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*Continuous Monitoring of High#Rise  
Buildings Using Seismic Interferometry*

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# Front Matter

## Title

Continuous monitoring of high-rise buildings using seismic interferometry

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## 1 Abstract

2 The linear seismic response of a building is commonly extracted from ambient vibration mea-  
3 surements. Seismic deconvolution interferometry performed on ambient vibrations can be used  
4 to estimate the dynamic characteristics of a building, such as the shear-wave velocity and the  
5 damping. The continuous nature of the ambient vibrations allows us to measure these parame-  
6 ters repeatedly and to observe their temporal variations. We used 2 weeks of ambient vibration  
7 recorded by 36 accelerometers installed in the Green Building at the MIT campus to monitor the  
8 shear-wave speed and the apparent attenuation factor of the building. Due to the low strain of  
9 the ambient vibrations, we observe small speed changes followed by recoveries. We show that  
10 measuring the velocity variations for the deconvolution functions filtered around the fundamen-  
11 tal mode frequency is equivalent to measuring the wandering of the fundamental frequency in

12 the raw ambient vibration data. By comparing these results with local weather parameters, we  
13 show that the air humidity is the factor dominating the velocity variations in the Green Building,  
14 as well as the wandering of the fundamental mode. The one-day periodic variations are affected  
15 by both the temperature and the humidity. The apparent attenuation, measured as the expo-  
16 nential decay of the fundamental mode waveforms, is strongly biased by the amplitude of the  
17 raw vibrations and shows a more complex behavior with respect to the weather measurements.  
18 We have also detected normal mode non-linear interaction for the Green Building probably  
19 due to heterogeneity or anisotropy of its structure. We found that the temporal behavior of the  
20 frequency singlets may be used for monitoring.

21 **Keywords:** Building monitoring, ambient vibrations, deconvolution interferometry, relative  
22 seismic velocity changes, temporal variations, weather forcing, non-linearity.

## 23 **Main text**

### 24 **Introduction**

25 Seismic interferometry is a technique used to re-datum a source or sources recorded by two  
26 receivers to the location of one of the receiver and retrieve the wave propagation between the  
27 two receivers only (e.g., Schuster, 2009; Snieder et al., 2006; Wapenaar and Fokkema, 2006).

28 Seismic interferometry has been applied in several fields of seismology to image the subsurface  
29 at different scales with surface waves (Lin et al., 2008; Mordret et al., 2014, 2015; Picozzi et al.,  
30 2009; Shapiro et al., 2005) or with body waves (Draganov et al., 2009; Wapenaar et al., 2008).

31 When used with ambient vibrations (the so called seismic noise), seismic interferometry al-  
32 lowed seismologists to continuously monitor geological targets. Indeed, ambient vibrations can  
33 be recorded virtually continuously and everywhere on Earth, therefore, a repetitive utilization  
34 of seismic interferometry can be performed to follow the variations in time of the seismic wave

35 propagation between pairs of receivers. This monitoring method has been originally developed  
36 to monitor volcano pre-eruptive behavior (Anggono et al., 2012; Brenguier et al., 2008b; Mor-  
37 dret et al., 2010; Sens-Schönfelder and Wegler, 2006) and crustal effects of large earthquakes  
38 (Brenguier et al., 2008a, 2014; Froment et al., 2013; Minato et al., 2012; Wegler et al., 2009).

39 In civil engineering applications, seismic interferometry was first introduced as NIOM  
40 method by Kawakami and Haddadi (1998); Kawakami and Oyunchimeg (2003) and later gen-  
41 eralized by Snieder and Şafak (2006) to compute the time-domain impulse response function  
42 of the Millikan Library in Pasadena, California. The technique has become very popular since  
43 then (e.g., Ebrahimian et al., 2014; Kohler et al., 2007; Rahmani et al., 2015; Todorovska, 2009;  
44 Todorovska and Trifunac, 2008a,b). The aforementioned studies use earthquake records as in-  
45 put excitation to determine the dynamic characteristics of the buildings. Due to the random and  
46 isolated occurrence of earthquakes, these signals are not well suited for continuous monitoring  
47 of civil structures (Nakata et al., 2013). The use of ambient vibrations, on the other hand, is  
48 more appropriate. Ambient vibrations can be recorded anywhere and at any time and have been  
49 used for building monitoring purpose through the measurement of the wandering of the modal  
50 frequencies (e.g., Clinton et al., 2006; Ditommaso et al., 2010; Mikael et al., 2013; Nayeri  
51 et al., 2008). These studies showed that this parameter is very sensitive to irreversible changes  
52 in the building structure, like defects and cracks caused by earthquakes. It is also sensitive to  
53 reversible variations like ambient temperature or humidity changes.

54 Prieto et al. (2010) showed that seismic interferometry could also be applied to ambient  
55 vibrations to retrieve the impulse response of a building. More recently, Nakata and Snieder  
56 (2014) used seismic interferometry on ambient vibration data to develop a continuous mon-  
57 itoring technique. Their time resolution of four days and the arrival picking technique they  
58 used were not appropriate to draw any conclusion about the potential causes of the observed  
59 shear-wave velocity variations inside the building. In this paper, we extend the idea proposed

60 by Prieto et al. (2010) and Nakata et al. (2015) to show that with a finer temporal resolution  
61 of 6 hours and with more accurate seismic velocity variation tracking techniques, we are able  
62 to finely measure the relative velocity variations inside the Green Building (Massachusetts In-  
63 stitute of Technology campus, Cambridge, MA), as well as its apparent-attenuation variations.  
64 These temporal changes are then correlated with different local weather parameters like the  
65 temperature and humidity to infer which one affects the most the building.

## 66 **Data and Methods**

67 We used 15 days of data (between May 12 and May 27 , 2015) continuously recorded on 36  
68 accelerometer channels deployed inside the Green Building.

69 The Green Building, currently the tallest building in Cambridge, was designed by I.M. Pei  
70 and constructed during the period of 1962–1964. It has an elevation of 83.7 m with a footprint of  
71 16.5 m by 34 m. Mechanical rooms are located on the top two floors (i.e., 19th and 20th floors).  
72 Heavy meteorological and radio equipments are asymmetrically mounted on the roof (Fig. 1(b)).  
73 Three elevator shafts are located on the eastern side of the building (Fig. 1(c)) and two stairwells  
74 are placed symmetrically at the NE and NW corners of the building. The building is constructed  
75 of cast-in-place reinforced concrete. The eastern and western facades are composed of 25 cm  
76 thick shear walls running the height of the building. The thickness of floor slabs is typically  
77 10 cm. The basement floor has a depth of 3.8 m below the grade. Taciroglu et al. (2016)  
78 showed that the building’s dynamic behavior can be modeled by a simple shear beam. More  
79 detailed descriptions of the building characteristics can be found Çelebi et al. (2014); Taciroglu  
80 et al. (2016) and Sun et al. (2017), in which the sensor information and deployment are also  
81 given. The sensor array was designed for monitoring the NS and EW translational vibration,  
82 the torsion, and the base rocking motion. The sensor locations and orientations are shown in  
83 Fig 1a. Note that the sensors are installed below the floor slabs. Fig 1c illustrates the sensor

84 locations at a typical floor. Because of these locations, the acceleration in each direction ( $u_0$  for  
 85 EW direction,  $v_0$  for NS direction and  $\theta_0$  for torsional direction) needs to be decoupled and is  
 86 computed using the following equations:

$$u_1 = u_0 - \theta_0 y_1 \quad (1)$$

$$v_1 = v_0 + \theta_0 x_1 \quad (2)$$

$$v_2 = v_0 + \theta_0 x_2, \quad (3)$$

87 where  $u_1$  is the measured acceleration along the EW direction,  $v_1$  and  $v_2$  are the measured ac-  
 88 celerations along the NS direction close to the eastern and western shear walls respectively,  $x_1$ ,  
 89  $x_2$  and  $y_1$  are the sensor coordinates in the  $x - O - y$  coordinate system with  $O = (0, 0)$  shown  
 90 in Fig 1c (see Table I in Sun et al. (2017) for the numerical values of the station coordinates).  
 91 Therefore, the decoupled accelerations are:

$$\theta_0 = \frac{v_1 - v_2}{x_1 - x_2} \quad (4)$$

$$u_0 = u_1 + \theta_0 y_1 \quad (5)$$

$$v_0 = \frac{x_2 v_1 - x_1 v_2}{x_2 - x_1}. \quad (6)$$

92 Figure 2 shows the spectrogram of the decoupled NS acceleration recorded on the roof of  
 93 the Green building. The fundamental mode is observed as a constant spectral peak at 0.75 Hz,  
 94 the first overtone at  $\sim 2.55$  Hz, the second overtone at 5 Hz (Çelebi et al., 2014) and the third  
 95 overtone around 6.6 Hz. Obvious is the daily pattern of the man-made ambient noise with higher  
 96 amplitudes during working hours and smaller amplitudes during the nights. The two weekends

97 are also well observed (May 16-17 and May 23-25, with Memorial Day) with smaller noise  
 98 amplitudes.

### 99 **Pre-processing and Impulse response functions from deconvolution interferometry**

100 Before combining the data from the different sensors and applying deconvolution interferom-  
 101 etry, the records from individual channels are pre-processed to mitigate potential biases intro-  
 102 duced by the non-stationarity of the recorded ambient vibrations. The raw data are high-pass fil-  
 103 tered at 0.05 Hz, then, the amplitudes larger than 3 standard deviations of the 2 week-long record  
 104 are replaced by the 3 standard deviation threshold value. Then, the two-week long records are  
 105 chopped into 20 min long segments with 50% overlap and deconvolution interferometry is ap-  
 106 plied to each detrended segment such as:

$$D_{U_n}(z, z_0, t) = \mathcal{F}^{-1} \left( \frac{U_n(z, \omega) U_n^*(z_0, \omega)}{|U_n(z_0, \omega)|^2 + \alpha \langle |U_n(z_0, \omega)|^2 \rangle} \right), \quad (7)$$

107 where  $D_{U_n}(z, z_0, t)$  is the deconvolution function for vibration type  $U$  ( $U$  being the Fourier  
 108 transform of either  $\theta_0$ ,  $u_0$  or  $v_0$ ) between floors at elevations  $z_0$  and  $z$ , in which  $n$  is the index  
 109 of the 20 min segment ( $n = 1 \dots 2159$  in this study) and  $t$  the lag time. In the right-hand side of  
 110 equation 7,  $\mathcal{F}^{-1}$  is the inverse Fourier transform,  $\omega$  is the angular frequency,  $*$  is the complex  
 111 conjugate,  $\langle |U_n|^2 \rangle$  the average power spectrum of  $U_n$ , and  $\alpha = 0.5\%$  is a regularization param-  
 112 eter stabilizing the deconvolution (Nakata and Snieder, 2014). An estimation of the building  
 113 response function  $D_U(z, z_0, t)$  is given by the average of the deconvolution functions over the  
 114 two weeks:

$$D_U(z, z_0, t) = \frac{1}{N} \sum_{n=1}^N D_{U_n}(z, z_0, t). \quad (8)$$

115 We tested different pre-processing parameters, with an amplitude threshold of 1.5 standard

116 deviations instead of 3, a high-pass filtering at 0.1 Hz instead of 0.05 Hz and  $\alpha = 10\%$  in equa-  
117 tion 7. We observed that the different pre-processing approach affected only marginally our  
118 results, both for the velocity variation measurements and for the damping variation measure-  
119 ments. Figure 3 shows the central part of the estimated Impulse Response Functions (IRFs) for  
120 the north-south translational modes (Fig. 3a-d), the east-west translational modes (Fig. 3b-e) and  
121 the torsional modes (Fig. 3c-f), both in the time domain and in the frequency domain, for each  
122 floor, with a source at the ground level. We can clearly observe a wave pulse traveling up and  
123 down in the building, with varying speeds, depending on the type of vibration (the dashed-lines  
124 are for reference only, assuming a constant speed of  $\sim 365$  m/s,  $\sim 320$  m/s and  $\sim 600$  m/s for  
125 the NS translational modes, EW translational modes and torsional modes, respectively). These  
126 pulses result from the superposition of all normal modes of the building and their frequency  
127 spectra are discrete. At longer times only the resonance of the fundamental modes is visible  
128 because the fundamental mode attenuates more slowly (Snieder and Şafak, 2006, Fig. 4). We  
129 observe a clear symmetry between the negative and positive time-lags of the IRFs, both in phase  
130 and amplitude. While the phase symmetry is expected from the seismic interferometry theory,  
131 it should not be the case for the amplitudes because the attenuation always follows causality.  
132 The amplitudes should therefore increase with increasing negative time-lags (Snieder, 2007).  
133 The presence of ambient vibration sources inside the building may play the role of volumetric  
134 sources and balance the amplitudes at negative time-lags (Snieder, 2007).

135 Another way to measure the speed of the traveling waves inside the building is by looking at  
136 the deconvolution functions between the roof and the other floors, with the source on the roof. In  
137 this configuration, Rahmani and Todorovska (2013); Snieder and Şafak (2006) showed that the  
138 deconvolution functions are the superposition of an acausal up-going wave with a causal down-  
139 going wave. The speed of these waves is the shear wave speed of the building (Fig. 5). We note a  
140 discrepancy between the velocity of the NS modes measured with the source on the ground floor



141 and the source on the roof. This could be due to dispersion or reflections caused by the internal  
142 structure of the building (Rahmani and Todorovska, 2013; Snieder and Şafak, 2006). In this  
143 framework, the IRF is not a superposition of modes but a broadband pulse having a continuous  
144 frequency spectrum. According to the shear-beam model of (Rahmani and Todorovska, 2013;  
145 Snieder and Şafak, 2006) the up- and down-going pulses vanish at ground level and are not  
146 sensitive to the soil-structure interaction. Moreover, the wavelength of the waves (on the order  
147 of 100 m) is much larger than the typical floor height so the scattering inside the building  
148 should be minimal. However, at low frequency, we observe potential internal reflections in the  
149 EW direction (Fig. 5b)). At higher frequency, a clear coda is following the main pulse and may  
150 be the consequence of multiple reflections at the base and inside the building (Fig. 5d) Rahmani  
151 and Todorovska, 2013).

## 152 **Velocity-variation measurements**

153 For monitoring applications the absolute value of the velocity does not need to be evaluated:  
154 only the relative velocity variations are needed. It is then possible to use techniques which are  
155 much more accurate than picking the absolute travel-times of seismic pulses propagating inside  
156 the building. The basic principle to measure relative seismic velocity variations ( $dv/v$ ) is to  
157 compare a current waveform with a reference one by measuring their relative phase-shifts along  
158 the lag-time. Here, the current waveforms are the individual  $D_{U_n}$  waveforms averaged in a 6  
159 hours moving window (average of the  $n$ th deconvolution function with the 35 previous ones) and  
160 the reference one is  $D_U$ . We used two common techniques to measure  $dv/v$  within the Green  
161 building: the Moving Window Cross-Spectral (MWCS) technique (Clarke et al., 2011), which  
162 is performed in the frequency domain and the stretching technique (Hadziioannou et al., 2009;  
163 Sens-Schönfelder and Wegler, 2006), which is performed in the time domain. The comparison  
164 of the results from both independent methods allows us to assess the accuracy and consistency

165 of our measurements (Mordret et al., 2016).

166 The IRFs deconvolved by the ground floor present two distinct types of vibration: the prop-  
167 agating part at short lag times ( $-3 \text{ s} \lesssim t \lesssim 3 \text{ s}$ ), where the fundamental mode and the overtones  
168 are superposed, and the resonant part at large lag times ( $-25 \text{ s} \lesssim t \lesssim -6 \text{ s}$  and  $6 \text{ s} \lesssim t \lesssim 25$   
169 s), where the fundamental mode dominates. We chose to analyze separately these two kinds of  
170 vibration. The MWCS technique is performed within the previously described time windows  
171 using small sliding windows with a length 6 times the central period of interest. The small  
172 windows move by 0.1 s. For each small window, the cross-spectrum between the current and  
173 the reference waveform is computed. From this cross-spectrum, the coherence and the phase  
174 between the two signal as a function of the frequency is extracted. A weighted linear regression  
175 (weighted by the coherency) is performed on the phase in the frequency band of interest to ex-  
176 tract the phase delay between the reference and current correlation, as well as an error estimate  
177 of the slope. Thus, for each small sliding window we obtain 3 values: a time delay ( $t_{delay}$ , in  
178 s), an error for the time delay ( $errt_{delay}$ , in s) and the average coherency between the two sig-  
179 nals ( $coh$ ). Then, these measurements are used in a second step to evaluate the relative velocity  
180 variation  $dv/v = -dt/t$  between the reference and the current waveform. A weighted linear  
181 regression on the time delays with respect to the central time of the windows is used to calcu-  
182 late the final  $dv/v$  value and its uncertainty for a specific frequency band. Only the time delays  
183 with errors  $errt_{delay} < 0.03 \text{ s}$  and coherency  $coh > 0.8$  are used in the final linear regression  
184 to estimate  $dv/v$ . The uncertainty on the linear regression is taken as the uncertainties of the  
185 relative velocity variations.

186 The stretching technique (ST) is based on the assumption that if a small velocity change  
187 occurs homogeneously in the medium, then the current waveform will simply be a stretched  
188 or compressed version of the reference waveform. The stretching coefficient is therefore the  
189 relative velocity variation  $dv/v$ . Prior to the stretching measurement, the reference and current

190 waveforms are filtered in the frequency band of interest. The measurement is performed using  
 191 a grid search on the stretching coefficients. We sampled 300 stretching coefficients linearly  
 192 spaced between -5% and 5%. For each coefficient, the time axis of the current waveform is  
 193 stretched and then the current waveform is interpolated onto this new time axis. The correlation  
 194 coefficient between the window of the stretched current waveform and the reference waveform  
 195 is then computed and stored. The best  $dv/v$  measurement is chosen as the stretching coefficient  
 196 that maximizes the correlation coefficient between the current stretched and reference wave-  
 197 forms. To refine the estimation of  $dv/v$  we use the maximum correlation coefficient and its  
 198 nearest left and right neighbors. We perform a quadratic interpolation of these three points and  
 199 take the stretching coefficient corresponding to the maximum of the interpolated curve. The  
 200 error estimate is obtained from the expression derived by Weaver et al. (2011). The error is  
 201 related to the maximum correlation coefficient, the size and the position of the window in the  
 202 coda, the frequency bandwidth and the inverse of the central frequency of the signal. We notice  
 203 that in our context, the errors measured by the MWCS technique are most of the time larger than  
 204 the errors from the stretching technique. In the following, we only present the uncertainties are  
 205 resulting from the MWCS technique to keep conservative values.

## 206 **Damping measurements**

207 The damping ratio of each mode can be computed by measuring the slope  $\mu_i$  of the envelope  
 208 of the IRFs band-pass filtered within the half-power bandwidth (Prieto et al., 2010; Snieder and  
 209 Şafak, 2006; Sun et al., 2017). The damping ratio  $\xi_r$  is given by

$$\xi_r = \frac{1}{N_0 \omega_r} \sum_{i=1}^{N_0} |\mu_i|, \quad (9)$$

210 where  $N_0$  is the number of observations (typically the number of instrumented floors) and  $\omega_r$   
211 is the  $r$ th resonant frequency. Nakata and Snieder (2014) showed that with ambient vibration  
212 deconvolution interferometry, when noise sources are inside the building, the damping ratio  
213 measured by the amplitude decay of the deconvolution function is a combination of the intrinsic  
214 damping of the building and the radiation loss in the solid Earth at the base of the building. Here,  
215 we measure the damping separately on the acausal and causal sides of the IRFs and our final  
216 estimation of the damping is the average of both sides.

## 217 **Results**

218 Figure 6 shows the 2159 IRFs (smoothed by a 6 hours moving window) for the NS translational  
219 mode, measured on the roof with a source at the ground level. We can directly observe a tem-  
220 poral variation of the overall amplitudes of the IRFs as well as time shifts of the phases within  
221 the later parts of the waveforms. The phase shifts will be analysed through the velocity varia-  
222 tion measurements whereas the amplitude variations will be interpreted as damping variations  
223 and/or ambient noise sources variations.

## 224 **Velocity variations**

225 We measured the velocity variations in different lag-time windows along the waveforms and  
226 several frequency bands to assess the contribution of the propagation part from the resonant part  
227 and the contribution of the fundamental mode alone from the superposition of the overtones. In  
228 the following, we mainly analyze the NS translational modes, which have the higher signal-to-  
229 noise ratio and focus on records deconvolved either from the ground floor or from the roof. The  
230 two methods (MWCS and ST) are also compared in the aforementioned contexts.

231 Figure 7a) shows an example of  $dv/v$  measured in the central part of the IRFs ( $-3 \text{ s} < t < 3 \text{ s}$ )  
232 at each instrumented floor, for records deconvolved by the ground floor. The velocity variations

233 are similar at each floor. This is certainly because the Green building has not suffered strong  
234 damages, but one might expect this to change if damages are present. If this is the case, records  
235 at each floor can be used to invert for the variations of the floor stiffnesses (Sun et al., 2017) and  
236 therefore, a high density seismic network is absolutely necessary to localize a damage. On the  
237 other hand, in a low seismic risk area where buildings are less likely to be strongly damaged,  
238 the similarity between the  $dv/v$  at all floors shows that the number of sensors in a seismic  
239 array (to monitor the long term ageing of the structure for example) can be drastically reduced.  
240 Figure 8a) and b) show a comparison of the  $dv/v$  measurements performed with the MWCS and  
241 ST methods for the central part ( $-3 \text{ s} < t < 3 \text{ s}$ ) and the later parts ( $15 \text{ s} < |t| < 24.5 \text{ s}$ ) of the  
242 IRFs, respectively. The two methods behave similarly in both cases, however, the  $dv/v$  signals  
243 differ depending on the analyzed time lags. The central part presents larger  $dv/v$  variations ( $\pm$   
244 1%) with a noticeable daily periodicity and uncertainties on the order of 0.5%. The later part of  
245 the waveforms exhibits smaller  $dv/v$  fluctuations ( $\pm 0.5\%$ ) and the daily periodicity is weaker;  
246 the uncertainties fluctuate around 0.25% in average. Certain periods present a strong scattering  
247 of the  $dv/v$  measurements in the late part measurements which correspond to departures of the  
248 ST measurements from the MWCS measurement in the central part. These periods correspond  
249 to times when the apparent damping is the strongest (Fig. 9) and, therefore, where the signal  
250 to noise ratio is the poorest in the coda. From these observations we can see that the ST is  
251 more sensitive to local ambient vibrations amplitudes variations than the MWCS technique. We  
252 also observe a longer term  $\sim 8$  days period on both measurements. The  $dv/v$  measurements  
253 performed on IRFs obtained by deconvolving by the roof (see Figure 5) instead of the ground  
254 floor exhibit similar features (Figure 10). For these IRFs, we take the central part as ( $-1 \text{ s} < t <$   
255  $1 \text{ s}$ ) and the coda parts as ( $0.5 \text{ s} < |t| < 3 \text{ s}$ ). The IRFs computed with the virtual source on  
256 the roof are less sensitive to the ground coupling (Petrovic and Parolai, 2016; Rahmani and  
257 Todorovska, 2013; Snieder et al., 2006; Taciroglu et al., 2016) therefore, the strong similarity

258 between velocity variation measurements carried from the roof virtual source IRFs and ground  
259 floor virtual source IRFs (Figure 10) shows that the observed variations are, at a first order, due  
260 to changes within the building. Moreover, according to the model of Rahmani and Todorovska  
261 (2013); Snieder et al. (2006), the broadband pulses generated by the roof deconvolution should  
262 vanish due to a null reflection coefficient at the ground level. We observe in the case of the  
263 Green Building that although small, the reflection coefficient is non-zero (and may be negative)  
264 and a clear coda exists after the main pulse. The nature of the waves in this coda is not clear in  
265 the context of ambient vibration interferometry with internal sources of vibration. In the case  
266 of earthquake interferometry however, Rahmani and Todorovska (2013) showed that the coda  
267 is made by the superposition of internal reflections and reflections at the base of the building  
268 (Figure. 5d)). The coda carries the same velocity variation information as the direct waves  
269 (Figure 10).

### 270 **Apparent damping variations**

271 Figure 9a) shows the time-series of the damping variations measured at each instrumented floor.  
272 Again, the curves are extremely similar at each floor, presenting a local minimum almost every  
273 day during morning hours and a maximum during the afternoon. This correlates strongly with  
274 the amplitudes of the raw ambient vibrations (Figure 9b)) and might indicate that the measured  
275 attenuation is biased and may only be apparent. Given equation 7, it is expected that some  
276 amplitude information of the raw records is kept in the deconvolution functions. The non-  
277 propagating ambient vibrations from sources inside the building are not corrected for by the  
278 deconvolution of the ground floor records. However, the apparent damping presents a clear  
279 non-linear relationship (Guéguen et al., 2016) with respect to the ambient vibration amplitude  
280 (Figure 9c)): above a certain level of vibration, the apparent damping seems to stabilize around  
281 5.5 %.

282 As shown by Nakata and Snieder (2014), in theory the amplitude decay of the waveforms  
283 depends on both intrinsic attenuation of the building and ground coupling and cannot be easily  
284 separated. The observed apparent damping variations are therefore difficult to relate to a simple  
285 cause and difficult to interpret. In our case, when the amplitudes of the ambient vibrations are  
286 too small, the amplitude of the deconvolution functions are strongly biased by the amplitudes  
287 of the deconvolved waveforms and the damping measurements are unreliable. Above a certain  
288 level, however, when the SNR is high enough, the damping measurements seems to converge  
289 toward a constant value. We hypothesize that at low amplitude, the non-propagating noise  
290 dominates the raw signal and the amplitude information of the IRFs is not reliable whereas  
291 when the amplitudes are larger, the propagating vibrations are larger than the noise and the IRFs  
292 amplitude information is more reliable. Because of this apparent non-linearity, the correlation  
293 with weather parameters is difficult to estimate. The temperature, recorded on top of the Green  
294 Building shows a slight link with the apparent damping (the two curve are anti-correlated at  $\sim$   
295 55 %, Figure 11a-b). We also observe a  $\sim$  6 hours delay between the air humidity variations and  
296 the damping variations but these estimations should be taken cautiously. There is no significant  
297 correlation with the temperature (Figure 11c-d).

## 298 **Discussion**

### 299 **Link with the modal frequency wandering**

300 Tracking the wandering of the fundamental mode frequency is a well-known technique to mon-  
301 itor the temporal variations of the stiffness of a building (e.g. Clinton et al., 2006; Mikael et al.,  
302 2013; Nayeri et al., 2008). Here, we show that monitoring the velocity variations of the up-going  
303 IRFs filtered around the fundamental mode frequency is equivalent to measure the wandering of  
304 the fundamental mode frequency. For a simple 1D oscillator, the relative variation of frequency

305  $f$ ,  $\Delta f/f$  is given by Haney et al. (2015):

$$\frac{\Delta f}{f} = \frac{\Delta v}{v} - \frac{\Delta l}{l} \quad (10)$$

306 where  $v$  is the shear-wave velocity of the building and  $l$  its length. If we assume that the length  
307 of the building does not change, we find that the relative frequency variations are equal to  
308 the relative velocity variations. In the ideal shear-beam case, the equality between velocity and  
309 frequency variations is also true for their absolute variations (Çelebi et al., 2016). This is clearly  
310 illustrated by Figure 12 where we see that the relative velocity variations, independently on  
311 the measurement technique, follow closely the wandering of the NS fundamental translational  
312 mode frequency. This interferometry-based technique is not limited to the fundamental modes  
313 but can be applied to overtones as long as their frequency can be easily isolated in the IRFs. In  
314 our example, we chose the simplest method to measure the frequency wandering, i.e. tracking  
315 the maximum of the fundamental resonance peak in the spectrogram shown in Fig. 2, between  
316 0.5 and 1 Hz (Clinton et al., 2006). This technique is limited by the size of the signal sample  
317 used to compute the amplitude spectrum which gives a finite frequency resolution. Other more  
318 robust techniques, providing higher frequency resolution exist, such as the Random Decrement  
319 Technique (e.g., Mikael et al., 2013), but it was not necessary to use them here to illustrate our  
320 example. In any case,  $dv/v$  measurements from interferometry are as robust as modal frequency  
321 wandering observations and can provide independent information about the continuous dynamic  
322 behavior of a building.

### 323 **Influence of local weather parameters**

324 The main goal of structural health monitoring is to detect (and locate) any structural damage  
325 affecting a building through measurement of its dynamic behavior (Sohn, 2007). The main



326 assumption behind this concept is that any damage will modify the stiffness and/or energy dis-  
327 sipation of the building. Therefore, monitoring parameters sensitive to stiffness or attenuation,  
328 such as shear wave velocity and damping of the normal modes of a building should allow us  
329 to detect such damage. By comparing the dynamic response of the building between an ‘intact  
330 state’ and a ‘damaged state’, we should be able to assess the extent of the damage and take  
331 action in a safety perspective. However, defining what an ‘intact state’ is quite difficult because  
332 any structure responds to environmental forcing by reversibly changing its dynamic parameters.  
333 In order to detect damages as early as possible, we must be able to detect small damages and  
334 therefore we must correct our dynamic parameters measurements for these changes which are  
335 not associated with damages.

336 Here we show that the interferometric approach can be used to monitor continuously (and  
337 potentially in real-time) the ‘intact state’ dynamics of a building and the effects environmental  
338 parameters, such as temperature and air humidity, can have on its shear-wave speed propaga-  
339 tion. Figure 13 shows the comparison and correlation between relative velocity measurements  
340 and air temperature and humidity time series. We display  $dv/v$  measured on the central part  
341 of the down-going IRFs and up-going IRFs for the temperature and humidity, respectively, but  
342 measurements on the later parts of the IRFs show similar results. We show only the positive  
343 time-lag of the cross-correlation between the  $dv/v$  and weather data because we are only inter-  
344 ested in the causal actions of the weather onto the building. We observe a stronger correlation  
345 between  $dv/v$  and humidity than between  $dv/v$  and temperature. The humidity correlation is  
346 dominated by the longer period trend whereas the temperature exhibits a stronger daily period  
347 correlation. It seems that the temperature is negatively correlated with the velocity variations  
348 but we cannot rule out a positive correlation with a 12 hours delay. On the other hand, the  
349 positive correlation between the  $dv/v$  and the humidity is more robust and it seems that there  
350 is a 1 day delay between them. Time series longer than two weeks could help to determine the

351 correlations between the parameters with more accuracy. It is also possible that the relationship  
352 between the weather forcing and the velocity variations depends on the actual forcing period  
353 (the daily forcing having a different linear relationship from the weekly forcing). It might also  
354 be a non-linear relationship, which would explain the small correlation coefficient between the  
355 temperature and the  $dv/v$  measurements.

356 As stated by Mikael et al. (2013), the temperature effect on high-rise building does not  
357 have a clear trend and may depend on the building itself. Some studies observe a positive  
358 correlation between stiffness and temperature (e.g. Clinton et al., 2006; Mikael et al., 2013;  
359 Yuen and Kuok, 2010) whereas others observe a negative correlation (Mikael et al., 2013; Xia  
360 et al., 2012) or even a mixed behavior (Mikael et al., 2013). In the case of the Green Building,  
361 the anti-correlation in phase is clear but the correlation in amplitude seems less robust. It can  
362 be noted, as observed by Simon and Strong (1968) that the direct solar heating on the southern  
363 face of the building has a strong influence compared to air temperature variations. We are  
364 lacking data of the amount of sunshine during the studied period to be able to corroborate these  
365 observations.

366 The humidity influence on modal frequencies has been less studied and most observations  
367 focused on the effects of heavy rainfalls. Clinton et al. (2006) report an increase of the fun-  
368 damental mode frequency of the soil-structure system of the Millikan library after heavy rain-  
369 falls. This has been confirmed with modeling experiments by Todorovska and Al Rjoub (2006,  
370 2009). However, they do not provide a comparison with the actual local air humidity. Results  
371 from Mikael et al. (2013), looking at rainfalls, are inconclusive by lack of strong events. The  
372 variations observed at the Green Building are unlikely caused by heavy rainfalls: only a small  
373 shower ( $\sim 10$  mm) occurred on May 19 around 12PM and was not followed by clear effects.  
374 Herak and Herak (2010) observed a high positive correlation between air humidity and fre-  
375 quency changes over a 19 months period, however, it is not clear if the correlation still holds

376 on the daily or weekly period. In most cases, the humidity effect on vibrational behavior of  
377 a building is interpreted to be caused by changes in the soil-structure coupling more than by  
378 changes in the structure itself. The fact that we observe a strong correlation between the  $dv/v$   
379 measured on the down-going IRFs, which are supposedly not sensitive to the ground coupling,  
380 and the humidity might indicate that the wetting of the concrete plays a significant role in the  
381 observed stiffness changes. Because of its age, the structural concrete of the Green Building  
382 (directly exposed to the weather conditions) most likely exhibits an increased porosity which  
383 in turn enhances its gas and water permeability by several order of magnitude compared to un-  
384 cracked concrete (e.g., Wang et al., 1997). The diffusion rate of moisture in cracked concrete  
385 can reach several centimeters per hour (Kanematsu et al., 2009; Wang et al., 1997), enough to  
386 penetrate the entire thickness of the shear walls of the Green Building. The moisturizing of the  
387 grain contacts induces a weakening of the concrete (e.g., Murphy et al., 1984; Pimienta et al.,  
388 2014) that leads to a reduction of the shear-wave speed.

### 389 **Can non-linear mode interaction be used as a new monitoring tool?**

390 A close inspection of the spectrogram presented in Figure 2 shows that the resonance peak  
391 around 6.6 Hz is actually made of, at least, three peaks. They are clearly observed on the  
392 blow-up in Figure 14a). Modal analysis applied on the up-going IRFs (Sun et al., 2017) shows  
393 that these frequencies correspond to the 4th NS translational mode: considering either the three  
394 frequencies altogether or separately, we observe the same mode shapes (Fig. 14b). This result  
395 is in contradiction with the work of Trocha (2013), reported by Taciroglu et al. (2016), who  
396 found the 3rd NS translational mode at 8.25 Hz. This phenomenon is not visible on the EW  
397 spectrograms, ruling out an imperfection in our horizontal components decoupling procedure.

398       Regardless the exact nature of this mode, we observe a clear wandering of these frequencies.  
399 This wandering has a similar temporal fluctuation profile than the wandering of the fundamental

400 mode and the first overtone. It also exhibits the same relative variations with respect to the mean  
 401 frequency (Fig. 15). The three frequency peaks present a parallel temporal behavior which could  
 402 suggest a bilinear behavior of the 4th NS translational mode. A Single-Degree-Of-Freedom  
 403 bilinear system is characterized by two frequencies  $f_1$  and  $f_3$  which correspond to two different  
 404 states of the system (with two different stiffnesses, for example). These frequencies interact to  
 405 give rise to a third frequency  $f_2$  called bilinear frequency (Chu and Shen, 1992):

$$f_2 = \frac{2f_1f_3}{f_1 + f_3}. \quad (11)$$

406 Such behavior can be caused by the coupling of one translational mode with a torsional mode  
 407 of nearby frequency (Boroschek and Mahin, 1991). In the case of the Green building, how-  
 408 ever, modeling suggests that there is no torsional mode around 6.5 Hz. Bilinearity can also be  
 409 observed in beams with breathing cracks where the two states of the system correspond to the  
 410 open crack and the closed crack (e.g. Bovsunovsky and Surace, 2015; Chondros et al., 2001;  
 411 Chu and Shen, 1992; Yan et al., 2013, and references therein). This model could suggest the  
 412 presence of ageing or fatigue cracks in the building. The fact that the splitting only affects the  
 413 4th translational mode would indicate that the cause of the bilinearity is well localized along  
 414 the height of the building, potentially where floor drift is the largest.

415 Nonetheless, Figure 15 shows that the two strongest singlets (Mode  $4_1 = f_1$  and Mode  $4_3 =$   
 416  $f_3$ ) behave similarly to Mode 1 and Mode 2 but seem to lack their daily periodicity. Interest-  
 417 ingly, the difference between  $f_1$  and  $f_3$  shows a stronger daily periodicity while still retaining  
 418 a similar fluctuation behavior as Mode 1 and Mode 2. This can be seen in Figure 16 where  
 419 the cross-correlation between the weather parameters and both the Mode 4 wandering and the  
 420  $f_3 - f_1$  fluctuations show results similar to  $dv/v$  measurements. The temporal variations of the  
 421 non-linear behavior of Mode 4 could give new valuable informations about temporal changes

422 of some asymmetries or heterogeneities of the Green Building. Given the high frequency of  
423 the 4th mode, this non-linear interaction would be sensitive, on first approximation, to hetero-  
424 geneities on the order of the wavelength ( $\sim 50$  m in this study). If confirmed, the study of high  
425 frequency modes non-linear interaction would not only be useful for damage detection but also  
426 as a first step in damage localization due to their localized sensitivity. We believe that the first  
427 observations presented in this paper can stimulate future studies in this direction.

## 428 **Conclusion**

429 We show with this study that deconvolution interferometry performed on continuous ambient  
430 vibrations can be used to monitor the structural dynamics of a building during ‘normal con-  
431 ditions’ by computing empirical IRFs. By deconvolving the vibrations recorded inside the  
432 building either by the records at the ground floor or the records on the roof, we are able to repet-  
433 itively measure the speed of the up- or down-going shear waves traveling inside the building and  
434 to track their temporal variations. The study of the exponential decay of the IRFs waveforms  
435 give access to the temporal changes of the building (and ground coupling) apparent damping  
436 which is strongly biased by the amplitudes of the raw records. Our data processing and the  
437 velocity monitoring techniques used, fairly simple to implement, allows us to obtain a temporal  
438 resolution of 6 hours and an accuracy on the order of 0.1 to 0.5 %.

439 We show that measuring the seismic velocity variations on IRFs filtered around a specific  
440 mode frequency is equivalent to measure the actual relative wandering of this modal frequency,  
441 a technique widely used to monitor buildings. Therefore, with the deconvolution interferometry  
442 technique we provide an independent and potentially complementary way to perform building  
443 monitoring. We compared our  $dv/v$  results with weather parameters and found a strong positive  
444 correlation with air humidity and a possible negative correlation with temperature. Longer time  
445 records would be necessary to clarify these relationships. Deconvolution interferometry can

446 then be used as a powerful tool to study buildings dynamics under normal conditions. A better  
447 understanding of these natural and reversible variations would allow us to correct for them to  
448 be able to better detect structural damages.

449 Finally, we speculate that the fourth NS translational mode of the Green Building is split due  
450 to non-linear interaction in its structure. The temporal variations of the singlet difference seem  
451 to correlate with our  $dv/v$  and frequency wandering observations as well as with the weather  
452 data. If this observable is confirmed, we believe that it could provide a new tool to efficiently  
453 monitor building and potentially help to locate damages.

## 454 **Data and Resources**

455 Seismograms used in this study were collected as part of an USGS experiment. Data can be  
456 obtained from Dr. Mehmet Çelebi (celebi@usgs.gov), last accessed 30 May 2015.

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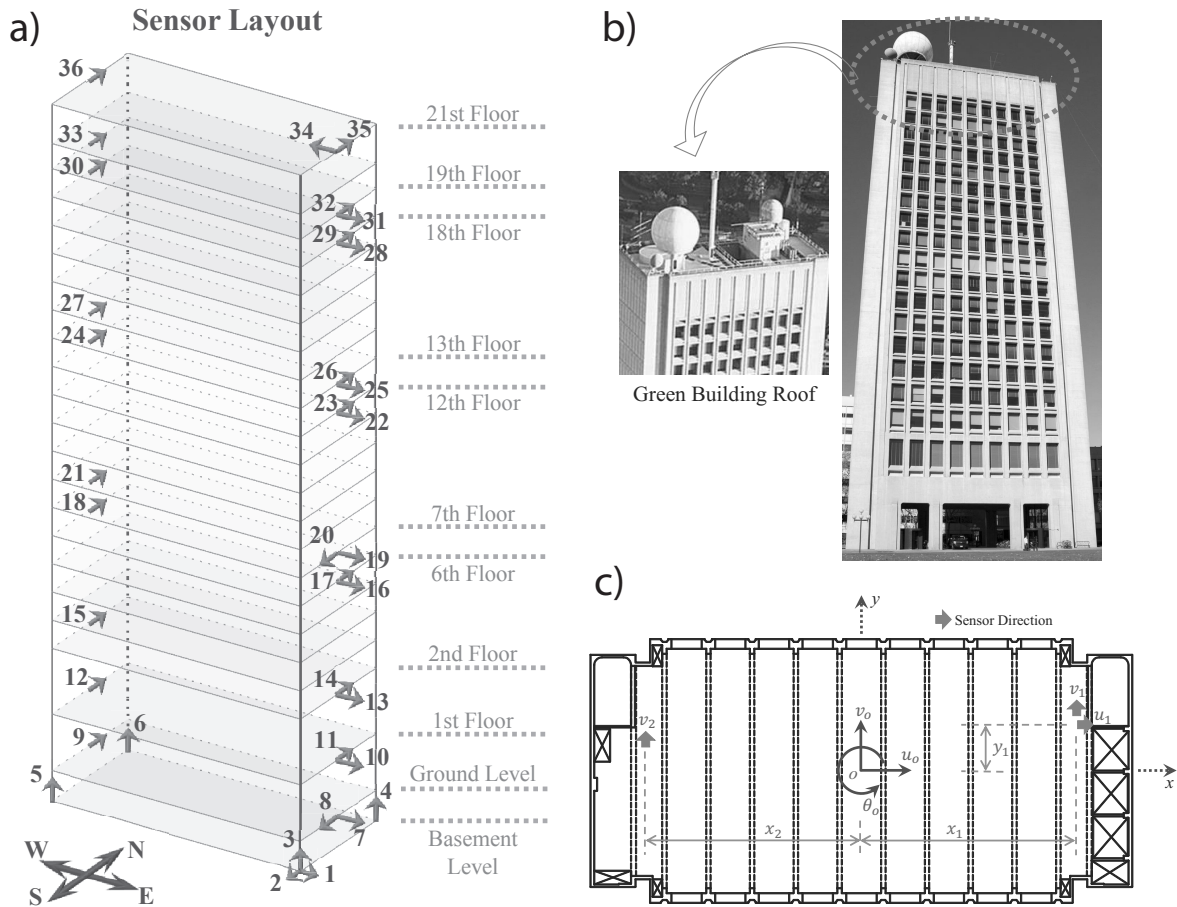


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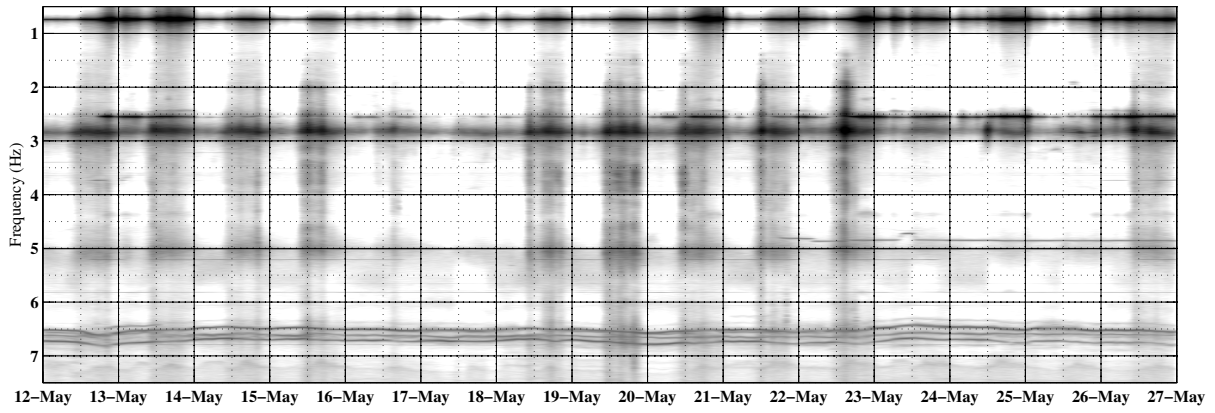


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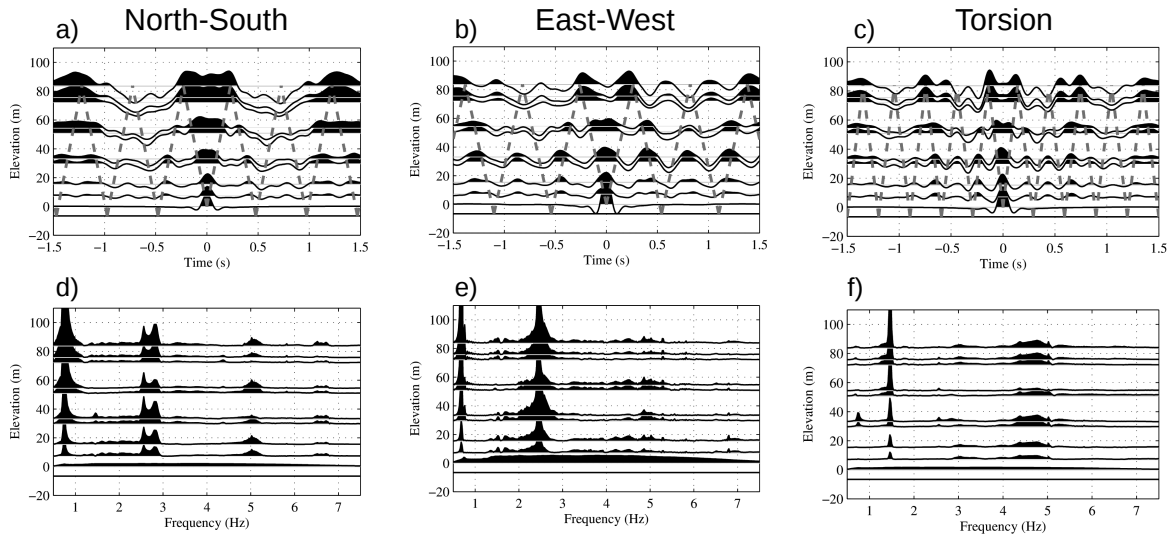


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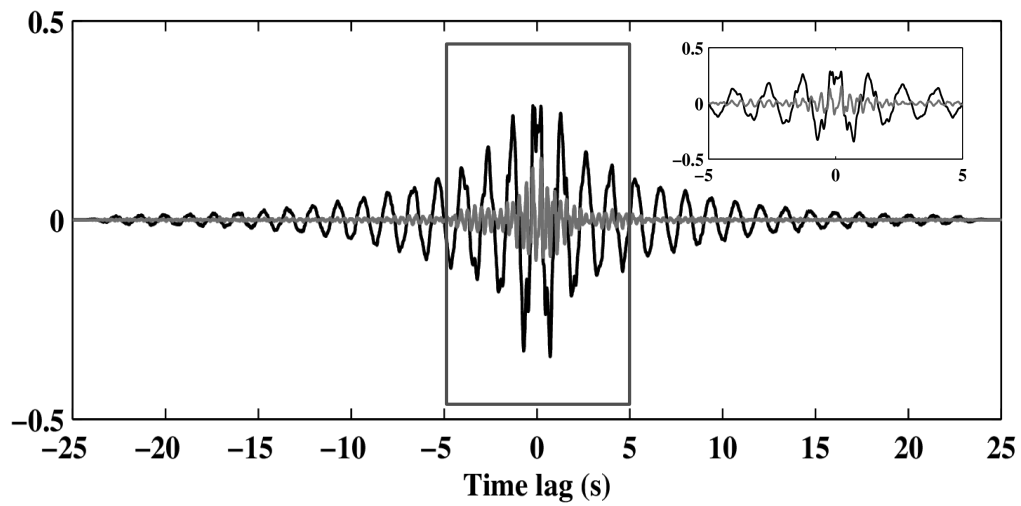


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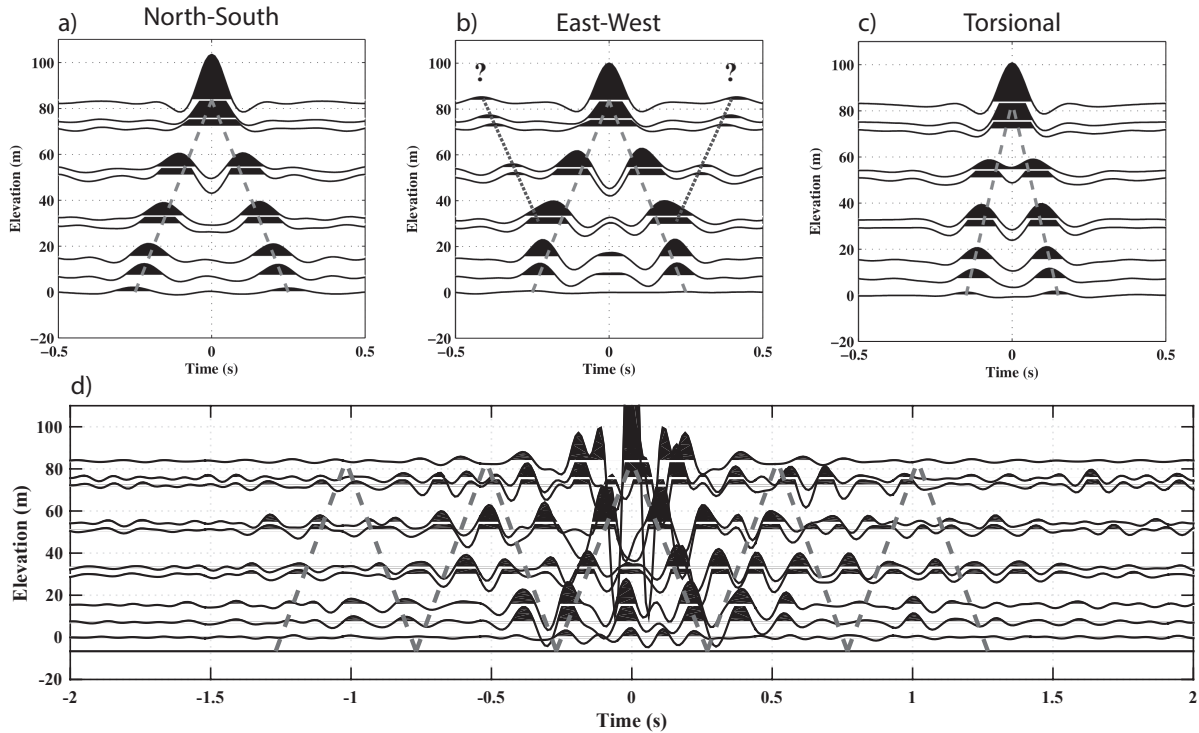


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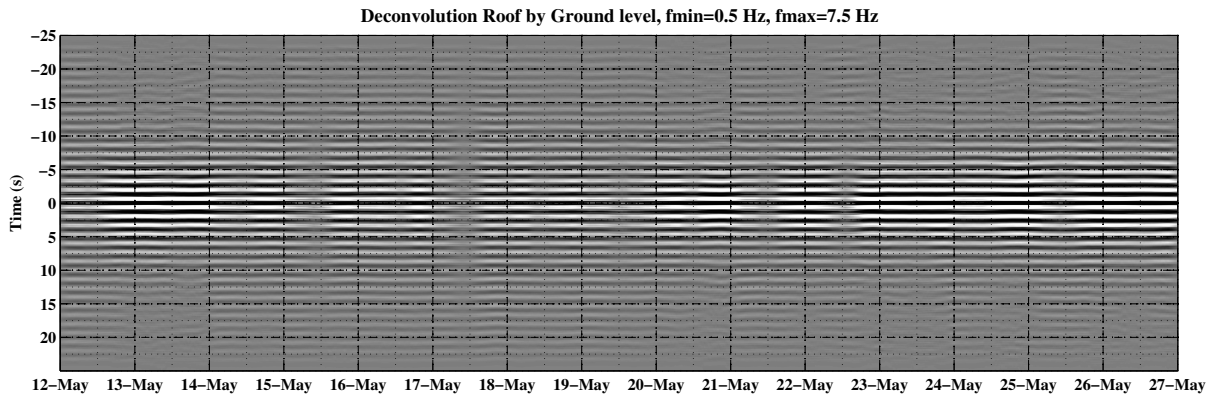


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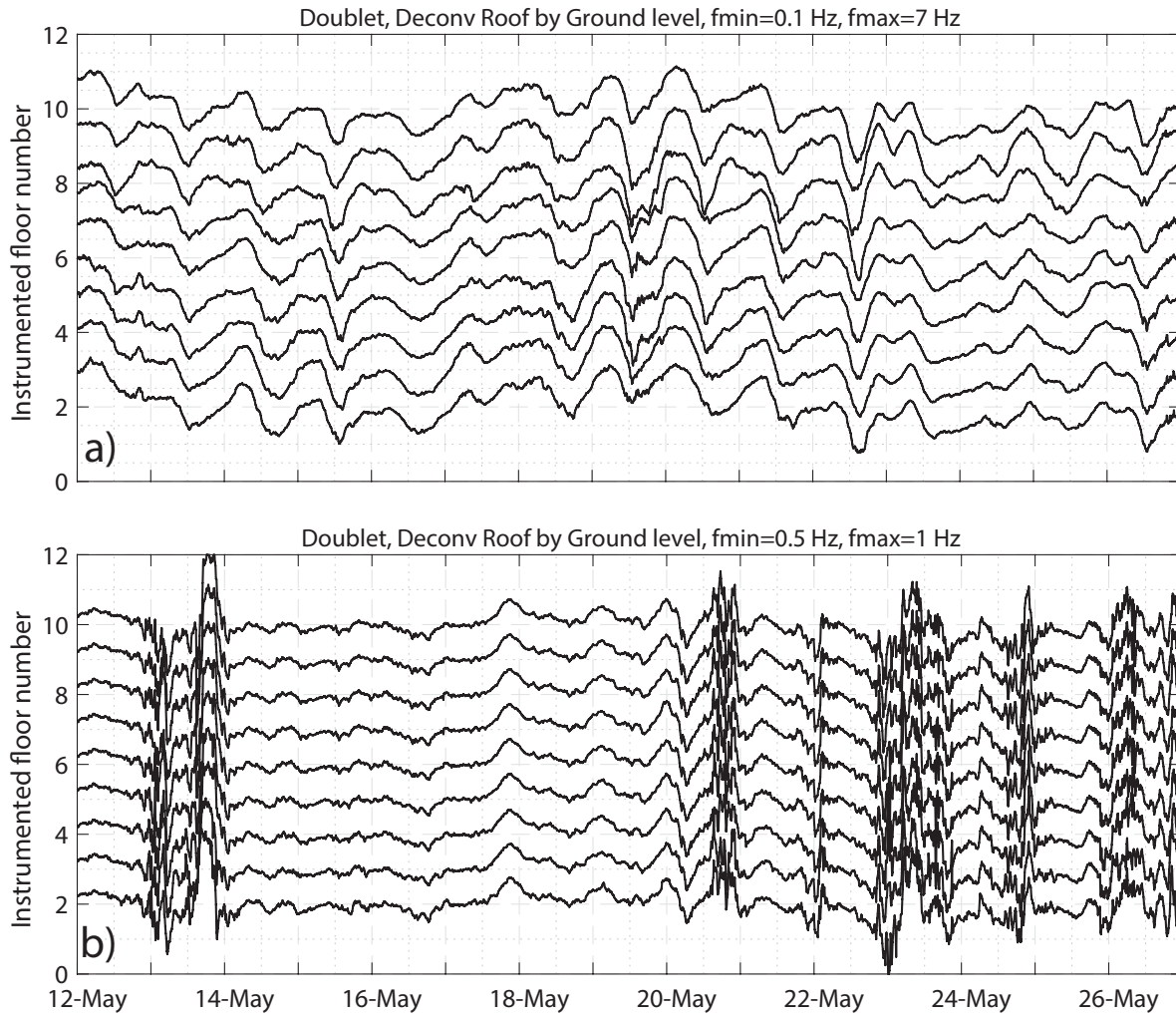


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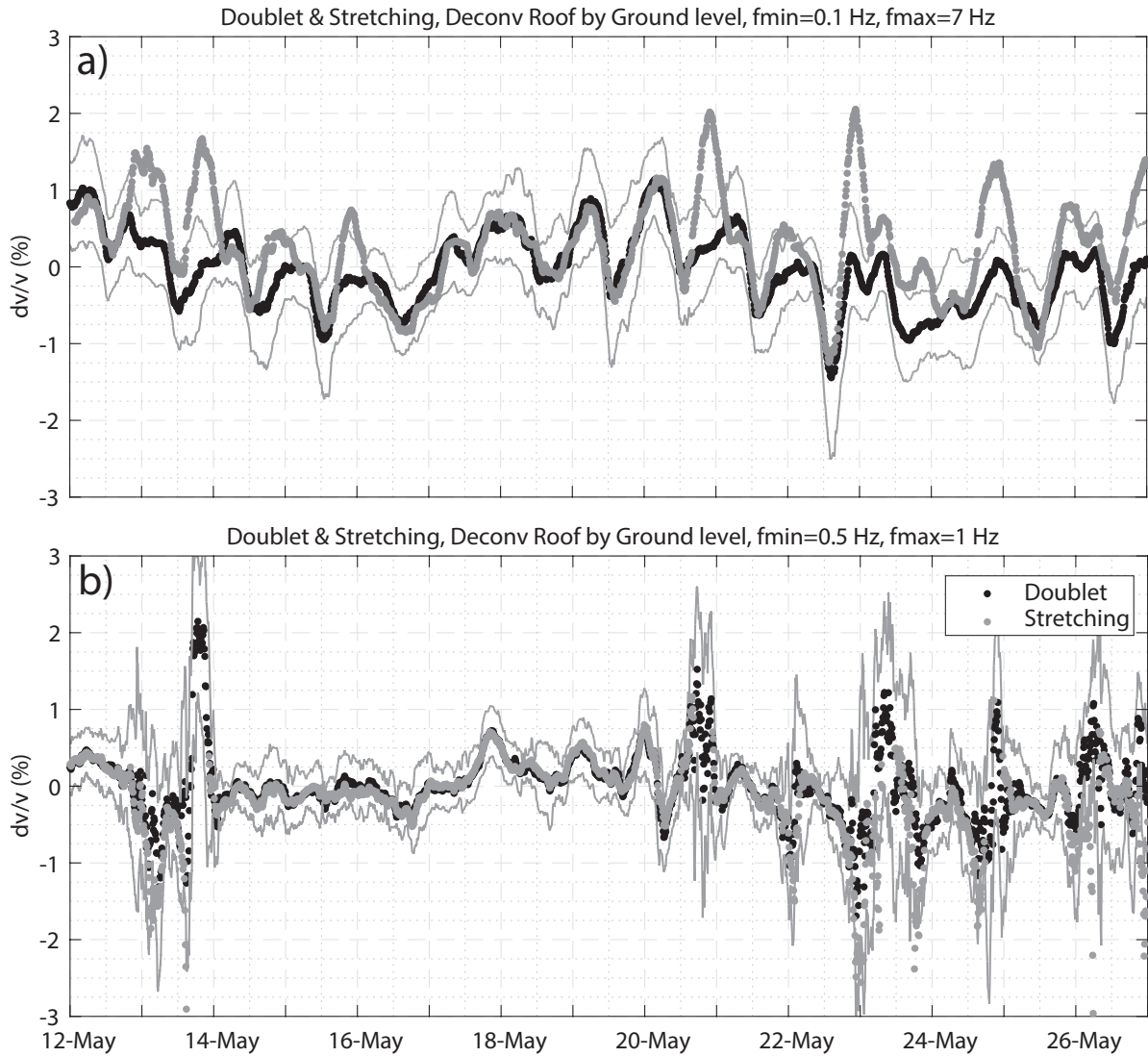


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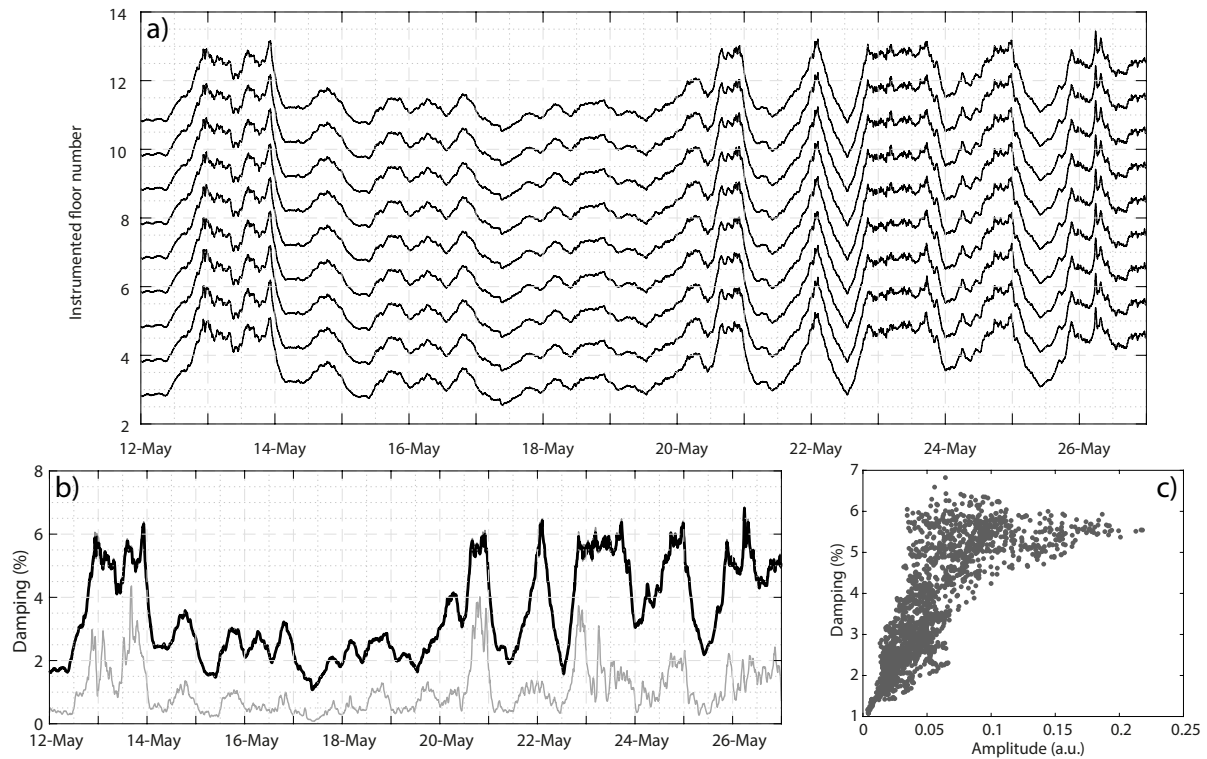


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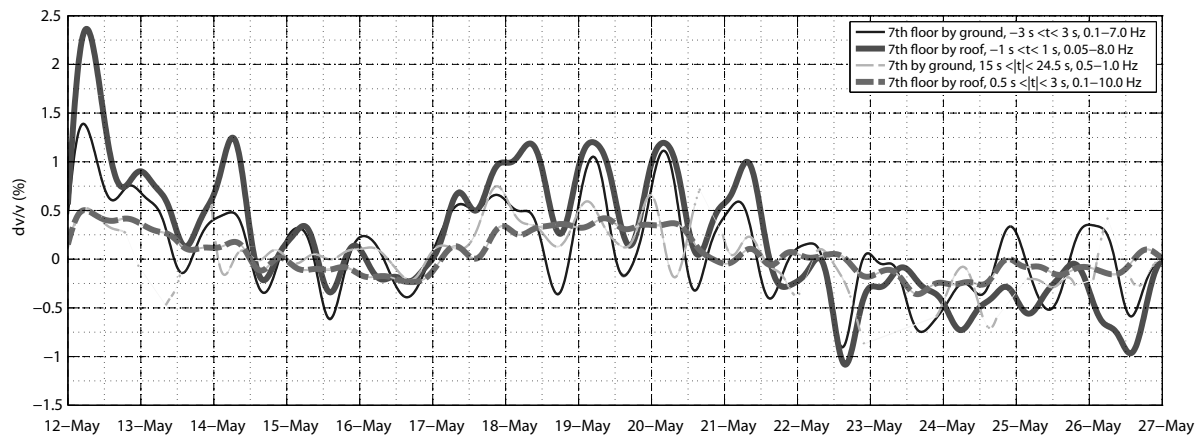


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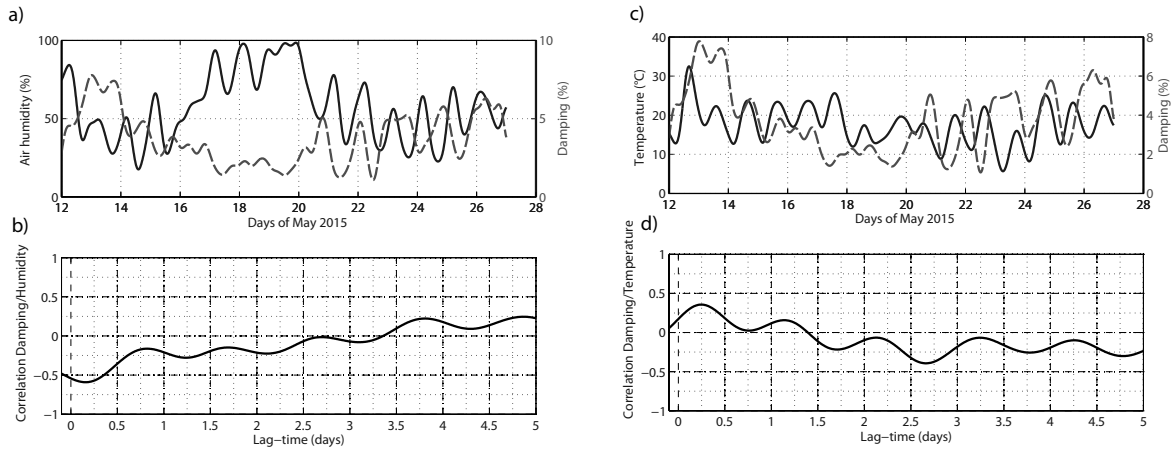


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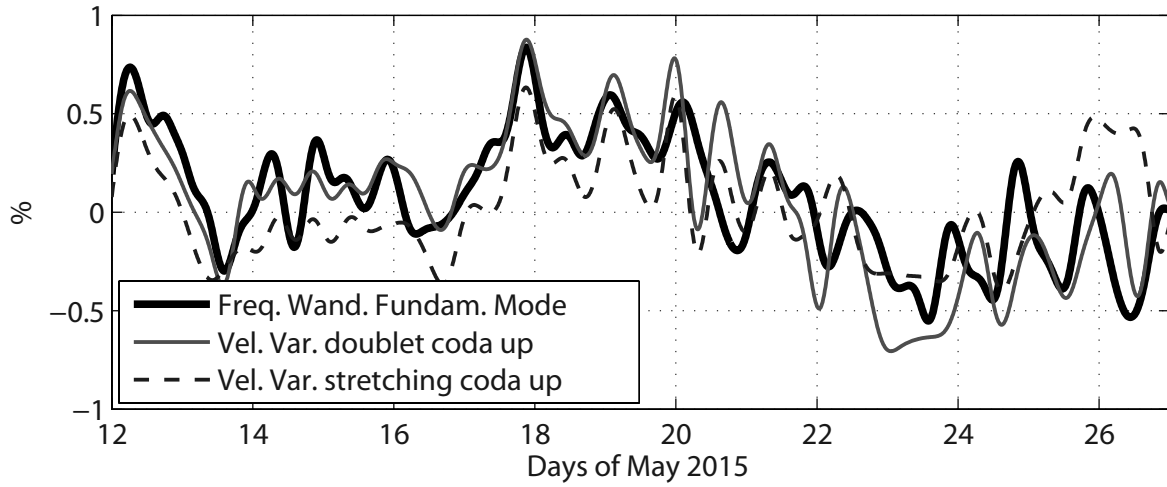


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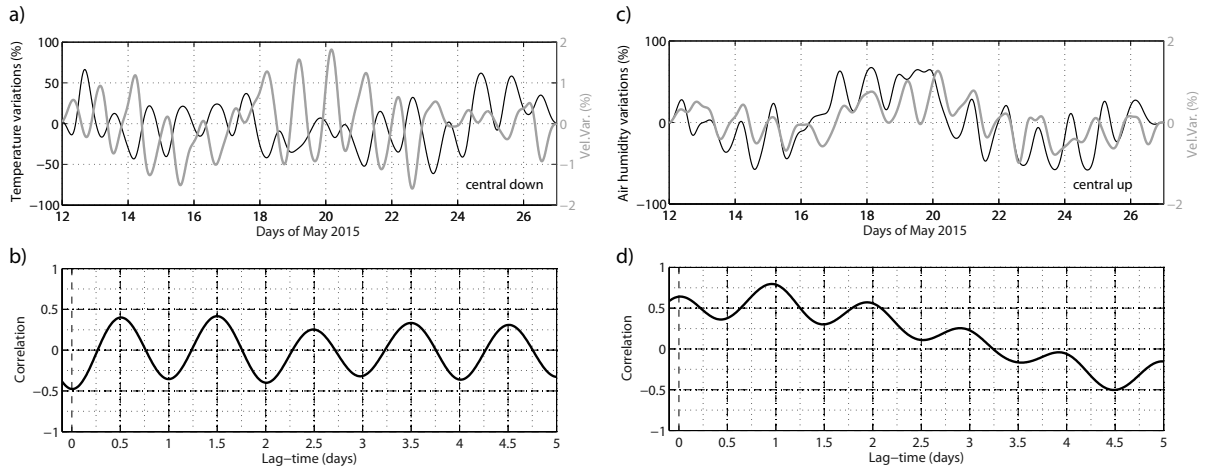


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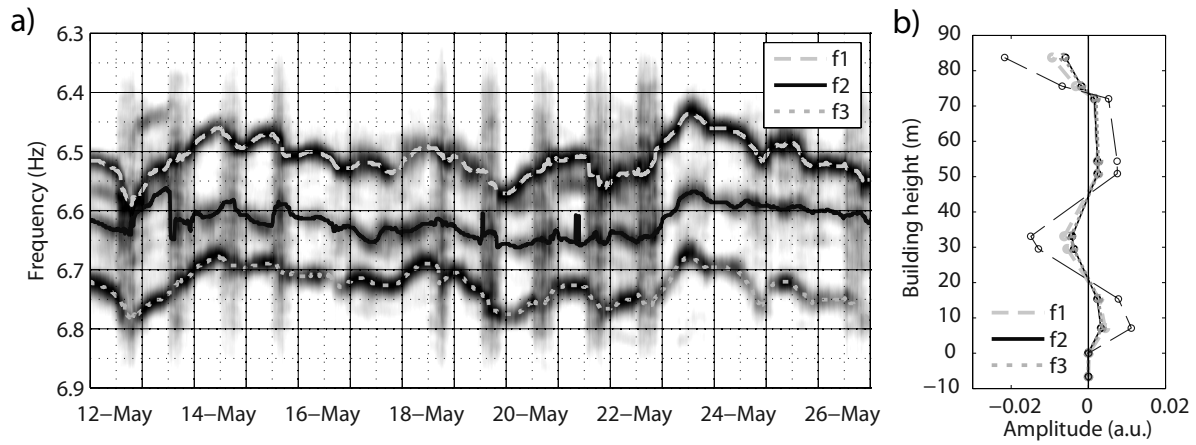


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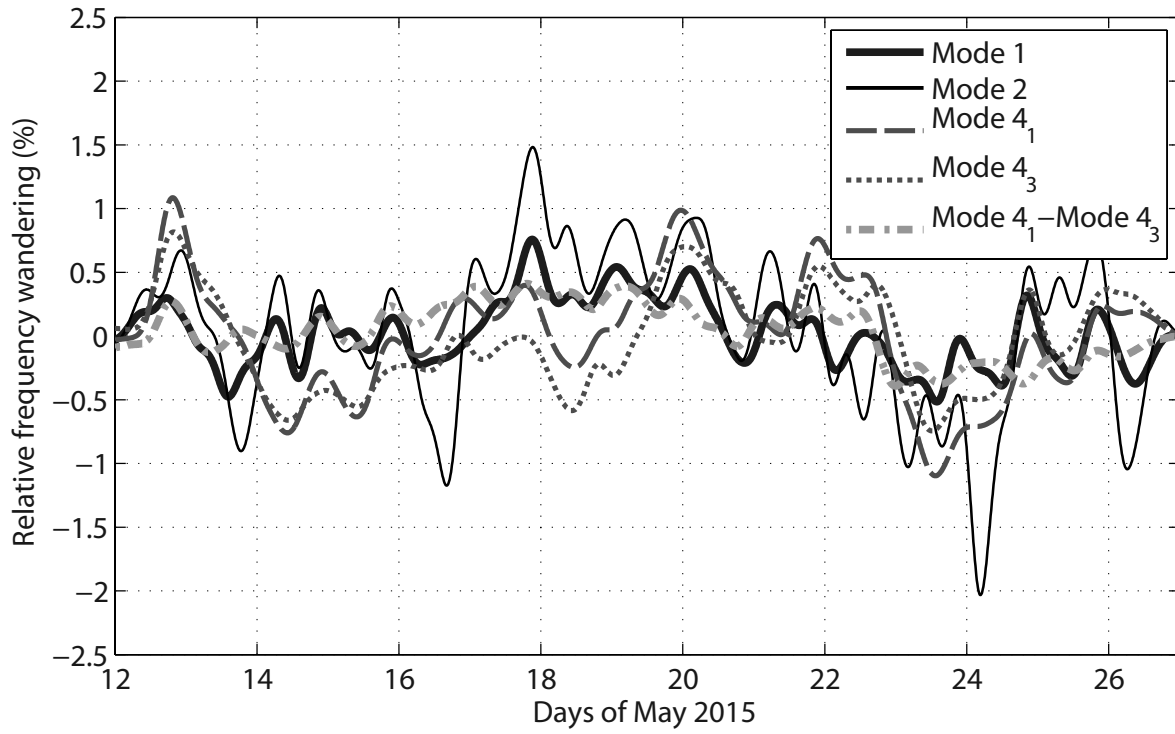


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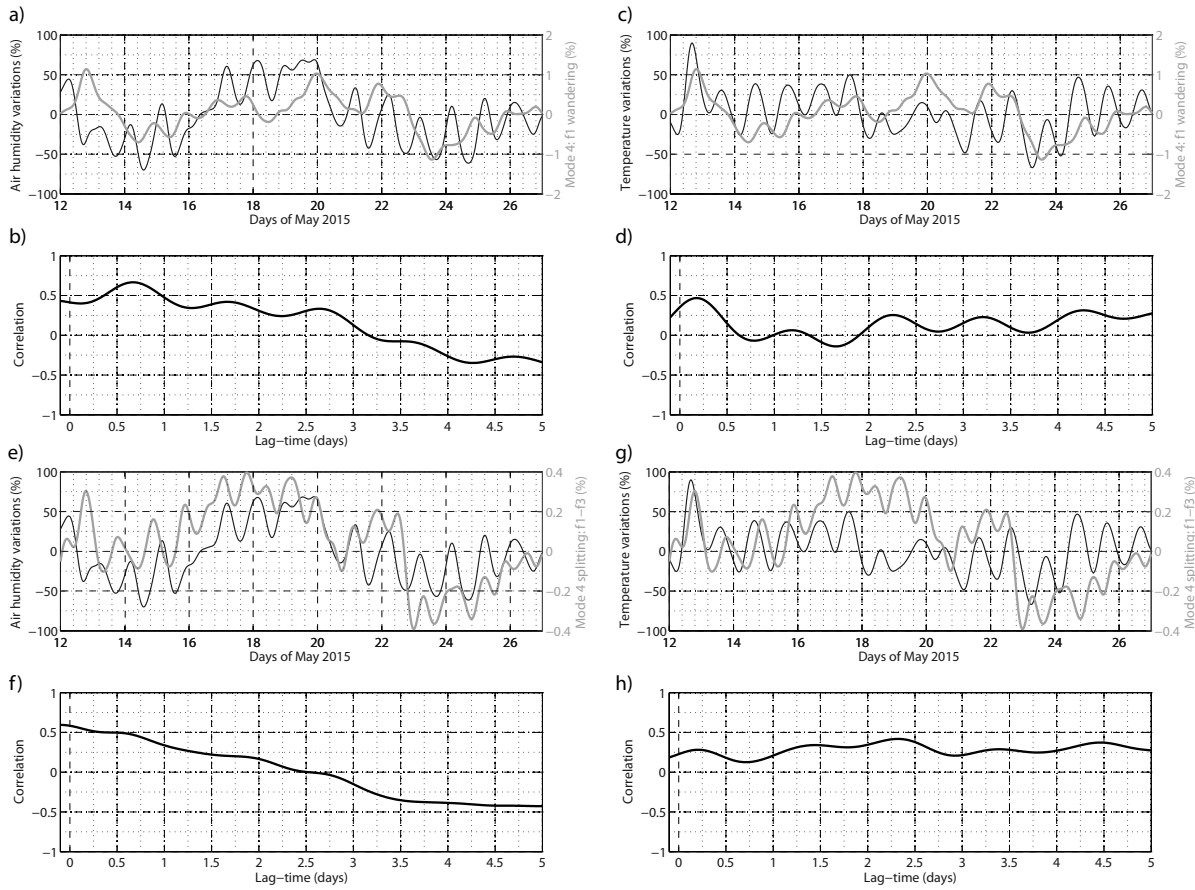


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