Detection of Coherent Low-Frequency Atmospheric Pressure Oscillations Across Central Europe

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Long-term atmospheric pressure measurements across Central Europe reveal coherent oscillations at ultra-low frequencies (4 – 7 μHz), persisting over two decades. Using a demodulation technique adapted from signal processing, we identify reproducible spectral lines with complex phase modulation patterns. These signals are synchronized across geographically distant sensors and exhibit modulation periods ranging from months to decades. A prominent annual modulation suggests a correlation with Earth's orbital motion, implying a non-local origin. The inferred wave propagation speed ($\sim 2.4\times10^6$ m/s) and wavelength ($\sim 5 \times 10^{11}$ m) exceed known atmospheric dynamics, challenging current geophysical models. While the source remains unidentified, the findings suggest the presence of a previously unrecognized class of long-range atmospheric oscillations with potential astrophysical relevance.

1 Introduction

Atmospheric pressure variations are typically attributed to meteorological phenomena or gravitational influences from celestial bodies within the solar system. However, long-term pressure data collected across Central Europe reveal persistent, low-frequency oscillations that cannot be explained by known terrestrial or solar system dynamics. These signals exhibit remarkable coherence across geographically distant sensors and maintain stable modulation patterns over decades.

Previous studies have focused on high-frequency atmospheric dynamics or transient pressure anomalies. In contrast, this work investigates ultra-low-frequency oscillations using a demodulation technique adapted from signal processing. The findings suggest the presence of a previously unidentified class of long-range pressure waves, potentially originating from non-local sources. This study aims to characterize these signals, assess their reproducibility, and explore possible interpretations within geophysical and astrophysical frameworks. Some technical terms are explained in section 12.

2 Methods

Data Acquisition: Atmospheric pressure data were obtained from the German Weather Service (DWD), comprising hourly measurements from over 100 barometric stations across Germany between 2000 and 2020. Only stations with at least ten years of continuous operation were included. To enhance signal-to-noise ratio (*SNR*), pressure records were coherently summed across all stations. Correcting for long-term trends is unnecessary because the demodulation method only evaluates the signal amplitude within an extremely narrow frequency band ($\Delta f < 4$ nHz). This corresponds to averaging over a period of approximately ten years.

Sensor Calibration: All pressure sensors used by the DWD are temperature – compensated and conform to international standards, with a measurement range of 500-1100 hPa and an accuracy of ±0.1 hPa. Instrumental drift and data gaps remain unchanged because they do not produce continuous signals of constant frequency.

Signal Processing: Since we are only looking for phase-modulated signals [1], a well-known demodulation method similar to that used in GPS is applied [2]. The method iteratively identifies and compensates for constant modulation frequencies and concentrates the signal energy in a narrow spectral line. Unlike conventional FFT-based spectral methods, this approach preserves phase information and enables the detection of weak, phase-modulated signals below the noise threshold.

Demodulation of a PM signal cannot be achieved using standard methods such as the Welch spectrum, as this cannot analyze signals with SNR < 1.

Frequency Resolution: In order to achieve a frequency resolution better than 1 nHz, the minimum observation time T_{min} was set to 20 years, thereby satisfying the uncertainty principle [3] $T_{\text{min}} \cdot \Delta f \geq 1$. This long-term integration enables the detection of modulation periods ranging from months to decades. The long-term stability of the barometers does not need to be taken into account. An incorrect value could influence the amplitude of the signal, but would not generate PM. The frequency drift of the signals is smaller than the bandwidth of the method and can be easily measured and compensated for using the superheterodyne method.

3 The Spectrum

Air pressure is not measured continuously, but at fixed time intervals of, for example, one hour ($T_s = 1$ hour). The inverse of T_s is called the sampling frequency f_s. Although the signal does not pass through an analog low-pass filter with a cutoff frequency of $0.5 \cdot f_s$ before measurement, aliasing effects are virtually eliminated when sampling atmospheric pressure hourly. This is especially true for $f < 20$ μHz, because the amplitudes in the lowest range are at least a factor of 10^5 higher than the spectral lines and the noise in the high frequency range ($f > 150$ μHz).

The spectrum in Figure 1 clearly consists of a continuum and a few strong spectral lines that are well known. If the continuum were instrument noise, the noise amplitude should decrease approximately proportionally to $1/f$. Indeed, in the range $f < 20$ μHz, it decreases approximately proportionally to $1/f^3$. One possible explanation is that the continuum describes the frequency of previously unknown sources. The causes of the strong spectral lines are known:

- Although the atmosphere roughly replicates the shape of Earth, it is not perfectly spherically symmetric. Since the density, pressure, and temperature of the atmosphere also depend on the time of day, barometers measure periodic changes in the frequencies $f \approx n \cdot 11.57$ $\mu\text{Hz} = n/(24 \text{ hours})$ with $n \in 1, 2, 3, ...$

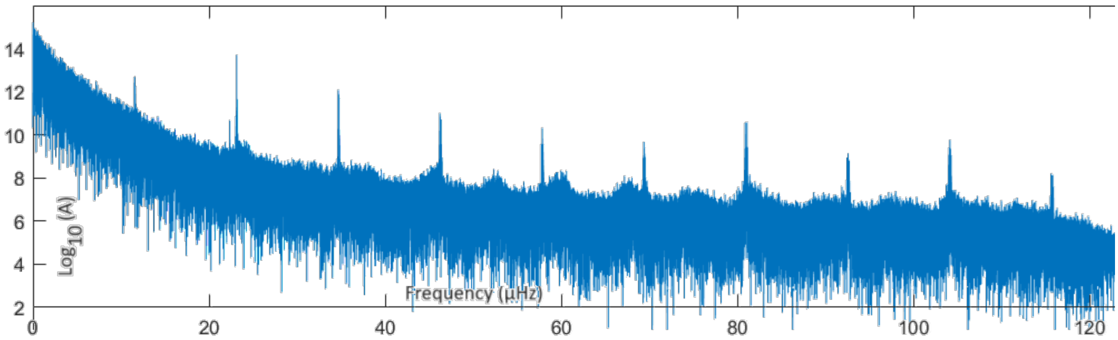

Figure 1): *Spectrum of air pressure in Germany, one measurement per hour. The data is based on the average air pressure between 2000 and 2020. The striking maxima lie well above the frequency range examined.*

- A special feature is the solitary peak at 22.3643 μHz. This is the strongest frequency at which the Moon deforms the Earth and the atmosphere (tides). These and many other 'astronomical' lines [4] are easy to identify because their frequencies are constant and unmodulated.

All spectral lines in Figure 1 lie well below the lowest natural frequency of the Earth ($_0S_2$ at 300 μHz). This refutes the frequently expressed assumption that resonant antennas are needed to detect oscillations generated by extraterrestrial sources.

4 The search area

Table [4] contains several frequency ranges *without* spectral lines generated by celestial bodies in the solar system. Indeed, in the wide gap at 4.1 μHz $< f <$ 7.45 μHz, one finds several matching lines measured at widely separated locations in Europe (see Figure 2). Adding the raw data *before* the spectrum calculation shows that not only the frequencies of the air pressure but also the phases are consistent across Europe. Since there is no known cause for this synchronous pulsation of the air mass in Central Europe, the properties of several striking coincidences are examined in detail.

The synchronicity of the oscillations implies that the wavelength λ must be significantly greater than the distance between the locations mentioned in Figure 2. Assuming $\lambda \approx 6 \times 10^7$ m, the propagation speed of these waves is calculated to be at least $v = \lambda f \approx 300$ m/s. This is approximately the speed of sound in air.

5 Data source and preparation

From the figure 2, we can see that the frequency resolution Δf should be better than 1 nHz. This value can only be achieved by analyzing sufficiently long data chains. Using Küpfmüller's equation [3]

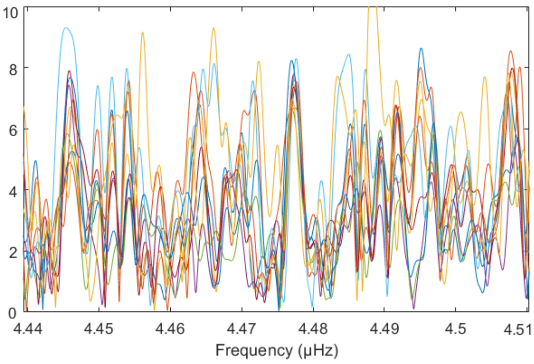

Figure 2): *The superposition of a narrow range of air pressure spectra in Amsterdam, Berlin, Brussels, Bern, Budapest, Dublin, London, Paris, Vienna, and Stockholm between 1990-01-01 and 2022-07-01 reveals surprising similarities with no known cause.*

$$T_{min} \cdot \Delta f \geq 1 \qquad (1)$$

we calculate the minimum duration $T_{min} > 16$ years. The German Weather Service (DWD) stores air pressure data from many barometers, which, after some preliminary work, constitute a good data source. Atmospheric pressure is inherently band-limited, and an hourly sample is sufficient to represent all relevant variations. To reduce the influence of local peculiarities and isolated data gaps, we aggregate the records of as many barometers as possible that are distributed throughout Germany and have been in operation for at least ten years. We found 64 data chains between 2000 and 2009, and only 51 between 2010 and 2019. Between 2000 and 2009, 64 data chains were found, compared to only 51 between 2010 and 2019. The coherent addition of many records improves the *SNR* and reveals spectral lines that would otherwise disappear in the noise when analyzing individual data chains. If barometers occasionally need to be replaced, discontinuities may occur in the records. These discontinuities are never synchronized and therefore only increase the noise level. This does not impair signal analysis because discontinuities cannot excite a persistent interference signal of a defined frequency.

Possible climatic influences and seasonal cycles have time constants that exceed the oscillation period of the signals under investigation (approximately two days) by orders of magnitude. Therefore, correction of the barometer data is unnecessary.

6 How do you receive signals in noise?

In the early years of radio technology, the prevailing view was that weak signals can only be detected if the signal amplitude is greater than the noise amplitude ($SNR > 1$). We now know that this is not always true for phase-modulated signals. Systematic studies show that with special modulation techniques such as *spread spectrum*, messages can be reliably transmitted even if the signal amplitude does not reach the noise level. A good example is the GPS method for determining location [2]. The signals are so weak that it is hard to detected them in the FFT spectrum ($SNR \ll 1$). However, if the signals are received over a sufficiently long period T and the exact modulation is known and taken into account, the signals can be detected. The transmitted data can be deciphered accurately even if multiple satellites are transmitting on the same frequency – because they are phase-modulated differently. Even poor receiving antennas, such as those found in mobile GPS devices, are no obstacle.

A prerequisite for success is highly developed demodulation technology. For coherent detection systems, the following approximately applies:

$$SNR \propto A \cdot \sqrt{\frac{T}{B}} \tag{2}$$

In this equation, A is the amplitude of the signal. Increasing observation time T improves the SNR while increasing bandwidth $B \approx \Delta f$ reduces it. However, the two quantities T and B in Equation (2) cannot be chosen independently of each other. They are related by the Küpfmüller uncertainty principle (1), which means: $T \cdot B \geq 1$. This simplifies Equation (2) to

$$SNR \propto A \cdot T \tag{3}$$

In other words, the lower the amplitude A, the longer the observation time required to decode the signal using coherent demodulation. The method used here integrates the signal over a total period of 20 years.

Through precise synchronization, the receiver specifically locates the signal components that correlate with the carrier – the noise, on the other hand, is random and averages out. Therefore, coherent demodulation can detect even weak traces in the noise as long as it knows what it is looking for. In technical processes such as GPS, the modulation is defined in such a way that signal transmission is robust. In the case of the continuous oscillations investigated here, we have to determine experimentally whether and how they are modulated. We estimate the parameters and then optimize them iteratively.

7 Demodulation reduces the signal bandwidth

Signals are never perfectly monochromatic, and deviations allow conclusions to be drawn about the properties of the source and the transmission path. Essential information is lost if one restricts oneself to observing one – usually the strongest – spectral line. This information is contained in the sidebands on either side of the carrier frequency and is referred to as modulation. Unlike in technical applications, in astronomy there are rarely any clues as to where and how strong these accompanying frequencies might be. If the signal is phase-modulated (often unavoidable due to the Earth's orbital velocity), the structure of the spectrum can be very complex and is then barely distinguishable from noise.

As Figure 3 shows, the total energy of a phase-modulated signal can be distributed across several spectral lines—and some lines can disappear in the noise. The initially

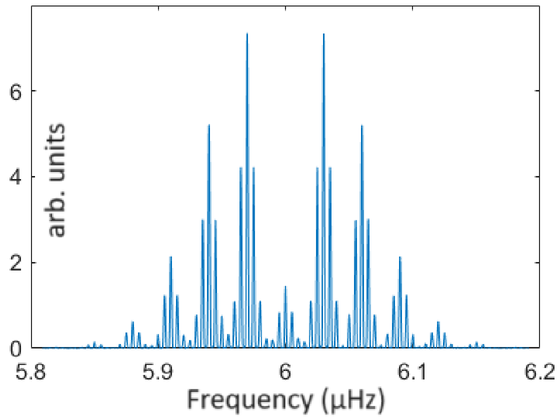

Figure 3): *Spectrum of a signal with a carrier frequency of 6 μHz, phase-modulated with only two different frequencies (without noise). The total energy is distributed across more than 40 weak spectral lines covering a wide frequency range (Carson bandwidth). With an unfavorable modulation index, the sidebands are stronger than the actual signal frequency.*

unknown modulation index determines the exact frequency, amplitude, and phase of each line. With weak signals, it is almost impossible to identify each line in the noise, assign it to the desired signal, and measure it with the required accuracy. However, the biggest disadvantage is that the spectral lines in question must be searched for over a wide frequency range to ensure that no relevant lines are excluded. A large bandwidth always results in a high noise level that drowns out weak signals. This means that only strong signals can be detected.

The search for weak signals with the frequency f_{signal} requires working with the smallest possible bandwidth—in other words, avoiding any modulation. Technically speaking, you first have to eliminate the modulation in order to concentrate all the energy on a single spectral line, and only then can you reduce the bandwidth. With a phase-modulated signal, this is relatively simple: you modulate a local auxiliary oscillator with a slightly different frequency f_{osc} so that its modulation matches the modulation of the signal. This requires experimentation and patience. If the imitation is successful, the difference frequency $f_{signal} - f_{osc}$ is constant and a clear and easy-to-control criterion. The difference frequency and amplitude are checked using a lock-in amplifier: This is a special phase-sensitive detector that uses correlation to extract signals that are up to 10^5 times smaller than the noise.

The method significantly improves the signal-to-noise ratio: the total energy of the signal, which was previously distributed across many lines, is now concentrated on a single spectral line with greater amplitude. This signal can be easily identified in the noise even without a narrowband filter (see Figure 4). The following investigation is therefore limited to phase modulation.

The method described cannot perform miracles and convert uncorrelated noise into a coherent signal with high spectral purity. An increase in the amplitude of the difference frequency $f_{signal} - f_{osc}$ requires that a signal be hidden in the noise whose phase modulation matches that of the auxiliary oscillator. The good *SNR* of the demodulated signal (Figure 4) is not the result of extremely narrow filters that suppress all sidebands. The good *SNR* is achieved exclusively by the phase-correct addition of all sidebands that are present but not recognizable in the original signal mixture (Figure 2).

8 The search method

Every signal transmission requires a certain bandwidth, which is often significantly smaller than the signal frequency. This allows the frequency of a sufficiently wide range around the carrier frequency to be reduced to approximately 0.3 μHz (superheterodyne method) and the interval between two data points to be spread by a factor of a thousand (decimation to $T_s = 1000$ hours). The consequences: The time required for all calculations is significantly reduced, only slow modulations with periods of several weeks can be detected and Kurzfristige ($< T_s$) Wetterphänomene haben keinen Einfluss.

It makes little sense to search for symmetrical structures like those in Figure 3 in a noisy signal mixture like the one in Figure 2. This is primarily because a spectrum destroys all phase information. The demodulation method described above avoids this problem: It contains no FFT, no magnitude generation, and does not destroy phase information. It therefore detects related spectral lines and combines only these. It ignores noise and interfering spectral lines from other signal sources that do not fit the frequency and phase scheme of phase modulation (PM).

This search method iteratively determines the values of a slow frequency drift and several periodic phase modulations of a signal. Which and how many f_{mod} are searched for and can be confirmed after a longer iteration period (see equation (5)) is a matter of experimental skill and patience. The more modulations are found and eliminated, the higher the total energy of the signal in a narrow range around the central frequency. This increases the amplitude of this spectral line, which can significantly exceed the noise level (Figure 4).

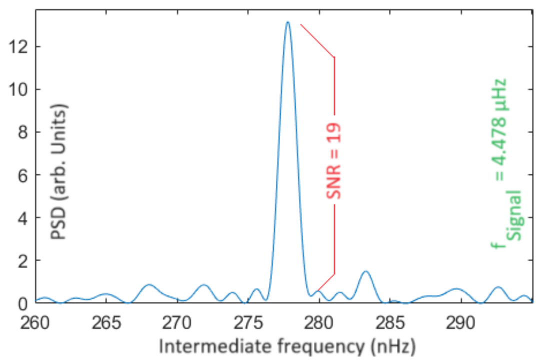

Figure 4): *Power spectrum of the signal (Welch method) at a frequency of* $f = 4.478$ *µHz after successful demodulation. Phase modulation compensation (see table 1) eliminates the sidebands and increases the amplitude of the carrier frequency. The method shifts the signal frequency to a value of* $f_{IF} = 1/(1000$ *hours).*

We emphasize that the described reconstruction of the carrier frequency has nothing to do with spectral analysis. PM distributes the energy of the carrier frequency across a bundle of many sideband frequencies that occupy a certain bandwidth (Figure 3). The amplitudes, phases, and exact individual frequencies follow from the laws of PM. The demodulation process does the opposite, as in GPS [2]: it detects these sideband frequencies *without spectral analysis* and regenerates the original carrier frequency (Figure 4). This increases the amplitude of f_{signal}, and the noise is largely ignored.

9 Results

The spectra of widely scattered barometers in Germany show several matching lines where none are expected. The following tables show the modulations of some of the outstanding signals.

Table 1): *The signal at* $f = 4.47803 \pm 0.00014$ *μHz is phase-modulated at six different frequencies. The frequency drift is* $\dot{f} = 45.2 \times 10^{-20}$ *Hz/s.*

	Mod-1	Mod-2	Mod-3	Mod-4	Mod-5	Mod-6
f_{mod} (nHz)	0.934	3.42	14.28	31.638	38.70	94.96
P (years)	33.9	9.26	2.22	1.0012	0.819	0.334
φ	4.07	5.44	0.93	4.84	1.79	3.86
η	1.83	2.99	4.59	4.24	4.22	3.62

Table 2): $f = 5.854$ *μHz. The frequency drift is* $\dot{f} = 0.88 \times 10^{-20}$ *Hz/s*

	Mod-1	Mod-2	Mod-3	Mod-4	Mod-5	Mod-6	Mod-7
f_{mod} (nHz)	0.963	4.45	9.219	16.78	31.496	40.907	57.13
P (years)	33	7.1	3.44	1.89	1.006	0.775	0.55
φ	0.62	2.84	4.33	5.08	0.797	-0.017	0.766
η	0.39	0.93	2.32	1.59	1.795	0.917	2.07

Table 3): $f = 6.3158$ *μHz. The frequency drift is* $\dot{f} = 35.5 \times 10^{-20}$ *Hz/s*

	Mod-1	Mod-2	Mod-3	Mod-4	Mod-5	Mod-6	Mod-7
f_{mod} (nHz)	0.946	1.236	4.187	12.03	32.3021	39.26	57.51
P (years)	33.5	25.7	7.6	2.64	0.982	0.808	0.55
φ	1.69	0.671	4.724	2.87	0.074	4.56	1.96
η	1.44	1.595	4.90	2.652	3.383	5.722	2.00

Where:
–Line-2: The modulation frequency of the signal
–Line-3: The oscillation period $P = 1/f_{mod}$
–Line-4: The individual phase shift of the modulation. The reference time is the start of the measurements on 2000-01-01
–Line-5: The modulation index η of the phase modulation

It is difficult to detect periodic processes extending over even longer periods in data sets with a time span of 20 years. Therefore, we refrained from looking for modulations with $P \geq 40$ years, as it is difficult to distinguish them from linear frequency drift.

Each spectral line exhibited complex phase modulation, characterized by up to seven distinct modulation frequencies ranging from 0.93 to 95 nHz. The most prominent modulation period was approximately one year, consistent across all signals. After iterative demodulation, the *SNR* of the carrier frequencies increased by up to a factor of 20, revealing previously obscured spectral structure.

The observed frequency drift of the carrier signals was linear and positive, with rates between 0.88×10^{-20} Hz/s and 45.2×10^{-20} Hz/s.

A change in the sensitivity of the barometers can only affect the (irrelevant) signal amplitude, but not the value of f_{signal}. The measurement accuracy of f_{signal} is extremely high: a lock-in amplifier follows the signal maximum (see Figure 4) with a precision of $df \approx \pm 0.2$ nHz. If this limit is exceeded, f_{mod} and the drift $\dot{f}$ are adjusted. This results in an accuracy of $\sim 4 \times 10^{-5}$ for f_{signal}. The same applies to a jitter Δt of the sampling times of the sensors: Before data analysis, decimation to $T_s = 1000$ hours is performed. Therefore, a random or systematic fluctuation of a few seconds is irrelevant ($\Delta t/T_s \approx 10^{-6}$).

This concludes the description of the technique and results of the signal analysis.

10 Interpretation of the Results

Instrumental drift or seasonal influences cannot produce sharp spectral lines in the range of 4–7 µHz with precisely defined frequencies and a total duration of 20 years. This is because the coherent demodulation method used extracts the carrier frequency f_{signal} (see Figure 4) from more than 40 different sideband frequencies (see Figure 3) while observing stringent phase conditions, all 40 spectral lines would also have to be generated with the same precision. It is impossible for this constellation to occur frequently enough and with low deviations in noise.

Some weather phenomena can be predicted from measurements of atmospheric pressure. However, forecasts become unreliable after a few days. The spectrum in Figure 1 also shows regularities that persist over the long term but have little effect on the weather. These spectral lines can be divided into two groups: Either they are caused by the rotation of the Earth, in which case the frequencies are $f \approx n \cdot 11.57$ μHz $= n/(24$ hours$)$ with $n \in 1, 2, 3, ...$ Or they are 'astronomical' lines produced by neighboring celestial bodies and have very different amplitudes [4]. These lines are easy to identify because their frequencies are constant and unmodulated.

In atmospheric physics, *normal modes* are well known. These are oscillations with periods of several hours, which are excited by earthquakes, for example. Rayleigh and acoustic waves exist at all altitudes, while tsunami and gravity waves only exist at high altitudes, where they are damped by attenuation [6]. These oscillations are not recognizable as spectral lines in the low-frequency range ($f < 10$ μHz) of Figure 1 because they only last for a short time and because the frequencies are easily influenced. Nowhere are periodic air movements of defined frequency observed—neither over short nor over longer periods of time. This also supports the theory: In [7], Figures 3 and 4 show that there are oscillations with periods between 7 and 12 days, but the values can only be specified very imprecisely.

However, in a narrow frequency range at 5 μHz, spectral lines are found (Figure 2) that do not belong to any of the groups mentioned and that should not actually exist. What is astonishing is the extraordinarily high frequency constancy over a period of twenty years and the strong PM (large modulation index η) with few discrete frequencies. This raises questions: What mechanism generates these continuous oscillations? What mechanism modulates their phase?

The following investigation is limited to modulation with a period of $P \approx 365$ days, because this can be interpreted as the Earth's orbital period and because it is a common feature of all measurements. Astronomers conclude from this period that the sources of these mysterious waves lie outside the solar system. However, they would be surprised to learn that distant stars can influence the atmosphere.

The striking improvement in *SNR* between the original signal in Figure 2 and the demodulated signal in Figure 4 is *only* the result of removing the PM and can be described using the approach

$$y = sin(2\pi t \cdot f_{signal} + \phi_{modulation}) \tag{4}$$

The two parameters f_{signal} and $\phi_{modulation}$ must be adapted to the problem: The frequency f_{signal} can change proportionally to time and $\phi_{modulation}$ can be the sum of several sine functions. If the modulation consists of a single frequency f_{mod}, the equation is

$$y = sin(2\pi t(f_{signal} + t\dot{f}) + \eta \cdot sin(2\pi t f_{mod} + \varphi)) \tag{5}$$

A sinusoidal PM causes the instantaneous frequency of the signal to fluctuate periodically between the limits $f_{signal} + \Delta f$ (maximum blue shift) and $f_{signal} - \Delta f$ (maximum red shift). The quantity Δf is referred to as the frequency deviation. The instantaneous frequency at a given point in time is difficult and inaccurate to measure, as it is never constant over a longer period of time. It is easier and more common to determine the modulation index η using equation (5) and calculate $\Delta f = \eta \cdot f_{mod}$. The results can be found in Table 4. Below, we discuss what could cause the waves with the values of f_{signal}, Δf, and f_{mod}.

10.1 Sources within the earth?

Earthquakes excite the earth into damped natural modes, which can also influence the atmosphere and fade away after a few weeks. The value of the lowest natural frequency is ~ 300 μHz, which is well above the frequency range investigated. The frequency of the *Slichter triplet* is assumed to be ~ 50 μHz, but this has not yet been proven. No continuous signals with constant amplitudes are generated in the earth.

10.2 Sources within the atmosphere?

The PM of a constant-frequency signal is based on physical mechanisms that change the temporal position of the oscillation without directly affecting its frequency or amplitude. When an externally generated signal—such as light—travels through a medium with a variable propagation velocity, the phase can be modulated. In atmospheric physics, there are several possibilities:

- A variable propagation velocity modulates the phase of the wave—a classic case of dispersive PM. Doppler PM caused by wind fields arises from the following mechanism: a moving air parcel changes the effective phase of a signal that is 'reflected' by scatterers. This can be used to determine the velocity of aerosol particles and cloud droplets. The detection requires a coherent detection method and is used in Doppler lidar or radar wind profilers. There is no reason to assume that the scattering bodies perform periodic movements with precisely defined frequencies around 5 μHz.

- Interference of coherent wave fields. Mechanism: The superposition of several coherent atmospheric waves (such as planetary waves, Kelvin waves) can lead to constructive or destructive interference. This can modulate the phase of a signal through the relative phase position of the superimposed waves. Application: Analysis of reanalysis data to identify mode coupling or resonance phenomena.

- PM through mode coupling of atmospheric eigenmodes. Natural resonance modes exist in the free atmosphere, such as Lamb waves, Rossby waves, and acoustic-gravitational modes. When several of these modes are excited simultaneously and overlap, mode coupling can occur.

  Mechanism: The phase positions of the modes differ. Coupling results in a time-varying phase relationship that manifests itself as PM in the overall signal. This can be particularly relevant in nonlinear coupling processes, such as through interaction with large-scale flows or thermodynamic gradients. Application: In your analysis of coherent pressure oscillations, such couplings could appear as a slow drift in the phase position.

The mechanisms described do not generate signals, but they can modulate (optical) test signals. In all cases, the cause of the modulations is that light is scattered by aerosol particles and cloud droplets and received at a different frequency. The frequency difference is proportional to the velocities of these scattering bodies, poorly defined, and certainly not limited to a few precisely measurable individual values (see f_{mod} in Tables 1..3). Even more seriously, no scattering body and no Kelvin wave in the atmosphere moves with periods of several years.

The lowest natural frequency of the atmosphere is $f_{resonance} \approx 11.57$ μHz (Figure 1) and is the synodic rotation frequency of the Earth. Neither on the Earth's surface nor in the atmosphere are there any known mechanisms that generate continuous oscillations of air pressure at lower frequencies with high spectral purity for decades, for example at $f = 4.47803 \pm 0.00014$ μHz. Therefore, there is no need to discuss how PM could occur at defined frequencies f_{mod}.

10.3 Sources in the solar system, but outside the atmosphere?

Nearby celestial bodies periodically deform the Earth and the atmosphere at different rhythms. Table [4] lists about 13,000 frequencies, none of which are phase-modulated with frequencies specified in Tables 1.. reftab:6.316. The values of f_{signal} in Table 4 were chosen so that they lie within a wide gap in [4]. Thus, there are no sources in the solar system that generate the observed waves.

10.4 Sources outside the solar system?

Since there are no sources for the observed waves on Earth or in the atmosphere, external sources could exist. The assumption of sources far outside the solar system provides a simple explanation for the observed periodic PM with $f_{mod} \approx 31.7$ nHz. The reciprocal is almost exactly the orbital period of the Earth around the Sun. If the source is located near the plane of the ecliptic, we measure a higher frequency for six months because the distance between the source and Earth decreases at a maximum speed of 30 km/s. The opposite is true in the following six months. The Doppler effect enables the evaluation of this frequency shift and is a fundamental principle of astronomy.

We do not discuss what generates the waves there. We assume that the signal propagates at the speed of light c and we use the relativistic equation

$$\Delta f = f_{signal} \cdot \left(\sqrt{\frac{c+v}{c-v}} - 1 \right), \tag{6}$$

where v is the relative velocity between the source and the Earth. When the source is conveniently located near the plane of the ecliptic, the Earth's velocity oscillates in the range -30 km/s $< v <$ 30 km/s and the Doppler shift in the range -0.5 nHz $< \Delta f <$ 0.5 nHz. These limits should apply to all values of f_{signal} in Table 4, but are about a factor of 100 smaller than the results Δf in this table. The discrepancy can only mean one of two things: Either the sources are not outside the solar system, or the waves do **not** propagate at the speed of light.

10.4.1 Speculative solution to the contradiction

A total of five different signal frequencies were investigated, all of which are phase-modulated with the frequency $f_{mod} \approx 31.7$ nHz. The striking proximity to the sidereal orbital frequency of the Earth tempts us to let our imagination run wild: Could it be that the sources are located outside the solar system and emit waves that do *not* propagate at the speed of light?

For $v_{signal} \ll c$, it is usually assumed that the wave propagation occurs in a medium. If the signal source is at rest and the observer moves with the velocity $v_{observer}$, the Doppler equation is

$$\Delta f = \frac{v_{observer} \cdot f_{signal}}{v_{signal}} \tag{7}$$

The measurements show that all signals are phase-modulated and have sinusoidal components due to equation (5). As in Section 10.4, we assume that the source is located near the plane of the ecliptic. The velocities calculated from equation (7) in column 5 of Table 4 are much smaller than the speed of light and deviate significantly from the (unconfirmed) predictions of general relativity. There is no known wave phenomenon with $v_{signal} \approx c/100$.

Table 4): *The speed of the signals for $f_{mod} \approx 31.7$ nHz, assuming $v_{observer} = 30$ km/s*

f_{signal} (μHz)	P (year)	η	Δf (nHz)	v_{signal} $\times 10^6$ (m/s)
4.478	1.001	4.24	134.2	1.00
4.678	1.003	1.095	34.7	4.04
5.4992	0.989	2.425	77.7	2.12
5.854	1.014	1.795	56.1	3.13
6.316	0.981	3.383	109.3	1.73

The mean value of v_{signal} is $(2.41 \pm 0.54) \times 10^6$ m/s. This result is reproducible and cannot be explained by the physics of sound or the physics of light. The corresponding wavelength $\lambda = v_{signal}/f_{signal} \approx 5 \times 10^{11}$ m exceeds the diameter of the Earth by at least a factor of 10^4. This confirms the observation that all barometers in Europe pulsate synchronously, which means that the phase shift is negligible. The attempt to provide a theoretical foundation for v_{signal} would go beyond this context.

10.5 The direction of the sources

The phase angle φ in equation (5) allows us to calculate the day DOY $= 365 \cdot \varphi/2\pi$ (day of the year) on which we receive the maximum signal frequency. Six months later, the largest redshift value is measured. If the Doppler effect generates the PM of the signals and the speculation in section 10.4.1 is correct, the time of maximum blue shift has a special significance: the instantaneous frequency of the signal reaches its highest value because the Earth is "flying" towards the source. This statement could make it possible to narrow down the location of the source.

Table 5): *The most important properties of the analyzed signals*

f_{signal} (μHz)	P (year)	φ	Blueshift DOY	Redshift DOY	η	v_{signal} $\times 10^6$ m/s
4.478	1.001	4.84	281	99	4.24	1.00
4.678	1.003	3.023	176	358	1.095	4.04
5.4992	0.989	3.81	221	39	2.425	2.12
5.854	1.014	0.797	46	229	1.795	3.13
6.316	0.981	0.074	4	187	3.383	1.73

The meaning of the columns in table 5:
Column 1: The signal frequency; measurement error $\Delta f < 1$ nHz
Column 2: Oscillation period of the signal modulation with $P \approx 1$ year
Column 3: The measured phase angle in equation (5)
Column 3: Day of the year in which the highest signal frequency is measured
Column 4: Day of the year in which the lowest signal frequency is measured
Column 5: Modulation index of the PM frequency 31.7 nHz ($P = 1$ year)
Column 6: Wave propagation speed according to equation (7)

11 Discussion

The detection of coherent, low-frequency pressure oscillations across Central Europe over a 20-year period presents a novel atmospheric phenomenon. The signals exhibit remarkable phase stability and reproducibility, with modulation patterns that suggest a structured, non-random origin. The presence of a consistent annual modulation across all signals strongly implies a link to Earth's orbital motion, which in turn suggests that the source is external to the solar system.

The inferred propagation speeds ($\sim 2.4 \times 10^6$ m/s) and wavelengths are incompatible with known atmospheric wave modes, such as Rossby or gravity waves, which are typically dispersive and lack the observed spectral sharpness. Furthermore, the modulation frequencies do not correspond to known meteorological cycles or planetary harmonics. These findings challenge current geophysical models and suggest the existence of a previously unrecognized class of long-range atmospheric oscillations.

The result of v_{signal} is reproducible and cannot be explained by either sound or light physics. The corresponding wavelength $\lambda = v_{signal}/f_{signal} \approx 5 \times 10^{11}$ m exceeds the diameter of the Earth by at least a factor of 10^4, which confirms the observation that all barometers in Europe pulsate synchronously, meaning that the phase shift is negligible.

The surprisingly high value of v_{signal} and the large-scale synchronicity of the oscillations lead to the following interpretation: The waves do not pass through the atmosphere tangentially. Plane waves come from outside from a certain direction (see section 10.5) and move the entire atmosphere as a unit like a hard but light spherical shell. Since the more massive Earth moves differently within it, the atmospheric pressure at the interface, which is measured by barometers, oscillates. This model can be verified: In New Zealand—on the “other” side of the globe—a measurement of atmospheric pressure should yield an opposite-phase signal. It remains unclear why the atmosphere and the Earth move differently.

One possible interpretation, albeit speculative, is that these signals are manifestations of astrophysical wave phenomena, such as continuous gravitational waves (cGWs) from binary star systems. However, general relativity predicts that such waves would be far too weak to have a measurable effect on atmospheric pressure. This model also offers an explanation for the additional PMs with periods of up to 30 years: planets orbiting the binary star system generate a PM. Alternatively, the signals could be caused by an unknown coupling mechanism between astrophysical sources and the Earth’s atmosphere.

It can also be ruled out that the measured signals are caused by errors in the analysis program: the signal does not undergo Fourier analysis to examine its frequency bands. The reasons: Inappropriately selected parameters of the Fourier method can lead to misinterpretations. Furthermore, only signal mixtures with an SNR > 1 can be meaningfully examined using spectral analysis. Fourier analysis is well suited for finding unmodulated signals. Demodulation requires more subtle communication technology methods that enable the reconstruction of existing phase modulations.

The demodulation method used here—adopted from coherent communication systems such as GPS—proves effective in isolating weak, modulated signals below the noise threshold. The demodulation methodology introduced here may serve as a valuable tool for detecting weak, structured signals in other domains of geophysical and astrophysical research.

12 Technical terms

Describing signal analysis requires defined terms from communications engineering. Their use can complicate the understanding of the procedure and lead to misinterpretation. Therefore, some terms are explained in more detail below:

–**Oscillation, waves**: If a stone is thrown into a calm lake, waves are created that spread outward in a circular pattern. Initially, only the water molecules near the point of impact oscillate up and down, which repeats after a characteristic time—the oscillation period. The distance between neighboring maxima is the wavelength. It takes some time for the wave front to reach the shore. The propagation speed is determined from the distance traveled and the time required. This can also be determined by comparing it with another, known speed.

– **Carrier frequency**: Each radio station is assigned a precise transmission frequency that must be adhered to. It used to be thought that this frequency 'carries' the transmitted information (speech or music), transporting it to the receiver. This is incorrect; the name has stuck. The carrier frequency only transmits the information: “I am switched on”. All other information, such as speech or music, is transmitted on adjacent frequencies, all of which together require a certain minimum 'bandwidth.' If the required

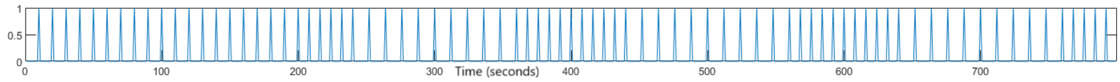

Figure 5): *Example of a phase-modulated signal. First, the carrier frequency is displayed ($f = 0.1$ Hz, i.e., 10 pulses per 100 seconds). Then, the modulation changes the transmission times. The pulses are generated repeatedly too early, then too late, and then too early again...*

bandwidth is restricted, the information can only be transmitted incompletely.

– **Demodulation**: To make the information readable, the receiver must know the carrier frequency. The demodulator evaluates the amplitudes and phases of the surrounding frequency range (within the bandwidth) and generates the transmitted information from them. There are different modulation methods, such as amplitude or frequency modulation, which can also be transmitted simultaneously. A good demodulator evaluates only one type and ignores all others.

– **Phase modulation** [1]: An unmodulated signal consists of pulses that are always generated at fixed times—for example, every 20 seconds (Figure 5, left part). With a phase-modulated signal, the pulses are generated either too early or too late. The demodulator measures the distance from the target time and reconstructs the information from this. The average value of the carrier frequency remains unchanged and is of no interest.

– **Superhet**: When receiving high frequencies, the frequency should be reduced because low frequencies can be amplified and demodulated more effectively. The nonlinear components that used to shift the frequency are increasingly being replaced by digital multipliers, as these do not distort the signals. Superhets used to be circuits made up of transistors and inductor filters; today, they are computer programs that process the data in a specific order using adders and multipliers.

– **FFT spectrum**: A data chain is the chronological enumeration of measured values, generated, for example, by barometers. Often, however, it is not important *when* a noticeable pressure fluctuation was recorded, but whether it occurs regularly, i.e., with a certain frequency. A spectrum, usually calculated using the FFT method, can provide the answer. See figures 1 to 4.

13 Data sources and programs

The German Weather Service [5] stores all historical measurement results from German weather stations (raw data). Data synchronization is accurate to the second and is guaranteed by the DWD. Deviations in the range of seconds are irrelevant given the selected sampling period of 3600 seconds. The few data gaps in isolated barometers are too rare and irregular to simulate signals with precisely defined frequencies. The summed, error-corrected barometer files are also available from the author upon request. Since only extremely narrow frequency ranges were examined using the integrative method described above, modifications and corrections to the data are unnecessary.

All programs were written in MATLAB R2020a and will be made available and explained by the author upon request.

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