Gravitational Clock: Near Space Proof-of-Concept Prior to Deep Space Measurement of G — Part I

Richard Benish

4243 E Amazon Dr, Eugene, OR, 97405, USA

E-mail: `rjbenish@comcast.net`

December 20, 2016

Abstract. Motivated by the benefits of improving our knowledge of Newton's constant G, Feldman *et al* have recently proposed a new measurement involving a gravitational clock launched into deep space. The clock's mechanism is supposed to be the linear oscillation of a test mass falling back and forth along the length of a hole through the center of a spherical source mass. Similar devices—ones that would have remained in orbit around Earth—were proposed about 50 years ago for the same purpose. None of these proposals were ever carried out.

Further back, in 1632 Galileo proposed the thought experiment of a cannonball falling into a hole through the center of Earth. Curiously, *no one has yet observed the gravity-induced radial motion of a test object through the center of a massive body.* Also known as a *gravity-train*, not a one has yet reached its antipodal destination. From this kind of gravitational clock, humans have not yet recorded a single tick.

The well known reliability of Newton's and Einstein's theories of gravity may give confidence that the device will work as planned. Nevertheless, it is argued here that a less expensive apparatus—an Earth-based *Small Low-Energy Non-Collider*—ought to be built first, simply to prove that the operating principle is sound. Certain peculiar facts about Schwarzschild's interior solution are discussed here; and a novel way of interpreting gravitational effects will be presented in Part II, together adding support for the cautious advice to more thoroughly look before we leap to the outskirts of the Solar System.

PACS numbers: 04.80.Cc — Experimental tests of gravitational theories

1. Introduction: Grumbles, Questions, and a Course of Action

The predicted linear oscillation of a test mass through the center of a material body—sometimes referred to as a *gravitational clock* or *gravity train*—is the basis for Feldman *et al's* [1] recent proposal to measure Newton's constant G in deep space. Though the idea of dropping a test mass into a hole through the center of a larger body has been in the literature at least since Galileo's proposal of 1632 [2], *the predicted oscillatory behavior has not yet been observed.* Strictly speaking, we do not yet know for a fact that the apparatus would function as a clock. Not even a rudimentary device operating by the same principles has ever been built; we've not yet witnessed even a single tick. Therefore, it would be prudent to first build a preliminary model, to demonstrate the concept in action—at least roughly—before sending an intricate apparatus to deep space.

1.1. Newton, Einstein, Quagmire

The sensibleness of this strategy becomes yet more evident by investigating a few theoretical questions. According to Newton's theory, gravity is a force of attraction between massive bodies. According to Einstein's theory, General Relativity (GR), gravity is a manifestation of spacetime curvature. Since Newton's conception is the simpler of the two, even though we know Einstein's theory to be more accurate, the Newtonian framework still plays a major role in the education and the careers of most physicists and astronomers. Whether the constant G relates to the magnitude of force between bodies or to the magnitude of curvature such bodies produce, its role in both frameworks is fundamental, and certainly motivates the endeavor to measure its value more accurately.

An improved measurement of G would be welcomed by all, but nothing concrete can yet be said about how or whether this would change our understanding of the phenomenon itself or its still mysterious connection to the rest of physics. That two such different frameworks (Newtonian vs. Einsteinian) both vie for our attention may be seen as one of several indications of the puzzle-ridden status of gravity in modern physics. Sometimes this state of puzzlement is denied [3–5], ignored, or camouflaged under common assumptions or seemingly innocent, yet revealing vernacular. *Matter tells spacetime how to curve; spacetime tells matter how to move.* In no case that I'm aware of do we find this almost clichéd expression accompanied with a discussion about how very much is hiding behind the word *tells*. What exactly does matter *do* to make spacetime curve? How exactly—or even *roughly*—are these orders carried out? Surely these are relevant physical questions.

A seemingly more innocent example is the common expression, *downward pull of gravity*, which is used even among scholars of GR, according to which there really is no such thing. In fact, in discussions about one of GR's inspirational bases, the Equivalence Principle (EP) gravity is sometimes described as being better understood (at least locally) as the *upward acceleration* of the ground we stand on. [6–9] From this we could get the impression that confusion exists over even the simplest question about the *direction* of gravity. [10]

Unfortunately, the meaning and significance of the EP is itself a matter of some dispute. In their attempts to clarify the EP's role and its implications, Okon and Callender have recently suggested that "there are almost as many equivalence principles as there are authors writing on the topic." [11] Similar assessments arguably apply to the enigmatic problem of the *energy* of a gravitational field [12–14] and to the possible role of Mach's Principle. [15] Add to these fuzzy issues the problem of singularities in the strong-field regime, a pair of persistent "dark" problems in astrophysics and cosmology, and, not least, the problem of connecting Newton's constant to the other constants of physics (unification) and we begin to see the sense in Elias Okon's assessment of the current state of fundamental physics:

> It is the opinion of at least a sector of the fundamental theoretical physics community that such field is going through a period of profound confusion. The claim is that we are living in an era characterized by disagreement about the meaning and nature of basic concepts like time, space, matter and causality, resulting in the absence of a general coherent picture of the physical world. [16]

Since inadequate understanding of gravity is the root cause of this unsatisfactory state, we are well-advised to proceed cautiously. Bold ideas are certainly needed. But this does not mean sacrificing the scientific ideal of requiring that such ideas have (or can feasibly receive) the needed empirical testing and support. Is boldness even needed to suggest testing well-established theories where they have not yet been tested? No, this should be standard procedure—especially if the uninspected physical domain is both vast and well within reach. Therefore, even if the only shortcoming of our understanding of gravity were our mediocre knowledge of G, it would *still* be advisable to construct a working model of a gravitational clock prior to sending one to outer space. And even if there were no such deep space plans, it would *still* be advisable to construct a working model of the apparatus, because none has yet been built; the interior solution representing the most ponderous half of the gravitational Universe has not yet been tested. The unanswered questions about gravity only *amplify* the case for re-ordering our priorities, to check and re-check what we think we already know before venturing too far, either theoretically or experimentally.

1.2. Preview

In §2 we go over some history of G measurement proposals and other gravity experiments pertaining to the present situation. Against this background, we suggest proof-of-concept options, as economical precursors to the Feldman *et al* apparatus, that could be conducted in near-space or in an Earth-based laboratory. Since the clock-like quality of such devices has not yet been established, we refer to them by the more accurately descriptive name, *Small Low-Energy Non-Colliders.*

Instead of a Newtonian force of attraction, the cause of motion of free bodies according to GR is the difference in the rates of clocks. GR's *exterior* Schwarzschild solution—which represents the curved spacetime metric *outside* a spherically symmetric body of matter—indicates that *clock rate* differences correspond to *radial length* differences of the same magnitude. At every point in an exterior field, time and space are both affected equally. GR says this is no longer true inside matter. The *interior* Schwarzschild solution predicts that, from the surface inward, clock rates continue their trajectory of *decrease* to a central *minimum.* Whereas, radially oriented rod lengths *increase* back to their flat space *maximum.* Gravity's effect on clock rates is a maximum at the *center*, whereas its effect on radial lengths is a maximum at the *surface*. Questions surrounding this curiously diverging relationship—going from exterior to interior—are raised in §3.

Our concluding §4 adopts the philosophical principle to be wary of "proofs by ethos," as discussed in a recent paper by Uggerhøj *et al* concerning the rates of clocks inside matter. [17] It is argued that, though Uggerhøj *et al* conscientiously apply the principle at one level of analysis, they fail to extend it to the level of empirical evidence. Taking this last step, to test one's calculations prior to asserting them as physical facts, is the surest, if not the only way to avoid the pitfall of proof by ethos.

2. Interior Testability

Almost all of what we know about gravity has been deduced from observations *outside* the surfaces of dominant gravitating bodies, such as the Earth or Sun. Comparatively few experiments have yielded gravitational data concerning the *insides* of material bodies, especially near their centers. A notable exception is the experiment conducted by Hoskins *et al* [18] which established the validity of the inverse square law inside a long thick-walled hollow cylinder. The object of most experiments of this kind has been to measure a *static* force at fixed points in space. Whereas the *motion* this force is supposed to produce has not been observed over any significant stretch of interior radial distance.

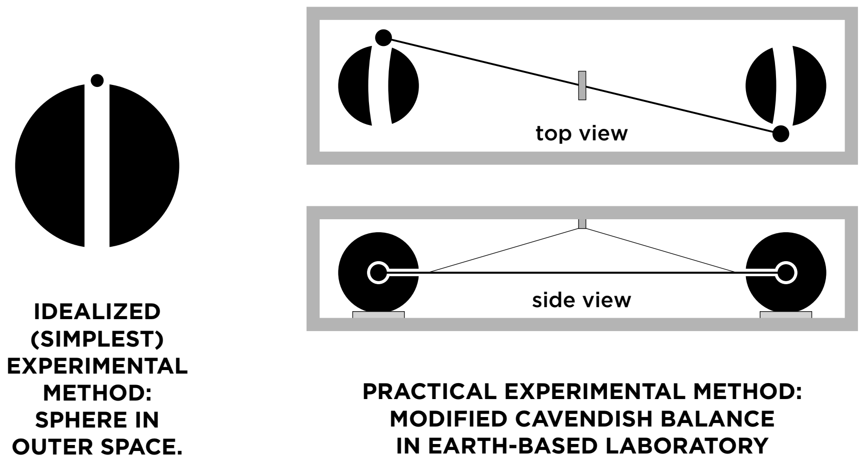

Figure 1. Small Low-Energy Non-Colliders—Apparatus Schematics. Left: The single source mass method, which resembles Galileo's original cannonball idea, could be done in an orbiting satellite. A small rotation would need to be given to the source mass so that the hole through its center would remain parallel to Earth's surface (Moon-like orbit). Right: A more practical method would be to use a modified Cavendish balance, whose support system poses the biggest challenge. A fluid or magnetic support would be needed to allow a full range of angular motion with no restoring force. The arced path deviates from the ideal, but suffices to at least roughly reveal the character of the motion.

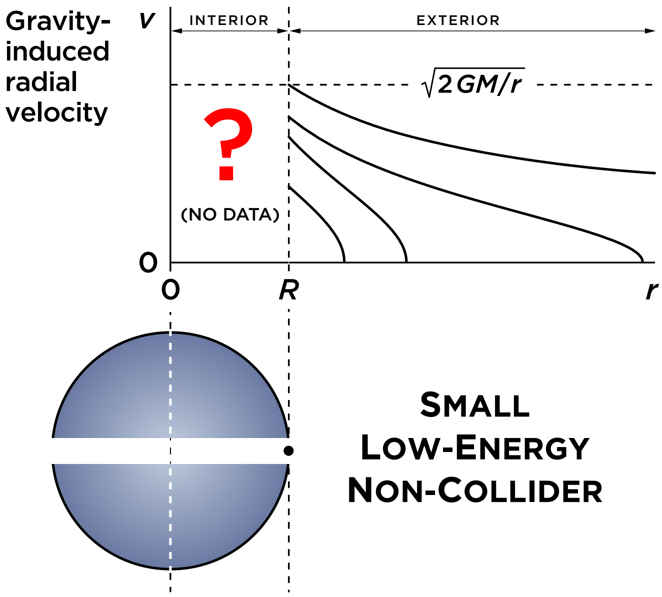

Figure 2. Evidence gathered from above the surfaces of large bodies of matter like the Earth or Sun allow plotting the curves for the exterior region as shown. In the case of Earth, some evidence has been gotten from shallow holes close to (essentially *at*) the surface. But from well below the surface, especially near the center, we have no data. The data is there to be gotten, not from astronomical bodies, but from laboratory sized bodies of matter. Instead of merely *assuming* that we know how to complete this graph for the interior region, conducting a preliminary demonstration on or near Earth would be a prudent first step before sending such a device to deep space.

Due to the dominant gravitational influence of Earth, experiments that would probe gravity-induced motion through the centers of source masses are challenging—but not impossible. In 1975 Larry Smalley reviewed the status of several "gravitational clock" proposals to measure G using near-space Earth-orbiting satellites. [19] Among these, a few were similar to the recent proposal by Feldman *et al.* Due to certain technological and practical issues, it was concluded at that time that the proposed tests were not likely to significantly improve our knowledge of G, so none of them were carried out. Note that even back then, none of the proposals included plans to demonstrate the working principles with a more economical prelimary test.

Happily, it is not necessary to send a probe into space to make the needed demonstration. A modified Cavendish balance in an Earth-based laboratory would fulfill our relatively modest goal. [20] (See Figure 1.) Such an apparatus would clearly not serve as an especially accurate or durable clock. But it should suffice to observe the general character of the interior motion, at least as a first approximation. The physicist and apparatus-builder George Herold, of the Buffalo, NY company Teachspin, has expressed an interest in building just such a device. [21] Perhaps now would be a good time. With a proof-of-concept demonstration in our store of experience we could then confidently proceed to build a suitable G-measuring device, which may turn out to be *something other than* a Small Low-Energy Non-Collider.

The conspicuous gap in the graph in Figure 2 represents *what we do not know* about gravity-induced radial motion. It serves to illustrate the importance of replacing the question mark with real physical data. The implications of this graph will be supplemented in what follows by ideas and observations intended to pique our curiosity, to clarify the need to *confirm* the predicted radial oscillation as an essential first step toward any space mission that would otherwise and unwisely rely on untested assumptions.

3. Metric Coefficients, Gravitational Potential, and the Speed of Light

3.1. Divergence of Interior Metric Coefficients

Radial falling problems are treated rather differently as between Newtonian gravity and GR. Specifically, unlike the Newtonian *force* of gravity, in GR force-like effects are instead attributable to differences in the *rates of clocks.* Outside matter, the GR Schwarzschild *exterior* solution predicts that *clock rate* differences correspond to *radial length* differences of equal magnitude. The magnitudes of the corresponding coefficients are reciprocals of each other. (EXTERIOR):

$$\text{TIME}: \quad \left(1-\frac{2GM}{rc^2}\right) \qquad \text{RADIAL DISTANCE}: \quad \left(1-\frac{2GM}{rc^2}\right)^{-1}, \tag{1}$$

where M is the mass, r is the coordinate radius and c is the light speed constant.

Expressions (2) and (3) represent the corresponding coefficients for the Schwarzschild interior solution, where M is again the mass of a spherical body, whose density must now be specified as uniform, and R is its surface radius. (INTERIOR):

$$\text{TIME}: \quad \left(\frac{3}{2}\sqrt{1-\frac{2\,GM}{Rc^2}}-\frac{1}{2}\sqrt{1-\frac{2\,GM}{c^2}\frac{r^2}{R^3}}\right)^2 \tag{2}$$

$$\text{RADIAL DISTANCE}: \quad \left(1-\frac{2\,GM}{c^2}\frac{r^2}{R^3}\right)^{-1}. \tag{3}$$

The Schwarzschild interior solution is not very realistic for astronomical bodies, whose densities tend to rise steeply near their centers. But for spherical bodies whose gravity is very small compared to their other cohering forces, the solution is expected to accurately represent the curvature of spacetime found therein. Figure 3 shows a graph of expressions (2) and (3) for a few strong-field cases, the most prominent one being $r = 3GM/c^2$.

Clearly indicated by this graph and these expressions is that the reciprocal relationship of (1) no longer holds inside matter. The Schwarzschild *interior* solution predicts that, as the center is approached, the temporal coefficient shrinks further below its flat space value of unity. Whereas the spatial coefficient approaches, and at the center

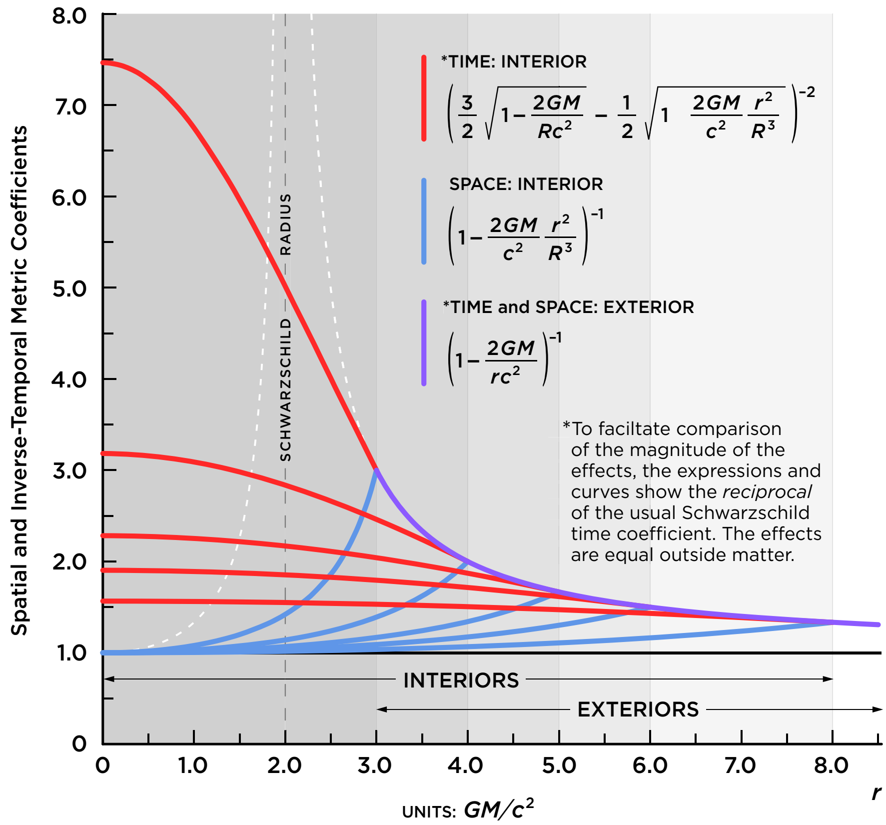

Figure 3. Schwarzschild exterior and interior metric coefficients for a few strong-field cases. (The most extreme case $R = 2GM/c^2$ is indicated by the broken white curves.) Widely understood as representing a uniformly dense sphere—which is not generally realistic for astronomical bodies—the Schwarzschild interior solution is nevertheless supposed to be an excellent approximation for less extreme, laboratory-sized bodies of matter. Within the latter bodies, gravitational stresses and deviations in clock rate are extremely small. The strong-field cases graphed here have been chosen to visually emphasize the *character* of the divergence as between space and time coefficients when passing from exterior to interior.

reaches, its flat space value of unity. Note that Figure 3 makes the pattern visually conspicuous by graphing the *reciprocal* of the time coefficient—to make it > 1 instead of < 1. If the magnitudes of the effects on space and time inside matter were the same, the single curve for the exterior would extend as a single curve into the interior. Clearly, the symmetry is broken. Why is that? Why should space and time be affected by the *same* magnitude outside matter, but by *different* magnitudes inside matter? The spatial flatness at the center seems intuitive enough, *by symmetry*. But then why doesn't such symmetry-based reasoning apply to clock rates? What does the surrounding matter *do* to disrupt the pattern and continue diminishing (to a central minimum) the rates of interior clocks?

3.2. Force, Potential, Geometry

The *physical* answer to these questions is unknown; nor are the predictions supported by empirical evidence. The *theoretical* answer has to do with the assumptions underlying Einstein's creation of GR. Einstein's theory does not explicitly refer to a downward force of gravity. But it carries over from Newtonian theory the concept of gravitational *potential*.

It is well known that outside matter the concept of gravitational potential is well-supported by empirical evidence. As an attractive force, gravity's field magnitude corresponds to the negative gradient of the potential. The potential—being itself a negative quantity, because attractive—is supposed to get more negative when passing from exterior to interior. The gradient (force) goes to zero as the potential reaches its central minimum. Under the typically unquestioned assumption that energy is conserved, this scheme is perfectly reasonable. Applied to the oscillating clock of Feldman *et al*, the system's *total* energy remains constant, as the test object's energy smoothly changes, for every half-period, from potential to kinetic energy and back again.

Einstein explicitly assumed that, for weak-field cases, Newtonian gravity suffices as a good approximation, both outside and inside matter. In fact, the Newtonian potential $-GM/r$ is the main factor in Einstein's metric coefficients: $(1 - 2GM/r)$. As noted in the introduction to their paper on the predicted difference in age between Earth's surface and its core, Uggerhøj *et al* state: "The potential influences the rate at which time passes." [17] The potential may thus be seen as a kind of conceptual/mathematical bridge connecting Newton's to Einstein's theory.

3.3. Is Gravitation Geometry?

As mentioned in the Introduction, we'll return to comment on a key theme in Uggerhoj *et al's* paper in §4. Presently, note that the decreasing potential and decreasing clock rate indicate also a corresponding decrease in the *coordinate speed of light*. According to Einstein's geometrical approach to gravity, we may identify light paths as *null geodesics* ($ds^2 = 0$) in the interior Schwarzschild field. Doing so facilitates calculating that, at the center, $dr/dt = c\,(\frac{3}{2}\sqrt{1 - 2GM/Rc^2} - \frac{1}{2})$. The coefficient is the same factor by which clocks are supposed to be slowed.

These are the kinds of results that sometimes evoke the common assertion that *gravitation is geometry*. Nobody knows what physical process lies behind these effects. What exactly makes clocks tick slow? What exactly makes the speed of light decrease? What does a material body *do* to curve its surrounding space and time? An analogy has sometimes been proposed, that such behaviors exist because space is like a medium of variable refractive index n. [22–24] More commonly, no attempt is made to physicalize the static geometry beyond the solutions to Einstein's equations. In 1936 Einstein admitted that "[GR does not] consider how the central mass produces this gravitational field." [25] This is still true today. The question, *how can it be?* remains unanswered, again reminding us of the humbling statement of despair by Okon quoted earlier (§1.1).

Admitting our ignorance inspires the need to proceed with caution; to be alert to opportunities to *check* our basic assumptions, so that we do not lead ourselves astray.

On a more positive note, the Schwarzschild exterior solution's prediction concerning coordinate light speed has been resoundingly supported by the Shapiro time delay test. [26] And the predictions concerning both coordinate light speed and variation in clock rate have been resoundingly supported by the Vessot-Levine experiment (*aka* Gravity Probe A). [27] Unfortunately, we have not yet obtained corresponding evidence for the interior field.

3.4. Implications of Tangherlini, Klotz

As a way of questioning the widely adopted, though tacit assumption that validity of the interior is guaranteed by empirical support for the exterior, it should be mentioned that some work by Tangherlini implies the opposite. In his 1962 paper *Postulational Approach to Schwarzschild's Exterior Solution with Application to a Class of Interior Solutions*, [28] Tangherlini derives the usual exterior Schwarzschild solution from the same set of basic assumptions that lead to some rather novel interior solutions. This arguably means that each solution needs to be tested in it own right. The validity of one does not necessarily establish the validity of the other. (Further discussion of Tangherlini's work is found in [29].)

Another paper of relevance to this situation is one by Klotz, [30] who recently recalculated the hypothetical transit time of a test object falling into a diametric tunnel through Earth. Klotz has gone beyond the common textbook problem that assumes uniform density. Due to the non-uniform density inside a more realistic Earth, Klotz calculated a shorter transit time, just as Uggerhøj *et al* calculated a greater surface/center age difference than what would follow from the simpler uniform density case.

It is important to bear in mind the tight relationship between the kinematic prediction (oscillation through the center) and the clock rate prediction. The latter is virtually untestable as an actual clock rate difference because, for all accessible bodies of matter, the effect is very small. But the connection: [clock rate differences → potential differences → force → motion of test object] goes both ways, and means that a test of the oscillation prediction serves also as a rather convincing test of the clock rate prediction.

4. Proof by Ethos?

In their paper on the predicted age difference between Earth's surface and its core, Uggerhøj *et al* make a special point of illuminating a curious sociological aspect of the situation. They tell of how the late, illustrious Richard Feynman had once mentioned a surface/core age difference on the order of a few *days*. [31] Whereas a simple calculation and their more elaborate one both indicate the "correct" answer as being that the Earth's center is younger by a few *years*. Concerning the discrepancy, the authors refer to a "philosophical" issue discussed in a book written by one of the co-authors (Faye) [32]. The issue is the danger of accepting *proof by ethos*. Feynman's reputation was so lofty that a few authors repeated or, having had the opportunity to do so, failed to correct his age prediction. Uggerhøj *et al* therefore ask:

> Why did famous, respectable and clever physicists publish Feynman's claim (although not verbatim, actually) that "[Feynman] concluded that the center of the Earth should be 'a day or two younger than its surface'"?
>
> It seems likely that they knew that the qualitative effect had to be there, and simply trusted that Feynman and his transcribers had got the number right. This is here considered an example of 'proof by ethos.'
>
> The term 'proof by ethos' refers to cases where a scientist's status in the community is so high that everybody else takes this person's calculations or results for granted. In other words, nobody questions the validity of that scientist's claim because of the particular ethos that is associated with that person. The result is accepted merely by trust. Indeed, the proof by ethos is not really a proof, as it does not follow logically from a set of premises. [17]

The reader may already see the irony in these remarks and anticipate my next point. The kind of "proof" that Uggerhøj *et al* refer to above is one that may well apply in the field of mathematics or formal logic. But the context here is supposed to be *physics*. Feynman's rough calculation was off by two orders of magnitude. Uggerhøj *et al* conducted "a more elaborate analysis" which yielded a purportedly more accurate number. But the *physically* most important step has yet to be taken. Uggerhøj *et al* suppose Feynman's followers "*knew* that the qualitative effect had to be there." But *how* did they "know"? Is this "knowledge" not also a presumption—a proof by ethos resting, in this case, not on Feynman, but on Einstein (and indirectly, Newton)? Nobody has yet *tested* either calculation, nor the improved calculation of Klotz concerning whether Earth's (or any other body's) mass would produce linear oscillation through its center.

The seriousness of the oversight is made more evident by the way Uggerhoj *et al* give the impression that their example of catching Feynman's goof suffices as an instance of science adequately correcting itself. They write: "Realising that even geniuses make mistakes may make the scientist more inclined towards critically examining any postulate on his/her own." Re-examining postulates is to be recommended, of course. But how about examining the *real world* that the postulates allegedly refer to? Ignoring this question, Uggerhøj *et al* conclude: "In spite of the small numerical mistake, Feynman's *observation* that the center of the Earth *is* younger than its surface is a fascinating *demonstration* of time dilation in relativity." [My emphasis.]

What Uggerhøj *et al* evidently fail to appreciate is that neither Feynman nor themselves have yet made any *observation* or *demonstration* of time dilation. What they have done may be likened to fixing a few mis-spellings in a (Feynman-authored) sentence whose truth content remains empirically unquestioned. Uggerhøj *et al* have thus not yet justified their claim (echoing Feynman's) that the Earth's core *is* younger than the surface. They categorically *do not* "know" whether this is true or not.

Various followers of Feynman had ill-advisedly accepted his work as proof by ethos. Uggerhøj *et al* have now committed the same error. They have merely transferred the problem up one level of authority: from Feynman and themselves to Newton and Einstein. In the realm of empirical science this is clearly not sufficient. The scientist's work is not done, no "proof" of any real value will have been obtained until the predictions that the assumed premises lead to have been judged in the court of *Nature*; until our "observations" and "demonstrations" refer not to mere abstract mathematical extrapolation, but to the irrefutable verdict of physical reality.

One may of course argue that Uggerhøj *et al's* calculation, Klotz's calculation, and Feldman et al's clock *must* be physically valid constructs because they are based on the validity of such well-worn ideas as that gravity is a force of attraction, and that energy must be conserved. In response, one might wonder: If Galileo were alive today and if he had the resources to build a laboratory version of a Small Low-Energy Non-Collider, would he decline the idea of putting his thought experiment to the test, saying "No need to perform a real experiment; I already know what happens?" Or would he embrace the opportunity to demonstrate seemingly well-established laws and principles in a domain where their validity has not yet been tested? Of course, we can't know for sure, but a reasonable guess would be that the veritable *Father of Modern Science* would opt for consulting Nature on the matter: By all means, do the experiment—the sooner the better.

References

[1] Feldman M R, Anderson J D, Schubert G, Trimble V, Kopeikin S M and Lämmerzahl C 2016 Deep Space Experiment to Measure *G Class. Quantum Grav.* **33** 125013

[2] Galileo G 1967 *Dialogue Concerning the Two Chief World Systems—Ptolemaic & Copernican, Second Edition* Translated by Drake S (Berkeley: University of California Press) pp 22, 227, 236

[3] Hossenfelder S 2016 "We Understand Gravity Just Fine, Thank You" <http://backreaction.blogspot.com/2016/09/we-understand-gravity-just-fine-thank.html> Accessed November 10 2016

[4] Carroll S 2013 "Yes I do understand gravity, I even wrote a whole textbook about it" <http://www.preposterousuniverse.com/blog/2013/01/04/the-world-of-everyday-experience-in-one-equation/> Accessed December 20 2016

[5] Sohnius M F 1985 "Gravity as a phenomenon is obvious" Introducing Supersymmetry *Physics Reports* **128** pp 39–204

[6] Gott J R 2001 *Time Travel in Einstein's Universe* (New York: Houghton Mifflin) p 86

[7] Lilley S 1981 *Discovering Relativity for Yourself* (Cambridge: Cambridge University Press) p 272

[8] Epstein L C 1988 *Relativity Visualized* (San Francisco: Insight) p 152

[9] Unruh W 1995 Time, Gravity, and Quantum Mechanics *Time's Arrow Today—Recent Physical and Philosophical Work on the Direction of Time* (ed) S Savitt (Cambridge: Cambridge University Press) p 31

[10] Benish R 2011 The Direction of Gravity <http://adsabs.harvard.edu/abs/2011AstRv...6g...8B> or <https://www.academia.edu/5914271/The_Direction_of_Gravity> Accessed November 10, 2016

[11] Okon E and Callender C 2011 Does quantum mechanics clash with the equivalence principle—and does it matter? *European Journal for Philosophy of Science* **1** January pp 133–145

[12] Penrose R 1990 The Mass of the Classical Vacuum *The Philosophy of Vacuum* (eds) S Saunders and H Brown (Cambridge: Cambridge University Press) pp 21–26

[13] Curiel E 2000 The Constraints General Relativity Places on Physicalist Accounts of Causality *Theoria: An International Journal for Theory, History and Foundations of Science* **15** pp 33–58

[14] Bozhkov Y and Rodrigues W A Jr 1995 Mass and Energy in General Relativity *General Relativity and Gravitation* **27** pp 813–819

[15] Barbour J and Pfister H 1995 Index of [21] Different Formulations of Mach's Principle *Mach's Principle, From Newton's Bucket to Quantum Gravity* (eds) J Barbour and H Pfister (Boston: Birkhäuser) p 530

[16] Okon E 2009 On the Status of the Equivalence Principle in Quantum Gravity <http://jamesowenweatherall.com/SCPPRG/OkonElias2009QEP.pdf> Accessed November 10, 2016

[17] Uggerhøj U I, Mikkelsen R E, and Faye J 2016 The Young Center of the Earth *European Journal of Physics* **37** 3

[18] Hoskins J K, Newman R D, Spero R and Schultz J 1985 Experimental Tests of the Gravitational Inverse-Square Law for Mass Separations from 2 to 105 cm *Phys. Rev. D* **32** 15 December pp 3085–3095

[19] Smalley L 1975 *Gravitational Clock: A Proposed Experiment for the Measurement of the Gravitational Constant G* NASA Technical Memorandum, NASA TM X-64920 January 24

[20] Benish R J 2011 Missing Measurements of Weak-Field Gravity *Progress in Physics* **1** January pp 40–42

[21] Herold G 2009 Personal communication

[22] Moller C 1972 *The Theory of Relativity* (Oxford: Clarendon Press) p 394

[23] Okun L 2000 Photons and Static Gravity *Modern Physics Letters A* **15** pp 1941–1947

[24] Evans J, Nandi, K K, Islam A 1996 The Optical-Mechanical Analogy in General Relativity: New Methods for the Paths of Light and of the Planets, *American Journal of Physics* **64** pp 1404–1405

[25] Einstein A 1982 Physics and Reality *Ideas and Opinions* (New York: Crown) p 310

[26] Reasenberg R D and Shapiro I I *et al* 1979 Verification of Signal Retardation by Solar Gravity *Astropysical Journal* **234** L219–L221

[27] Vessot R F C and Levine M W A Test of the Equivalence Principle Using a Space-Borne Clock *General Relativity and Gravitation* **10** p 181

[28] Tangherlini F R 1962 Postulational Approach to Schwarzschild's Exterior Solution with Application to a Class of Interior Solutions *Il Nuovo Cimento* 25(5) p 1081

[29] Benish R 2012 *Maximum Force Derived from Special Relativity, the Equivalence Principle and the Inverse-Square Law* <http://vixra.org/abs/1209.0004> Accessed December 20 2016

[30] Klotz A 2015 The Gravity Tunnel in a Non-Uniform Earth *American Journal of Physics* **83** p 231

[31] Feynman R 1995 *Feynman Lectures on Gravitation* (ed) B Hatfield (Reading, Massachusetts: Addison-Wesley) p 69

[32] Faye J 2014 *The Nature of Scientific Thinking: On interpretation, explanation and understanding* (New York: Palgrave Macmillan)