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Solid Earth Discussions

Interactive comment on "Seismic noise variability as an indicator of urban mobility during COVID-19 pandemic in Santiago Metropolitan Region, Chile" *by* Javier Ojeda and Sergio Ruiz

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All line numbers added in this reply refer to line numbers in the updated "clean" manuscript i.e. that without the track changes.

1 General comment

The paper is well written and straightforward. Although several cases of the noise level decrease due to lockdowns, curfews, quarantines in different places have been documented in several countries during last year, it is welcome to have another example from a big city that correlates the decrease with some social index. I recommend the paper for publication after some review.

Thank you for your comment and the following suggestions to improve our manuscript.

2 Queries and technical corrections

1. **Abstract: Please, consider to mention in the abstract the results with other stations in Chile (section 3.3)**

   Thanks for your suggestion, we added a brief sentence about other stations in Chile (L9):

   "The same results are observed in other cities such as Iquique, La Serena, and Concepción."

2. **Line 24: real time to real-time**

   This has been changed. (L14)

3. **Line 25: high density to High-density**

   This has been changed. (L16)

4. **Line 35: risk of the spreading of the virus to risk of the virus spreading.**

   This has been changed. (L19)

5. **Line 65: Please, consider to include large and long-scale events in big cities. I believe that this is important to stress.**

   This has been changed. (L49)

6. **Line 76: Is there any particular reason for the installation of the stations in the capital?**

   The stations are part of the National Seismological Network, a permanent network that allows monitoring the seismic activity in the Metropolitan Region, the largest region with a higher population along Chile. This network was recently improved by the Centro Sismológico Nacional (CSN) to further monitor seismogenic faults along the Andes mountain belt, which represents a risk exposure to the inhabitants of the Metropolitan Region.

   More about the development of CSN can be found in Barrientos (2018).

   Barrientos, S. (2018). The seismic network of Chile. Seismological Research Letters, 89(2A), 467-474.

7. **Line 76: Please, provide further information on the conditions where those five stations are installed. Any special treatment because they are inside the city?**

   Regarding the conditions of the five stations installed in the city, we cite the work of Leyton et al. (2018a) and Leyton et al. (2018b), who gives more details about the installation and geophysical characterization like velocity profile and therefore soil conditions, that also can be found in the CSN website: evtdb.csn.uchile.cl. We do not know other specific studies about the soil conditions in those stations. Also, we did not apply special treatment to the stations within the Metropolitan Region.

   To give more information in our manuscript, we added the next sentence (L58):

   "Further information about geophysical characterization and soil conditions where stations were deployed can be found in Leyton et al., (2018a) and Leyton et al., (2018b)."

8. **Line 80: Although you are using the horizontal components to see the noise decrease, I recommend to perform the noise polarity analyses to check the direction(s) of the noise origin(s). I believe it is important to check with the direction of the park, airport.**

   Thanks for your suggestion. We analysed the horizontal ASN amplitudes for MT14 station (Figure R1). The three-component seismic noise shows similar trends and variation over time, supporting the findings of Lecocq et al. (2020).

   On the other hand, we perform Noise Polarization analysis (Park et al., 1987) to one hour of three-component continuous seismic records for three stations: MT18 (near park and hippodrome), MT05 (the nearest station to the airport), and MT14. Moreover, we calculate over three different days between 15h-16h p.m. (local time):

   - 10 March 2020
   - 31 March 2020
   - 27 April 2020

   We selected these days because in those we see important changes in ASN amplitudes in station MT14.

   These Noise polarization analyses perform the ground motion in a range of frequencies composed principally by Rayleigh waves, propagated in the direction of the P waves. Our preliminary results are presented in Figures R2, R3 and R4.

   For station MT05 (Figure R2), we do not see significant differences between the time period analysed. The major amplitudes come from directions SE (110°-170°) and NW (290°-350°), probably due to that in the other directions we can see

the hills and a tiny population (see Figure A1c). The source generates Rayleigh waves, and it is probably a superficial source due to the 80°-90° of maximum amplitude in their vertical component.

For station MT18 (Figure R3), the noise source come preferably from SW (180°-270°), showing that the noise source could be associated with the hippodrome instead of the activity in the Park. Regarding the vertical component, we distinguish a broad range of sources.

For station MT14 (Figure R4), we observed heterogeneous noise source in their horizontal component. Probably due to the multiple directions of generation of Rayleigh waves. For those stations, we can not see a pattern between each period.

Despite these results, we prefer not to show these preliminary polarization analyses, because we think that is out of the main scope of our work and more importantly, we understand that this analysis deserves further work and discussions, such as ellipticity (Kulesh et al., 2007), rectilinearity (Montalbetti and Kanasewich, 1970), or planarity analysis (Jurkevics, 1988). Furthermore, we think that to obtain a robust conclusion, we need to include different periods of time and maybe daily and continuous data to analyse the noise source over-time. Undoubtedly, these results could be an important issue for the special edition, but we prefer to improve our analysis in future work.

References: Jurkevics, A. (1988). Polarization analysis of three-component array data. Bulletin of the seismological society of America, 78(5), 1725-1743.

Kulesh, M., Diallo, M. S., Holschneider, M., Kurennaya, K., Krüger, F., Ohrnberger, M., Scherbaum, F. (2007). Polarization analysis in the wavelet domain based on the adaptive covariance method. Geophysical Journal International, 170(2), 667-678.

Montalbetti, J. F., Kanasewich, E. R. (1970). Enhancement of teleseismic body

phases with a polarization filter. Geophysical Journal International, 21(2), 119-129.

Park, J., Lindberg, C. R., Vernon III, F. L. (1987). Multitaper spectral analysis of highâĂŘfrequency seismograms. Journal of Geophysical Research: Solid Earth, 92(B12), 12675-12684.

9. **Line 83: For all stations we processed to For all stations, we processed**

   This has been changed. (L67)

10. **Line 93: Normalized in relation to what? Normalized individually or among then?**

    We normalised the seismic RMS amplitudes individually. In Figure 2, we first obtain the RMS displacement for each frequency band, then we clipped the data above the 95th percentile and subtract the minimum value. Finally, we divided by the RMS displacements by the maximum value which is recorded in the period before Lockdown 1 (23 Jan. 2020 – 25 Mar. 2020).

11. **Line 103-104: The median day-time amplitudes between 5h and 22h local time obtained from the seismometer and the accelerometer exhibits similar trends and behaviour to "The median day-time amplitudes between 5h and 22h local time obtained from the seismometer and the accelerometer exhibit similar trends and behaviour".**

    This has been changed. (L81)

12. **Line 105: Please, provide an explanation of why Saturday is the noisier day of the week, according to 4a. Is it due to the of people in the park? But Sunday is equivalent to Friday. Some explanation is in line 214. Just call attention to that.**

    Thanks for your comment. We added the new sub-section 3.1 on Results, where we answer your question

"3.1 Lockdown, curfew and ASN amplitudes

We analysed the seismic effect caused by the first lockdown in Santiago City using the 24-h clock plots in station MT18 (Figure 4a, 4b). Although we observed a gradual reduction in ASN amplitudes on weekdays due to the day-cares, schools and universities near the station closed (16 March), we also notice a strong reduction on weekends, especially between 11h and 19h local time. Figure A1b shows the area close to MT18 in which we can distinguish the hippodrome "Club Hípico de Santiago" and the O'Higgins Park. The highest ASN amplitudes observed on Saturday before Lockdown 1 (Figure 4a) is explained by the activities of the hippodrome on Saturdays (and some Thursdays during January-February). The hippodrome closed on 21 March 2021, which is in agreement to the decrease in the ASN amplitudes observed after Lockdown 1 (Figure 4b).

We also distinguish the lockdown effect in the hourly grid representation (Figure 4c). The large ASN amplitudes observed during holidays are associated with near activities in both hippodrome and O'Higgins Park, which only persist on weekends during March. After the implementation of Lockdown 1, the ASN amplitudes drop, especially on weekends. Moreover, we observed a systematic behaviour of lower ASN amplitudes between 22h and 5h local time due to the overnight curfew implemented at the same hours, imposed from Lockdown 1 and remain during the full time-window studied."

13. **Line 106: This reduction on the weekends, are you talking about the figs 4a and 4b? In 4c it is not easily identified.**

    Yes, we refer only to Figures 4a and 4b clock plots.

14. **Line 106: Please write the date of the Lockdown, beginning and end?**

    Thanks for your suggestions, we added a new line according to the comments of Referee 1. Also, we added Table A2 with the dates when Lockdown and other phases started and ended in the different cities where stations are located.

15. **Line 110: Is it possible to indicate the park in figure 1?**

    This has been changed. We added the park location in Figure 1, and in the new Figure A1b.

16. **Line 111: Sorry if I misunderstood the sentence but how does a curfew between 22 h and 5 h reduce amplitudes between 5 h and 22 h?**

    Thanks for this comment, we were wrong about the order of the hours. We rewrote this sentence (L121):

    "Moreover, we observed a systematic behaviour of lower ASN amplitudes between 22h and 5h local time due to the overnight curfew implemented at the same hours, imposed from Lockdown 1 and remain during the full time-window studied"

17. **Line 116: Website of the Ministry.**

    Corrected (L88): "Our study integrates epidemiological data available in the website of the Chilean Ministry of Science"

18. **Line 118: Please, provide further explanation of the Re. What does it mean and how is it measured?**

    Thanks for your query, we complete section 2.3 in which we qualitatively describe the Re indicator, as well as how ICOVID Chile (2020) measured (L88):

    "One of the primary indicators of the spreading of viruses and contagion dynamics is the estimation of the effective reproductive number (hereafter Re) from confirmed positive cases of COVID-19 since the date of the beginning of symptoms. The Re indicator is defined as the actual average number of secondary cases generated by a primary case during the epidemic outbreak (Caicedo-Ochoa et al., 2020; Tariq et al., 2021), their estimation is helpful to the assessment of public policies, to estimate population immunity, to monitor near real-time changes

in transmission of the viruses over time, among others (Gostic et al., 2020). To control an epidemic outbreak, the Re indicator needs to be reduced below one (Riley et al., 2003). Herein, we used the estimation provided by ICOVID Chile (2020) who described the function Re depending on the proportion of susceptible individuals to be infected, a transmission coefficient and the infectious life expectancy. In other words, the Re accounts for the coefficient between the new infections and the recovery rates plus mortality rates (Contreras et al., 2020). ICOVID Chile (2020) used the method proposed by Cori et al. (2013) to monitor Re in real-time, modelling the transmission like a Poisson process calculated on the basis of the last seven days. We considered only the Re median and 95% credible interval estimated for the urban area in the MR, according to the data given by the Health Service of Santiago City."

19. **Line 120: What is ICOVID? An intitution?**

    ICOVID Chile is an initiative created by Universidad de Chile, Pontificia Universidad Católica de Chile and Universidad de Concepción, as a collaboration with the Ministry of Health and the Ministry of Science. Since the first months of the pandemic, they are analysing different key indicators that represent a full view of the health situation caused by the SARS-CoV-2 viruses. Website: https://www.icovidchile.cl/que-es-icovid-chile

20. **Line 124: How is the Apple data measured? Change in relation to what?**

    Apple gives mobility trends data, which is available for a limited time during the COVID-19 pandemic. The data is based on cell phone locations for a diverse range category such as “Public walking” or “Public driving” of each country-city (including Santiago de Chile). They shared this information and the change is relative to the baseline value from 13th January (first day available). We recognise that this mobility data is biased by people who are carrying their phones and use the map applications. We modify the sentence by:

    “The mobility data we analysed is provided by Apple mobile-phone locations in Santiago City, which corresponds to the percentage of change in the public’s walking and driving in relation to a baseline value from 13 January (Apple, 2020)”

21. **Line 130: Could you plot the airport location in figure 1?**

    This has been changed. We added the airport location in Figure 1, and in the new Figure A1c.

22. **Line 139: Is there a website where we can find the ppsd (Probabilistic Power Spectral Densities) from all stations?**

    Unfortunately, this is not available. The CSN does not provide this information.

23. **Line 139: Were you able to identify some decrease during the holidays? Like Christmas, Good Friday.**

    In general, yes, we can identify the decrease in some important holidays such as Christmas and New Year’s Day (especially if those dates break the continuity during the weekdays, e.g., 2018). Also, we notice a decrease in the National Holidays during September, especially in 2019. However, these changes in ASN amplitudes are not easy to visualize at this scale and would need an additional figure to do mention in the manuscript.

24. **Line 145: Just call the attention of the reader that the average amplitude is different for each station. Like MT18 is 15 nm and MT16 is 1.5 nm?**

    Thanks for your question, we did not write too much about the ASN amplitudes and their difference from each station, although we decide to add the next sentence to clarify (L140):

    “Concerning the ASN amplitude variability, we observed that the quieter stations in the urban area of MR correspond to MT05, MT14, MT16 and MT03, stations that are located over hills, unlike the MT18 and MT15 stations which are deployed

in the valley. Despite the ASN present an average amplitude difference between each station, the temporal variations can be observed within Santiago City"

25. **Line 159: Just to make it easier for the reader, please provide the information about the approximate distance between urban and rural stations.**

    Corrected. We added the next sentence (L146): "Notice that the rural stations analysed are deployed within the MR at a distance of about 15 km to 60 km from the stations installed in urban areas (see Figure A1)."

26. **Line 169: This peak is not so clear in the for the MT18. Some explanation for that? By eye, I believe the MT18 and Re correlation is worst, am I right? Same for Apple's data**

    We agree with your comment, the matching pattern between mobility data, Re and ASN amplitudes in MT18 and other stations within city is poorly constrained. The only comparable station with MT14 could be MT16 which is located in the same municipality (Las Condes). Unfortunately, MT16 has data gaps just in the scope time-window. Regarding your question, we think that this behaviour has a socioeconomic explanation. According to recent studies, the lockdowns in high-income zones (such as Las Condes) have more effectiveness than in low-income zones (such as Santiago and other communes within MR urban area), due to different economical activities, the possibility to work at home, etc. Also, the low-income zones have higher mobility than high-income zones during lockdowns, which can explain why the seismic noise level in station MT18 did not match with the Re indicator.

    We explain this in the Discussion section (L220):

    "The matching pattern between the mobility data, the Re indicator and the high-frequency ASN amplitudes is well established for the station MT14 located in Las Condes. Nonetheless, this did not occur with other stations in urban areas such as MT18 placed in Santiago downtown. This observation can be further

explained due to the heterogeneity in policy effectiveness against the COVID-19 spread in MR. Bennett (2021) showed that social distancing, quarantines and testing availability are affected by geographical and socioeconomic factors, in which the lockdowns have been more effective in high-income zones (such as Las Condes) rather than lower-income zones (such as the other station analysed in the MR urban area). Furthermore, the people living in high-income zones can reduce their mobility by around 60% while people in low-income zones only reduce their mobility by around 20% during lockdown (Carranza et al., 2020)."

27. **Line 174: Where is the airport?**

    The airport is approximately 5 km western of MT05 station. We added the airport location in Figure 1, and in the new Figure A1c.

28. **Line 175: I am sorry, I believe the is a problematic sentence: Is there any confirmation by the government that Lockdown 2 was responsible for the mitigation?**

    We agree and changed the sentence to the following (L158):

    "After Lockdown 2, in mid-July, the Chilean government proposed the step-by-step programme to mitigate the propagation of SARS-CoV-2 virus towards a gradual re-opening and increase mobility in different counties as a public health policy (see Table A1)."

29. **Line 176: Please, explain the five phases. Just a short sentence is enough.**

    Thanks for this comment, we added Table A1 that includes more information explaining the step-by-step programme with the five phases

    In addition, we added the next line in the Introduction section (L21):

    "During this first period, the main public health policy addresses the isolation and social distance, including the closure of schools, universities and other educa-

tional centres (16 March), national night-time curfew (23 March), and the lockdown of communes. From 19 July 2020, the Chilean government implemented the step-by-step programme, which considers a gradual open of each commune by five phases, based on the monitoring of epidemiological and health system indicators (see Table A1; Tariq et al. (2021))."

30. **Line 188: Please, make reference that the reader can see where those cities are located in Chile looking at Fig 1.**

    Thanks, we mention now the Figure 1 (L167) "High-frequency ASN changes were also recorded in other cities along Chile (Figure 1)."

31. **Line 195: CCSP shows an average of 30 nm "noisier" the MT18. some explanation?**

    We added the next sentence to explain the ASN amplitude observed (L177):

    "The ASN amplitudes in Concepción are at least 30 nm noisier than Santiago (MT18), which could be explained by their location on residential areas, but also the different soil conditions where the stations were installed"

32. **Line 197: MG01 shows a strange pattern. Like a strong decrease in January.**

    We agree, the strange pattern could be explained by the station located near an airfield in Puerto Williams. The airport operates on different days a week, probably explaining the strange patterns in seismic noise levels.

    We added the next paragraph (L181):

    "Nevertheless, this station shows a strange pattern before Lockdown. The first one corresponds to a high drop in mid-December until the first days of January associated with holidays festivities (Christmas and New Year Day). The second pattern observed is the temporal variability that could be associated with the activity of the airfield near the site where the station is operating. Unfortunately,

    we don't have access to the aeroplane activity in those weeks to support our assumption."

33. **Line 231: transmission of virus to transmission of the virus**

    This has been changed. (L208)

34. **Line 272: implemented in other high density cities to implemented in other high-density cities**

    This has been changed. (L255)

35. **Line 272: Please, cite some examples where we can find those networks and the impact of their study not just in the mobility but as a tool to teach seismology to school students and the society like Barcelona for example. https://doi.org/10.3389/feart.2020.00009**

    Thanks for your recommendation. We agree with it, and we added the next sentence (L252):

    "These seismometers are typically used for the management of seismological networks in urban areas; however, recent studies show the potential opportunity to use them as a tool to teach seismology to school students (e.g., Subedi et al., 2020) and increase the interest of society toward Earth Sciences (e.g., Diaz et al., 2020)."

36. **Figure 1: I would recommend decreasing the coastline thickness, it is blending with the stations** This has been changed

37. **Figure 2: Is it just an impression or the gaps for the 1-10 Hz are narrower than the others? Just some "illusion" played by the colours?**

    Yes, the data gaps are the same for each frequency analysed.

38. **Figure 3: End of the lockdown 2?**

    After Lockdown 2, the government implemented the program step-by-step which include five different phases mentioned in the new Table A1. This program was implemented in mid-July. Since then, the Lockdown 2 lifts on 17 August 2020 (Phase 2). Now, we include these dates in Table A2.

39. **Figure 3: Difference between the blue and white background.**

    Corrected, we added the next sentence in Figure 3 caption:

    "The grey and white background correspond to weekdays and weekends, respectively."

3 Figure captions

- Figure R1. ASN amplitudes for MT14 station in their components: (a) HHZ, (b) HHN, (c) HHE.
- Figure R2. Polarization analysis for station MT05. (a) On 10 March 2020 at 15h-16h local time, (b) on 31 March 2020 at 15h-16h local time, and (c) on 27 April 2020 at 15h-16h local time. The left panel show horizontal variation and the right panel shows vertical variation in theta. If we considered that the noise sources come from P and superficial waves, we can interpret that the horizontal angle (θ_H) is defined by $0^\circ = N$, $90^\circ = E$, $180^\circ = S$, $270^\circ = W$, and the vertical angle (θ_V) in which we can infer 0° from deep sources and 90° from shallower sources.
- Figure R3. Polarization analysis for station MT14. (a) On 10 March 2020 at 15h-16h local time, (b) on 31 March 2020 at 15h-16h local time, and (c) on 27 April 2020 at 15h-16h local time.

- Figure R4. Polarization analysis for station MT18. (a) On 10 March 2020 at 15h-16h local time, (b) on 31 March 2020 at 15h-16h local time, and (c) on 27 April 2020 at 15h-16h local time.

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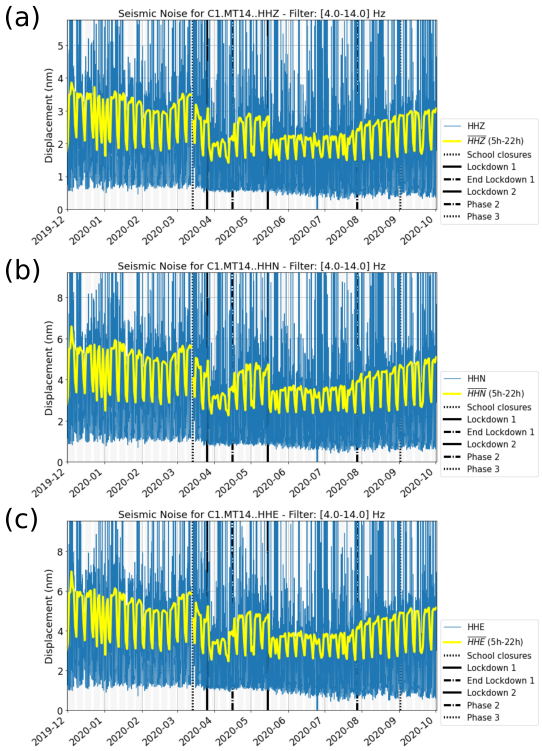
(a)
Seismic Noise for C1.MT14..HHZ - Filter: [4.0-14.0] Hz
Displacement (nm)
HHZ
HHZ (5h-22h)
School closures
Lockdown 1
End Lockdown 1
Lockdown 2
Phase 2
Phase 3
(b)
Seismic Noise for C1.MT14..HHN - Filter: [4.0-14.0] Hz
Displacement (nm)
HHN
HHN (5h-22h)
School closures
Lockdown 1
End Lockdown 1
Lockdown 2
Phase 2
Phase 3
(c)
Seismic Noise for C1.MT14..HHE - Filter: [4.0-14.0] Hz
Displacement (nm)
HHE
HHE (5h-22h)
School closures
Lockdown 1
End Lockdown 1
Lockdown 2
Phase 2
Phase 3

Fig. 1.

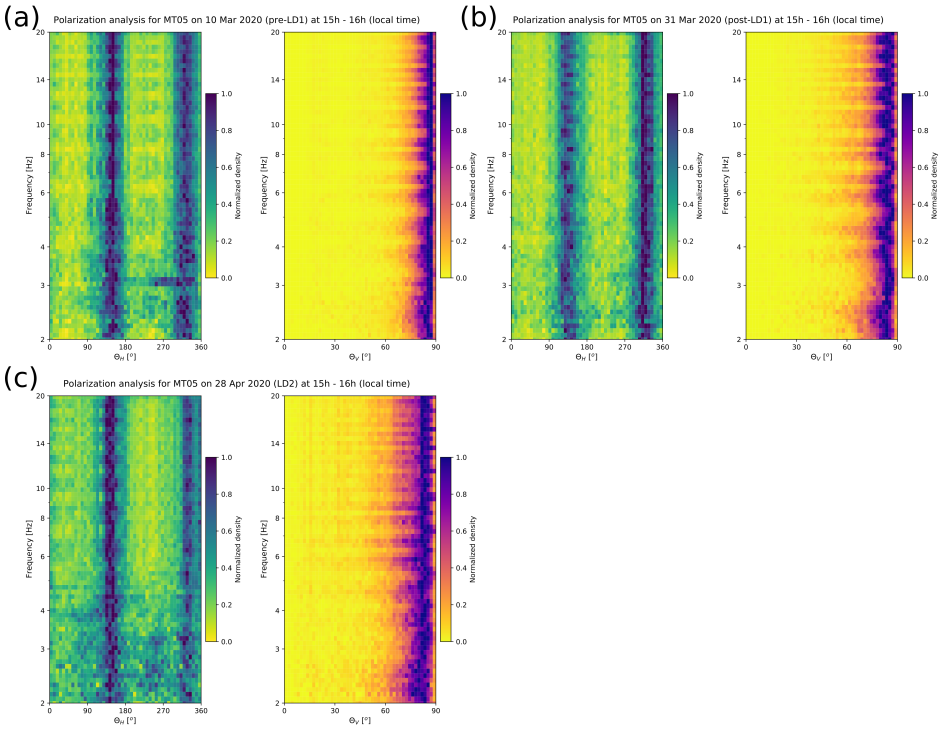
(a)
Polarization analysis for MT05 on 10 Mar 2020 (pre-LD1) at 15h - 16h (local time)
(b)
Polarization analysis for MT05 on 31 Mar 2020 (post-LD1) at 15h - 16h (local time)
(c)
Polarization analysis for MT05 on 28 Apr 2020 (LD2) at 15h - 16h (local time)
Frequency [Hz]
Normalized density

Fig. 2.

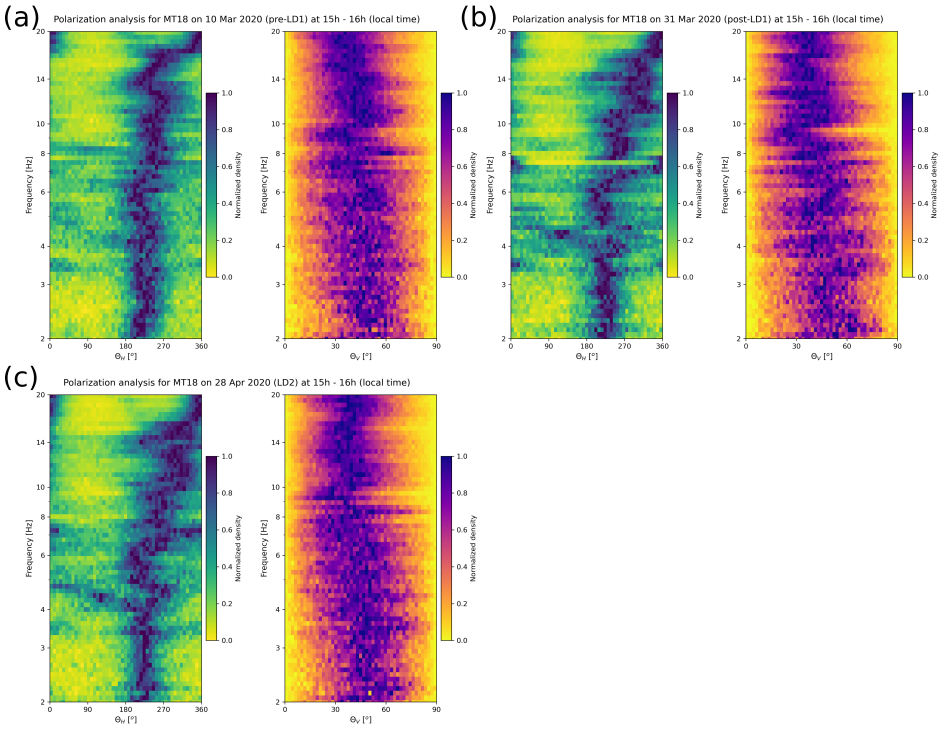
(a)
Polarization analysis for MT18 on 10 Mar 2020 (pre-LD1) at 15h - 16h (local time)
(b)
Polarization analysis for MT18 on 31 Mar 2020 (post-LD1) at 15h - 16h (local time)
(c)
Polarization analysis for MT18 on 28 Apr 2020 (LD2) at 15h - 16h (local time)
Frequency [Hz]
Normalized density
Θw [°]
Θv [°]

Fig. 3.

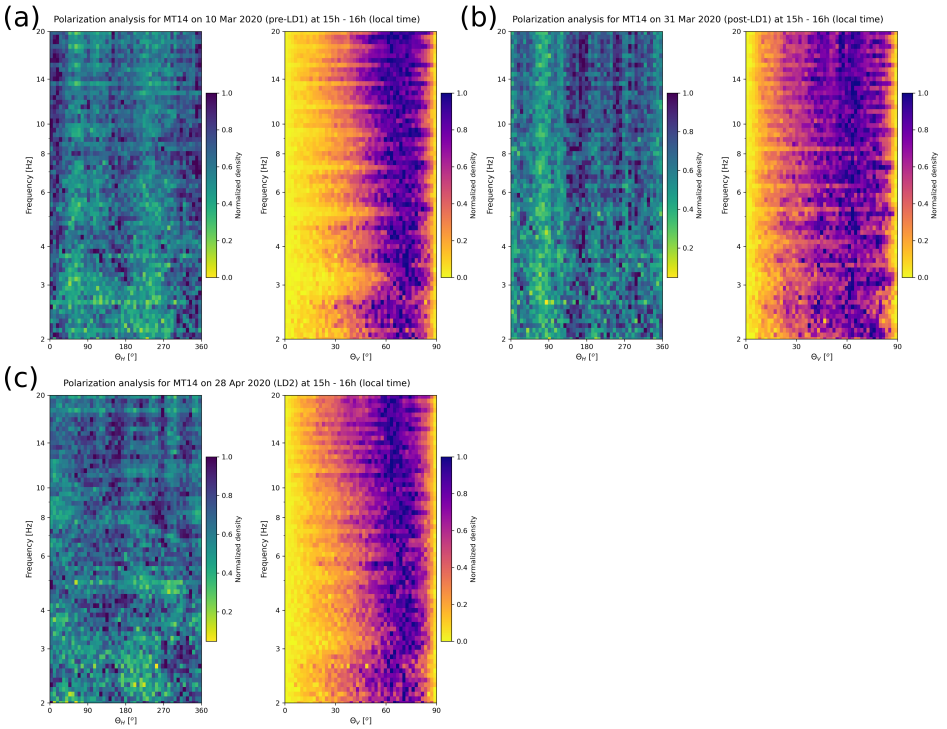
(a)
Polarization analysis for MT14 on 10 Mar 2020 (pre-LD1) at 15h - 16h (local time)
(b)
Polarization analysis for MT14 on 31 Mar 2020 (post-LD1) at 15h - 16h (local time)
(c)
Polarization analysis for MT14 on 28 Apr 2020 (LD2) at 15h - 16h (local time)
Frequency [Hz]
Normalized density
Θw [°]
Θv [°]

Fig. 4.