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Final results from the WABG tower gravity experiment

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A test of the inverse-square law, conducted on a 610 m television transmitter in Inverness, Mississippi, measured gravity at five elevations on the WABG tower, and compared these data with the Newtonian predictions using potential theory. The largest observed-minus-model discrepancy, at 493 m above ground, was (-33 ± 30) μGal (1 μGal$=10^{-8}$ m s^{-2}). These data have since been supplemented with additional gravity data taken on the tower at a higher elevation. The results confirm the predictions of Newtonian gravity, with a discrepancy of (32 ± 32) μGal at 568 m. The tower experiments, along with current lake experiments, place very tight constraints on any possible non-Newtonian forces. [S0556-2821(97)01408-2]

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INTRODUCTION

In 1990 the Phillips Laboratory in collaboration with Purdue University began work on a tower gravity experiment using the 610 m WABG tower in Inverness, MS. This was a follow-up to an earlier experiment completed in 1988 which utilized the WTVD tower in Clayton, NC [1]. The WABG experiment was essentially completed in 1993; comparing gravity data with the predictions of Newtonian gravity using potential theory indicated no departure from the inverse-square law [2]. The aim of the WABG experiment was to obtain gravity measurements at six elevations on the tower, but due to some unknown systematic effects every measurement attempt at the sixth elevation (571 m) proved unsuccessful. As a result, the highest elevation with available gravity data was at 493 m. These problems have since been overcome, and in 1995 we succeeded in obtaining readings at 568 m above ground level. These readings, along with the previous results on the WABG and WTVD towers, allow for even tighter constraints on the non-Newtonian force parameters α and λ [see Eq. (1) below]. Furthermore, we can now combine our tower data with data from lake experiments to give very tight constraints on the non-Newtonian coupling constant α over the entire geophysical window (10 m to 10 km).

DEALING WITH THE RADIO FREQUENCY INTERFERENCE PROBLEM

The data collection at all lower tower elevations on the WABG tower proved difficult due to persistent high wind speeds ($\nu>20$ km h^{-1}), but a sufficient number of calm days allowed data to be eventually obtained at the lower elevations. However, our initial attempts at obtaining gravity measurements at the top elevation of the tower (labeled T6), failed since the gravimeter became disabled at this elevation. On the WABG tower, the top platform is approximately 9 m closer to the actual transmitter than the one on the WTVD tower. Moreover, using a field strength meter we observed a leak in the transmission line of about 50 W m^{-2} at T6. It was therefore possible that the problem was caused either by the leak or by the transmitter located at the top of the tower. Although previous tests indicated that this level of radio frequency (rf) signal would not affect the reading line of the gravimeter, even though it disabled the galvanometer, we decided to work under the assumption that the rf was the source of the problem. If the problem is indeed rf, there are two possible solutions, either shield the rf source or move

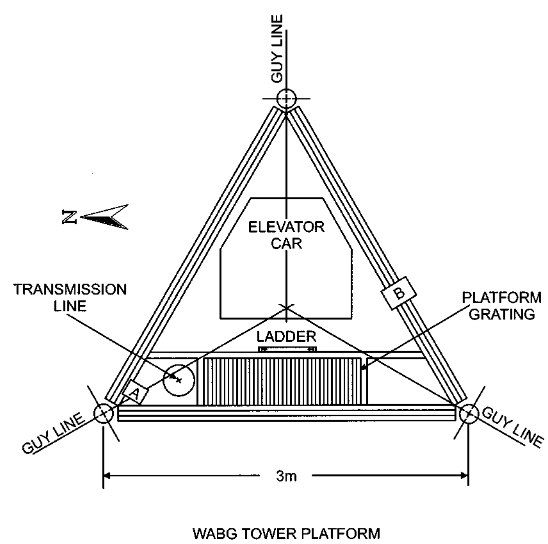

FIG. 1. Horizontal cross section of the WABG tower showing the elevator, platform grating, guy lines, transmission line, and locations of the gravimeter. Note, location C is not shown but is 2.3 m directly below location B.

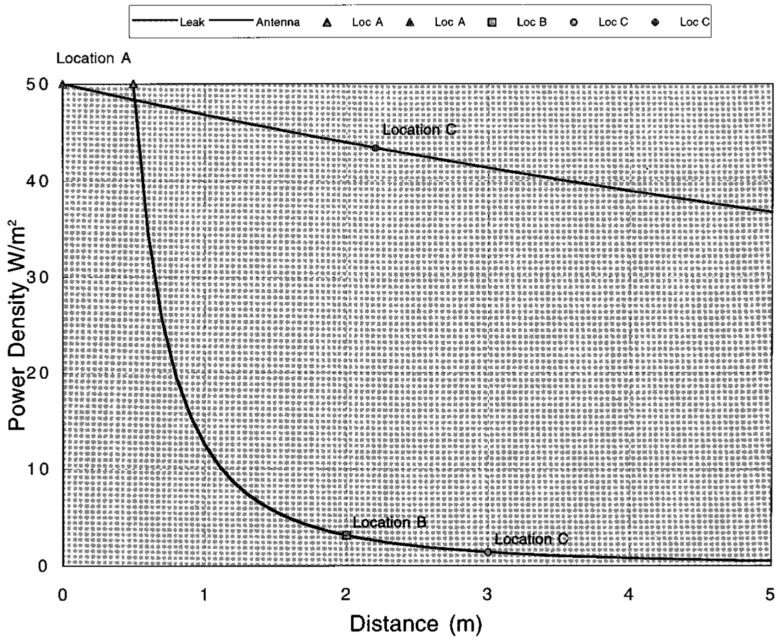

FIG. 2. Radio-frequency (rf) power density as a function of distance from the source, along with gravimeter locations. The lower curved assumes that the rf power arises from a leak in the transmission line, and the upper curve assumes that the source is the transmitter. For the upper curve, the distance from the source is the abscissa plus 30 m.

farther away from its influence. Not knowing whether the problem was caused by the leak in the transmission line or from the transmitter itself, shielding the transmitter or the transmission line were not viable options. It was thus decided to move away from the rf source.

Since power falls off with distance, it should be possible to move far enough away from the source to obtain a successful measurement, assuming the problem was a leak in the transmission line at T6. Figure 1 depicts a horizontal cross section of the tower showing the platform grating where the measurements were carried out. Location A denoted the position where the gravimeter was placed during the initial unsuccessful attempts; it is in close proximity to the transmission line (and hence the leak), as can be seen from the figure. Placing the gravimeter at location B, which is approximately 1.5 m farther away from the transmission line than location A, improved the situation but did not fully correct the problem. However, when the gravimeter was moved to location C, which is 2.3 m directly below location B, the gravimeter behaved properly. At location C both the galvanometer and reading line moved freely between stops with no discernible impediments.

The nominal operation of the gravimeter at location C establishes conclusively that the problem was in fact caused by a leak in the transmission line and was not due to the actual transmitter, nor due to any other source of rf. The reason can easily be seen from Fig. 2, where two curves are depicted: The lower curve assumes the source of the measured 50 W m^{-2} is a leak in the transmission line, and the upper curve assumes it is the transmitter. The transmitter is approximately 30 m from both locations A and B. As such, the signal intensity would have already decreased by almost three orders of magnitude, and an additional 2.3 m to location C would not make much difference. As Fig. 2 readily displays in the upper curve, the 50 W m^{-2} signal at location A is only reduced to about 43 W m^{-2} at location C. By contrast, if the 50 W m^{-2} signal is caused by a leak, then moving from location A, nearest the source, to locations B and C results in a large signal decrease to about 3 and 1.5 W m^{-2}, respectively.

OBTAINING AND ANALYZING THE FINAL RESULTS

Previous measurements had resulted in readings at five elevations (T1–T5) up to a maximum elevation of 493 m. Even though the rf problem at T6 had been overcome, we still had to contend with the winds that continued to thwart our efforts at data collection. As was the case on previous surveys, the wind speeds at most times exceeded 20 km h^{-1}. Fortunately, there were periods during which the winds diminished enough to allow the collection of additional data including data at the 568 m elevation. These data were merged with the previously obtained tower data and were processed in a least-squares adjustment. The completed tower survey consists of 12 observations in six data collection loops. The error analysis portion of the data processing indicates that the data at T6 are precise to 25 μGal (1 μGal$=10^{-8}$ m s^{-2}). The surface data were analytically continued, assuming the validity of the inverse-square law, by the same Fourier-Bessel/numerical integration technique used previously [2]. The gravity data at the six tower eleva-

TABLE I. The observed-minus-model discrepancies at the six tower elevations along with the values at the base. Elevations are measured above ground and errors are one standard deviation (1σ).

Site	Elevation (m)	Observed$-$model (μGal)	Error (μGal)
$T0$	0.000	9	56
$T1$	93.845	18	26
$T2$	194.363	-16	25
$T3$	292.564	-8	26
$T4$	388.511	-33	27
$T5$	493.589	-33	30
$T6$	568.913	32	32

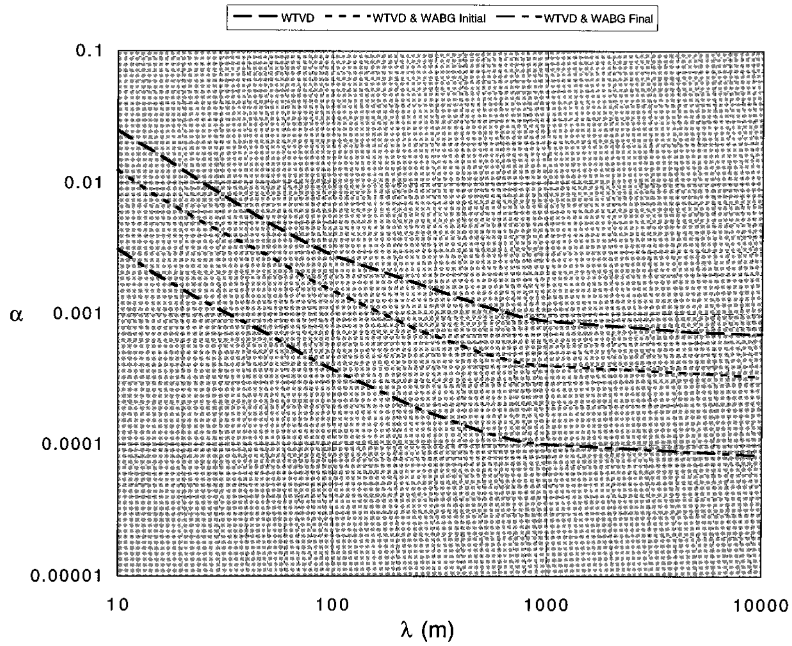

FIG. 3. Constraints on α and λ arising from the WTVD and WABG results. The region above each curve is excluded by the corresponding data at the 1σ level.

tions were then compared with the corresponding predicted values and displayed in Table I. These data represent the final results from the WABG tower. The experiment essentially yields a null result with five out of the seven discrepancies within 1 σ and all the discrepancies within 2σ.

The addition of the data point at T6 caps a nearly five-year long effort. The additional data reported here are important in constraining the coupling constant and scale length in the usual model of non-Newtonian gravity. If $V(r)$ denotes the potential energy of two masses m_i and m_j located a distance r apart, then we assume $V(r)$ can be written in the form

$$V(r)=\frac{-Gm_im_j}{r}\,(1+\alpha e^{-r/\lambda}), \qquad (1)$$

where G is the Newtonian gravitational constant, and α, λ are the parameters we wish to constrain. In this model the difference $\Delta g(z)$ between the observed gravity $g_0(z)$ and the modeled gravity $g_m(z)$ at a height z above the ground is given by

$$\Delta g(z)=g_0(z)-g_m(z)=2\pi\rho G\alpha\lambda(e^{-z/\lambda}-1), \qquad (2)$$

where ρ is the average density of ground soil in the vicinity of the tower. Figure 3 shows the 1σ limits on α and λ as a result of the WTVD and WABG tower experiments. The upper curve represents the limits derived from the WTVD data, the middle curve shows the constraints from the combined WTVD and WABG results prior to the addition of T6, and the lower curve presents the final results. These addi-

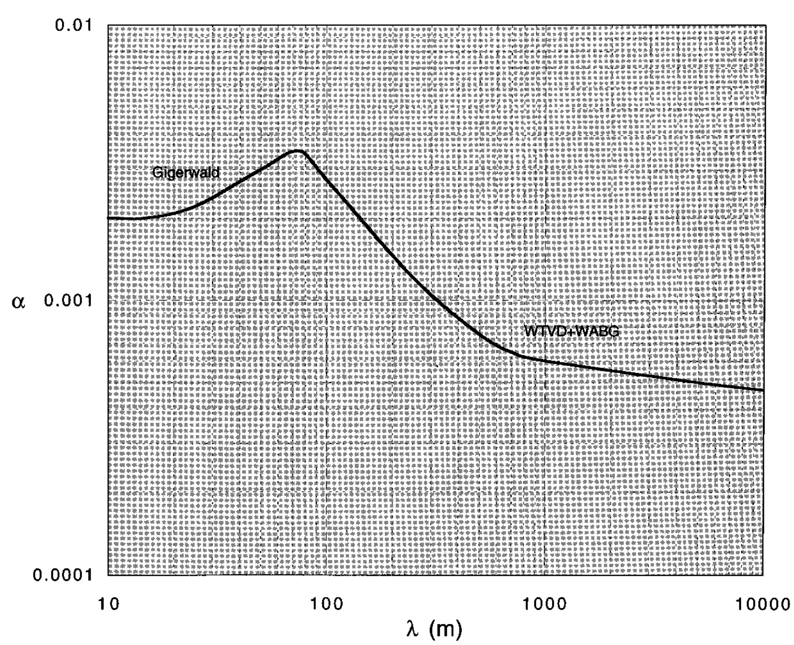

FIG. 4. Constraints on α and λ arising from combining the final results of both towers and the results of the Gigerwald Lake experiment. The region above each curve is excluded by the corresponding data at the 2σ level.

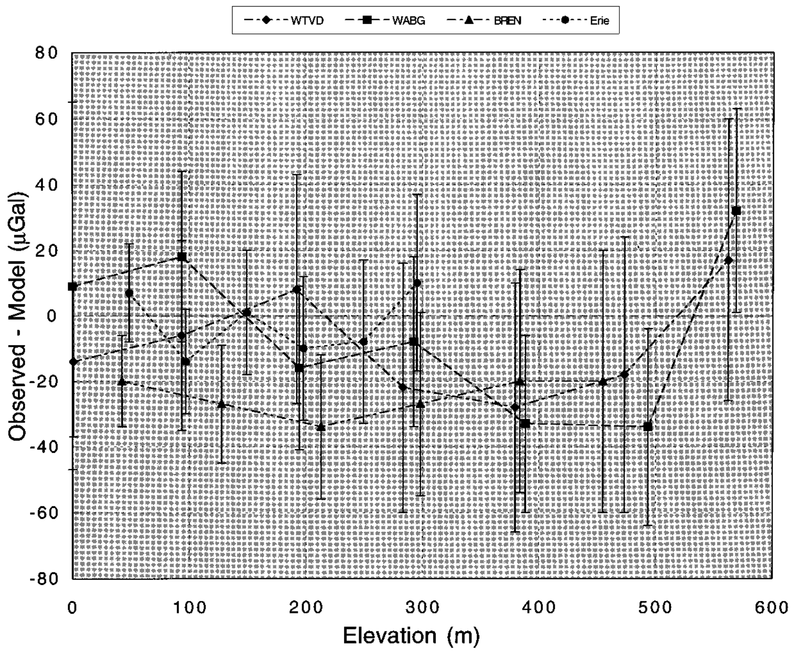

FIG. 5. The final observed-minus-model discrepancies from the existing tower experiments as a function of elevation.

tional data significantly improve the constraints on α and λ and, at the low end of the λ scale, the precisions are now approaching those of the lake experiments. This can be seen from Fig. 4 which depicts the tower data combined with the results of the Gigerwald Lake experiment in eastern Switzerland [3]. The curve represents the 2σ limits on α and λ arising from the combined tower and lake experiments. Gigerwald Lake was chosen because it yields the tightest constraints among the known lake experiments [3–6].

CONCLUDING REMARKS

The results presented here conclude a 10-year series of experiments by Phillips Laboratory to test Newtonian gravity using tall towers. The first successful measurement of gravity on a tall tower was carried out by PL in 1986 [7], and since then three groups have completed experiments four different towers [1,2,8,9]. The results of all tower experiments to date are shown in Fig. 5 from which we can draw two major conclusions: First, the addition of T6 on the WABG tower effectively brackets the value of α between about 0.0004 and -0.0001 for $\lambda=100$ m. This results in the tightest constraints to date on the non-Newtonian coupling constant. Second, all the tower experiments are in excellent agreement within their respective errors.

Tower gravity experiments have been invaluable in testing the validity of the inverse-square law [10–14]. Figure 6 shows the constraints on α as a function of λ in 1981, and then again in 1996. Up until 1981 our knowledge of gravity over the intermediate range (10 m to 10 km) was woefully inadequate, especially between 10 and 100 m. Experiments on towers have now filled the gap in our understanding of gravity by providing much-needed information within the ''geophysical window.'' Not only have these experiments

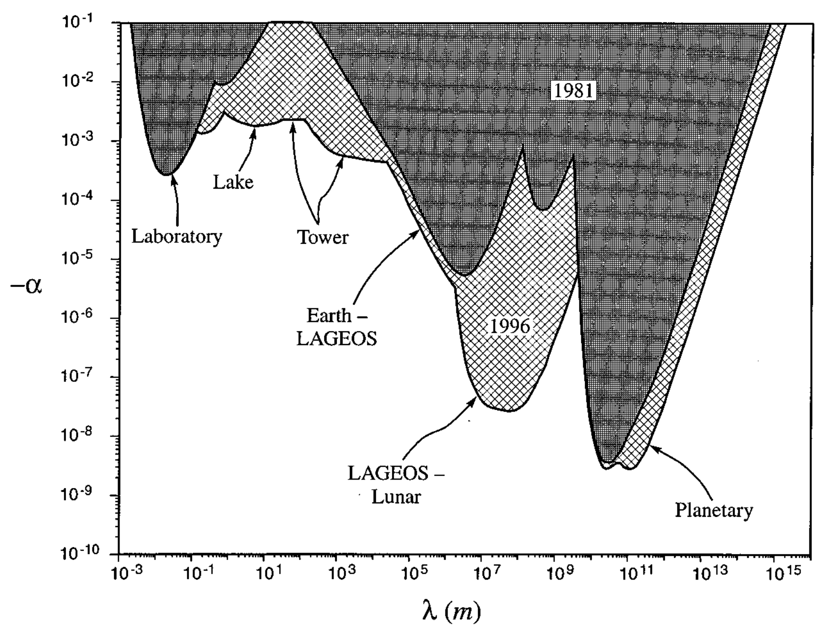

FIG. 6. The constraints on α as a function of λ in 1981 (dark region) and again in 1996 (hatched region) after including the most recent experimental results.

TABLE II. The observed-minus-model discrepancies for all towers: Δg_1=WABG, Δg_2=WTVD, Δg_3=(BREN), Δg_4=Erie [example: $\Delta g_{13}=\Delta g$ (WABG)$-\Delta g$ (BREN), where Δg is given in Eq. (2)].

Elevation (m)	Δg_{12}	Δg_{13}	Δg_{23}	Δg_{14} (μGal)	Δg_{24}	Δg_{34}	Δg_{rms}
110	18	38	21	25	7	14	23
205	19	18	37	6	19	23	22
310	14	20	7	16	29	36	23
385	5	13	8				9
474	16	13	2				12
565	11						11

provided new constraints, but they have also been surprisingly consistent: If we take all tower experiments and compare the observed-minus-model discrepancies for comparable elevations, we find that the results differ by a root mean sum (rms) of only 23 μGal. The agreement can be seen in Table II, where we have interpolated all results to common elevations.

The overall rms is a mere 20 μGal, and given the variation in the sites and the differing backgrounds of all the agencies involved in this study, this level of agreement is remarkable. It is important to note that in each of these experiments, the gravity measurements on the tower are uncorrelated whereas the analytically continued values are highly correlated. The reason is that the modeled gravity data even at different elevations are all derived from the same surface data; hence any errors in the surface data will systematically propagate to all the predicted values. Conversely, the tower gravity measurements, which are independent of one another, will tend to have only random errors. In summary, we conclude from existing tower experiments that at the present time there is no evidence for any significant deviation from the inverse-square law for $\lambda \approx 10^3$ m.

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