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Testing the Inverse-Square Law of Gravity in Boreholes at the Nevada Test Site

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Stacey *et al.* have reported evidence for a breakdown of Newton's law based on measurements in a deep mine. We have tested the reproducibility of this result by analyzing gravity data from boreholes in Nevada. One interpretation of our results suggests a breakdown of the Newtonian theory which is much larger than the effect previously reported. But the lack of consistency between the results suggests that it is not fundamental physics that has failed, but rather the experiments are subject to large systematic uncertainties which are caused by mass anomalies at intermediate distances from the holes.

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Stacey *et al.*[1-3] have pioneered the modern techniques of testing the inverse-square law of gravity by measuring gravity in deep boreholes. One of their experiments showed an apparent breakdown of Newtonian gravity; and in an elegant series of papers they have considered the various sources of systematic uncertainty and have found it difficult to make the effect go away. The remaining uncertainty in their work, they suggest, is the possibility of an anomalous gravity gradient caused by unmapped mass anomalies in the ground around the hole.[4]

The purpose of this work was to test the reproducibility of Stacey *et al.*'s result.

The basic principles of a borehole experiment. —Consider a spherical, nonrotating, earth composed of several homogeneous layers. We can test Newtonian theory by measuring gravity $g(r)$ at various depths beneath the surface of the earth. The measurements can then be compared to a Newtonian model of the gravity field. The test is better illustrated by considering the gravity gradient inside this simple earth:

$$\frac{dg(r)}{dr}=\frac{-2g(r)}{r}+4\pi G_{\text{local}}\rho_{\text{local}} ,$$

where G is the gravitational constant and ρ the density of the rock. The first term on the right-hand side is called the free air gradient because it is the gradient one would measure outside the earth and its magnitude is determined by mass sources far from the surface (i.e., it represents the point mass at the center of the sphere). The second term is twice the standard Bouger term and is the result of differentiating $M(r)$. The differential step to greater depth is explicitly a local phenomenon and so the Bouger term is sensitive to the local average density and a local effective gravitational coupling constant.

Our test of the Newtonian hypothesis is then to measure the gravity gradient as a function of depth, measure the local average density, and model the free air gradient. A simple balancing of terms tells us whether G_{local} is equal to G_∞ as required by the Newtonian theory.

But the real Earth is neither spherical, stationary, nor homogeneous. The nonspherical figure of the Earth, and its rotation, are important but can be precisely calculated. We refer the reader to the papers by Stacey *et al.* for a complete description of these terms. The nonhomogeneous nature of the Earth below the surface is more of a problem and any model of the gravity gradient must take these mass anomalies into account. Therefore, an accurate map of the terrain and underlying geology is essential. At depth, where there are no data, it is customary to assume that all layers are horizontal and homogeneous. (One can, in principle, avoid this assumption by measuring the surface gravity field at a large number of points, correct the measurements for the known masses below ground, interpolate them to all points on the surface, and then downward continue the field to yield a prediction of the gravity gradient underground. But no one has done this, yet, to a precision

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better than about 1 mGal/km and this is about the size of the previously reported non-Newtonian signals.)

Gravity measurements at Nevada Test Site.—The U.S. Government tests its nuclear weapons at the Nevada Test Site and as part of this program they drill deep holes in the desert ranging from a few hundred meters to 4 km depth. The holes are often clustered together with a 2–5-km spacing. The holes are vertical and they are large, typically 3 m in diameter. Before a weapon can be exploded, the geology around the hole must be characterized to show that there is sufficient mass over the bomb to contain the blast and to show that there are no nearby faults which could be activated. Consequently, the density of the rock is measured in every hole and gravity $g(Z)$ is measured at various depths in some of the holes. The gravity measurements are used as a probe of the mass structures between holes and in regions that have not been directly accessed by drilling.

Typically, gravity is measured every 15 m down a hole. The density of the rock wall is measured continuously with a γ-γ logging tool (essentially a γ-ray attenuation measurement) and averaged on a 3-m interval. In some holes, the rock density is directly measured with a coreing tool. The density of the rock is low, about 2.0 g/cm^3, and it is dry. (The water table is below the bottom of these holes at ≈ 600 m depth.) The grain densi-

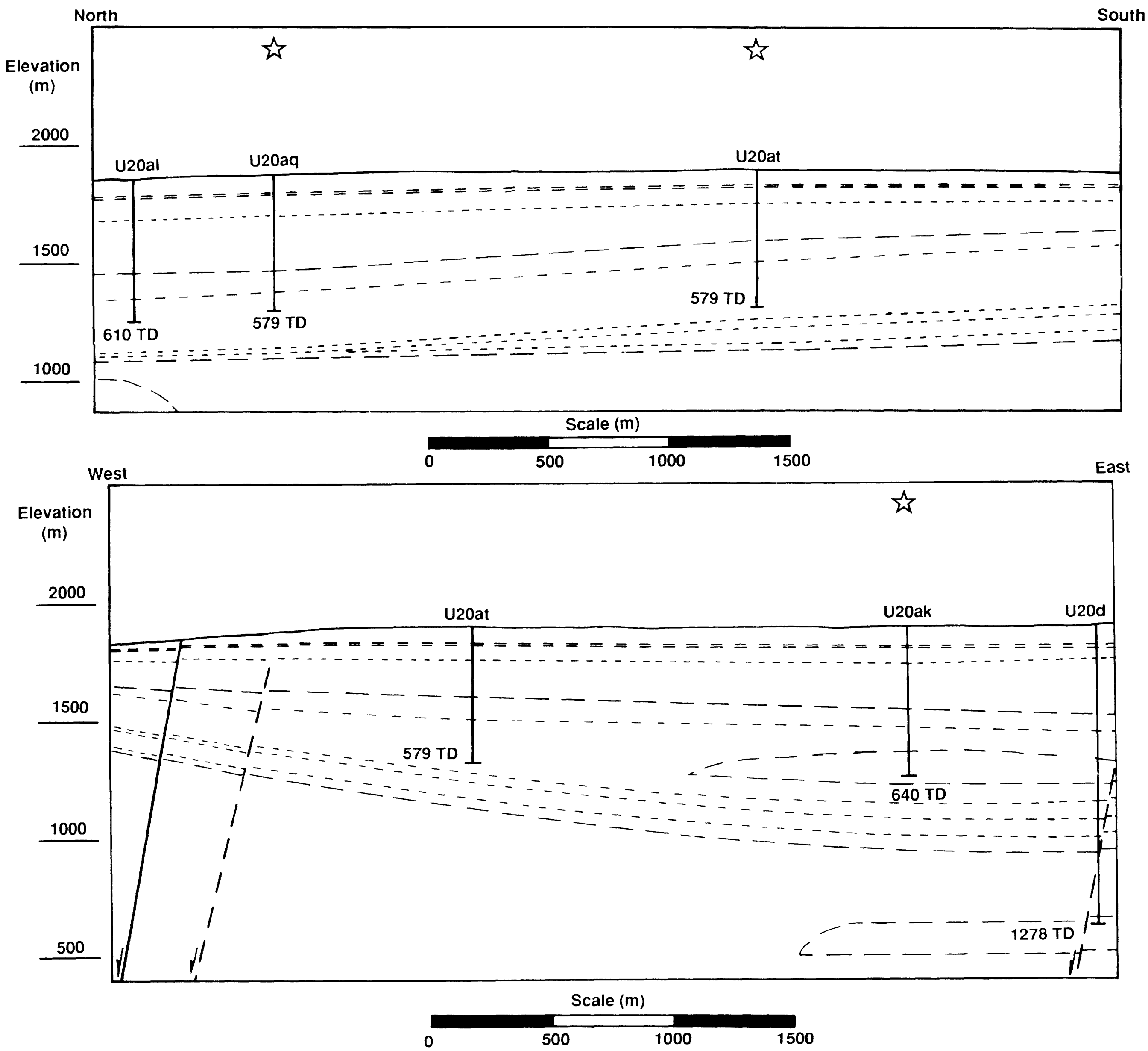

FIG. 1. The geologic strata in area 20 of the Nevada Test Site are typically a series of horizontal lava flows interspersed with alluvial material. Borehole U20AK is at the center of a cluster of five holes that we have studied. North-South and East-West cross sections through this area are shown, adopted from Ref. 7.

ty of a sample of crushed rock is also measured every 3 m, as well as water content, CO_2 content, porosity, seismic wave velocity, and hole diameter. The depths to the geologic horizons for the different rock types are also recorded as the holes are drilled.

Fortuitously, for 1 or 2 km beneath the surface of the Nevada Test Site (NTS), the geology is dominated by a series of overlapping, horizontal, lava flows and alluvial layers (see Fig. 1), although the deep structure beneath NTS is fairly complex.[5] But we cannot use the existing maps and models of the geologic structures because they are based, in part, on gravity measurements and the map makers analyzed the data assuming Newtonian theory was valid.

We have concentrated on a group of five closely spaced holes in area 20 of NTS. They have been designated U20AT, U20AL, U20AK, U20AR, and U20AO.[6-10] Three of these are shown in North-South and East-West profiles in Fig. 1. The other two are similar but are spaced about 2 km away in different directions. Hole U20AK is surrounded by the others and so we expect to be able to do a complete density correction to the data from this hole. But, the outer holes cannot be fully corrected without relying on the geologic models of the region that are based in part on gravity measurements. Therefore, we assumed that the densities measured at the sides of the holes extended laterally to infinite distance. Hole U20AK was then further refined by extending the observed strata in U20AK, linearly, towards the same strata found at a slightly different depth in each of the outer holes.

All gravity measurements were corrected for the Earth's tide, the terrain on the surface out to 168-km distance, and the excavation of the hole.[11]

We could have included the terrain effects in the *model* but instead chose to follow the customary practice of applying the terrain corrections to the *data*. The important point is to examine the difference between the data and the model; how the comparison is made is not important.

Figure 2 compares the gravity gradient observed in U20AK to the gradient observed in the Hilton Mine, Australia, by Holding, Stacey, and Tuck.[2] The data are reported as gravity residuals, that is to say the difference between the measured and the modeled gravity at depth relative to the surface. The gravity model includes local, lateral, mass anomalies but assumes that matter beneath the hole occurs in homogeneous ellipsoidal layers. The units of g are milligals (1 Gal = 1 cm/sec^2) and are approximately 1 part per million of the surface gravity field.

The nonzero slope of the Hilton data suggested to Stacey *et al.* that G underground could be 0.7% larger than the laboratory value of G. The data from U20AK might support the breakdown of Newton's universal law of gravitation but it requires a modification of G by 4%.

Systematic errors.—The obvious sources of error in the NTS data are (i) a calibration error in the gravimeter, (ii) an error in the density measurements, and (iii) an error in the gravity gradient model.

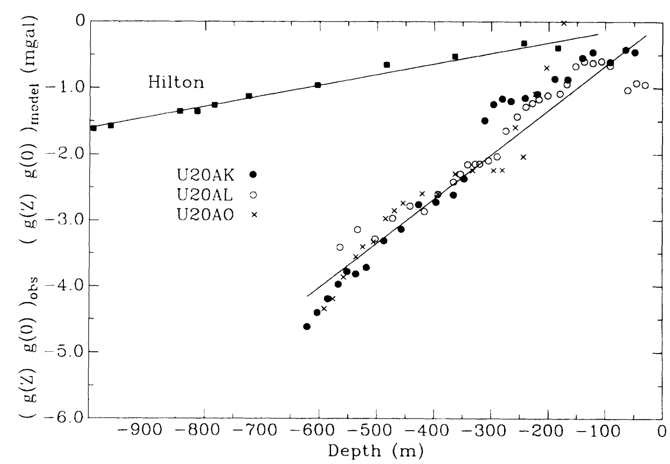

FIG. 2. Gravity observations made in three NTS boreholes are compared to the observations made in the Hilton Mine, Australia. The data are reported as gravity at depth Z minus the surface value. A Newtonian gravity model is subtracted from the data (i.e., a Newtonian result would lie on the horizontal axis). Both the U20AK and the Hilton data sets have been corrected for mass anomalies that occur out laterally from the holes. Holes U20AO and U20AL are shown in order to assess the errors in the γ-γ density log.

The gravity measurements are absolutely standard. Geophysicists routinely measure surface gravity to ± 20 μGal (≈ 20 ppb) whereas the "non-Newtonian" discrepancy we are discussing is milligals. All measurements reported here were measured relative to several absolute gravity stations available at NTS. Similarly, the correction for Earth tides, terrain, etc., are more than adequate for this work; the largest error would be in the terrain correction which might have a systematic error as large as ± 100 μGal.

The density of the rock in each hole was measured with a γ-γ logging tool. This technique relies on Compton scattering to measure the bulk density of electrons in a test sample. Before each run, the tool is calibrated against known samples of rock which are maintained in a calibration laboratory at NTS. And because the geology encountered in each hole can be predicted fairly well, these calibration measurements can be quite accurate. We have compared several down-hole γ-γ measurements to sample cores taken by the U.S. Geologic Survey in these holes. Typically, individual density measurements agree to within 0.5% between the two techniques but occasionally large excursions occur (up to 10%). The cause of these excursions is fairly easy to identify. The γ-γ tool is sensitive to how far it is from the rock wall and sometimes this wall is not smooth and flat, and can have sloughing and cave-ins. So, the distance to the wall is measured at each station and a correction is applied to the data. We are also aided by the fact that the analysis requires the average density from the point of observation to the surface. Thus, we may average the continuous density measurements from the bottom of the hole to the top and achieve a much better estimate of the average density than any one measurement would suggest. Thus, we believe the average densities for the geologic strata are known about as well as the bulk, long-range, homogeneity of the rocks in the strata. That is, we estimate that the average densities are known to 1%. This is smaller than the apparent 4% change in G (or ρ) required by our data.

An alternate way to estimate the uncertainty in the densities is to look at the gravity gradients measured in the other holes (also shown in Fig. 2). These data have been corrected for the local-density anomalies as described above, but only U20AK has a complete correction since it was surrounded by the other four. The outer holes have random structure effects, and, in particular, have different density errors due to the sidewall distance corrections. The fluctuations in these three gravity profiles are representative of the error in the average densities as determined by the γ-γ tool. It is difficult to quantify the fluctuations but they are small with respect to the apparent 4% change in G required by the data.

The uncertainty in the gradient model cannot be so easily dismissed. All of the data have been corrected for lateral density anomalies but not for deep anomalies. We were forced to assume a homogeneous structure deep beneath NTS and this is probably not true anywhere on Earth, especially not in Nevada. It is well known that there is a seismic reflection barrier at about 10 km depth under Nevada. This may indicate a density contrast and may be the source of anomalous gradients. We are thus uncomfortable with the hypothesis that gravity gradients measured in Nevada suggest non-Newtonian gravity.

We are similarly uncomfortable with the suggestion that any place on Earth is sufficiently flat and homogeneous to test Newtonian gravity in boreholes without the help of an extensive surface gravity survey. A surface survey can be used to estimate the underground gradients. Solving Poisson's equation inside the Earth yields a Newtonian extrapolation of the surface field, in principle, but is difficult to implement, in practice, because noise in the data is amplified by the downward continuation. Stacey, Tuck, and Moore have reported initial progress with this technique on the Hilton data[12] and we have tried it using the NTS data. But, we were unable to achieve an uncertainty better than 1 mGal/km in the comparison between measurements and the extrapolated field[13] due to noise and uncertainties in the source terms. We feel that more precise results can be achieved by extrapolating the surface gravity field upwards using Laplace's equation, and then to compare the predictions to measurements made on a tall tower[14-18] because noise in the surface data is dampened in an upward continuation.

In conclusion, we have shown that the gravity gradients measured in Nevada and Australia are different and do not describe a consistent non-Newtonian interaction and we conclude that this is likely to be the case at other borehole locations around the Earth.[13,19] This variability is the result of an analysis where we compared measured gradients to a model gradient and the model implicitly assumes an earth with uniform and homogeneous layers at depths beneath the hole. We believe this to be an insufficient test of Newtonian gravity simply because undetected mass anomalies, located out laterally[20] or perhaps deep in the crust or upper mantle, have not yet been eliminated as an explanation for the experimental results. All of the existing borehole experiments suffer from this problem.[21,22]

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[1] F. D. Stacey *et al.*, Phys. Rev. D **23**, 2683 (1981).

[2] S. C. Holding, F. D. Stacey, and G. J. Tuck, Phys. Rev. D **33**, 3487 (1986).

[3] F. D. Stacey *et al.*, Rev. Mod. Phys. **59**, 157 (1987).

[4] F. D. Stacey, G. J. Tuck, and G. I. Moore, in *Proceedings of the Seventh Moriond Workshop; New and Exotic Phenomena,* edited by O. Fackler (Editions Frontieres, Gif-sur-Yvette, France, 1987).

[5] H. L. McKague, P. P. Orkild, and S. R. Mattson, *The Geology of the Nevada Test Site,* Guidebook T186 (American Geophysical Union, Washington, DC, 1989).

[6] G. Pawloski, LLNL Memorandum No. CP 85-19.

[7] S. Clark and G. Pawloski, LLNL Memorandum No. CP 86-56.

[8] N. Howard, LLNL Memorandum No. DM 78-5.

[9] N. Howard and J. Wagoner, LLNL Memorandum No. CP 85-76.

[10] J. L. Wagoner, LLNL Memorandum No. CP 84-49.

[11] W. Heiskanen and H. Moritz, *Physical Geodesy* (Freeman, San Francisco, 1967).

[12] F. D. Stacey, G. J. Tuck, and G. I. Moore, J. Geophys. Res. **93**, 10575 (1989).

[13] J. Thomas *et al.*, in *Proceedings of the Fifth Marcel Grossman Meeting, Perth, Australia 1988,* edited by D. Blair and M. J. Buckingham (World Scientific, Singapore, 1989).

[14] D. Eckhardt *et al.* Phys. Rev. Lett. **60**, 2567 (1988).

[15] C. Jekeli *et al.*, Phys. Rev. Lett. **64**, 1204 (1990).

[16] J. Thomas, Phys. Rev. D **40**, 1735 (1989).

[17] J. Thomas *et al.*, Phys. Rev. Lett. **63**, 1902 (1989).

[18] J. Faller *et al.*, Phys. Rev. Lett. **64**, 825 (1990).

[19] J. Thomas, P. Vogel, and P. Kasameyer, in *Proceedings of the Twenty-Third Recontre de Moriond and Eighth Moriond Workshop on Fifth Force and Neutrino Physics, Les Arcs, France, 1988,* edited by O. Fackler and J. Tran Thanh Van (Editions Frontieres, Gif-sur-Yvette, France, 1988).

[20] D. F. Bartlett and W. L. Tew, Phys. Rev. D **40**, 673 (1989).

[21] A. Hsui, Science **237**, 881 (1987).

[22] M. E. Ander *et al.*, Phys. Rev. Lett. **62**, 985 (1989).