WAVELET TRANSFORM OF GRAVITY TIME SERIES IN HURBANOVO

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Abstract

The Hurbanovo Observatory has been part of the International Geodynamics and Earth Tide Service (IGETS) since 2021 and provides measurements utilizing the gPhoneX108 spring gravimeter. In this study, a wavelet decomposition using multiple types of wavelets was performed on the gravity time series with a 1-minute step. The study was performed on the gravity measurements during the February 2023 earthquakes in Turkey and Syria. The primary objective was to eliminate the influence of seismic events in the gravity time series using wavelet transform, aiming to find a balance between maintaining long-period signal components and minimising distortion of the original signal.

Keywords

Continuous gravity measurements, wavelet decomposition, gPhoneX, earthquake

1 INTRODUCTION

Continuous gravity measurements are often used in scientific studies focusing on earth tides, ocean, and atmospheric loading [1], [2], polar motion [3], [4], volcanic activity [5], hydrogeology, and other geodynamic processes, which are detailed in publications such as [6]. Observations of temporal changes in gravity acceleration using gravimetric methods are typically performed by relative station gravimeters, with superconducting gravimeters (SG) [7] being the predominant choice due to their long-term stability, low level of instrumental noise, and low instrumental drift. The reliability of superconducting gravimeters (SGs) makes them a well-suited tool for studying both long-term and short-term changes in the gravity field caused by geodynamic processes and human activity. In contrast, relative spring gravimeters are characterized by less long-term stability and large instrumental drift. The gPhoneX gravimeter is a new generation of LaCoste-Romberg gravimeters with a zero-length spring, succeeding the PET (Portable Earth-Tide) relative spring gravimeter [8]. The feedback system in these instruments enables precise digital measurements at the level as fine as 0.1 μGal [9]. However, due to the instrument's sensitivity to external temperature, gravimeter tilts caused by temperature change and usually non-linear drift. Consequently, relative spring gravimeters are considered less suitable for monitoring long-term changes in the Earth's gravity field [5], [10]. Testing of gPhone gravimeters was performed by several authors, e.g., [11] and [12]. In the study [9], the authors tested the effect tilt-controlled platform on the long-term stability of the instrument, where the correlation coefficient between gPhoneX and a superconducting gravimeter reached a value of 0.99. Spring gPhoneX gravimeters are, however, a suitable tool for monitoring non-periodic high-frequency phenomena such as earthquakes [10].

The wavelet transform (WT) is a mathematical approach employed in signal analysis that allows the decomposition of a time series into small parts, called wavelets with different frequencies and lengths. The wavelet transformation offers an alternative to short-term Fourier transform (STFT) [13], which is used to determine frequency and phase of periodic content in a time series [14]. Unlike STFT, which uses one analytical window, WT uses short windows at high frequencies and long windows at low frequencies [13]. In gravimetry, wavelet transform was used to test the effect of local atmospheric pressure on gravitational acceleration using Daubechies wavelet [15]. The authors in the article created a time and frequency-dependent coefficient of atmospheric pressure effect on gravity acceleration thanks to wavelet decomposition of the time series. Filtering continuous gravimetric measurements using Daubechies wavelet was also performed to eliminate noise and estimate the gravitational factor of Chandler's period at four gravimetric stations in Europe [16]. After processing with wavelet filtering, measurements from superconducting gravimeters provide parameters of Chandler's oscillation with a much smaller root mean square deviation than previous studies. For instance, Hu et al. [17] processed measurements from a superconducting gravimeter during an earthquake in Sumatra and Andaman applying wavelet method to remove local fluctuations of atmospheric pressure from changes in gravity acceleration. Their research demonstrated the importance of continuous gravity measurements with a superconducting gravimeter in seismology, and that the

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use of wavelet filters can also contribute to the enhancement of signal-to-noise ratio (SNR) in SG measurements. According to authors Bogusz et al. [18], who applied wavelet transform to decompose time series of gravity acceleration from SG at Bad Homburg and Wettzell stations, this method is a suitable tool for interpolation and filtering of gravimetric measurements and elimination of noise.

International Geodynamics and Earth Tide Service (IGETS) [19] was established to monitor temporal variations in the Earth's gravity field using continuous gravity measurements by relative gravimeters, tiltmeters, and other geodynamic sensors. It has been operating since 2015 as a continuation of the previous activities of the Global Geodynamics Project (GGP) [20], [21]. Currently, IGETS provides data from almost 50 gravimetric stations located around the world. Correction of the perturbations in gravity time series such as spikes and earthquakes are performed by using a threshold on the derivative of the gravity residuals [19], [22].

2 METHODOLOGY

The Hurbanovo Gravimetric Observatory stands as the only tidal gravimetric station in Slovakia and has been part of IGETS since 2021 [23]. The Hurbanovo Observatory is in a joint area with the Hurbanovo Geomagnetic Observatory (Earth Science Institute, SAS) and the Slovak hydrometeorological institute and has been part of the integrated HUVO station since 2019. Continuous gravity measurements are ensured by a relative spring gravimeter featuring a zero-length spring, specifically the gPhoneX#108. The coordinates of the gravimeter is 47.8724° north latitude and 18.1932° longitude. The instrument is strategically located within a low building on an isolated concrete pillar, which serves to eliminate the influence of building tilts on measured gravity acceleration and microseismic building noise. To further ensure accuracy, the room where the gravimeter is located is thermally stabilized to approximately 26 °C using an air conditioning unit. Additionally, the gravimeter is also surrounded by polystyrene insulation to minimize possible temperature fluctuations in the room.

The gPhoneX#108 gravimeter was temporarily located in the building of the Faculty of Civil Engineering of the Slovak University of Technology in Bratislava from 2016 to 2019. A detailed analysis of continuous measurements of gravity acceleration and atmospheric pressure in the STU premises can be found in publication [10]. Since the faculty is in the centre of the capital city of Slovakia and is characterized by a high level of microseismic noise, placing a gravimeter at this location was not suitable in terms of long-term stability, microseismic noise caused by traffic, and other environmental influences. The gPhoneX gravimeter was transferred to Hurbanovo in autumn 2019 and has been performing continuous measurements of gravity acceleration there since May 2020.

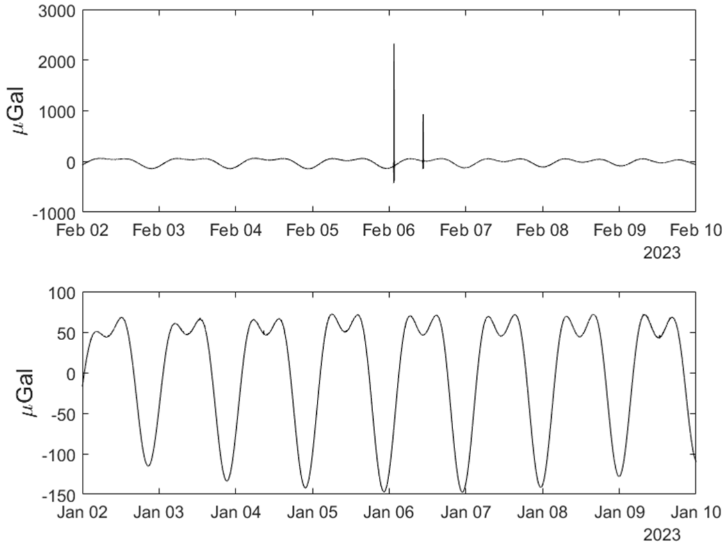

Fig. 1 Gravity time series in Hurbanovo (bottom: quiet period; top: earthquake).

Minute data from measured gravity acceleration in Hurbanovo were used in this study. The analysed data related to two periods: a quiet period when the gravimeter operated without any perturbations, and a period during the earthquake in Syria and Turkey in February 2023 (Fig 1). The earthquake under investigation occurred on February 6, 2023, at 1:17 UTC impacting southern and central Turkey and northern and western Syria. The seismic event reached a magnitude M_W of 7.8. The epicentre was in Pazarcık district of Kahramanmaras province.[24].

The earthquake had a maximum intensity according to Mercalli scale XII around the epicentre and in Antakya. It was followed by an earthquake with a magnitude M_W of 7.7 at 13:24 [24].This earthquake had an epicentre 95 km northeast of the first epicentre. The earthquake caused extensive damage and tens of thousands lost their lives.

Wavelet decomposition

Wavelet transform is a mathematical approach to signal analysis that allows for the decomposition of the signal into small parts. The basis of wavelet analysis are base functions, called wavelets. Wavelets are a form of waves with effectively limited duration with zero mean value and non-zero form [25]. In comparison with sinusoidal waves, which form the basis of Fourier transforms, sinusoids do not have a limited length but continue from negative infinity to positive infinity [25]. Wavelets are obtained from the basic wavelet by stretching and shrinking and shifting. Therefore, in WT, the concept of scale is introduced as an alternative to frequency, leading to so-called time-scale representation. This means that the signal is transformed into a time plane (equivalent to the time-frequency plane used in STFT) [13]. This allows for better localization and identification of events in the signal that could be difficult to record using Fourier transform.

Wavelet transform is performed using convolution of the signal with the wavelet function. There are several types of wavelet transform depending on the application. Discrete Wavelet Transformation (DWT) is the most used form of wavelet transform.

For discrete wavelet transform, the following defining relationships apply:

For DWT using a low-pass filters:

$$cA[j+1](t) = \sum(h[k] \cdot cA[2j-k] \;\; \text{for}\, j = 0, 1, \ldots J-1 \tag{1}$$

For DWT using a high-pass filter:

$$cD[j+1](t) = \sum(g[k] \cdot cA[2j-k] \;\; \text{for}\, j = 0, 1, \ldots J-1 \tag{2}$$

where: $cA[j]$ and $cD[j]$ are low-pass and high-pass coefficients at the j-th resolution, $h[k]$ and $g[k]$ are coefficients of the low-pass a high-pass filter (wavelet function), J is the maximal level of the decomposition.

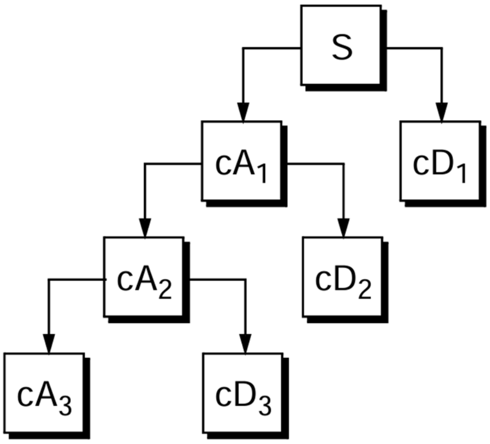

Fig. 2 Wavelet Decomposition Tree [25].

The low-pass filter in DWT typically captures low-frequency components of the signal and eliminates higher frequencies, thereby creating an approximation of the signal. On the other hand, the high-pass filter in DWT captures higher frequencies of the signal and eliminates low-frequency components. The output from the high-pass filter represents the details or edges of the signal. The decomposition process can be repeated, with subsequent approximations being gradually decomposed into further iterations. This process is called a wavelet decomposition tree (Fig. 2). Since the analysis process is iterative, it can theoretically continue indefinitely. Decomposition can continue only until each individual detail is composed of a single sample or pixel [25].

There are many types of wavelets. The choice of a suitable wavelet depends primarily on the nature of the data, the required resolution, and the required number of decomposition levels, as well as other properties of wavelets, such as orthogonality, symmetry, or compactness. The process of choosing a suitable type of wavelet can sometimes be an experimental process where it is necessary to try different wavelets and observe which one provides the best results for a specific problem.

Gravity time series were decomposed using three orthogonal wavelets: Daubechies 8 (db8), discrete Meyer [26], and Vaidyanathan [27]. Daubechies 8 (db8) wavelets themselves are compact, orthogonal, and have eight coefficients, which means they can very well capture both short-term and long-term changes in the signal. The discrete Meyer wavelet is known for its ability to capture fine details in the signal, while Vaidyanathan wavelets are characterized by their symmetry and perform well in compressing signals with minimal dispersion. The compatibility of the original signal and reconstruction was demonstrated at a level of 7^{-10} μGal, which significantly exceeds the accuracy of the gravimeter. The result of time series decomposition is a breakdown of the time series into components, where each component represents a different frequency of the signal. The number of decomposition levels depends on the length of the time series. In each decomposition diagram, cD_1–cD_{12} are individual frequency components of the signal (Tab. 1). Oscillations at the beginning and end of the frequency component series are an artificial effect caused by trimming the signal.

Tab. 1 Frequency ranges of individual decomposition levels.

Level of decomposition	**Period (min)**
1	*2–4*
2	*4–8*
3	*8–16*
4	*16–32*
5	*32–64*
6	*64–128*
7	*128–256*
8	*256–512*
9	*512–1024*
10	*1024–2048*
11	*2048–4096*
12	*4096–8192*

The principle of filtering continuous gravity measurements using wavelet decomposition lies in the reconstruction of the signal from decomposition levels corresponding to the frequencies of tidal waves, or other significant periodic phenomena. Decomposition levels corresponding to earthquakes are not considered in this case, ensuring their elimination. With the aim of leaving only earthquakes from the measurements, and storing as much information as possible at higher frequencies, we used all levels of decomposition for signal reconstruction. In detail levels 1 to 8, we excluded coefficients exceeding the value of triple dispersion corresponding to the same level of detail during a quiet period.

3 RESULTS

The filtering results using individual wavelets (Fig. 3), reveal a reduction in the earthquake effect in gravity time series. However, there is also a slight distortion observed in the time series caused by the oscillations at the beginning and end as mentioned above. To address this, it is advisable to use longer time series to allow for subsequent trimming of these undesirable effects. The most fitting filtered time series during the earthquake appears to be the Vaidyanathan wavelet since the character of the sin waves was not as deformed compared to other wavelets. The use of the Vaidyanathan wavelet resulted in the best elimination of the earthquake's influence on gravity time series, striking a balance between preserving long-period signal components and minimizing deformation of the original signal.

The standard deviation (STD) of the residual gravity series (Tab. 2) for the filtered time series in contrast to the original time series and silent period was evaluated. Residual gravity time series represent the data after standard corrections were performed, such as solid Earth tides, polar motion, and ocean loading effects as described in [19], [28], [29]. STD values show a significant decrease for filtered time series compared to the STD of original gravity measurements. However, compared to the silent period of all filtered time series the STD is still significantly higher. It is important to note that the aim of the experiment is not to eliminate the effect of earthquakes completely, as this is impossible to achieve, but to reduce the influence as much as possible. The differences in STD between the wavelets used are less than 1 microgal. Considering the overall STD value, we can consider these differences to be irrelevant, although according to statistics, Meyer has the smallest STD, and Vaidyanathan the largest.

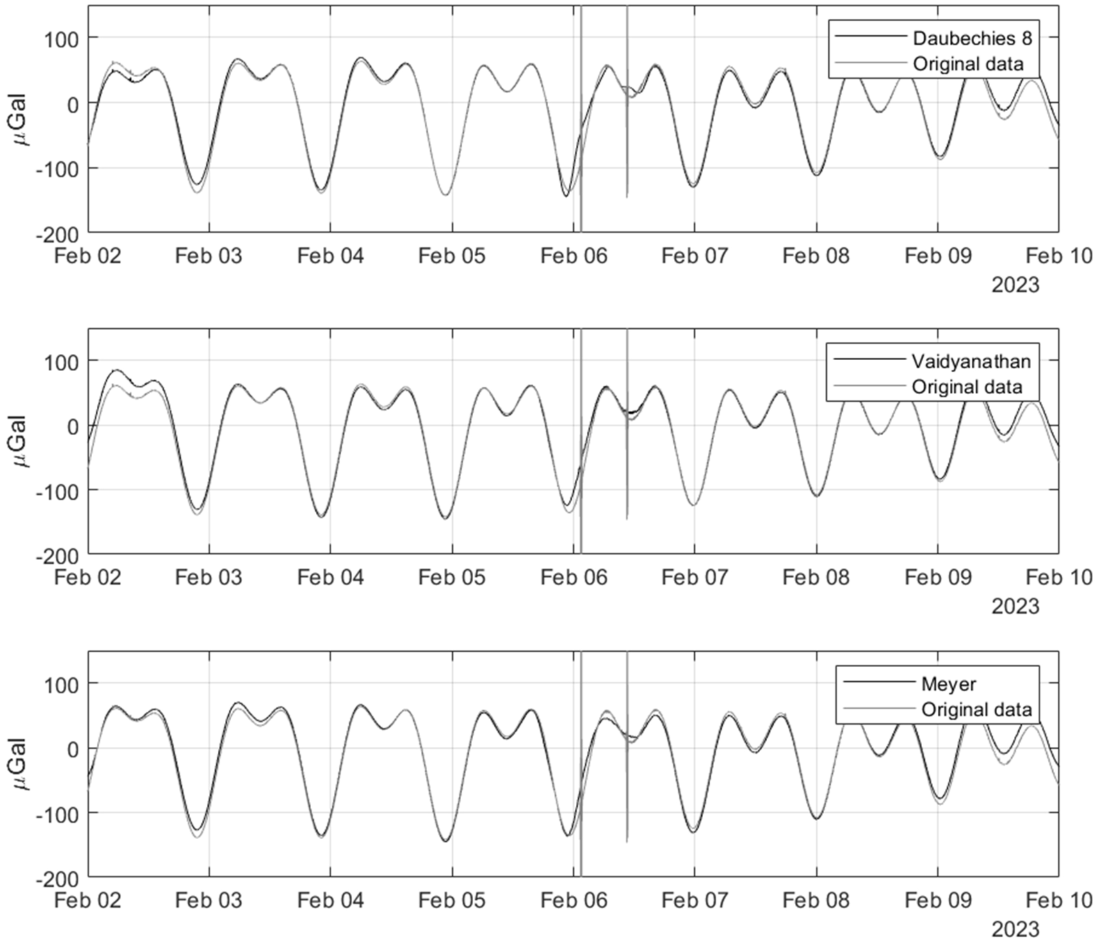

Fig. 3 Filtered time series using Daubechies 8, Vaidyanathan and Meyer compared to original time series.

Tab. 2 Standard deviation of gravity time series of original dataset, filtered time series using different wavelets and time series during silent period.

Time series	STD (μGal)
Original time series	*39.707*
Daubechies 8	*8.466*
Vaidyanathan	*8.667*
Meyer	*7.953*
Silent period	*0.756*

A scalogram is a visual representation of the time-frequency characteristics of a signal, displaying how its frequency content changes over time. The scalogram of the original and filtered gravity time series (Fig. 4) shows a reduction decrease of the earthquake effect in the higher frequencies after using wavelet filtering. In gravity time series after wavelet filtering, we can see two significant frequencies belonging to diurnal and semidiurnal periods of Earth tides. However, it can be seen, that the filtered signal still contains small parts of the earthquake signal in all types of wavelet filters. A closer look at the individual scalograms reveals several pieces of information. First, for the Daubechies 8 and Meyer wavelets, the higher frequencies (around 1 mHz) appear to be almost eliminated from the time series. As for the Vaidyanathan wavelet, in this case the part of the signal corresponding to the higher frequencies is preserved. Secondly, compared to the original time series, the spectrogram corresponding to frequencies in the interval 0.1 to 0.2 (semi-diurnal tidal signal) has partially changed its character when using Daubechies 8 and Meyer wavelet. In this case the Vaidyanathan wavelet best matches the waveform of the original signal.

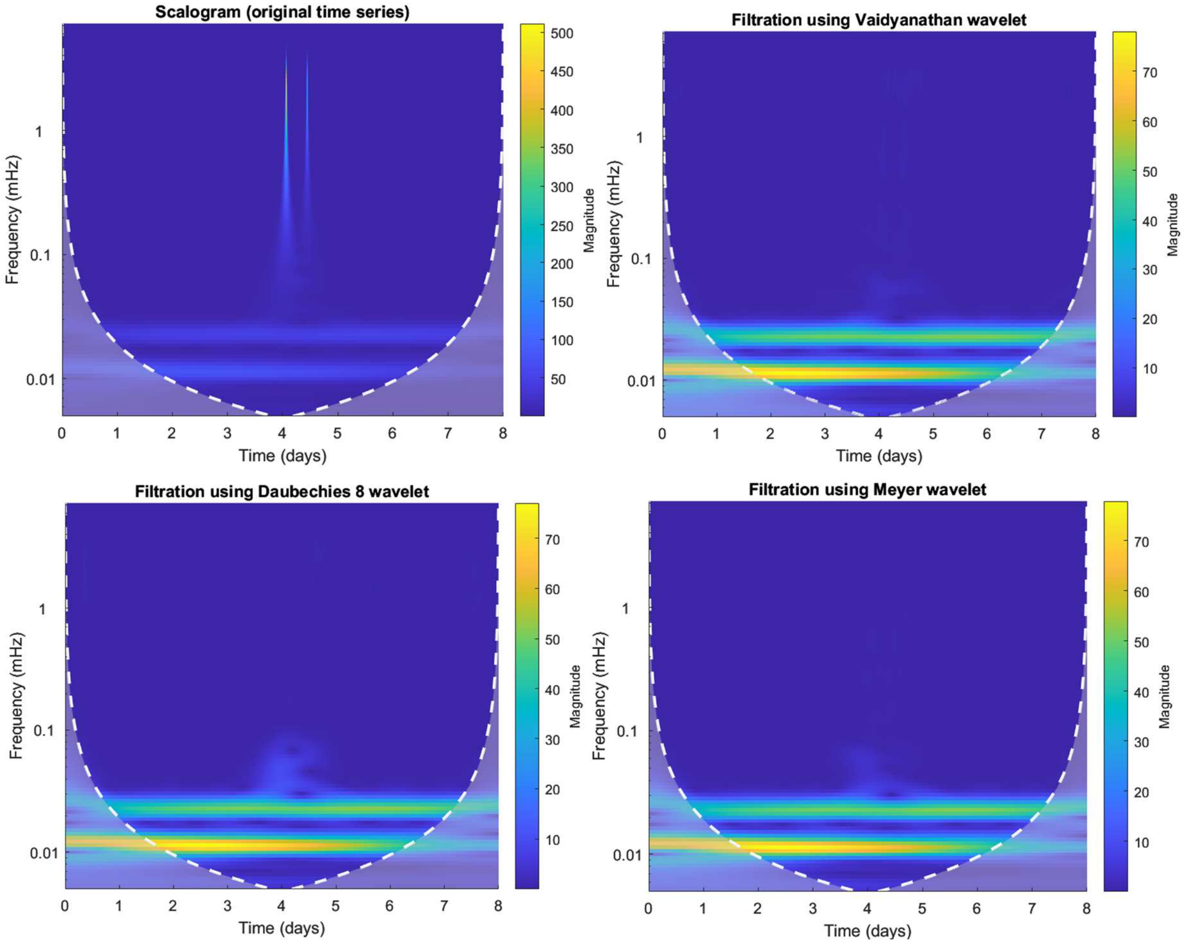

Fig. 4 Scalogram of the original (top left) and filtered time series using Vaidyanathan wavelet (top right), Daubechies 8 (bottom left) and Meyer wavelet (bottom right).

4 DISCUSSION

Wavelet decomposition is indeed a powerful tool in the analysis of time series of gravity acceleration. It allows for a detailed examination of the gravimeter's response depending on frequency and amplitude. This method is widely used in geophysics and seismology, as it enables a better understanding of the behaviour of the Earth's surface during various events, such as earthquakes. In wavelet decomposition, the gravity time series is broken down into various frequency components using special functions called wavelets. The essential property of wavelets is that they are localized in the time domain and in the spectral domain at the same time. However, due to the uncertainty principle, neither of these localizations is ideal. In contrast, the basic functions of the Fourier transform provide an ideal localization in the spectral domain, and hence no localization in the spatial/time domain.

5 CONCLUSION

The use of wavelet decomposition as a band-pass filter has a very wide range of applications for any type of data in order to reduce the influence of unwanted effects with known frequencies. In order to eliminate earthquake effect from measurements and retain as much information stored at higher frequencies as possible, all decomposition levels were used to reconstruct the signal. Based on the results (Fig. 3 and 4) obtained in this case study, it can be seen that when using this approach to eliminate earthquakes in gravity time series, the most suitable type of orthogonal wavelet was Vaidyanatha. The application of the Vaidyanathan wavelet provided the most effective reduction of the earthquake effect on the gravity time series, finding a compromise between maintaining long-period signal components and minimising distortion of the original signal. Reconstructing the time series from the wavelet decomposition causes fine oscillations at the beginning and end of each component's series, which is an artificial effect caused by the trimming of the signal. Therefore, it is advisable to work with a longer time period in similar studies so that the studied effect remains unaffected by this phenomenon. In the future, interesting results could be obtained by using other types of wavelets, which currently exist in large quantities, and by empirically determining the boundary at which coefficients corresponding to higher frequencies are still part of signal reconstruction. Further investigation of the Vaidyanathan wavelet using datasets from different instruments securing continuous gravity measurements and during multiple earthquakes should be carried out in the future.

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