A network of precision gravimeters as a detector of matter with feeble nongravitational coupling

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Abstract
Hidden matter that interacts only gravitationally would oscillate at characteristic frequencies when trapped inside of Earth. For small oscillations near the center of the Earth, these frequencies are around 300 $\mu$Hz. Additionally, signatures at higher harmonics would appear because of the non-uniformity of Earth’s density. In this work, we use data from a global network of gravimeters of the International Geodynamics and Earth Tide Service (IGETS) to look for these hypothetical trapped objects. We find no evidence for such objects with masses of up to on the order of $10^{13}$ kg. It may be possible to improve the sensitivity of the search by several orders of magnitude via better understanding of the terrestrial noise sources and more advanced data analysis.

1 Introduction
A classic result in Newtonian gravity is that if a small mass is orbiting inside a large mass of uniform density, such that the orbit is entirely contained in the interior of the large mass, the period of the orbit is be fixed by the density of the large mass, and independent of the particulars of the orbit. This is because the system can be described as a three-dimensional harmonic oscillator. In the case of a mass inside a sphere with uniform density equal to the average density of the Earth, the period of such orbits would be approximately 80 minutes. Such
a scenario is impossible with masses comprised of ordinary matter because of non-gravitational interactions. However, the situation may, in fact, be hypothetically realized if the small mass is comprised of some “hidden matter” (we call it a hidden internal object, HIO) that has only feeble, if any, non-gravitational interactions with normal matter. Furthermore, it is known that such hidden matter exists: evidence from many independent observations point to the existence of dark matter [1], an invisible substance which may interact with ordinary matter primarily via gravity. If some fraction of this hidden matter is gravitationally bound [2, 3, 4] within the Earth, this hypothetical scenario of a hidden internal object could be realized.

This suggests a tantalizing scenario. Perhaps, one can detect the presence of such HIO via sensitive measurements of gravitational acceleration at the surface of the Earth. An attractive feature of this idea is that the method does not depend on any specifics of what the orbiting matter is composed of and, in the case of uniform density, would lead a signal at a well-defined frequency. Unfortunately, the latter condition does not hold for the case of the Earth: the density profile of the Earth [5] (Fig. 1) is far from being uniform. Nevertheless, there may be situations leading to distinct spectral features, for example, if the HIO undergoes small oscillations near the center of the Earth where the density is nearly uniform.

Sensitive gravimetry measurements are performed with a variety of instruments [6]; among the most sensitive ones is a global network of gravimeters, the International Geodynamics and Earth Tide Service (IGETS [7]) discussed in more detail in Sec. 4. If HIOs exist inside the Earth, each gravimeter in the network would see a weak periodic signal at its characteristic frequencies, with a phase depending on the geometry of the orbit and location of the gravimeter. The presence of such frequency components in a Fourier analysis of the gravimeter time-sequence data could indicate the presence of a HIO if it can be adequately differentiated from naturally occurring spectral features.

There are also entirely different scenarios that can lead to signals in principle observable with gravimeters. For example, ultralight scalar dark-matter field can lead to effective variation of fundamental constants, including the mass of the baryons [8]. This would cause a sinusoidal variation of the Earth mass at a frequency equal to the oscillation frequency of the dark-matter field. This could be, for example, the background galactic dark matter nominally oscillating at the Compton frequency of the underlying boson [8], an Earth-bound halo [9], or a the field in a “boson star” encountering the Earth [10] and leading to a transient (rather than a persistent) signal. Some such scenarios have been recently analyzed by Rees L. McNally and Tanya Zelevinsky (private communication). The data from the gravimeter network was also used in Ref. [11] to set limits on a possible violation of Lorentz invariance.

In this paper, we survey the scenarios that could potentially lead to observable effects of the HIO, discuss the sensitivity of a gravimeter network, and present a preliminary analysis of a historical record of the IGETS data. Finally, we assess the prospects of the future HIO searches based on these techniques.
Figure 1: The density profile of the Earth based on the Preliminary Reference Earth model (PREM) [5]. \( r_e = 6371 \text{ km} \) is the radius of the Earth, \( \bar{\rho} = 5.51 \text{ g cm}^{-3} \) is the average density of the Earth, and \( \rho_0 = 13.1 \text{ g cm}^{-3} \) is the density of the Earth’s core.
2 Capture/formation scenarios and their difficulties

A natural question to ask is what sequence of events could lead to a HIO being gravitationally captured and confined to orbits within the Earth? In general this is a difficult problem for non/minimally interacting objects. An object starting far from the Earth following a trajectory that will bring it within the interior of the Earth starts with a gravitational potential energy above the necessary energy to surpass the Earth’s escape velocity. In order to be captured in the interior of the Earth, the object needs to dissipate energy. A HIO might be expected, in general, to have nearly dissipationless interactions with ordinary matter. However, this does not necessarily exclude dissipation due to self-interactions or interactions with other forms of dark matter in the hidden sector. For example, one possible capture scenario is that HIOs originate from a diffuse “cloud” in which a small part is sheared away and gets captured by the Earth in an effective “three-body” collision. Such scenarios are not uncommon in celestial dynamics, where gravitational tidal forces can rip apart bound objects and capture material [12]. This scenario requires the matter being captured to have non-trivial self-interactions, which could lead to virialization upon capture. We emphasize that a specific consistent scenario for HIO formation in this manner is yet to be worked out.

The velocity of objects in the galaxy relative to the Earth is generally on the order of the virial velocity of 220 km s$^{-1}$, whereas the escape velocity for the Earth is 11 km s$^{-1}$, so some strongly inelastic process is needed for the capture.

A possibility of bosonic-matter “halos” bound to the Earth and the Sun was recently discussed in the literature (see, for example, [9] and references therein), including halos entirely contained in the Earth, i.e., being HIOs. Another model suggests that axion quark nuggets (AQN) [13] explain the similarity of the dark and visible cosmological matter densities: in this model annihilation of anti-AQNs with visible matter produces a terrestrial halo of axion dark matter when AQNs hit the Earth. Although only a small fraction ($\approx 10^{-17}$) of the emitted particles stay bound, the accumulation of axions over the history of the Earth can still result in a measurable halo (see [14] for a detailed discussions of the process), although in this scenario the halo is external, virial, and of order 0.1 kg and thus not suitable for detection with gravimeters.

Another problem common to the scenarios discussed above is that, if the captured matter is virialized inside the Earth, it would not orbit as single object and would thus avoid detection using gravimeters.

3 Detection signatures

As mentioned above, the non-uniformity of the Earth’s density leads to broadening in the spectrum of the HIO orbital frequencies, nominally removing the attractive feature of the original idea that one may just look for orbits at a single unique and predictable frequency.
Figure 2: A diagram of the contribution of the HIO to gravitational acceleration on the Earth’s surface with the distance of the HIO to the center exaggerated for clarity. CM stands for the center of mass of the system, which defines the stationary frame, E is the center of the Earth and S is the location of a gravimeter station. $\vec{a}_e$ is the acceleration of the Earth, and $\vec{g}_h$ is the gravity provided by the HIO. They both contribute to the overall gravitational acceleration.

For small one-dimensional oscillations of a HIO near the center of the Earth, however, the time period of such oscillations is

$$T = \frac{2\pi}{\omega_h} = \frac{2\pi}{\sqrt{\frac{4\pi}{3} G \rho_0}} \approx 55 \text{ min},$$  \hspace{1cm} (1)$$

where $\omega_h$ is the angular frequency of the oscillation. In such a model, the HIO contributes to the gravitational acceleration on the Earth’s surface via two terms: the gravity of the HIO ($\vec{g}_h$) and the acceleration of the Earth due to the HIO $\vec{a}_e$; see Fig. 2. Since the components transverse to the main acceleration of the Earth’s gravity would only have second-order corrections to the readings of a scalar gravimeter, the overall effect of a HIO is reduced to:

$$\delta g \approx g_h + a_e \cos \alpha.$$  \hspace{1cm} (2)$$

Let us introduce an Earth-centered coordinate system with its $z$ axis pointing to the North Pole and denote the direction of an oscillating HIO as $(\theta_h, \phi_h)$.  

5
Suppose a gravimeter is placed at \((\theta_m, \phi_m)\) on the surface. The relationship between \(\alpha\) and the Earth-centered coordinate system is:

\[
\cos \alpha = \sin \theta_h \sin \theta_m \cos(\omega_0 t + \phi_m - \phi_h) + \cos \theta_h \cos \theta_m, \tag{3}
\]

where \(\omega_0\) is the angular frequency of the rotation of the Earth. Thus, the gravitational acceleration due to the HIO would contribute to the gravimeter signal as:

\[
\delta g = \frac{G m_h}{r_e^2} + (2 + \frac{\rho_0}{\bar{\rho}}) \frac{G m_h}{r_e^2} A_h \sin \theta_h \sin \theta_m \cos(\omega_0 t + \phi_m - \phi_h) + \cos \theta_h \cos \theta_m \cos \omega_h t, \tag{4}
\]

where \(m_h\) and \(A_h\) are the mass and amplitude of the HIO oscillation, \(\bar{\rho} = 5.51 \text{ g cm}^{-3}\) is the average density of the Earth, and \(\rho_0 = 13.1 \text{ g cm}^{-3}\) is the density of the Earth’s core. In this scenario, the HIO acts as a harmonic oscillator with a specific frequency, and the frequency is split because of the rotation of the Earth. Due to the non-uniformity of the Earth density (see Fig. 1), this spectral pattern holds for oscillations not exceeding \(\approx 0.1 r_e\) in amplitude. Note that the second term in Eq. (4) is smaller than the first term by roughly an order of \(\gamma = (2 + \frac{\rho_0}{\bar{\rho}}) \frac{A_h}{r_e}\), so assuming that \(A_h \approx 0.1 r_e\), \(\gamma \approx 0.4\).

If the amplitude of such oscillation is large, there will appear spectral harmonics of the signal at the third and higher odd harmonics (see Fig. 3). If the orbit is nonlinear, the motion is generally not periodic.

One can generally consider three regimes for the size of the HIO distribution: a compact HIO near the center of the Earth undergoing motion on a spatial scale smaller than \(\approx 0.1 r_e\), a bigger HIO with a size comparable to \(r_e\), and an object extending beyond the Earth.

In the first case, the signals produced by the HIO would be similar to the one-dimensional oscillation case, as now the core of the Earth can be taken as a uniform sphere. For the other two cases, different orbital frequencies of the components would produce incoherent signals as we have verified by numerical modeling. For a halo which is much larger than the Earth, the Earth can be approximated as a point mass. Numerical models of a halo of non-interacting particles on orbits around a point mass have shown that any overall coherent oscillations of the halo would damp out on orbital time scales and become unobservable. This can be seen intuitively by noting that each particle in the halo has (generally) a different orbital frequency, thus the overall oscillations will not add coherently.

4 Precision gravimeters

IGETS uses superconducting gravimeters [6] to record gravitational acceleration at the Earth’s surface. The gravity sensing units of the network’s gravimeters utilize superconducting coils to levitate a superconducting mass (typically, a
Figure 3: The theoretical spectrum of the HIO orbiting near the center of the Earth, the supposed mass of HIO here is $10^{16}$ kg, and the amplitude of the oscillation is $0.1\, r_e$. In the spectrum, there are signals centered near the first (around 303 $\mu$Hz) and higher (around 606 $\mu$Hz and 909 $\mu$Hz) harmonics due to the non-linearity of the force. Rotation of the Earth (seen as a small lowest-frequency peak) also leads to splitting of the first- and second-harmonic lines.
one inch diameter hollow niobium sphere, which weighs between 4 and 8 g). The sphere is hollow to reduce the weight and correspondingly the magnetic field required for levitation in order to keep the field significantly below the superconductor’s critical field and avoid flux penetration into the sphere. The gravitational acceleration is acquired by monitoring the feedback currents necessary to keep the position of the superconducting mass stationary. Typically, the precision of superconducting gravimeters is 1 pm s\(^{-2}\) with an integration time of a few seconds \cite{15}.

The currently operating network of gravimeters stems from the 1986 proposal of the Global Geodynamics Project (GGP). Since then, the number of gravimeter stations keeps increasing steadily. As a continuation of the GGP, the network is currently managed by IGETS which is hosted by the École et Observatoire des Sciences de la Terre (EOST), University of Strasbourg, France. There are 44 stations spread all over the world, with a data set for 392 station-years in total. Different stations may use different types of superconducting gravimeters and their data-set lengths also vary \cite{16,17}.

The IGETS data set is publicly available via the information system and data center (ISDC) at the Geo Forschungs Zentrum (GFZ) in Potsdam, Germany. Typically, the stations produce two kinds of data: the raw gravity feedback signal sampled at 1 or 2 seconds. Along with the gravity data, many auxiliary parameters such as environmental data (e.g., atmospheric pressure and room temperature) and instrument parameters (e.g., tilts) \cite{6} are also recorded. ISDC then processes the data into three levels of data sets: the level 1 set consists of raw gravity data and local pressure data. The level 2 data sets are the ones corrected for instrument perturbations. The level 3 data sets are the residuals after removing particular geophysical factors, including solid-Earth tides, polar motion, and tidal and non-tidal loading effects \cite{7}. The level-2 and level-3 data are filtered and re-sampled to 1 min cadence (i.e., 1 min intervals between data points).

The stated 1 pm s\(^{-2}\) sensitivity with a measurement time of a few seconds provides grounds for optimistic estimates of what one might hope to ultimately achieve with a network of such sensors. For example, assuming there are 44 stations whose signals are added coherently and on the order of a month of averaging time, the cumulative sensitivity could, in principle, reach on the order of \(10^{-7}\) nm s\(^{-2}\). This estimate is based on a assumption that the noise properties of the system (described, for instance, by Allan variance) support averaging over such long times and that seismic noise can be suppressed to a negligible level. In practice, the sensitivity is likely to be significantly worse (see Sec. 5); however, the naive estimate above gives us an idea of what the ultimate sensitivity might be.

Taking an average oscillation amplitude of \(A_h = 0.1 r_e (\approx 637\text{ km})\), if we use current gravimeters to form a network, the smallest detectable mass of such network would be:

\[
m_{\text{min}} = (2 + \frac{\rho_0}{\bar{\rho}})^{-1} \frac{\delta Gr_e^3}{GA_h} = 1 \times 10^8 \text{ kg}. \tag{5}
\]
For comparison, the total amount of dark matter enclosed in a sphere with a radius equal to that of the solar system (under the assumptions of the standard halo model and assuming uniform density of the dark matter) is \( \approx 3 \times 10^{17} \) kg, while that contained in a sphere with the radius of the Earth is on the order of 1 kg. Another interesting mass to compare is obtained by considering the volume \( V \) traced out through the galaxy by the Earth as it has travelled through space since its formation: \( V = vAT \approx 10^{36} \) m\(^3\), where \( v \approx 2 \times 10^5 \) m/s is the speed of the Earth relative to the galactic rest frame, \( A \approx 10^{14} \) m\(^2\) is the Earth’s cross-sectional area, and \( T \approx 4.5 \times 10^9 \) years is the age of the Earth. Multiplying \( V \) by the average dark matter density \( \rho_{dm} \approx 0.4 \) GeV/c\(^2\)/cm\(^3\) \( \approx 7 \times 10^{-22} \) kg/m\(^3\) (here \( c \) is the speed of light), we get that the total dark matter mass the Earth has passed through is about: \( \mathcal{M} \sim 10^{15} \) kg. In this estimate, we neglected the motion of the dark matter itself with respect to the galaxy, which would slightly increase the result. The gravimeters are sensitive to a HIO mass that is a small fraction of this quantity.

5 Analysis and preliminary results

The IGETS level 3 data set consists of historical gravimeter data from 44 stations spread all over the Earth. Different stations have contributed data over different amounts of time, some with only 1-2 years of data, others with over 30 years. Our initial analysis technique involves taking the discrete Fourier transform of each one-month block of data from all stations, obtaining the power spectral density, subtracting the background, and averaging. The background subtraction was done by fitting to a function of the form:

\[
y(f) = \frac{A}{f} + \frac{B}{f^2} + \frac{C}{f^3} + y_0
\]

with the result subtracted from each spectrum to remove the overall baseline. This results in a single averaged spectrum with a noise level under 25 nm s\(^{-1}\) Hz\(^{-1/2}\) (with lower noise at higher frequencies; see Fig. 4a). There are features in the data that do not generally appear in the raw gravity data from superconducting gravimeters and are possibly artefacts from reduction models. This will be subject of further investigation.

In order to estimate the mass of a HIO we would be sensitive to, we fit a Lorentzian (with a full width at half maximum of 50 \( \mu \)Hz, obtained in our simulations, see Fig. 3) and a linear baseline to the frequency range of interest (highlighted in orange in Fig. 4b). Integrating over the Lorentzian yields an acceleration of \( \delta g \approx 0.02 \) nm s\(^{-2}\). This result shows the statistical power of the analysis. However, the appearance of pronounced features in Fig. 4 necessitates further analysis of their origin to gain confidence in the result at this level. Never the less, if we consider that an acceleration of \( \delta g \approx 0.02 \) nm s\(^{-2}\) is generated by a HIO with an amplitude oscillation of 637 km (\( \approx 0.1 \) \( r_e \)), it would have a mass of

\[
m = (2 + \frac{\rho_0}{\rho})^{-1} \frac{\delta g r_e^3}{G A_h} = 3 \times 10^{13} \text{ kg.} \tag{7}
\]
Figure 4: (a) The amplitude spectral density of the IGETS level 3 data sets, with background removal performed prior to averaging. The inset (b) shows details around 303 $\mu$Hz, where the signal from a HIO orbiting near the center of the Earth would lie. The vertical orange strip highlights the range used to look for HIO related oscillations. The large spike around 800 $\mu$Hz is due to the $0S_0$ “breathing” mode of Earth [5, 18].
Although this is relatively small ($\approx 10^{-11}$ of Earth’s mass), the current sensitivity is still several orders of magnitude short of the estimated sensitivity in Eq. (5). This difference arises from various factors. Although the contributions of the instrument drift and pressure are largely removed already, the employed data-fix techniques may introduce errors. Also, there are tides and non-tidal loading factors, rainfall and other hydrological factors, station disturbances, seismic factors, and other natural and anthropological contributions to the overall acceleration. Tides generally produce clear, discrete lines in the spectra that are harmonics of the tidal frequency (period $\approx 12$ hrs), which have little impact on the region of interest (period $\approx 55$ min). As for the seismic influences, there are both persistent oscillations, which are a response to other periodic driving forces, which can be roughly evaluated by the Earth model and transient incidences (for example, earthquakes), which, along with other transient factors, can be removed by data selection. Data selection is also an effective technique for dealing with non-tidal and hydrological loading factors which can have an effect as big as $\approx 1 \times 10^3$ nm s$^{-2}$ over a few days. These effects produce noise-like spectra, deteriorating the sensitivity of the network to HIO signals [6].

In the future stages of this work, one should be able to enhance the precision substantially by performing a phase sensitive analysis. Furthermore, the phase information would enable us to approximately determine the specific orbit of the HIO within the Earth, as the phases of a gravimeter signal should depend on its location on Earth’s surface.

The stated $10^{-17}$g sensitivity is based on the assumption that the signals of different stations are completely correlated. In the case where HIO move as a single object inside the Earth, the signal obtained by different stations are indeed correlated. However, if other possible scenarios are to be considered, then the correlation would be incomplete and the sensitivity would deteriorate.

We note that correlation-analysis techniques are currently employed by the existing sensor networks such as LIGO/VIRGO [19] for the detection of gravitational waves, as well as by magnetometer (GNOME [20]) and clock (for example, GPS.DM [21]) networks for the detection of the galactic dark matter.

6 Conclusions and outlook

We have analyzed various possible scenarios of the hidden gravitationally bound objects that have weak or no interactions (other than gravitation) with normal matter, and have discussed their possible influence on the total gravitational field measured at the surface of the Earth. With data sets from IGETS, we used Fourier analysis to search for characteristic spectral lines that could be an indication of the existence of such objects. Although no evidence has been found, we estimate that the smallest detectable mass using the current network can ultimately reach as low as $\approx 1 \times 10^8$ kg. Such hidden gravitationally bound objects could be a subdominant part of the nonbaryonic dark matter.

An alternative scenario to HIO trapped in the Earth is a change of the
Earth’s gravitational field under the influence of some background bosonic field, for example, that due to dilatons. Serving as dark matter candidates, dilatons and other bosonic fields can have linear interactions with nucleons, changing their effective masses at the Compton frequency associated with the mass. Under appropriate conditions, the mass of the Earth could oscillate slightly at the particle frequency [8]. The superconducting gravimeter data considered in this note are resampled to the once per minute cadence, so the smallest frequency that can be detected is \(1/120\) Hz, corresponding to a particle mass of \(3.5 \times 10^{-17}\) eV. The modification of the Earth mass by the presence of an oscillating field \(\phi = \phi_0 \cos \omega_\phi t\) is described by

\[
m_{\text{eff}} = (1 + \frac{\sqrt{\hbar c \phi}}{\Lambda_1})m_e,
\]

where \(m_e\) is the mass of the Earth, \(\omega_\phi\) is the frequency of the oscillating field, and \(\phi_0 = \hbar \sqrt{2 \rho_{DM} / (m_\phi c)}\) is related to the mass of the bosonic particle \(m_\phi\) and the local density of dark matter \(\rho_{DM}\). \(\Lambda_1\) is the coupling constant averaged over all the Earth’s atoms.

Assuming the optimistic sensitivity of \(10^{-17}\) g discussed in Sec. 4, the network can detect such variance if

\[
m_\phi c^2 \Lambda_1 \leq 2.5 \times 10^{14}\text{ eV}^2,
\]

which is compatible to the sensitivity of future atom interferometers discussed in [8] and performing better than current equivalence-principle tests if \(m_\phi \leq 1 \times 10^{-18}\) eV.

Another possibility is that there could be “boson stars” encountering the Earth that affect the gravitation field. Supposing such influence is only detectable when the distance between the star and the Earth is closer than \(10r_e\) and taking the characteristic relative velocity of the Earth and the boson star as the galactic virial velocity \(\approx 10^{-3}c\), such transient signal would possibly last \(\approx 5\) min, which means that its timing is ideal for detection using IGETS’s level-2 and level-3 data sets. According to an estimate in [10], the maximum acceleration felt during an encounter is \(10^{-19}\) g, so a significant improvement in sensitivity would be needed if one is to detect such events using gravimeters.

In conclusion, advanced gravimeter networks could be useful for detection of exotic matter and future improvements in the hardware and, particularly, in advanced data analysis may enable mounting competitive searches.

**Note added at submission**

In the final stages of preparation of the current manuscript, we became aware of similar work [22]. The content of the current manuscript has not been altered based on the information in [22].
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