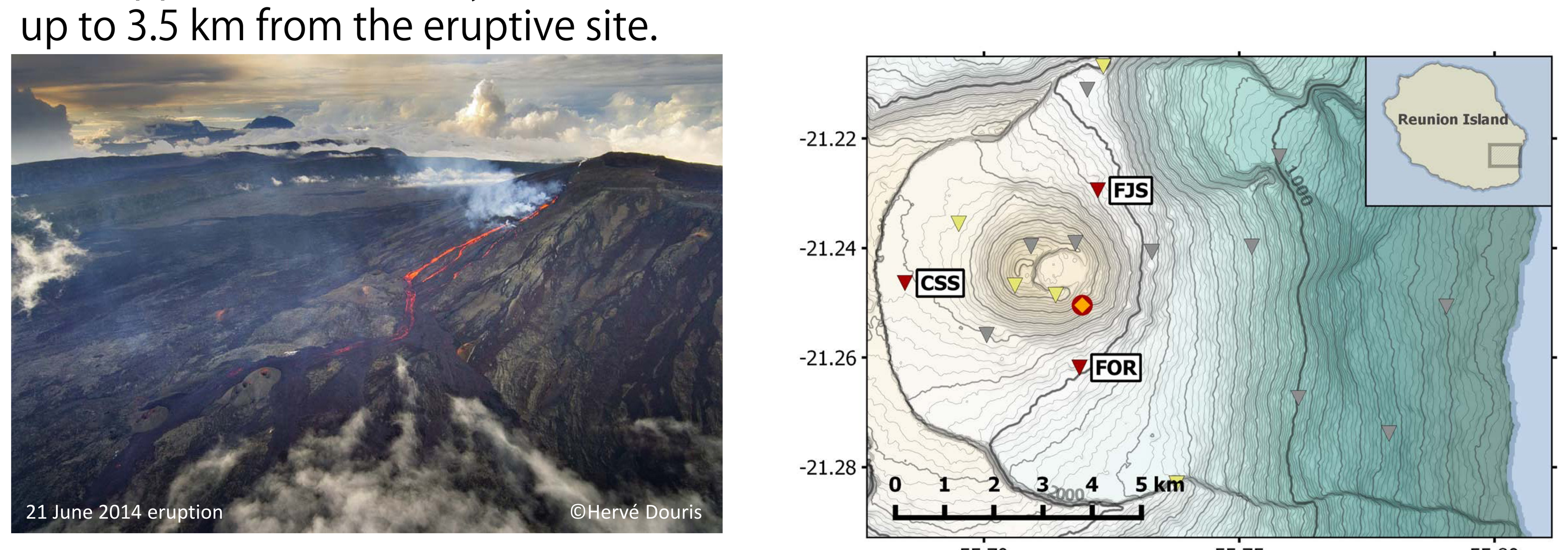




UPPER LEFT: Cartoon illustrating how the cross-correlation of seismic noise recorded at two stations reconstructs a virtual seismic wave generated a one station and recorded at the second one. **MIDLLE AND LOWER LEFT:** Illustration of how looking further in the coda of the CCF corresponds to a longer travel time of the virtual seismic wave. **RIGHT:** The conventional processing workflow to measure seismic velocity variations using seismic ambient noise.

PITON DE LA FOURNAISE VOLCANO

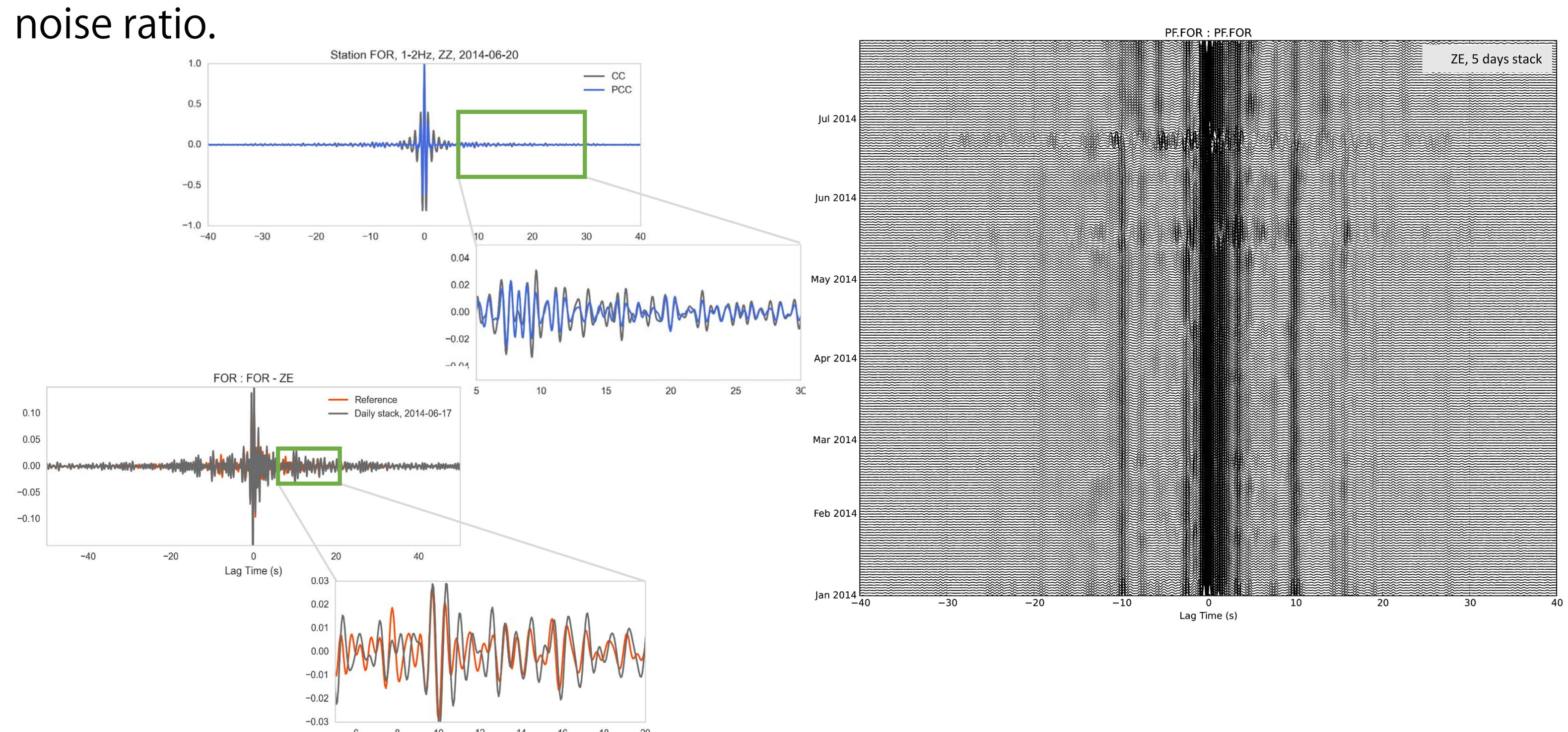
The Piton de la Fournaise (PdF) in Reunion Island is a very active volcano with a remarkable multi-disciplinary continuous monitoring. Over the past decade, this volcano was increasingly studied using the traditional cross-correlation technique [e.g., *Rivet et al.*, 2014] and therefore represents a unique laboratory to validate a new approach. Our study focused on data from 2014 recorded at stations located up to 3.5 km from the eruptive site.



LEFT: Eruption of the PdF Volcano, Reunion Island. **RIGHT:** Map of the stations used for this study (red triangles) and the Piton de la Fournaise Volcano Observatory Network (triangles). The yellow triangles represent Short period seismometers, the remaining are broadband seismometers. Station FOR is closer to the 2014 fissure eruption (circle).

THE SINGLE STATION APPROACH

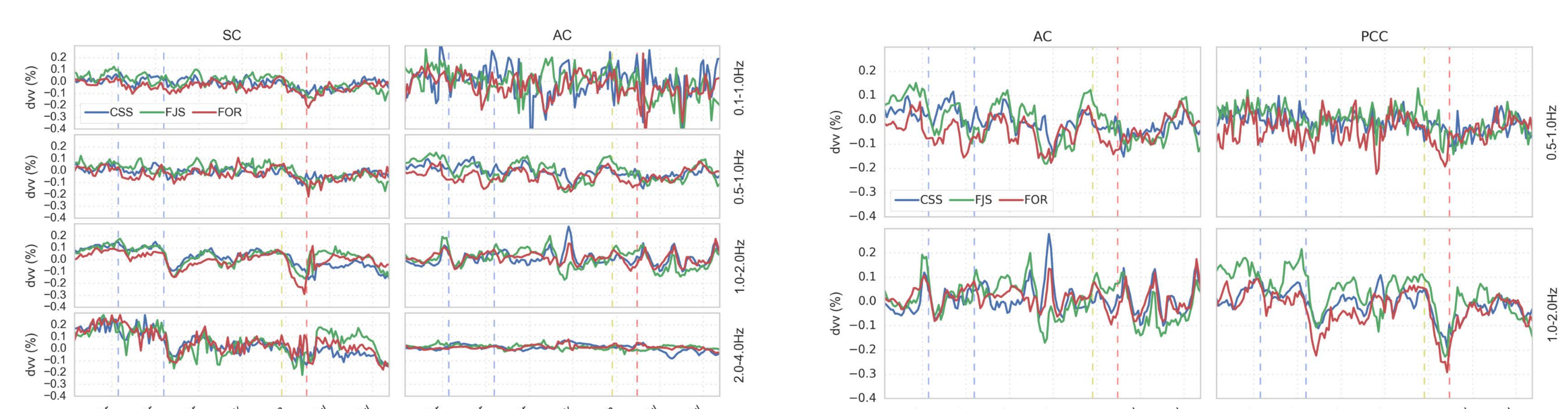
We performed two types of processing based on the single station approach: Single station Cross component (SC), and each component with itself or Auto Correlation (AC). The spectral whitening was not applied for AC since only the phase of the signal would remain and the auto-correlation of such a signal does not contain information on the medium anymore. Phase Cross-Correlation [PCC, *Schimmel et al.*, 2011] is amplitude unbiased and was tested for AC against the conventional cross-correlation. For both AC and SC the data was filtered in different frequency ranges (0.01-1.0Hz, 0.5-1.0Hz, 1.0-2.0Hz and 2.0-4.0Hz) before being computed and averaged with a 5-days linear stacking to maximise the signal-to-noise ratio.



UPPER LEFT: Cross correlation functions (CCF) from the traditional (CC) and Phase Cross correlation (PCC) for station FOR, component pairs ZZ. **LOWER LEFT:** Comparison between the reference CCF and a daily CCF 4 days before the eruption. **RIGHT:** Plot of the CCFs with time for station FOR, components pair ZE and 5-day stack. The data was filtered between 1 and 2 Hz and clipped in the time domain at 3 times the standard deviation. Stable phases can clearly be identified up to about 30 sec of lag time.

RESULTS

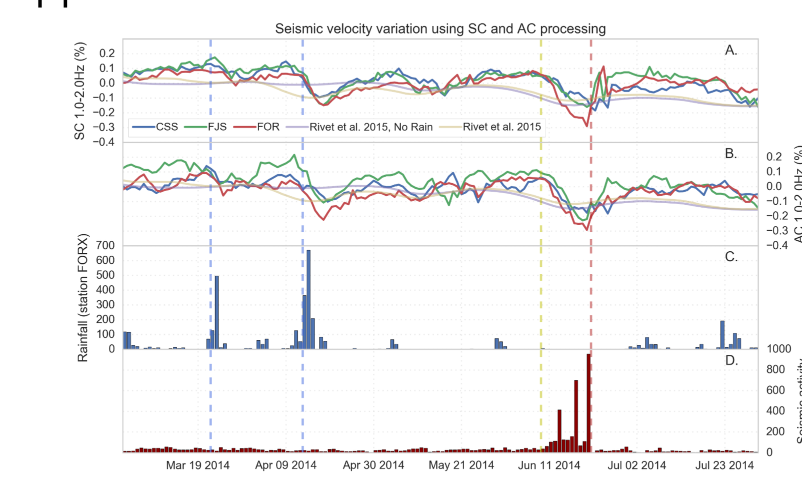
The pre-eruptive drop can clearly be identified at all frequencies for SC, with a higher signal-to-noise ratio in the 1-2Hz frequency band. SC also displays a sensitivity to heavy rainfall (blue vertical lines). AC is sensitive to heavy rainfall and the volcanic eruption in the 0.5-1.0 Hz frequency bands. However, it is also contaminated by very strong winds that have little to no effect on the SC processing between 10 and 20 May and in early July. This contamination almost completely disappears when PCC is used. The pre-eruptive drop is always larger at station FOR, which is the closest to the eruptive site whereas the drop associated to heavy rainfall has a similar amplitude at all stations.



LEFT: Variation of seismic velocity for 3 stations (CSS, FJS, FOR) and 4 frequency ranges (from top to bottom, 0.1-1.0 Hz, 0.5-1.0 Hz, 1.0-2.0 Hz and 2.0-4.0 Hz) measured using Single station Cross components (SC, left) and Auto Correlation (AC, right). The vertical lines represent high rainfalls (blue), increasing seismicity (yellow) and the eruption day (red). **RIGHT:** Variation of seismic velocity for 3 stations (CSS, FJS, FOR) at 0.5-1.0 Hz at 1.0-2.0 Hz measured using autocorrelation with conventional cross-correlation (AC, left) and Phase Cross-Correlation (PCC, right). The vertical lines represent high rainfalls (blue), increasing seismicity (yellow) and the eruption day (red).

RESULTS

With the single station approach, we archived similar performance in the detection of volcanic eruption as *Rivet et al.* [2015] did using the traditional 'cross-station' approach with data from the 27 stations.



LEFT: Seismic velocity variations calculated using Single station Cross components (A., SC, 1.0-2.0 Hz) and Auto correlation (B., AC using PCC, 1.0-2.0 Hz) at Piton de la Fournaise volcano (5-days stacking) along with the rainfall (C.) and the seismic activity (D.) between March and July 2014. The vertical lines represent high rainfalls, increasing seismicity and the day of the eruption in blue, yellow and red, respectively. Results digitized from Rivet et al. [2015] are shown for comparison.

CONCLUSIONS

Both the SC and the AC performed as well as the traditional Cross Correlation approach implemented by *Rivet et al.* [2015] to detect the pre-eruptive seismic velocity drop along with other extreme climatic perturbations in 2014.

The volcanic eruption and the rainfall can be discriminated when measured at distinct stations. Heavy rainfalls have a similar impact on all the stations while the volcanic eruption has a greater effect on the closest station.

The AC exhibits poorer results than the SC in terms of stability along with a sensitivity to strong amplitude events that the SC does not have. This contamination of AC by strong amplitude events can be mitigated by using PCC over conventional cross-correlation. The best performance for the SC and the AC are obtained in the 1-2 Hz frequency bands.

These results open the possibility to use noise cross-correlation techniques on volcanoes equipped with only one of too few instruments, or poorly correlated station pairs, and also show that short period seismometers could probably be used with the single station approach.

REFERENCES

De Plaen, R. S. M., T. Lecocq, C. Caudron, V. Ferrazzini, and O. Francis (2016), Single station monitoring of volcanoes using seismic ambient noise, *Geophys. Res. Lett.*

Lecocq, T., C. Caudron, and F. Brenguier (2014), MSNoise, a Python Package for Monitoring Seismic Velocity Changes Using Ambient Seismic Noise, *Seismol. Res. Lett.*

Rivet, D., F. Brenguier, and F. Cappa (2015), Improved detection of preeruptive seismic velocity drops at the Piton de La Fournaise volcano, *Geophys. Res. Lett.*

Schimmel, M., E. Stutzmann, and J. Gallart (2011), Using instantaneous phase coherence for signal extraction from ambient noise data at a local to a global scale, *Geophys. J. Int.*

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