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Estimation of anthropogenic noise effect on relative gravimeters using the COVID-19 pandemic period

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Abstract: The COVID-19 pandemic caused by the SARS-CoV-2 virus has brought many, mostly negative, effects and consequences on human lives, health, and economic issues. However, one of the very few positive side effects of lockdown measures was a less noisy and less loaded natural environment on a global scale. Many accurate geophysical instruments are negatively affected by the noise forced by all kinds of human activities, such as traffic, mining, construction, and others. In this paper, we present our attempt to estimate the influence of anthropogenic noise in the seismic band on five superconducting gravimeters and one spring gravimeter incorporated in International Geodynamics and Earth Tide Service (IGETS) using a comparison of gravity records before and during the lockdown period. For quantification of a noise, the mean power spectral density (PSD) was used. Based on this experiment we can compare and quantify how much particular IGETS stations and instruments are affected by the anthropogenic noise. For our experiment, we used Level 1 IGETS data on selected stations with a 1-second sampling rate or 1-minute time resolution where 1-second was not available. For selected stations we estimated the contribution of anthropogenic noise to the total noise in a seismic frequency band for a particular station and instrument.

Key words: superconducting gravimeters, spring gravimeters, gPhoneX, International Geodynamics and Earth Tide Service, power spectral density, anthropogenic noise

1. Introduction

Main goal of this paper is to estimate anthropogenic noise (part of the environmental noise caused by human-related activities) and compare it to total noise. Total noise sensed by gravimeters is given by a combination of environmental and instrumental noise. Comparing the total noise during the strict lockdown period and normal working days, or sometimes even weekends and holidays with working days, we can estimate the anthropogenic noise at particular gravity sites. Finally, we can express the ratio of

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anthropogenic noise and total noise and relatively quantify how much the particular sites are affected by anthropogenic noise.

The stable and seismically quiet location of a gravity station is the key condition to acquiring high-quality gravity measurements. From this perspective, it is necessary to know the surroundings of the gravity station, both in terms of natural and human-related (anthropogenic) noise. Since the outbreak of the COVID-19 pandemic, some gravity observations had been recorded under low influence of anthropogenic environmental noise. Environmental noise can be described in many ways and there is not a unique definition. Anthropogenic part, in the seismic frequency band, is mainly caused by the traffic (road, rail, air), industry and also by recreational activities. Another part of the environmental noise is caused by natural phenomena. In this paper, we estimate the noise magnitude in the seismic band (frequency range from 1.667 mHz to 2.941 mHz which corresponds to periods from 340 to 600 seconds) unless it is stated otherwise.

Several attempts to unify the system of noise level estimation for terrestrial gravimeters in seismic and sub-seismic bands have been made in the past. Useful software tool SGNoise has been developed by *Vaľko and Pálinkáš (2015)* which can evaluate a noise level of SG gravimeters from 1 second data. A detailed study of the instrumental and the environmental noise level was studied by *Rosat and Hinderer (2018)*, using several superconducting gravimeters at the Strasbourg gravimetric observatory. The procedure of a noise level estimation of continuous gravity measurements at seismic frequencies was recommended by *Banka and Crossley (1999)*. They suggested quantifying the noise level by Seismic Noise Magnitude (SNM) computed from mean Power Spectral Densities (PSD) of gravity residuals for selected frequency band for 5 days in a year with the lowest root mean square error (RMSE). This procedure was used in several other studies (*Rosat et al., 2003; Rosat and Hinderer, 2011; Zhang et al., 2016*). In our study, we partially follow this concept but prefer using different time periods (separately weekdays and weekends) to compute the mean PSD.

International Geodynamics and Earth Tide Service (IGETS), see *Boy et al. (2020)*, formerly Global Geodynamic Project (GGP), see *Crossley et al. (1999)*, *Crossley and Hinderer (1995)*, covers the global network of gravity observatories. The main objective of IGETS is to support the monitoring of temporal variations in the Earth's gravity field using long-term records from ground gravimeters and other geodynamic sensors, see `https://ggos.org/item/igets/`. The first four-year period of the IGETS operation (2015–2019) is described in *Boy et al. (2020).* The detailed status of the IGETS database in 2016 is presented in *Voigt et al. (2016).*

The data itself from individual IGETS stations are provided on three levels. Level 1 data comprise the raw gravity and atmospheric pressure data in typically 1-minute intervals, some of them also in 1-second intervals. Several stations provide additional hydrological data in station surroundings, such as groundwater level, precipitation and soil moisture. Level 1 data are uploaded by operators of IGETS sites. Level 2 data contain gravity and atmospheric pressure measurements prepared for the tidal analysis. Level 3 data includes 1-minute gravity residuals obtained from level 2 data after applying the conventional temporal corrections, namely the solid Earth tides, polar motion, atmospheric pressure and ocean loading effects (*Voigt et al., 2016*). Level 2 data were formerly prepared by the University of French Polynesia. Since 2023 level 2 and level 3 data have been compiled at École et Observatoire des Sciences de la Terre, Strasbourg, France.

Temporal gravity variations are commonly studied using gravimetric methods, typically employing relative monitoring gravimeters. Among these, superconducting gravimeters (SG) (*Goodkind, 1999*), are favoured for their enduring stability, low instrumental noise, and stable linear drift. Conversely, relative spring gravimeters exhibit reduced long-term stability and larger instrumental drift. The feedback system enables highly accurate digital measurements with a resolution of 0.1 μGal (*Fores et al., 2019*). Spring gravimeters perform well in observing effects like short-period tides or normal modes of the Earth oscillation, however, due to nonlinear drift, they are less suitable for monitoring long-term gravity variations, i.e., with periods larger than several days (*Carbone et al., 2019; Hábel et al., 2020*).

Noise level of relative spring gravimeters was estimated by *Zhang et al. (2017)*, where the SNM and SSNM (Sub-Seismic Noise Magnitude) were computed based on the observations of 36 gPhone gravimeters evenly distributed throughout China. Comparison of noise level of gPhone gravimeters to SGs at several stations in China were performed by *Zhang et al. (2018).* SNM and SSNM of the gPhone gravimeters were in general larger than the noise magnitudes of superconducting gravimeters.

2. Gravimetric stations and tested periods

Strict anti-pandemic regulations in most European countries started in March and April 2020. Therefore, we focused on the analysis of level 1 IGETS data from April 2020 and compared them with April data from three previous years 2017, 2018 and 2019. Time series of different instruments, with 1-second sampling (where available) or 1-minute sampling, were used in this study. We analysed data from IGETS stations Trappes (France) (*Merlet and Pereira dos Santos, 2020*) and Rochefort (Belgium) (*Van Camp et al., 2021*) with transportable SG instruments (iGrav), and Yebes (Spain), Onsala (Sweden) (*Scherneck and Mouyen, 2022*), and La Plata (Argentina) (*Wziontek et al., 2017*) with observatory SG instruments (OSG). Additionally, we also analysed data from IGETS station Hurbanovo with the spring gravimeter gPhoneX but over different time intervals. Basic information about the selected stations is shown in Table 1.

Table 1. List of IGETS stations considered in this study.

	Sampling rate	**Instrument**	**Latitude** [°]	**Longitude** [°]	**Elevation** [m]
Trappes	1 second	iGrav 005	48.76066	1.98373	170.52
La Plata	1 second	OSG 038	−34.8732	−58.1400	20.50
Yebes	1 second	OSG 064	40.5238	−3.0902	917.70
Onsala	1 minute	OSG 054	57.3858	11.9266	7.93
Rochefort	1 minute	iGrav 019	50.1552	5.2256	225.00
Hurbanovo	1 second	gPhoneX 108	47.8724	18.1932	112.34

The location of a superconducting gravimeter (SG) can significantly affect the quality of the measurements. One of the most important requirements for the location of a long-term gravity station, depending also on the main purpose of the gravity station, is low environmental noise. This includes avoiding (if possible) sources of intensive seismic activity, electromagnetic interference, and human activity. Most of the IGETS gravimeters are in specialized facilities located in remote areas, far away from human activity. It is therefore unusual to find SGs close to infrastructure or in the cities where there may be the higher levels of environmental noise. However, there are several exceptions where SGs have been installed in urban areas or near the traffic or industrial infrastructure.

Stations Trappes (France), Rochefort (Belgium), La Plata (Argentina) and Hurbanovo (Slovakia) are located on sites close to larger cities and infrastructure. Trappes (Fig. 1) is situated in the most frequented location of all stations included in our experiment. The Laboratoire national de métrologie et d'essais (LNE-Trappes), where the SG is located, is 30 km west of Paris and is surrounded by several logistics' centres close to the railway. A strict lockdown in France was established on 16. 3. 2020 and lasted until 11. 5. 2020 (*Adélaïde et al., 2021*). La Plata station is in the suburbs of Buenos Aires approximately 1 km from the city of La Plata at transportable integrated observatory (TIGO), which was moved from the previous location close to the city of Conception, Chile in April 2015 (*Antokoletz et al., 2019*). Argentinian lockdown was the longest in the world, lasting from 20. 3. 2020 to 16. 8. 2020 (*Ise et al., 2021*). Rochefort (Fig. 2) is also located in a very frequented area. The station is surrounded by the town of the same name, railways, and other city roads. Strict anti-pandemic restrictions were announced on 20. 3. 2020 (*Wagener et al., 2022*). Slovak station Hurbanovo (see next chapter) is also located in the middle of the smaller but industrial town Hurbanovo. We assume that these stations are more susceptible to human-related environmental noise, and there is a possibility that the COVID-19 pandemic could have led to a reduction in noise levels at these stations. Yebes and Onsala, are placed in more quiet zones with

Fig. 1. Location of the superconducting gravimeter at Trappes (France).

less traffic and industrial influence. Yebes is based on the campus of the Centro Astronómico de Yebes, about 30 km west of Madrid. There are no other towns within a radius of 2 km.

Fig. 2. Location of the superconducting gravimeter at Rochefort (Belgium).

2.1. Spring gravimeter gPhonex at Hurbanovo

The Hurbanovo Gravimetric Observatory (Fig. 3) represents the only tidal gravimetric station in Slovakia and has been a part of IGETS since 2021 (*Janak et al., 2021*). Situated in conjunction with the Hurbanovo Geomagnetic Observatory (Earth Science Institute, SAS) and the Slovak Hydrometeorological Institute, it forms part of the integrated HUVO station including a permanent GNSS station collocated with InSAR passive reflectors, Raspberry Shake 3D seismograph and other hydrological and meteorological sensors. Continuous gravity measurements are facilitated by a relative spring gravimeter gPhoneX#108. Positioned at 47.8724° north latitude and 18.1932° east longitude, the gravimeter is housed within a modest structure atop an isolated concrete pillar. This architectural configuration serves to mitigate the influence of building tilts on gravity measurements and to suppress microseismic building noise. Furthermore, the operating environment of the gravimeter is maintained at an approximate temperature of 26 °C using an air conditioning system. Additionally, polystyrene insulation is employed to minimize potential temperature fluctuations within the gravimeter's enclosure.

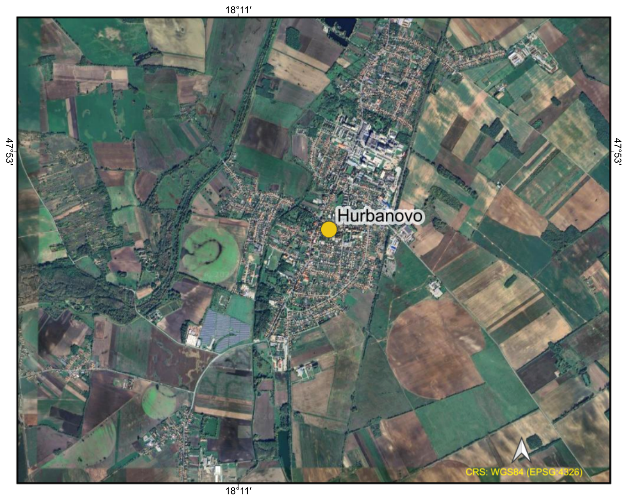

Fig. 3. Location of the gPhoneX gravimeter at Hurbanovo (Slovakia).

Previously, the gPhoneX#108 gravimeter was temporarily stationed within the premises of the Faculty of Civil Engineering at the Slovak University of Technology in Bratislava from 2016 to 2019. A comprehensive analysis of continuous gravity acceleration and atmospheric pressure measurements conducted during this period can be referenced in publication (*Hábel et al., 2020*). However, due to the inherent challenges posed by the urban environment, including high levels of anthropogenic noise attributed to vehicular traffic and other environmental perturbations, this location was deemed unsuitable for ensuring the requisite long-term stability of gravity measurements. Consequently, in autumn 2019, the gravimeter was relocated to Hurbanovo, where it has since been engaged in continuous gravity measurements starting from July 2020.

3. Noise level at selected frequency band observed by relative gravimeters

In this study we compute the noise level based on gravity time series with sampling rate of 1 s (if available) or 1 min from IGETS database – level

1 products based on procedure proposed by *Banka and Crossley (1999)*. Gravity time series were corrected for atmospheric pressure with admittance factor of $-0.3\,\mu$Gal/mbar. Given that tidal corrections do not significantly reduce noise in seismic frequencies (*Rosat and Hinderer, 2018*), this correction was not applied directly. To minimize residual instrumental drift and tidal effects, a best fitting 9th-degree polynomial was subtracted from the gravity time series on a daily basis. The Fast Fourier Transform (FFT) using the Hann window and the data padding with the zeros to the (next+1) power of 2 was calculated. The average of unnormalized amplitude spectra was computed and mean PSD value in frequency range from 1.667 to 2.941 mHz (periods from 340 to 600 s), was estimated. The upper frequency limit has been designated at approximately 3 mHz due to the decimation filters employed across SG sites within the range of 1 second to 1 minute (*Rosat and Hinderer, 2011*). SNM was then computed from the mean value of the PSD (μGal^2/mHz) according to Eq. (1) (*Banka and Crossley, 1999*):

$$\mathrm{SNM} = \log_{10}\left(mean\,\mathrm{PSD}\right) + 2.5\,. \tag{1}$$

Value of SNM is usually used for quantifying the noise magnitude. However, when computing the ratio of two noise values, the logarithmic scale might be a problem, and it is better to use the mean PSD value in a linear scale. Mean value of PSD was calculated for five quietest days with the lowest RMSE of gravity residuals for every year from 2017 to 2020. Similar procedure was chosen for calculation of mean PSD in the month of April in the same years but the days of the month were divided into weekdays (Monday to Friday) and weekends (Saturday to Sunday). April 2020 was chosen purposely, because this was the first complete month with the strict lockdown rules in most countries of the world. For three previous years we also used April to stay consistent. For the Hurbanovo station, we used a different approach because of a lack of data from the 2017–2020 period that was used for the other stations. Instead, we calculated the mean PSD values separately for weekdays (Monday to Friday) and weekends (Saturday and Sunday) for the whole year, or available part of the year from 2020 to 2023. Data in 2020 for Hurbanovo station started from July 2020.

The calculation of SNM for superconducting gravimeters on an annual basis (Fig. 4) serves as a valuable metric for assessing the relative performance of individual gravimeters. It gives the possibility of comparing the noise level with previous studies. The SNM values provide insights into the noise characteristics across seismic frequencies, showcasing the station at Yebes, where the OSG 065 is operating, as having the lowest noise level. Conversely, stations such as Rochefort, equipped with iGrav, and Onsala, employing OSG 054, exhibit different noise profiles.

We show the mean PSD values in a linear scale computed from 5 quietest days in a year and also for April in every year, separately for weekdays and weekends, as already mentioned above, see Table 2 and Fig. 5. From these results we can see a decrease of the mean PSD value for April 2020 at several stations. We can also see that the mean PSD value for weekends in April 2017 – 2020 is very similar to the mean PSD for 5 quietest days in a corresponding year. The most significant decrease in weekdays (Monday – Friday) mean PSD for April 2020 compared to previous years can be

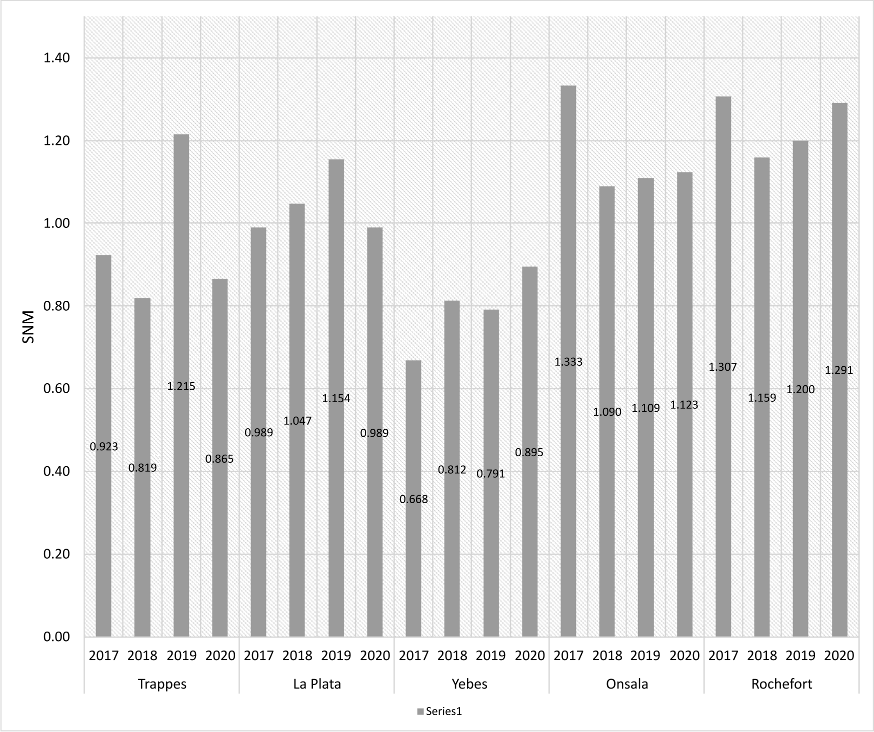

Fig. 4. Comparison of Seismic Noise Magnitudes (SNM) at the SG sites. Units are dB relative to $\mu\text{Gal}^2/\text{Hz}$.

Table 2. Mean PSD values in the frequency band from 1.667 to 2.941 mHz for five quietest days in the whole year, and for workdays and weekends in April each year. Values for the last two stations are computed from 1-minute sampled data.

Station	**Year**	**IGETS name**	**Mean PSD** (μGal^2/Hz)		
			5 quietest days	Monday – Friday	Saturday – Sunday
Trappes	2017	tr005	0.026	0.050	0.023
	2018		0.021	0.125	0.021
	2019		0.052	0.449	0.070
	2020		0.023	0.025	0.024
La Plata	2017	lp038	0.031	5.707	0.044
	2018		0.035	0.208	0.044
	2019		0.045	0.055	0.041
	2020		0.031	0.040	0.038
Yebes	2017	ys064	0.015	0.047	0.019
	2018		0.021	0.041	0.022
	2019		0.020	0.041	0.023
	2020		0.025	0.016	0.022
Onsala	2017	os534	0.068	0.069	0.044
	2018		0.039	0.197	0.144
	2019		0.041	0.083	0.092
	2020		0.042	0.065	0.065
Rochefort	2017	rc019	0.064	0.141	0.053
	2018		0.046	0.097	0.105
	2019		0.050	0.097	0.080
	2020		0.062	0.062	0.038

observed at the French station Trappes. It is noteworthy that mean PSD levels during weekdays in 2017, 2018 and 2019 at all stations generally surpass those in 2020. In most cases, the mean PSD for weekdays in 2017, 2018 and 2019 is larger than mean PSD for weekends except for the year 2020 during strict pandemic precautions, where the weekday PSD levels almost equalled those of the weekends.

Furthermore, several instances indicate that the mean PSD values for weekends in Apriles fall below those of the five quietest days, exemplified by observations from Trappes in 2017 and La Plata in 2019, a trend po-

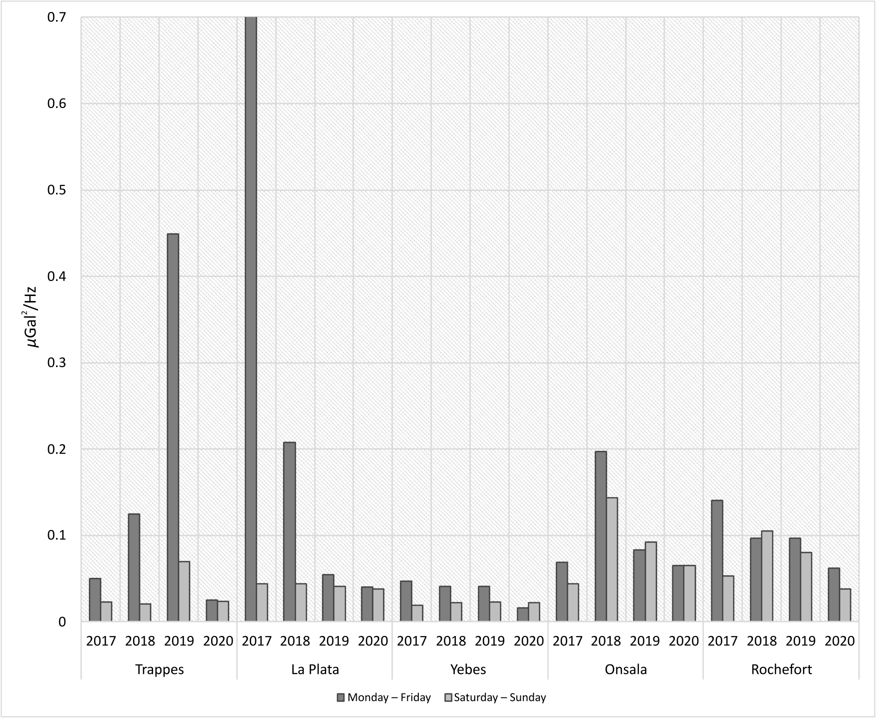

Fig. 5. Comparison of mean PSD values at the SG sites for weekdays (Monday – Friday) and for weekends (Saturday – Sunday).

tentially attributable to the methodology employed in selecting the quietest days. The selection criterion, based on the lowest RMSE of gravity residuals over the entire day, may not perfectly correspond with the computed mean PSD for selected frequencies, as noted in prior studies (*Banka and Crossley, 1999*).

Figure 6 shows the spectrograms of Trappes (iGrav 005) level 3 time series (after correction for solid Earth tides and ocean loading effects, correction for atmospheric pressure, polar motion, and instrumental drift), where we can clearly distinguish weekdays, weekends or holidays, even days and nights based on the PSD for almost all frequencies. Higher values correspond to the weekdays (especially working hours) and lower for the weekends. The difference between the weekdays and weekends is greatest in April 2019 and, on the contrary, smallest in April 2020, where we can hardly dis-

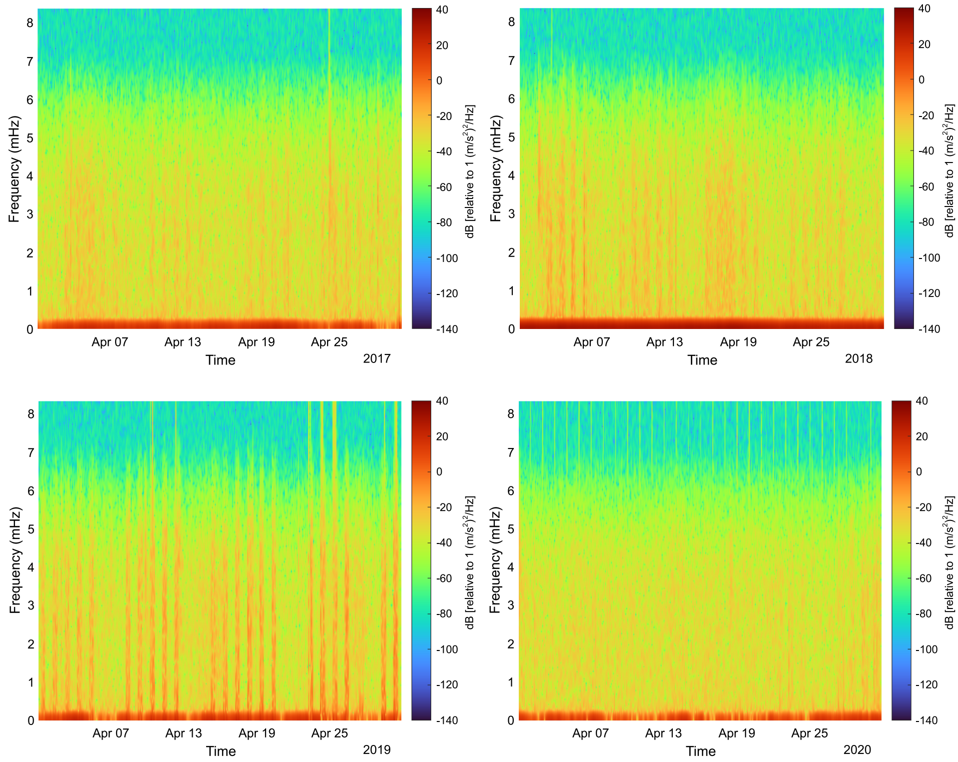

Fig. 6. Spectrograms of corrected gravity in April 2017 – 2020 at Trappes (France).

tinguish weekdays and weekends. Spectrograms were created using the FFT with a window length of 4 hours and a 50 % overlap. The spectrograms are computed for frequency range from 0.07 to 8 mHz and the noise is expressed in a logarithmic scale. Note that the units are different from Fig. 4.

Graphs in Figure 7 show mean PSD in a logarithmic scale for wider frequency band, from 0.05 to 500 mHz (corresponding to periods from 2 to 20000 s). Weekdays are on the left and weekends on the right. Here, a significant decrease of the noise computed for weekends compared to weekdays is apparent. Notably, for all depicted stations (Trappes, Yebes, and La Plata), the noise level during weekdays is lowest in April 2020, while in other years it tends to be higher across almost the entire frequency range. This suggests a notable reduction in anthropogenic noise levels during pandemic restrictions to a level comparable to weekends. Consequently, based on this

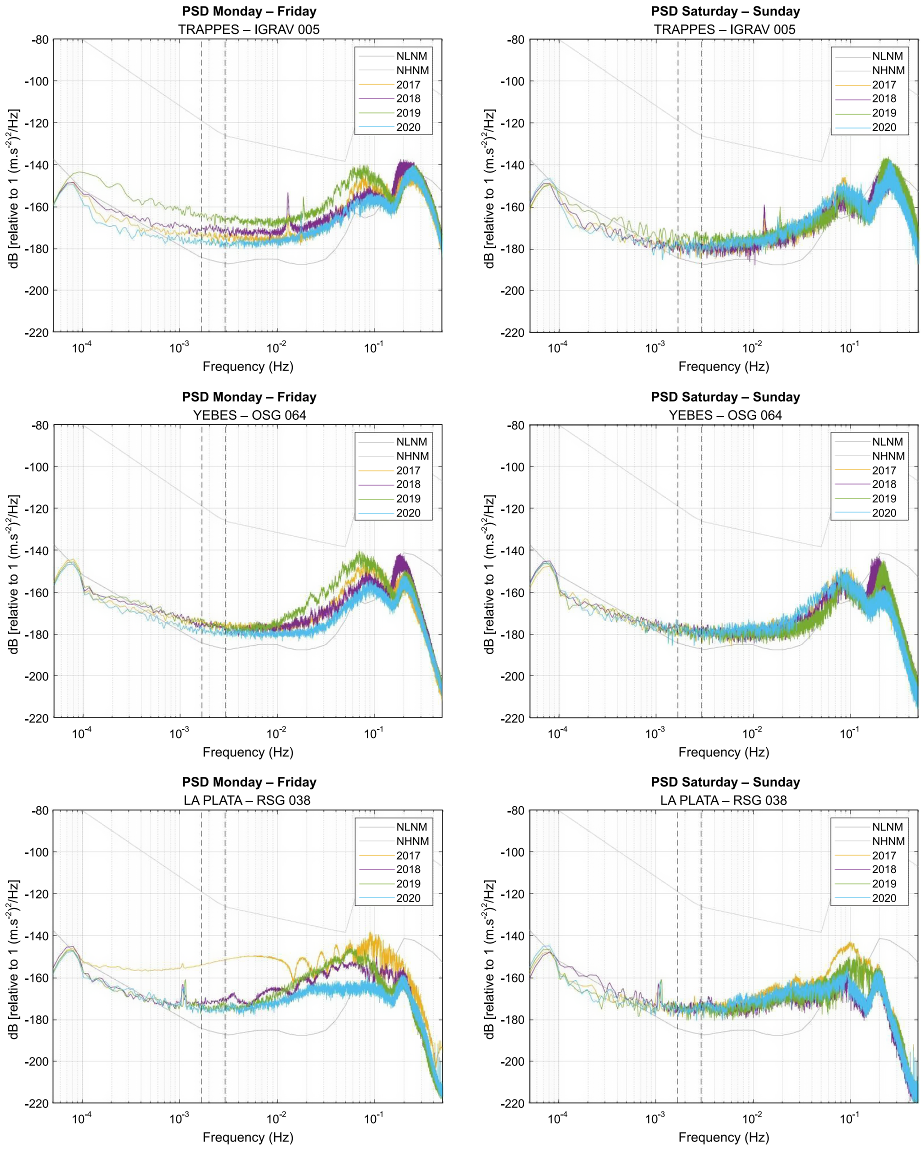

Fig. 7. Mean PSD for wider frequency range in logarithmic scale calculated separately for weekdays (left) and weekends (right) for selected IGETS stations (Trappes – top, Yebes – middle, La Plata – bottom) compared to the new low-noise model and new high-noise model (*Peterson, 1993*). Two vertical lines represent the frequency band where the SNM and mean PSD in Table 2 were computed.

observation, it becomes feasible to quantify anthropogenic noise and identify gravity stations more influenced by this part of the noise.

Results for Hurbanovo, mean PSD and SNM, were computed from July 2020 to December 2023 and are presented in Table 3 and Figs. 8 and 9. Results for Hurbanovo indicate that:

- Weekday mean PSD values are consistently higher than those for weekends, which aligns with increased anthropogenic noise during weekdays. Demonstration of this can clearly be seen in the spectrogram plotted for April 2021, see Fig. 8.
- Weekend mean PSD values are more stable and consistently lower than weekday values, highlighting reduced anthropogenic noise during weekends.
- Weekday noise in 2023 is much higher than in previous years, see Fig. 9. We suspect it might be due to an improperly filtered earthquake.

Separating data into weekdays and weekends proves to be a superior approach compared to relying on the "five quietest days" method. By focusing on mean PSD for specific time intervals, the influence of human activity can be evaluated more effectively and consistently.

Table 3. Average PSD and SNM for weekdays and weekends at Hurbanovo gravimetric station.

	Mean PSD (μGal^2/Hz)		**SNM** (dB relative to μGal^2/Hz)	
	Monday – Friday	Saturday – Sunday	Monday – Friday	Saturday – Sunday
2020	0.857	0.053	2.442	1.227
2021	0.514	0.041	2.211	1.116
2022	0.525	0.064	2.221	1.307
2023	2.087	0.078	2.820	1.392

4. Estimation of anthropogenic noise effect

For quantifying the anthropogenic noise effect relative to total noise observed by relative gravimeters we propose a relative quantity which we call the An-

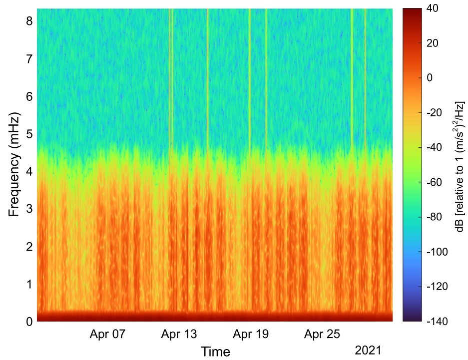

Fig. 8. Spectrogram of corrected gravity in April 2021 at Hurbanovo (Slovakia).

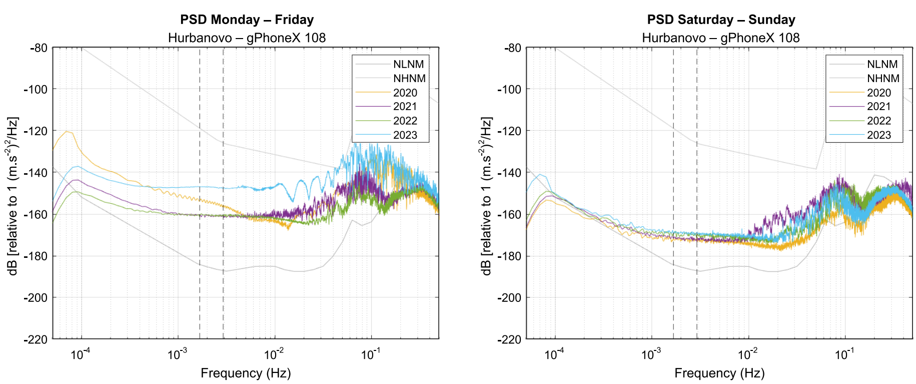

Fig. 9. Mean PSD for wider frequency range in logarithmic scale calculated separately for weekdays (left) and weekends (right) for Hurbanovo compared to the new low-noise model and new high-noise model (*Peterson, 1993*). Two vertical lines represent the frequency band where the SNM and mean PSD in Table 3 were computed.

thropogenic Noise Ratio (ANR) computed by Eq. (2). The larger the ANR value, the larger is the relative impact of anthropogenic noise to a particular station relative to total noise observed by the gravimeter. We assume that the anthropogenic noise was shut down during the strict lockdown period (April 2020) and especially during the weekends, so in the numerator of the second term of Eq. (2) we use the mean PSD computed for weekends in April 2020. This can be assumed as a reference value free from anthropogenic noise. For Hurbanovo station the numerator in Eq. (2) was chosen as the mean PSD computed for weekends in 2021 which was the lowest mean

PSD value in Table 3.

$$\mathrm{ANR} = 100\% - 100 * \frac{mean\,\mathrm{PSD(Sat - Sun)_{Lockdown}}}{mean\,\mathrm{PSD(Mon - Fri)_{Test\ period}}} \,. \tag{2}$$

Values of ANR, computed from values in Tables 2 and 3, for every station and for particular years are presented in Table 4.

Table 4. Anthropogenic Noise Ratio (ANR) for particular gravity stations and years.

Station	Year	Anthropogenic noise (%)
Trappes	2017	52.0
	2018	80.8
	2019	94.7
	2020	4.0
La Plata	2017	–
	2018	81.7
	2019	30.9
	2020	5.0
Yebes	2017	53.2
	2018	46.3
	2019	46.3
	2020	−37.5
Onsala	2017	5.8
	2018	67.0
	2019	21.7
	2020	0.0
Rochefort	2017	73.0
	2018	60.8
	2019	60.8
	2020	38.7
Hurbanovo	2020	95.2
	2021	92.0
	2022	92.2
	2023	–

Theoretically, the ANR value can be from 0 to almost 100%. It will, however, never reach 100% because the total noise (expressed by mean PSD on weekdays) cannot be infinite and the noise freed from the anthropogenic part (expressed by mean PSD during the pandemic period or weekends) cannot be zero. Two ANR values in Table 4 were not computed. Values for La Plata in 2017 and for Hurbanovo in 2023 were omitted because the mean PSD value for weekdays were unusually high which was most likely due to an unfiltered earthquake. The ANR value for Yebes in 2020 was negative, because the mean PSD on weekdays in April 2020 was surprisingly lower than the mean PSD on weekends computed over the same period. This shows that the ANR value is sensitive to the chosen reference value used in the numerator of Eq. (2) and we should be aware that the ANR values can slightly change according to how well we can estimate the mean PSD freed from anthropogenic noise. From Table 4 we can see that the ANR value for 2020 is far the lowest for all 5 stations where we have data during the strict pandemic restrictions.

Now, we can average the ANR values from Table 4 for 2017, 2018, 2019 for the first five stations and for 2020, 2021, 2022 for the Hurbanovo station and estimate the average ANR value for each station. These values together with the average total noise can help us to see how particular stations are sensitive to anthropogenic noise and how noisy they are on an average weekday, see Table 5.

Table 5. Average ANR values and average total noise magnitude.

Station	**Average ANR value** (%)	**Average total noise (weekdays)** Mean PSD (μGal^2/Hz)
Trappes (iGrav)	75.8	0.208
La Plata (OSG)	56.3	0.132
Yebes (OSG)	48.6	0.043
Onsala (OSG)	31.5	0.116
Rochefort (iGrav)	64.9	0.112
Hurbanovo (gPhoneX)	93.1	0.632

5. Conclusions

Comparing the noise at gravity stations and for various periods of time including the strict lockdown period was fruitful. It helped us to evaluate how much the examined stations are affected by the anthropogenic noise. Anthropogenic noise is one part of the environmental noise caused by human-related activities. Another part of the environmental noise, sometimes called background or natural environmental noise, caused by ocean waves, wind and other natural dynamic processes, is in many sites lower than the anthropogenic part. Environmental noise plus instrumental noise creates total noise sensed by relative gravimeters. In most cases we wish to employ the gravity time series to analyse certain natural dynamic phenomena and thus anthropogenic noise is not desirable to be dominant in gravity data. Results obtained in this paper helped us to make several conclusions.

- Gravity station Yebes is the least noisy station from all examined stations. Although the average ANR value is slightly larger than for the Onsala station, it is still less than 50 %. This means that the anthropogenic noise is not dominant in Yebes gravity time series. This station seems to be very convenient for observing and analysing the natural dynamic processes. Onsala is also a good candidate as it is relatively very little affected by anthropogenic noise (only about 30% of the total noise). In station La Plata about 50% of total noise has an anthropogenic origin.
- On the other hand, stations heavily affected by anthropogenic noise are Hurbanovo (more than 90% of the total noise comes from anthropogenic activities), Trappes (about 75%) and Rochefort (about 65%).
- Mean PSD values or SNM values during the weekends are quite uniform, with some exceptions, for all sites. They might indicate something about instrumental or natural environmental noise. These values are slightly larger in Onsala, Rochefort and Hurbanovo. However, it is also possible that part of the anthropogenic noise affected these data too.
- Estimation of the noise using 5 quietest days over a year based on *Banka and Crossley (1999)* does not always correspond to the noise level evaluated during the weekends and holidays. In some cases, the latter method gives a smaller noise level estimate. Our opinion of this discrepancy is that the criterion, based on the lowest RMSE of gravity residuals over the entire day, may not perfectly correspond with the computed average PSD for selected frequencies.

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References

Adélaïde L., Medina S., Wagner V., de Crouy-Chanel P., Real E., Colette A., Couvidat F., Bessagnet B., Alter M., Durou A., Host S., Hulin M., Corso M., Pascal M., 2021: Covid-19 lockdown in Spring 2020 in France provided unexpected opportunity to assess health impacts of falls in air pollution. Front. Sustain. Cities, **3**, 643821, doi: 10.3389/frsc.2021.643821.

Antokoletz E. D., Wziontek H., Tocho C., 2019: First six months of superconducting gravimetry in Argentina. In: Vergos G., Pail R., Barzaghi R. (Eds.): International Symposium on Gravity, Geoid and Height Systems 2016. International Association of Geodesy Symposia, **148**, Springer, Cham, doi: 10.1007/1345_2017_13.

Banka D., Crossley D., 1999: Noise levels of superconducting gravimeters at seismic frequencies. Geophys. J. Int., **139**, 1, 87–97, doi: 10.1046/j.1365-246X.1999.00913.x.

Boy J.-P., Barriot J.-P., Förste C., Voigt C., Wziontek H., 2020: Achievements of the first 4 years of the International Geodynamics and Earth Tide Service (IGETS) 2015–2019. In: Freymueller J. T., Sánchez L. (Eds.): Beyond 100: The Next Century in Geodesy. International Association of Geodesy Symposia, **152**, Springer, Cham, doi: 10.1007/1345_2020_94.

Carbone D., Cannavò F., Greco F., Reineman R., Warburton R. J., 2019: The benefits of using a network of superconducting gravimeters to monitor and study active volcanoes. J. Geophys. Res. Solid Earth, **124**, 4, 4035–4050, doi: 10.1029/2018JB017204.

Crossley D., Hinderer J., 1995: Global Geodynamics Project-GGP: Status report 1994. In: Proceedings of the Second IAG Workshop on Non-Tidal Gravity Changes: Intercomparison between absolute and superconducting gravimeters , Walferdange, Luxembourg, Sept., 6–8, 1994, **11**, 244–274, available at: https://www.eas.slu.edu/GGP/ggpsr94.html.

Crossley D., Hinderer J., Casula G., Francis O., Hsu H.-T., Imanishi Y., Jentzsch G., Kääriänen J., Merriam J., Meurers B., Neumeyer J., Richter B., Shibuya K., Sato T., Van Dam T., 1999: Network of superconducting gravimeters benefits a number of disciplines. Eos, **80**, 11, 121–126, doi: 10.1029/99EO00079.

Fores B., Klein G., Le Moigne N., Francis O., 2019: Long-term stability of tilt-controlled gPhoneX gravimeters. J. Geophys. Res. Solid Earth, **124**, 11, 12264–12276, doi: 10.1029/2019JB018276.

Goodkind J. M., 1999: The superconducting gravimeter. Rev. Sci. Instrum., **70**, 11, 4131–4152, doi: 10.1063/1.1150092.

Hábel B., Janák J., Papčo J., Val'ko M., 2020: Impact of environmental phenomena on continuous relative gravity measurements performed in urban area. Stud. Geophys. Geod., **64**, 3, 330–348, doi: 10.1007/s11200-021-0536-4.

Ise A., Villalba S., Clementi L., Carrizo S., 2021: Extra long Argentinian lockdown: Revising the energy regime. Glob. Transit., **3**, 43–54, doi: 10.1016/J.GLT.2020.12.002.

Janak J., Papco J., Novak A., 2021: GphoneX gravity data from Hurbanovo – Level 1. GFZ Data Services, doi: 10.5880/igets.hu.l1.001.

Merlet S., Pereira dos Santos F., 2020: Superconducting gravimeter data from LNE-SYRTE Trappes – Level 1. GFZ Data Services, doi: 10.5880/igets.tr.l1.001.

Peterson J. R., 1993: Observations and modelling of seismic background noise. U.S. Geological Survey Open-File Report 93-332, Albuquerque, New Mexico, doi: 10.3133/ofr93322, available online at: https://pubs.usgs.gov/of/1993/0322/ofr93-322.pdf.

Rosat S., Hinderer J., 2011: Noise levels of superconducting gravimeters: Updated comparison and time stability. Bull. Seismol. Soc. Am., **101**, 3, 1233–1241, doi: 10.1785/0120100217.

Rosat S., Hinderer J., 2018: Limits of detection of gravimetric signals on Earth. Sci. Rep., **8**, 15324, doi: 10.1038/s41598-018-33717-z.

Rosat S., Hinderer J., Crossley D., Rivera L., 2003: The search for the Slichter mode: Comparison of noise levels of superconducting gravimeters and investigation of a stacking method. Phys. Earth Planet. Inter., **140**, 1-3, 183–202, doi: 10.1016/j.pepi.2003.07.010.

Scherneck H.-G., Mouyen M., 2022: Superconducting gravimeter data from Onsala – Level 1. GFZ Data Services, doi: 10.5880/igets.os.l1.001.

Vaľko M., Pálinkáš V., 2015: SGNoise – a tool for the ambient noise level analysis at superconducting gravimeter stations. Stud. Geophys. Geod., **59**, 2, 188–199, doi: 10.1007/s11200-014-0928-9.

Van Camp M., Hendrickx M., Castelein S., Martin H., Rapagnani G., 2021: Superconducting gravimeter data from Membach – Level 1. GFZ Data Services, doi: 10.5880/igets.membach.l1.001.

Voigt C., Förste C., Wziontek H., Crossley D., Meurers B., Pálinkáš V., Hinderer J., Boy J.-P., Barriot J.-P., Sun H., 2016: Report on the data base of the International Geodynamics and Earth Tide Service (IGETS). Scientific Technical Report STR – Data; 16/08, Potsdam, GFZ German Research Centre for Geosciences, 24 p., doi: 10.2312/GFZ.b103-16087, available online at: https://gfzpublic.gfz-potsdam.de/rest/items/item_5003806_1/component/file_5003807/content.

Wagener A., Stassart C., Etienne A.-M., 2022: COVID-19 and its lockdown in Belgium: How limited access to environmental satisfaction impacts emotions? Psychol. Belg., **62**, 1, 34–46, doi: 10.5334/pb.1082.

Wziontek H., Wolf P., Häfner M., Hase H., Nowak I., Rülke A., Wilmes H., Brunini C., 2017: Superconducting gravimeter data from AGGO/La Plata – Level 1. GFZ Data Services, doi: 10.5880/igets.lp.l1.001.

Zhang K., Liu Z., Zhang X., Jiang Y., 2018: Comparison of noise-levels between superconducting gravimeter and gPhone gravimeter. Geod. Geodyn., **9**, 6, 498–503, doi: 10.1016/j.geog.2018.09.002.

Zhang M., Xu J., Sun H., Chen X., Zhou J., 2016: OSG-057 superconducting gravimeter noise levels in Lhasa (China). Terr. Atmos. Ocean. Sci., **27**, 6, 807-817, doi: 10.3319/TAO.2016.03.23.01(T).

Zhang X., Jiang Y., Zhang K., Zhang X., 2017: The influence of observation environment on background noise level of gPhone gravimeter. Geod. Geodyn., **8**, 6, 443–447, doi: 10.1016/j.geog.2017.06.002.