Urban seismology for the Moon: Seismic characterization of the subsurface and anthropogenic noise at the LUNA analog facility

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Reviewer 1, Round 1

Dear Editor,

The reviewed paper presents different aspects related to the seismic characterization of the site of the LUNA analog facility near Cologne. The authors prove their ability to use different seismic methodologies, from subsurface imaging to dynamic modelling. As far as I can see, the application of the methods and the interpretation of the results is done properly.

My main concern is that the paper seems more a patchwork of different investigations than a project with objectives, methods and results. In a first part, the authors present a seismic characterization based on active and passive studies of the subsurface, performed previously to the construction of the LUNA facility. In the second part, they include a first study on the use of a seismic array to track the movement of a car and a second study in which the deformation produced by the passage of buses is modeled. Beside, the authors show the signals related to arrival, departure and flyover of airplanes. In my opinion, these studies are of interest, but there are no relevant to obtain a long-term seismic characterization of the LUNA facility. In fact, the properties background seismic noise are commented briefly (1.5 pages) and using a broad-band seismometer located in a provisory location, at 300 m from the LUNA facility itself. I think that the background noise characterization of site should be far more extensive, including the effects on lower frequencies, a more detailed study of the seasonal variations around the microseismic peak, the discrimination between the effects of traffic, trains, evaluating the number of vehicles (including airplanes) at the different hours of the day, analyzing the effect of wind and rainfall etc. I also think that it makes more sense to do this study once the seismometer is installed in the facility, as the building can affect the characteristics of the noise.

My recommendation is to focus the paper on the seismic characterization of the subsurface, providing more details on the choice of the different methodologies and their parametrization. I think that will made a valuable paper, with a clearly defined objective. I think that the analysis of the car motion, the deformation produced by bus passages and the aircraft activity can deserve and independent paper focused on the analysis of transient signals. Finally, my recommendation is to reserve the analysis of background seismic noise to further on, when at least one year of data acquired in the LUNA facility itself

I want finally to point that the title “Urban seismology for the Moon” sounds to me more appropriate for a TV headline than for a scientific paper.

In the following, I add a list of detailed comments and minor corrections

Introduction

L34: Make more explicit that “EAC.1ª simulant” is a material that is supposed to mimic the properties on the Moon

Fig 1: It may be useful to include an inset with a more general view of the Cologne region. This will show that the city itself is far and that the anthropogenic noise will be dominated by nearby activity

Data and methods

L96: I suggest to rearrange the order of the Sup. Figures; S1a, S1b and S2 are related to refraction profiles, while S1c and S3 corresponds to MASW

L106: “compare results from MASWaves … and geopsy” is not very informative. Some comments on the parametrization used in each case should be included. It will be useful to explain which are the reasons to choose MASWaves

L 113 Geopsy (Upper case G)

L119: Reorder the sentence to explain first the differences between RayDec and HVSR methods and comment the results obtained in each case (Supp Fig S5)

Fig S5 I understand that H/V is the blue line, with standard deviation in gray and ellipticity is the red line, with the standard deviation colored

L141 It may be useful to wrap up the different methods that will be used; refraction seismic, joint inversion of dispersion, RW ellipticity, SPAC. Note that the data and methods described in Section 2 are mostly referred to the subsurface characterization, with scarce references to ambient noise

As stated before, I recommend to focus the paper in this part, providing a more extensive description of the methods used and the effect of the different possible parametrization in each of them

Results for subsurface

L147: Fig 2e is the cited before the other panels: reorder the panels in figure 2, starting by the P-wave and S-wave models

Fig 2. Panel b), corresponding to signed ellipticity angle from RTBF is not discussed in the text. It this panel is retained, explain the difference between “signed ellipticity angle” and “ellipticity angle” (Fig 2c), as both the angles and the frq ranges shown are very different

L185-205: I suggest to focus on the new results without highlighting the differences with Parolai basement depth estimations. You could just end the paragraph with something like “our basement depth estimations, constrained by multiple methodologies and consistent with boreholes, are 30 to 50 m shallower than previous estimations (Parolai et al)”

Ambient noise

As stated before, give some precision on the processing of the data; Sampling rate, Response removal, intervals used to calculate PPSD, smoothing, software used etc..

L219-227: In the text the description is based on periods, while Fig 3 show frequencies, please unify

The difference between winter and summer is not documented in the figure

L240: The relationship between the high level of noise during working hours in later January and the “continuous source of noise peaking 5-6.5 Hz” is not documented.

Fig. 4: The two firsts week of February have low noise; could this be related to activity in the campus??

The gap related to official time is not evident to me; verify that UTC is really used in the figure

Transient sources

Only two hours out of several months are shown. How representative is this sample; what happens at night, on week-ends etc…

L248-253: It is very hard to identify these narrow bands, separated by 1-2 Hz, in Fig 5, spanning from 0 tp 100 Hz)

Fig 5: Consider the use of a visually continuous colormap (as Viridis). The used colormaps enhance the difference in some bands (-200/-180) and minimize others (-160/-140)

L253:255: You state that cars are the source of transient signals between 10-30 Hz and airplanes of those above 30 Hz; How do you fix these limits and attribute the sources? If it is based only in the literature, please state it clearly

Cars

Clarify if the signal correspond to a random car or to a car displacement carried on by the research team specifically for this study (later on the authors refer explicitly to a Toyota Prius)

The exercise proves that beamforming works and that event location and Rayleigh wave polarization provide consistent information on backazimuth, but do not contribute so such to noise characterization

Note that the reader has to trust on the results of both “hyperbola method” and polarization, as there are not documented neither in the manuscript nor the supplementary material.

Fig 6 k, i: These features will not been described as “road damage” or “obstacles” in most parts of the world!!

There are many studies published on the seismic signals generated by cars and moving vehicles. Please refer to some of them and explain the specific interest of the new results.

As commented before, I don’t see the relationship between the seismic monitoring of a single moving car and long term characterization of the anthropogenic noise at LUNA analog facility.

Bus

L356: Should be Suppl Fig 8

L358: Suppl Fig 8b. I understand that the signal of interest is that labelled “0.063-0.125” This could be clarified in the text. A reference to the filtered traces in Fig 7 could also be included

Also, you could consider to use a spectrogram to show that the bus-related signal is observed at freq above 4 Hz, but also below 0.1 Hz

L360: The similarity with convective vortices should be shown

L365-366 Note that the signals recorded by DAS are strain, not acceleration, and hence more sensitive to quasi-static deformation

L409: Make an explicit reference at the beginning of the discussion to the symbols for Poisson ratio and Shear modulus

L416: Use of freq / period

L419: Differences between signal could also be related to changes in the ocean waves, as 0.02-0.1 Hz includes the PM peak

As far as I understand, the inversion analysis do not provide strong constraints on Poisson ratio / shear modulus and a direct comparison with velocity models is not possible. Should you conclude that the modeling of the bus passage is not really useful, at least for your objectives??

Airplanes

L450-456: I suggest to describe first your observations and proposed explanation (coupling during braking) and compare later to the previous observations in Greenland at the end

The higher amplitudes in take-off could correspond to the sonic waves generates when the planes start their acceleration

L461: Have you considered the orientation of the airtrack used for landing/departure? If landing do occur at larger distances from the seismometer than take-off, this may affect amplitudes

Fig. 8: Again, the use of “jet” colormap is beautiful, but can lead to misinterpretations due to its visually effect

Regarding flyby airplanes and helicopters, the author reproduce previous studies and make some estimation of velocity and closest distance of aircraft, similarly to previous studies.

Response to Reviews of Round 1

See appended PDF at the end of this document

Reviewer 2, Round 1

Dear Editor and Authors,

Thank you for allowing me the opportunity to review this study, which analyzes active and passive seismic data to provide subsurface structural information and to characterize sources of anthropogenic signal. I am pleased to recommend acceptance of this paper to Seismica. I believe that the paper itself is well-written and organized clearly, that the methodology is clear and well-substantiated, and that the analysis of data from a lunar analog testbed facility such as LUNA is particularly relevant.

The following are line-by-line comments and questions that I believe could be clarified within the text.

Lines 209-212: Probabilistic power spectral densities (PPSD) were also calculated for the broad-band station included in the array deployment on the LUNA site, covering only approximately 3 days in time. They show good agreement with the long-term data. The vertical-component PPSD (Fig. 3) show an elevated noise level, partly above the new high noise model…

> Point of clarification: in section 2 (Data and methods), the LUNA array consists of four short-period seismometers, without another instrument being mentioned. This PPSD is also not shown in Figure 3, and it is only the vertical-component PPSD for the broad-band seismometer in the MUSC building. Was the PPSD computed with only the MUSC station recordings, or was it compared to the data from the array deployed at the LUNA site?

Lines 251-253: Other frequency bands are only observed part of the time, e.g., adjacent lines at 24.7 and 24.9 Hz that are only observed until about 12:05 pm.

> Are these daily occurrences? Are they also associated with some kind of machinery? Is there any kind of periodicity that characterizes signals with these frequencies?

Line 272-276: [Meng et a1. (2021)] car-generated signals have an emergent onset, no clear internal structure, and rise in amplitude to a maximum before symmetrically decreasing again, with rise and decay times both on the order of 10 s. In contrast, our recordings of cars contain a number of short bursts of energy, generally with two distinct amplitude maxima per burst, and no gradual increase or decrease in amplitude.

> Could you elaborate on why there is no specific gradual rise/decay in the amplitude of signals associated with cars when we expect that from previous studies?
> Do all car signals have at least 2 distinct maxima? Signals with more than two maxima are associated with a more complex piece of roadwork. Is there ever a point where there is one maximum, and if so, what could be the potential cause of this?

Line 298-299: Finally, assuming the car-generated signals consist of Rayleigh waves — though we observe short impulses rather than clearly dispersed signals…

> Following this logic, can you elaborate on why using Rayleigh wave polarization to determine source direction would work?

Lines 355-356: The bus signal has some similarities to the car signal, in that it contains several sharp amplitude maxima, and energy at high frequencies above 20 Hz (Supplemental Fig. S6b)

> This figure (Fig S6b) appears to be missing in the Supplemental Information package provided. Supplemental Figure S6 shows the comparison of a seismic event recorded at the test installation and another broad-band station. Please include this figure, as it is very important.

Reviewer 1, Round 2

Dear Editor,

The authors have done an excellent job revising the manuscript, which in my opinion clearly improves the originally submitted version. The structure of the paper remains somewhat unusual, with a first part dedicated to subsurface structure characterization and a second part analyzing ambient noise sources, mainly focusing on transient signals of anthropic origin. I still believe that this work could potentially be divided into two separate contributions; however, I have no objection to the authors' decision to keep it as a single manuscript, as they justify this choice adequately in their response letter. Regarding the title modification, I consider the new version more appropriate for publication in *Seismica*.

The minor comments from my previous review have been properly addressed in the authors' response, either by implementing the suggested changes or by explaining in detail the reasons for not adopting the remaining ones.

Therefore, I consider the paper ready for publication.

Reply to Reviewers' Comments on Manuscript "Urban seismology for the Moon: Seismic characterization of the subsurface and anthropogenic noise at the LUNA analog facility" by B. Knapmeyer-Endrun et al.

In response to the submission of our manuscript "Urban seismology for the Moon: Seismic characterization of the subsurface and anthropogenic noise at the LUNA analog facility" to Seismica, we received detailed comments by two anonymous reviewers that helped us to improve the manuscript.

In our revision, we considered all of the comments and changed the manuscript accordingly, e.g. adjusting the title, adding new elements to Figs. 1 and 3 and two new figures to the Supplemental Information, rearranging and rewriting parts of the text, and clarifying the points raised by the reviewers. We provide detailed answers to the comments below. When providing line numbers, we refer to the track-changes version of the manuscript unless noted otherwise.

Reviewer#1:

Dear Editor, The reviewed paper presents different aspects related to the seismic characterization of the site of the LUNA analog facility near Cologne. The authors prove their ability to use different seismic methodologies, from subsurface imaging to dynamic modelling. As far as I can see, the application of the methods and the interpretation of the results is done properly.

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We thank the reviewer for his assessment. We agree that our manuscript might not fit the form of a "classical" paper with Introduction - Data - Method - Results - Discussion - Conclusion sections, which is also why we did not follow this structure in naming the sections (and we did not see that we are required to do so by Seismica). We rearranged and renamed some sections in the revised version to make their contents more transparent, specifically which parts are related to site characterization and which parts are related to the background noise or to anthropogenic transient signals.

Our main driver in submitting this paper is that all information contained therein is required by user teams in LUNA. We had two seismology-based campaigns in November 2024, and two more that lasted a total of three weeks have just concluded last month. The 2025 campaigns included seismologists from 8 different institutions in 6 different countries, and everyone was asking about information on the noise level, the structure below LUNA, and typical noise sources in LUNA. In addition to seismologists, we also have other campaign teams requesting data from the permanent seismometer in LUNA, and for these non-specialist it is even more important to understand the multitude of signals contained in the data that are not directly related to their campaign activities.

Our goal is to provide the information on site characterization, noise spectra and the characteristics and possible use of typical anthropogenic sources in a openly available, citeable reference that will still be accessible in 20 years time, even if LUNA is no longer operational by then (though this is not what we hope for). It is also important for the publication plans of the campaign teams themselves to have some reference for the seismological background of LUNA that they can point to, since the typical length or structure of a campaign might not allow for e.g. the thorough investigation of the background noise level or the structure below the hall, and it is sensible that not every study using e.g. the repeating car signals has to explain again why these are signals generated by cars and where they are excited.

We tried to go beyond merely showing the signals and considering this a data-based report as it is not a particular data set that we want to introduce, and we wanted to show some potential applications of the data we collected, also beyond immediate relevance for LUNA. We do think that it would not aid our goal of providing a reference for LUNA users to split the results shown here over multiple papers, likely in different journals, with no guarantee as to whether and when they would be published. While, based on the data it includes, this manuscript can only provide an initial reference for the seismic environment of LUNA, we strive to make it as comprehensive a reference as possible.

We agree that ideally, a background noise analysis should cover multiple years of data. However, at the submission of this manuscript, the permanent seismometer in LUNA had just been installed for 3 months, and even after the 6 months the manuscript spent in review, we still do not yet have one complete year of data available, while users require information e.g. on the diurnal variation of noise already now (and before now - see above) to plan their campaigns. The nearest permanent station that would fulfill the requirement of multiple years of data is Bensberg Observatory (BQ.BNS, as used in the Supplemental Information), which is located about 13 km away from LUNA, in a different town and on a different geology, both of which strongly diminishes its use as a reference. We believe that the analysis of the initial deployment of our sensor in a building 300 m away from LUNA is, on the other hand, relevant, because it will show similar characteristics in terms of anthropogenic noise on campus (e.g., the same road connects both buildings) and similar site effects, while also being comparable at longer, i.e. microseismic, periods. While it might not be the ideal data set for characterizing the background noise in LUNA, it is the best we can provide at this point in time.

In addition, the noise environment in LUNA is by no means static. New elements have already been added this year, e.g. the FlexHab habitat outside LUNA that required some preparatory ground work (including digging trenches for piping), and a demonstrator for the gravity off-loading system, more are expected in the coming year (ramp with compressor, gravity off-loading system for the complete hall, LUNA EDEN container with additional groundwork and utility connections), and LUNA is also expected to grow beyond this initial outfitting phase. All of these elements will generate their own share of seismic noise which needs to be characterized in the future, but is not relevant for campaigns taking place now as the elements are not here yet. However, current campaigns require an initial assessment of what to expect in their planning now.

We agree with the reviewer that meteorological phenomena have an impact on the noise level in LUNA; in fact, we have already observed a strong correlation between the long-period (10 s and more) noise on the horizontal components and wind speed as measured at CGN airport. However, the wind data from the airport are only available at hourly intervals, and with that resolution, it is difficult to go beyond just identifying a correlation. We have been in conversation with GFZ Potsdam for about a year now to install a weather station on LUNA that would provide e.g. wind data at a much higher resolution, but these data are not available yet, so a detailed study of this effect can indeed only be done in the future. This is also a reason why the paper mainly focuses on anthropogenic noise (as outlined in the title) on the DLR campus.

To clarify the goals of our paper better and to also make the limits of the present study more transparent, we

- Rewrote the Abstract
- Reordered large parts of the manuscript, specifically the "Data and Methods" section
- Added more text on the relevance and limits of the long-term data set (ll. 119-125, ll. 257-261)
- Added more PPSD data to Fig. 3 and introduced new Supplemental Figure S6
- Reordered and partly rewrote the Summary and conclusions

I want finally to point that the title "Urban seismology for the Moon" sounds to me more appropriate for a TV headline than for a scientific paper.

We removed part of the title to make it more suitable for a scientific paper.

In the following, I add a list of detailed comments and minor corrections

Introduction

L34: Make more explicit that "EAC.1ª simulant" is a material that is supposed to mimic the properties on the Moon

We changed the sentence to say:

"the 700 m² regolith yard filled with lunar mare regolith simulant EAC-1A" (l. 52)

Fig 1: It may be useful to include an inset with a more general view of the Cologne region. This will show that the city itself is far and that the anthropogenic noise will be dominated by nearby activity

We thank the reviewer for his comment and adjusted the figure to include a regional overview, as suggested.

Data and methods L96: I suggest to rearrange the order of the Sup. Figures; S1a, S1b and S2 are related to refraction profiles, while S1c and S3 corresponds to MASW

Figures S1a, b and c all show raw data acquired along the same profile with the same geophone layout, doing hammer shots at different locations, displayed in the same way. This is why they are combined in one figure. Figures S2 and S3 both show results of further processing of part of that data, using different methods, and are thus individual figures. We prefer not to change this order.

L106: "compare results from MASWaves ... and geopsy" is not very informative. Some comments on the parametrization used in each case should be included. It will be useful to explain which are the reasons to choose MASWaves

We added the requested information on the parameterization to the Supplemental Information. The only parameters to adjust in MASWaves are the frequency and phase velocity range and the sampling of both. Below, we show the results of Geopsy, using the same parameterization (frequency range of 2 to 60 Hz with a linear sampling at a step size of 1 Hz, and phase velocity range of 100 to 600 m/s, also with a linear sampling at a step size of 1 m/s), for the same axis settings as in Supplemental Figure S3. Results also stay the same if the standard (logarithmic) sampling is used in Geopsy. As visible in the figure, the Geopsy results overlap with those of MASWaves within their respective uncertainties, but seem to have a poorer resolution at low frequencies below about 12 Hz, where the results from MASWaves show a trend to increasing velocities that are consistent with the array results. As the investigation of the details and differences between different software implementations of MASW is not the purpose of our study, we removed the reference to Geopsy from the text to avoid confusing the reader.

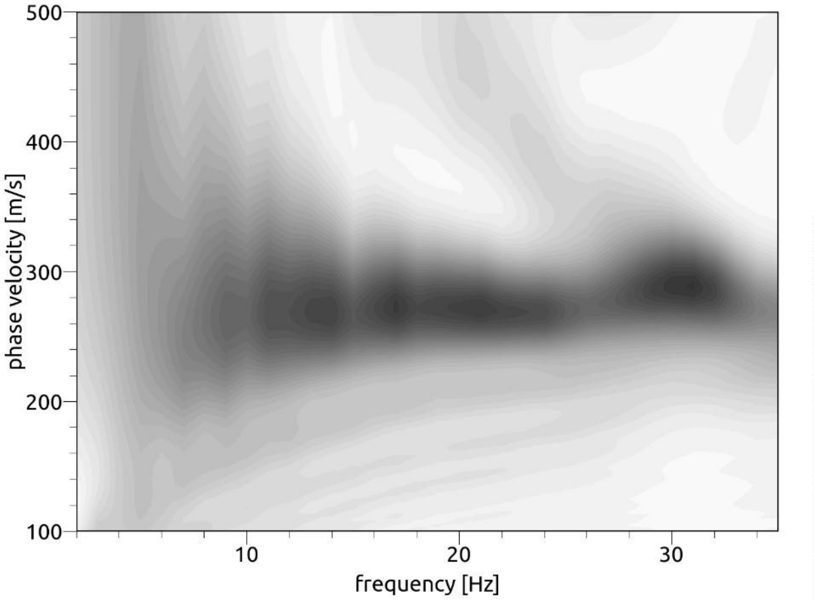

Figure 1: Results produced by applying MASW as implemented in Geopsy to the same dataset with the same parameterization as used for the MASWaves result shown in Supplemental Figure S3.

L 113 Geopsy (Upper case G)

We thank the reviewer for pointing this out, and changed all references to Geopsy to upper case G, in keeping with the use by Wathelet et al. (2020).

L119: Reorder the sentence to explain first the differences between RayDec and HVSR methods and comment the results obtained in each case (Supp Fig S5)

We rewrote the mentioned part of the text to read (ll. 159-164):

"HVSR (Nakamura, 1989; Bonnefoy-Claudet et al., 2006) were derived as well, but since their inversion in terms of Rayleigh wave ellipticity might be biased by the contribution of other wave types to the ambient wavefield (e.g. Bonnefoy-Claudet et al., 2008), we also applied RayDec (Supplemental Fig. S5a). RayDec aims to focus the analysis on time windows dominated by Rayleigh waves, thus providing a less biased estimate of Rayleigh wave ellipticity (Hobiger et al., 2009). Hence, the RayDec curve was used as inversion target."

Fig S5 I understand that H/V is the blue line, with standard deviation in gray and ellipticity is the red line, with the standard deviation colored

Actually, there is no blue line in Fig. S5. The H/V line the reviewer refers to has RGB values of 0.5/0.5/0.5, i.e. is 50% gray, aligning with the figure caption that HVSR results are shown in gray and ellipticity in color. It also shows up as gray both on screen and in print for us, which we also confirmed with a tool for simulation of color impairments. We cannot reproduce that the curve comes across as blue on the reviewer's device.

L141 It may be useful to wrap up the different methods that will be used; refraction seismic, joint inversion of dispersion, RW ellipticity, SPAC. Note that the data and methods described in Section 2 are mostly referred to the subsurface characterization, with scarce references to ambient noise

We summed up the methods in l. 123 of the original text as:

"The dispersion curve was inverted jointly with Rayleigh wave ellipticity information and SPAC using the Neighborhood Algorithm", and explaining before that the dispersion curves from MASW and array analysis were combined, as well as referring to ellipticity information from both RTBF and RayDec. We do not see the need to repeat this information, also in light of the length constraints imposed on the manuscript by Seismica.

We rearranged the sections to have separate data and method sections for subsurface characterization and ambient noise, and enlarged the ambient noise section to provide more information.

As stated before, I recommend to focus the paper in this part, providing a more extensive description of the methods used and the effect of the different possible parametrization in each of them

It was not our intention to write a methodological paper that compares the influence of different parameterizations on ambient noise analysis. We also believe that data from just one location, covered by only one array measurement, is too limited to provide meaningful results here, as compared to multinational experiments specifically designed to address these questions, as for example SESAME (Bard, 2002), NERIES (Bard et al., 2010) or InterPACIFIC (Garofalo et al., 2016). As stated previously, the aim of this manuscript is foremost to provide future users of LUNA with all the information they require to understand possible signals they might observe either due to the noise environment of the site or due to the subsurface structure, and to provide some indications of how these signals might be used for analysis, in LUNA and on the Moon. To broaden the scope, we also discuss our results with regard to site effects in the Lower Rhine Embayment, and provide some examples of traffic-related signals that have different characteristics from what was covered in the literature. Since Seismica also publishes Data Reports, we did not think that this focus would disqualify our manuscript from publication. We do not consider our submission a Data Report, though, since we include more analyses than typical for that kind of submission and we also do not want to promote a specific data set, other than the use of the future permanent seismic station in LUNA.

Results for subsurface

L147: Fig 2e is the cited before the other panels: reorder the panels in figure 2, starting by the P-wave and S-wave models

We followed the reviewer's suggestion and rearranged the panels of Fig. 2.

Fig 2. Panel b), corresponding to signed ellipticity angle from RTBF is not discussed in the text. It this panel is retained, explain the difference between "signed ellipticity angle" and "ellipticity angle" (Fig 2c), as both the angles and the frq ranges shown are very different

We stated that the signed ellipticity angle was derived from RTBF and used over the same frequency range as the Rayleigh wave dispersion curve derived from the array in the analysis in the original submission (ll. 155-156), which explains the different frequency ranges covered. We also described how we selected which part of the RayDec-derived curve to include in the analysis in ll. 192-199. The signed ellipticity angle is discussed in detail in Maran`o et al. (2017) and Wathelet et al. (2018), and a comparison between different methods to estimate Rayleigh wave ellipticity from ambient vibrations was provided by Hobiger et al. (2012). We included those references and added some more information to both the main text and the Supplemental Information to clarify the difference between the two estimates.

"As discussed in Wathelet et al. (2018), using the directional information contained in array recordings allows to distinguish between retrograde and prograde Rayleigh waves, producing an estimate of the signed ellipticity angle in addition to the Rayleigh wave dispersion curve from RTBF, whereas single-station methods can only provide an estimate of the absolute ellipticity value (Hobiger et al., 2012). Since the signed ellipticity angle is derived from beam forming, it is subject to the same constraints on resolution given by the array layout as the corresponding dispersion curve. Hence, we included the signed ellipticity angle from RTBF over the same frequency band as the Rayleigh wave dispersion curve in the inversion." (ll. 150-156)

" In addition, we include the signed ellipticity angle199 from RTBF that covers higher frequencies (Fig. 2d). The negative values of the signed ellipticity angle between 5.5 and 16 Hz indicate retrograde particle motion, which is expected for the fundamental mode Rayleigh wave at frequencies above the H/V trough frequency (Maran`o et al., 2017)." (ll. 199-202)

"In addition to a Rayleigh wave dispersion curve estimate, RTBF also provides an array-derived estimate of the Rayleigh wave ellipticity, including the sense of rotation of the Rayleigh wave particle motion (Hobiger et al., 2012; Wathelet et al., 2018), over the same frequency band as the dispersion curve. This is expressed in terms of the signed ellipticity angle (Maran`o et al., 2017), while single-station measurements only provide estimates of the absolute value. Negative angles point to retrograde particle motion, whereas positive angles indicate prograde particle motion. The peak and trough correspond to angles of 90^o and 0^o, respectively, and the relation between the ellipticity angle ϵ and the HVSR is given by

$$HVSR = |\tan\epsilon|$$

(p. 4 of Supplemental Information)

L185-205: I suggest to focus on the new results without highlighting the differences with Parolai basement depth estimations. You could just end the paragraph with something like "our basement depth estimations, constrained by multiple methodologies and consistent with boreholes, are 30 to 50 m shallower than previous estimations (Parolai et al)"

We do not agree with the reviewer for the following reasons:

- Replacing the whole paragraph with something like the suggested sentence would diminish the conclusions with regard to subsurface structure, which the reviewer suggested to focus on. In that paragraph, we compare two different relations between HVSR peak frequency and bedrock depth derived for the region with our data, not just Parolai et al. (2002), and report which provides a better match. We also discuss why the relation by Parolai et al. (2002) may overestimate bedrock depth, in that it is based on higher sediment velocities than we derive in our inversion, which is of potential interest to others working in the region. It was already pointed out by Hinzen et al. (2004) that sands, with their higher velocities, are more appropriate for conditions in the western part of the Lower Rhine Embayment (Ibs-von Seht and Wohlenberg, 1999), while silt and clay occur more frequently in its eastern part, where our measurement site is located. Finally, the last part of the paragraph (ll. 249-153) the reviewer suggests to omit deals with a different topic, i.e. a comparison to an equation to estimate bedrock velocity, which we believe is relevant on its own.
- It would also simplify things too much. We are talking about three different locations for which different information is available in this paragraph. The first one is the location of LUNA, for which we have a subsurface velocity model based on the inversion of MASW and array data (Rayleigh wave dispersion, SPAC and signed ellipticity angle) together with single-station ellipticity. The second location is the MUSC building at about 300 m distance from LUNA, a location the similarity of which for LUNA the reviewer questioned previously. For this location, we only have single-station ellipticity values, but also ground truth on the bedrock depth from a borehole. Since the ellipticity peak frequencies are different between the two locations (Supplemental Fig. S5), we hesitate to use the borehole data as ground truth information for the LUNA location. The third location is the one where Parolai et al. (2004) conducted their measurements, which is about 1 km away from LUNA. For this location, we have the reported peak frequencies as well as the derived bedrock depth from the above paper. This bedrock depth is 60 to 75 m larger than our results for LUNA and 30 to 70 m larger than the borehole data, implying a strong gradient. As described in the paragraph, we apply two different relations between ellipticity peak frequency and bedrock depth to the measured and reported peak frequencies, and find for locations 1 and 2 that the relation by Finger et al. (2025) provides a better match to both our velocity model at location 1 and the borehole data near location 2 than the relation by Parolai et al. (2002). We then apply the relation of Finger et al. (2025) to the reported peak frequencies for location 3 to provide an error estimate for the depths reported by Parolai et al. (2004), which amounts to 30 to 50 m. This argument is

not accurately reproduced by the sentence the reviewer suggests, and if we are asked to focus on the seismic characterization of the subsurface, we believe contextualizing our results properly is part of this.

Ambient noise

As stated before, give some precision on the processing of the data; Sampling rate, Response removal, intervals used to calculate PPSD, smoothing, software used etc..

Part of this information, i.e. the sampling rate, was already given in the Supplemental Information, and we already stated that we used obspy Version 1.4.0 to calculate and plot the PPSD in the "Data and code availability" section. The time interval covered is described in the text (l. 135f of the original submission). In response to the reviewer's request, we added the exact dates (which are partly also evident from Fig. 4) and some more details to the Supplemental Information:

"For the PPSD shown in Fig. 3a), we combined data from June, 21st 2023 to August, 10th 2023 and from December, 21st 2023 to April, 22nd 2024, whereas in Supplemental Figure S6, we show both time windows individually to better highlight differences between summer (Supplemental Fig. S6a) and winter time (Supplemental Fig. S6b). PPSDs were calculated with obspy (The ObsPy Development Team, 2022), using the default settings of one hour window length with 50% overlap for the calculation of spectra, and frequency binning at 1/8 of an octave while smoothing by averaging PSDs over a full octave around every central frequency.".

Note that response removal is automatically included in the PPSD calculation in obspy and not an extra step performed, and the stationXML-file that contains the response information is included in the Zenodo data package we provided (Knapmeyer-Endrun et al., 2025).

L219-227: In the text the description is based on periods, while Fig 3 show frequencies, please unify

We adjusted the text to uniformly refer to frequencies now, in keeping with the plot axes in Fig. 3 and Supplemental Fig. S6.

The difference between winter and summer is not documented in the figure

While we had hoped that the two maxima in the PPSD curves around 0.15 Hz were apparent, we now added Supplemental Figure S6 which shows the summer and winter time windows individually to substantiate our statement (see also above).

L240: The relationship between the high level of noise during working hours in later January and the "continuous source of noise peaking 5-6.5 Hz" is not documented.

To arrive it this statement, we looked at hourly spectrograms for the concerned months of data. It is impractical to add those figures to the paper as they would easily consume more memory than the actual data themselves. Instead, we added Supplemental Figure S7, which shows spectrograms over two weeks of data including the signal in question, from January 15th to January 29th, 2024. It is apparent that on each workday - except Monday, January 22nd, which also does not show an increased afternoon noise level in Fig. 4 - a strong signal in the described frequency range appears in the late afternoon.

Fig. 4: The two firsts week of February have low noise; could this be related to activity in the campus??
There is no obvious reason for lower activity on campus during the first two weeks of February (like bank holidays), other than Carnival Monday on February, 12th, which might also correlate with lower attendance on site on the previous Thursday and Friday and the following Tuesday. We are also not convinced that the noise level in these two weeks is a particularly noteworthy anomaly, as similar noise levels are observed during the first week of April and, with the exception of single days, in the first two weeks of March.

The gap related to official time is not evident to me; verify that UTC is really used in the figure
As stated in the figure caption, *"Time is in local time"*, i.e. UTC is not used in the figure. It is a feature of the SeismoRMS code (Lecocq et al., 2020b) that UTC is converted to local time for this type of plots since, when comparing the daily variation in anthropogenic noise level at stations all over the globe as done in Lecocq et al. (2020a), it makes little sense to use UTC. Accordingly, while our data are recorded with UTC time stamps, the timing is converted to CET, respective CEST, by the software when generating this type of plot. The change from CET to CEST in the night of March, 31st, 2024 means the clock is set to 3:00 am at 2:00 am, and the difference to UTC increases from 1 hour to 2 hours, so that one hour is missing in local time, as apparent in the plot, while UTC is of course continuous.

Transient sources

Only two hours out of several months are shown. How representative is this sample; what happens at night, on week-ends etc...
There seems to be a misunderstanding here since, in this figure, we show data from the array measurement at the actual location of LUNA, as stated in the caption, which just covered 3 days of data, not several months, and only one complete working day, for which this figure shows exemplary data. When putting together the manuscript, we tried to use as much data from the actual location of LUNA as possible since data from other locations on campus might be less representative. This refers to the measurements for subsurface structure, the analysis of car signals, and the analysis of airborne traffic. We only used data from the MUSC building for the long-term study of the noise level and its variability, since we did not (and do not yet) have adequately long-term data for LUNA, and for the analysis of the quasi-static deformation due to the bus since we did not measure similar signals during the measurements at the LUNA location.
It is the purpose of Fig. 4 to answer the questions regarding the difference between day time and night

time and weekends vs. work days. We show Fig. 5 in addition to introduce some of the transient noise sources analysed in more detail later. While the noise by cars is reduced during the night time (Supplemental Information S3), some machinery continues 24/7, and air traffic is also continues as the airport is an important transport hub (see ll. 548-554). We tried to clarify this by updating the main text, and adding some information to Supplemental Information S3:

"Fig. 5 provides a closer look at individual high-frequency noise sources from our array measurement at the future location of LUNA. Data shown are typical for a work-day with elevated anthropogenic noise." (ll. 329-330)

"During the weekend and during the nighttime, as expected, car traffic is low and mainly related to the on-site security service." (end of Supplemental Information S3)

L248-253: It is very hard to identify these narrow bands, separated by 1-2 Hz, in Fig 5, spanning from 0 tp 100 Hz)

Since there are many spectral lines at different frequencies in the data, we updated the list of frequencies to focus on those that are indeed continuously visible across the whole time window and well separated, to make identification easier for the reader.

Fig 5: Consider the use of a visually continuous colormap (as Viridis). The used colormaps enhance the difference in some bands (-200/-180) and minimize others (-160/-140)

We thank the reviewer for his comment and changed the colormap to Batlow, a perceptually uniform colormap (Crameri, 2018; Crameri et al., 2020).

L253:255: You state that cars are the source of transient signals between 10-30 Hz and airplanes of those above 30 Hz; How do you fix these limits and attribute the sources? If it is based only in the literature, please state it clearly

No, this is based on our own analysis of the data, including work with the known car signal and the identification of similar signals in the data (Supplemental Figure S9), as well as an undergraduate student project looking into the correlation of signals with the airplane schedule of CGN. The corresponding student, Olav Cornelius, is one of our co-authors. We changed the wording to

"Based on waveform analysis compared to a known car signal (Supplemental Figs S10, S11) and correlation with the CGN air traffic schedule, signals with dominant energy between 10 and 30 Hz can be related to passing cars, whereas transient events that have their main energy at higher frequencies, i.e. above 30 Hz, can be related to airborne traffic." (ll.337-341)

Cars

Clarify if the signal correspond to a random car or to a car displacement carried on by the research team specifically for this study (later on the authors refer explicitly to a Toyota Prius)

We thank the reviewer for pointing this out and changed the wording in the text to better outline the experiment we conducted:

"This hypothesis is validated by a test using the array data to track a known car (Toyota Prius) along a predefined route first driving out of the parking lot and from east to west along the road, then turning at around 368.25 E and driving back, entering a loop at the eastern end of the road near 368.53 E to turn again (Fig. 6), with a velocity approximately at the speed limit on campus of 30 km/h." (ll. 371-374)

The exercise proves that beamforming works and that event location and Rayleigh wave polarization provide consistent information on backazimuth, but do not contribute so such to noise characterization

We actually also want to characterize and outline typical transient noise sources that users might find in their own data, so that they can judge that what they see is not generated by activity within the hall, but actually by a car passing by outside, even though it looks different from some examples in the literature (e.g Meng et al., 2021; Chai et al., 2025; Hashima et al., 2025). This is especially important since there is also interest from non-seismologists in the data recorded by our station during their campaigns. Furthermore, since we can pinpoint the exact locations where the signals from the cars are generated, even with a single sensor, those also provide known sources, at least of Rayleigh waves, that could potentially be used for analysis in future experiments in LUNA. We think it is important to make users aware of this possibility.

Note that the reader has to trust on the results of both "hyperbola method" and polarization, as there are not documented neither in the manuscript nor the supplementary material.

This is neither a question nor a suggestion. The hyperbola method is a standard method covered in beginner's text books on seismology, and we also provide a reference for its original description now (Mohoroviˇci´c, 1915-1918). The polarization analysis is described in detail in the text, i.e. which angular sampling was used, and otherwise uses only standard processing steps (Hilbert transform and cross-correlation) that are a given functionality in most scientific software, and was implemented in about 10 lines of code. The results of both methods are indicated in Fig. 6 as solid blue lines and dashed cyan line, respectively.

Fig 6 k, i: These features will not been described as "road damage" or "obstacles" in most parts of the world!!

We used these phrases for lack of a better word, and provided the images in Fig. 6 k) and l) as illustration of what we refer to. We adjusted the description in the text by mainly using *"irregularity"* now.

There are many studies published on the seismic signals generated by cars and moving vehicles. Please refer to some of them and explain the specific interest of the new results.

We agree that there are many studies on seismic signals generated by cars, some of them being submitted, reviewed and accepted while our manuscript was under review (e.g. Chai et al., 2025; Liu et al., 2025). However, we noticed that most of these studies deal with noise generated by cars as a seismic source for imaging, without showing individual car signals (e.g. Nakata et al., 2011; Dou et al., 2017; Zhang et al., 2020; Song et al., 2022; Czarny et al., 2023; Lai et al., 2024; Mi et al., 2025), and in this way are not relevant to our study. Other studies use machine learning to identify car signals for use in traffic monitoring, and heavily focus on the AI aspects, which are also not relevant to our study (e.g. Ahmad and Tsuji, 2021; Chai et al., 2025; Liu et al., 2025). Studies using DAS or dense station arrays along roads often identify traffic signals by their moveout along stations, which is also not relevant to our study (e.g. Riahi and Gerstoft, 2015; Díaz et al., 2022; Sheng, 2023; Min et al., 2024).

We added references to some studies that depict individual car signals, as well as to studies that use the propagation of signals along a roadside array to identify cars. However, from the vague suggestion of the reviewer, it is unclear how many studies we are expected to cite and which studies he deems particularly relevant for our research, so we cannot judge whether this fulfils his request.

"Comparable signals, but with a shorter duration, are for example shown by Chai et al. (2025) and Hashima et al. (2025) for the passage of individual cars measured by stations directly next to the road, and used for traffic monitoring." (ll. 360-362)

"Since the road in our case is a tarmac road which, over the length shown in Fig. 1, contains a number of irregularities like manholes, cracks, and bumps, and the recorded pattern is distinct, depending on whether a car is driving eastward or westward (Fig. 6a), we hypothesize that the signals we observe are generated at specific points on the road that present some irregularity (Czarny et al., 2023; Liu et al., 2025), rather than continuously all along the road, and that the two maxima are caused by the motion of the two axles of the car over the corresponding irregularity." (ll. 364-369)

"This also demonstrates the feasibility of tracking a car along the road with a single station, as opposed to an array of sensors (e.g. Riahi and Gerstoft, 2015; Díaz et al., 2022; Sheng, 2023) or roadside DAS (e.g. Wang et al., 2020, 2022), based on Rayleigh wave polarization." (ll. 404-407)

As commented before, I don't see the relationship between the seismic monitoring of a single moving car and long term characterization of the anthropogenic noise at LUNA analog facility.

As replied before, our objective is not only the long-term characterization of the noise level or its variability with time of day or season, but to also present common anthropogenic signals that typically occur in the background wavefield. This serves the purpose to allow LUNA users to reliably identify these signals, even if they look different from what is shown in literature, to understand that they are not generated by activity within LUNA or glitches of their equipment, and to potentially, in the case of cars, use the Rayleigh waves as repeated sources, e.g. along a geophone line or DAS layout perpendicular to the road, as the locations where the waves are generated has also been determined in our study.

Bus

L356: Should be Suppl Fig 8

Adjusted - due a couple of new figures in the Supplemental Information added in response to the comments by the reviewer, the numbering had to be updated throughout the text.

L358: Suppl Fig 8b. I understand that the signal of interest is that labelled "0.063-0.125" This could be clarified in the text. A reference to the filtered traces in Fig 7 could also be included

Also, you could consider to use a spectrogram to show that the bus-related signal is observed at freq above 4 Hz, but also below 0.1 Hz

We adjusted the reference to the correct figure. Following the suggestion by the reviewer, we also explicitly state which frequency range we refer to, and we added a reference to Fig. 7:

"Besides, the passing bus generates an additional signal that is related to ground tilt and most clearly apparent in the 0.063 - 0.125 Hz octave band (Supplemental Fig. S10b, Fig. 7d-f)." (ll. 450-452)

To illustrate the frequency content of the signals, we decided to use the filtering in consecutive bands instead of a spectrogram here, as has also been applied for both martian (Clinton et al., 2021) and lunar (Zhai et al., 2024) seismic data. We agree that a spectrogram could also provide this information, but refrain from adding another figure to the already figure-heavy Supplemental Information. (The main text already contained the maximum number of figures and tables already upon original submission.)

L360: The similarity with convective vortices should be shown

The similarity to the signal generated by the passage of a convective vortice is demonstrated by figures in peer-reviewed publications depicting those signals both on Earth (Lorenz et al., 2015, , Fig. 3, 6) and, quite extensively, on Mars (Banerdt et al., 2020; Garcia et al., 2020; Lognonn´e et al., 2020; Charalambous et al., 2021; Murdoch et al., 2021). Our purpose in citing some of these references was to not having to reproduce figures contained in these papers ourselves. We now added some more of these references to the text as well as a few more words on the comparison between signals generated by convective vortices and the bus both in amplitude and frequency content.

"The low-frequency tilt signal of terrestrial convective vortices has been obtained in the 0.01-0.1 Hz frequency band, with amplitudes as much as 10 times higher than those of the bus signals we observe (Lorenz et al., 2015, Figs 3, 6), whereas observations from Mars were done between 0.05 and 0.3 Hz and show comparable or lower amplitudes than those observed here (Lognonn´e et al., 2020; Garcia et al., 2020; Charalambous et al., 2021; Murdoch et al., 2021)." (ll. 454-458)

L365-366 Note that the signals recorded by DAS are strain, not acceleration, and hence more sensitive to quasi-static deformation

We thank the reviewer for this comment and incorporated it in the text, as it also fits with our observation that we could not easily identify any quasi-static deformation related to passenger cars in our data: *"Besides, DAS records strain rate rather than velocity, which makes it more sensitive to quasi-static deformation than a seismometer."* (ll. 486-487)

L409: Make an explicit reference at the beginning of the discussion to the symbols for Poisson ratio and Shear modulus

The symbols for Poisson ratio and shear modules are already introduced in l. 480 when starting to derive the relevant equations. We think it is not common to explain the meaning of symbols multiple times in the same section. One reason why we chose to cover both the theory and equations and the results of the analysis together and not include all theory in a "Data and method" section up front is that we wanted the readers to find everything in one place, without having to switch back and forth in the text. This also includes the meaning of symbols.

L416: Use of freq / period

We changed the information on the resampling to sps since it is uncommon to provide the sampling rate as a period.

L419: Differences between signal could also be related to changes in the ocean waves, as 0.02-0.1 Hz includes the PM peak

We agree that changes in the microseismic noise could influence the signal amplitudes in the considered frequency band. As described in the text, the analysed signals occurred within less than 8 hours on June, 23rd 2023. As shown in Supplemental Figure S6, the level of primary microseismic noise is in general lower during summer than during winter, but also quite variable, so that we cannot exclude an influence of ocean waves based on this figure alone. Above, we show a helicorder plot of the vertical component velocity seismograms for the whole day, filtered between 0.02 and 0.1 Hz. It is apparent that the noise level is higher between about 00:20 am and 02:30 am UTC, and that there are a number of teleseismic events occurring later that day. However, during the specific bus signals analysed (as indicated by red boxes, compare time stamps in Fig. 7d), background amplitudes around the signal are small and on a similar level. In fact, one of the criteria for the selection of this specific signals for the inversion was a clear signal with a high SNR. Accordingly, the influence of variable microseismic background energy is considered to be of only secondary importance. We added a sentence to the text to clarify the selection criteria of the signals for the inversion:

"In addition, we chose clear signals with no discernible overlap with signals due to passing cars or an increases noise level in the primary microseismic band." (ll. 515-516)

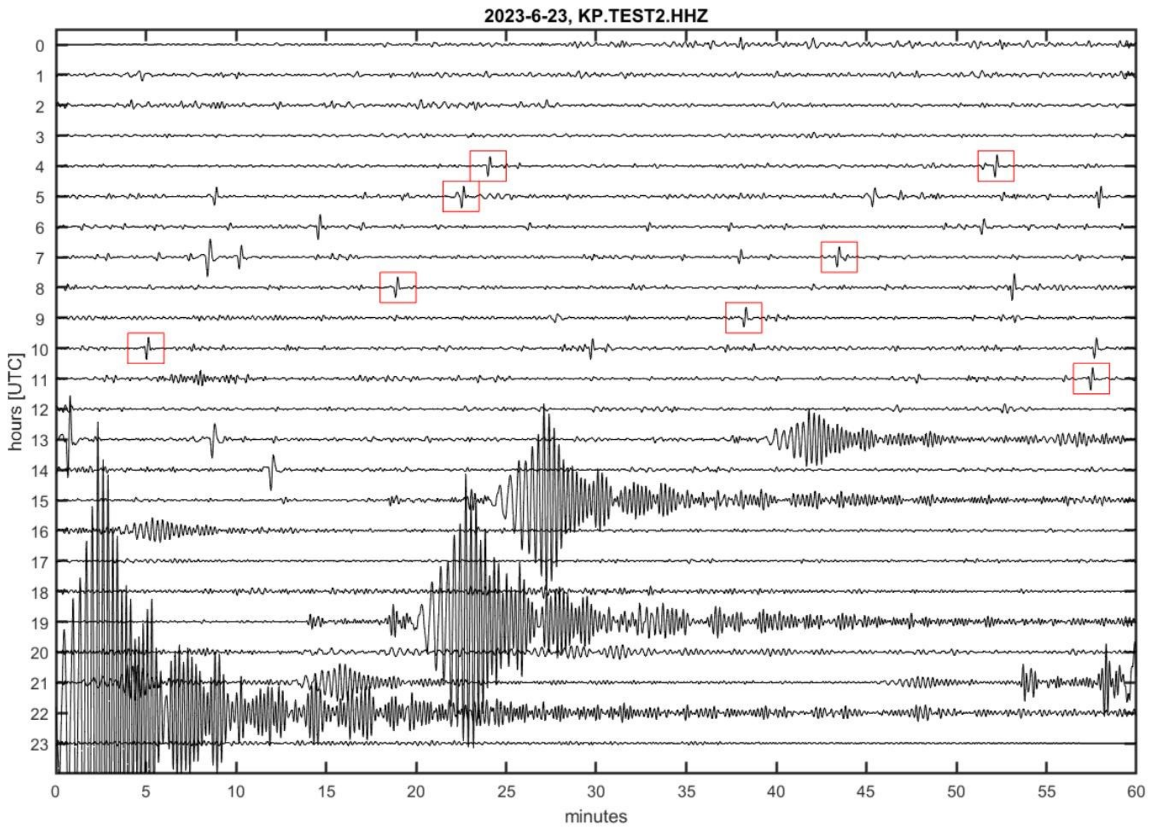

Figure 2: Vertical component velocity data, filtered between 0.02 and 0.1 Hz, to show the noise level around the analysed bus signals. Those signals are marked in red here.

As far as I understand, the inversion analysis do not provide strong constraints on Poisson ratio / shear modulus and a direct comparison with velocity models is not possible. Should you conclude that the modeling of the bus passage is not really useful, at least for your objectives??

We included a more detailed discussion in the text, including other approaches taken in the literature to avoid the observed trade-off:

"This might be avoided by tighter constraints on the actual velocity of the bus. Additional options include inverting for a combination of both elastic parameters (Murdoch et al., 2021), trying to separate them by just concentrating on the shape of the curve and ignoring the amplitude information (Yuan et al., 2020), or assuming a fixed value for one of them (Jousset et al., 2018)." (ll. 534-537)

We also provide additional perspectives for the characterization of elastic parameters by modelling of quasi-static deformation, for which the bus signal was just an example as it was contained in our data from the long-term test in the MUSC building. Note that the bus does not pass by LUNA, so this is not an experiment that can be repeated with the permanent seismometer there. Rather, the focus is on the possibility of extracting elastic parameters for the regolith simulant during rover tests in LUNA, and also for the actual lunar regolith in situ once for example the Lunar Terrain Vehicle is available there.

"The difficulties due to the measurement setup could be avoided in future attempts at regolith charac-

terization based on quasi-static deformation caused by passing rovers in LUNA, and on the Moon itself." (ll. 542-544)

Airplanes

L450-456: I suggest to describe first your observations and proposed explanation (coupling during braking) and compare later to the previous observations in Greenland at the end

Following the suggestion by the reviewer, we adjusted the text to read:

"While the take-off signal could include sonic waves generated by the engines during acceleration, the landing signal could be explained by the initial touch-down, followed by friction between tarmac and tires coupling the airplane motion into the ground during breaking. This would also explain the significantly longer signal duration compared to that recorded by DAS for an aircraft landing on the Northeast Greenland Ice Stream at a similar distance (Fichtner et al., 2023), where the interaction between ice and sled would produce less friction." (ll. 558-563)

The higher amplitudes in take-off could correspond to the sonic waves generates when the planes start their acceleration

We included the remark of the reviewer in the text, see above.

L461: Have you considered the orientation of the airtrack used for landing/departure? If landing do occur at larger distances from the seismometer than take-off, this may affect amplitudes

We did consider the orientation of the airstrips, and, more specifically, the direction in which the aircraft is taking off or landing from them, as this influences the distance of the actual touch-down or lift-off with respect to the seismometer position. CGN has three runways, all of which are used for departures and landings from both direction, so that there are 12 different sources of signal in total, which are however occurring with very different frequency. During the time frame of 1.75 days for which we have detailed data, almost 90% of the departures and landings occurred on the intercontinental runway, as stated in the text (ll. 567-569), which makes the data for the other airstrips too limited to be of use for statistics, e.g. just one landing in a specific direction on both of them, and no starts at all in a specific direction for one of them. (Note that one of the other runways is the cross-wind runway, which is only used in specific weather conditions, and is too short for large planes.)

For the intercontinental runway, one end is about 2.4 km from the sensor, and the other 3.2 km. However, the observation that signals from departures are significantly better visible than those from landings is true also when considering both directions individually, i.e. for lift-off and touch down at 2.4 km and for lift-off and touch-down at 3.2 km. For the departures, there are additional hints that the location of the actual lift-off seems to be important, since airplanes accelerating towards the end of the airstrip 2.4 km from the sensor produce more observable signals than those accelerating away from the sensor towards the end at 3.2 km distance. All of the examples shown in Fig. 8 are for departures from the closer end of the runway. The relationship for landings is less clear, and the examples shown in Fig. 8 are for touch-downs at both the closer (Fig. 8a) and the further end (Figs 8b and c) of the runway. However, depending on which wave types make up the signal, the subsurface structure might also play a role here, as well as the wind strength and direction. A more detailed investigation would require more data and is beyond the scope of our study, but is one possible use for future data from the permanent seismometer in LUNA.

Fig. 8: Again, the use of "jet" colormap is beautiful, but can lead to misinterpretations due to its visually effect
We changed the colormap to Batlow, as for Fig. 5 and 9 (Crameri, 2018; Crameri et al., 2020).

Regarding flyby airplanes and helicopters, the author reproduce previous studies and make some estimation of velocity and closest distance of aircraft, similarly to previous studies.
It was our intent to give examples of these signal types, and to also go beyond the immediate interest of future LUNA users in showing that data from the permanent seismometer in LUNA could be used for a more detailed study of aircraft fly-bys in the direct vicinity of an airport.

Reviewer #2

Thank you for allowing me the opportunity to review this study, which analyzes active and passive seismic data to provide subsurface structural information and to characterize sources of anthropogenic signal. I am pleased to recommend acceptance of this paper to Seismica. I believe that the paper itself is well-written and organized clearly, that the methodology is clear and well-substantiated, and that the analysis of data from a lunar analog testbed facility such as LUNA is particularly relevant.
We thank the reviewer for their positive assessment and interest in our study.

The following are line-by-line comments and questions that I believe could be clarified within the text.

Lines 209-212: Probabilistic power spectral densities (PPSD) were also calculated for the broad-band station included in the array deployment on the LUNA site, covering only approximately 3 days in time. They show good agreement with the long-term data. The vertical-component PPSD (Fig. 3) show an elevated noise level, partly above the new high noise model... Point of clarification: in section 2 (Data and methods), the LUNA array consists of four short-period seismometers, without another instrument being mentioned. This PPSD is also not shown in Figure 3, and it is only the vertical-component PPSD for the broad-band seismometer in the MUSC building. Was the PPSD computed with only the MUSC station recordings, or was it compared to the data from the array deployed at the LUNA site?

We thank the reviewer for noting this omission. We realized that the broad-band seismometer included in the seismic array was inadvertently only mentioned in the Supplemental Information. We adjusted the text now to provide information on that seismometer, and we included the vertical component PPSD calculated for that station in Fig. 3 as subplot b), also in response to the comments by Reviewer #1 on the relevance of the ambient noise observed in the MUSC building for the actual site of LUNA. Lines 144-146 now read:
"The central station of the short-period array was enhanced by placing a Nanometrics Trillium compact 120 s broad-band sensor next to the short-period seismometer."

Lines 251-253: Other frequency bands are only observed part of the time, e.g., adjacent lines at 24.7 and 24.9 Hz that are only observed until about 12:05 pm. Are these daily occurrences? Are they also associated with some kind of machinery? Is there any kind of periodicity that characterizes signals with these frequencies?
The described signal starts at about 06:13 am on that particular day. It is also observed on other work days, but, from a random sample of data, there seem to be no fixed occurrence times, and duration of the signal can be as short as 40 min, compared to the almost 6 hours on the day shown in Fig. 5. Also, on some days, the signal appears several times, e.g. for 3 hours 15 min, followed by a break of about 2 hours, and an additional occurrence for 1 hours 45 min. Timing can be as early as 7 am local time, and as late as 10 pm local time, which is well past usual working hours. There also seems to be some internal structure to the signal, i.e. a variation in intensity on the order of 15 s. Finally, some working days are completely free of the signal. To summarize, while we are sure that this signal is machine-generated, there is no clear pattern in its activity that helps to constrain its origin.

The many different institutes on the campus that work topics from jet engine development to solar power generation and from supersonic wind tunnels to aerospace medicine, and the fact that our data are basically point measurements when compared to the size of the campus prevent us from pinpointing the origin of this signal. As mentioned in lines 244-246 of the original submission, a dedicated measurement campaign with a network of a larger number of sensors distributed throughout the campus would be required to locate the source of this type of signal seismically. Since this signal was only mentioned as an example for additional, discontinuous machine-generated signals in the data, a more detailed analysis is beyond the scope of this study. In fact, the data shown in Fig. 5 contain at least three other discontinuous narrow-band signals around 14.8 Hz (12:14:00-12:17:30 pm), 18.3 Hz (12:03:30-12:11:00 pm), and 19.8 Hz (12:07:00-12:21:00) that can be attributed to turning on and off some kind of machinery. We added a sentence to the text for clarification, which now reads:
"Other frequency bands probably linked to the activation of machinery are only observed part of the time, e.g., adjacent lines at 24.7 and 24.9 Hz that are only observed until about 12:05 pm. While these bands are also observed on other days, there is no clear pattern to their start or end times or duration, and they are only one example for narrow-band, discontinuous signals generated by as yet unidentified

machinery." (ll. 333-337)

Line 272-276: [Meng et a1. (2021)] car-generated signals have an emergent onset, no clear internal structure, and rise in amplitude to a maximum before symmetrically decreasing again, with rise and decay times both on the order of 10 s. In contrast, our recordings of cars contain a number of short bursts of energy, generally with two distinct amplitude maxima per burst, and no gradual increase or decrease in amplitude. Could you elaborate on why there is no specific gradual rise/decay in the amplitude of signals associated with cars when we expect that from previous studies? Do all car signals have at least 2 distinct maxima? Signals with more than two maxima are associated with a more complex piece of roadwork. Is there ever a point where there is one maximum, and if so, what could be the potential cause of this?

The specific shape of the car-generated signals depend on how these signals are generated. The study by Meng et al. (2021) analysed car signals generated along a dirt road, with continuous friction between the wheels and the road leading to coupling of seismic waves into the ground. On the other hand, Czarny et al. (2023) found that the primary seismic noise sources for a roadside DAS experiment are related to utility holes and bumps in the road, and their interaction with passing cars generate the largest amount of Rayleigh wave energy. In fact, Liu et al. (2025) observe (and model) very similar signals to those we show, consisting of two distinct maxima for cars going over a speed bump, in a study that was both originally submitted and published during the 6 months our manuscript spent in review. A single maximum in their modeling corresponds to a single wheel, and this is not observed neither in their data nor by us (see Supplemental Figures S8a and S9). In our study, the signal generation was tested by driving a Toyota Prius along a known part of the road, with an approximately known velocity, as described in lines 281-283 of the original manuscript. In this scenario, the size of the signals we observe for a given obstacle on the road does not only depend on the distance from the array, which would lead to a rise and decay similar to the observations by Meng et al. (2021), but also on the height/depth of the obstacle and the resulting force on the ground when a car is passing over it. To clarify this, we amended the text as follows:

"Since the road in our case is a tarmac road which, over the length shown in Fig. 1, contains a number of irregularities like manholes, cracks, and bumps, and the recorded pattern is distinct, depending on whether a car is driving eastward or westward (Fig. 6a), we hypothesize that the signals we observe are generated at specific points on the road that present some irregularity (Czarny et al., 2023; Liu et al., 2025), rather than continuously all along the road, and that the two maxima are caused by the motion of the two axles of the car over the corresponding irregularity. The amplitude of the signal in this case not only depends on the distance from the array, but also on the size of the bump or crack.

This hypothesis is validated by a test using the array data to track a known car (Toyota Prius) first driving out of the parking lot and from east to west along the road, then turning at around 368.25 E and driving back, entering a loop at the eastern end of the road near 368.53 E to turn again (Fig. 6), *with a velocity approximately at the speed limit on campus of 30 km/h."* (ll. 364-374)

Line 298-299: Finally, assuming the car-generated signals consist of Rayleigh waves — though we observe short impulses rather than clearly dispersed signals... Following this logic, can you elaborate on why using Rayleigh wave polarization to determine source direction would work?

We follow the same logic as outlined by Liu et al. (2025): "Since the near-surface seismic wavefields are dominated by surface waves, we conduct our test using the surface wave part generated by vehicle traffic." As a vertical seismic source at the surface, a car passing over a bump will dominantly generate Rayleigh waves, even if we cannot observe clear dispersion in the signals themselves. Actually, the data shown in Yuan et al. (2020), i.e. in Fig. 2d, and Yuan et al. (2024) based on the same experiment, e.g. in the shot gathers in their Fig. 7a-c, do not show a clearly dispersed signal on individual traces, either, though the dispersion analysis in their Fig. 3a-b and Fig. 7e-f, respectively, clearly retrieves Rayleigh wave dispersion along the offset of 0 to 150 m. We accordingly removed the misleading reference from the text:

"Finally, assuming the car-generated signals consist of Rayleigh waves, we used polarization information to determine the source direction." (ll. 390-392)

Lines 355-356: The bus signal has some similarities to the car signal, in that it contains several sharp amplitude maxima, and energy at high frequencies above 20 Hz (Supplemental Fig. S6b) This figure (Fig S6b) appears to be missing in the Supplemental Information package provided. Supplemental Figure S6 shows the comparison of a seismic event recorded at the test installation and another broad-band station. Please include this figure, as it is very important.

We thank the reviewer for noting this. In fact, this was an error in referring to the figures in the Supplemental Information and it was intended to refer to Fig. S10b. We corrected this error in the text (see also comment by Reviewer #1).

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