International Refereed Journal of Engineering and Science (IRJES)
ISSN (Online) 2319-183X, (Print) 2319-1821
Volume 5, Issue 12 (December 2016), PP.36-42

Validation metric for gravitational constant measurement based on comparative uncertainty

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Abstract:- The existing spread of the measurement uncertainties of Newton's gravitational constant G is very poor compared with other physical fundamental constants. One of these uncertainties is the first-born uncertainty that depends on a number of recorded variables of the measurement scheme model, and has existed before field experiments started. By using the fundamentally novel approach based on information and similarity theories, a formula for calculating the new metric called comparative uncertainty is introduced. Analysis of the results of measurements of G made during 2000–2016 using the calculated interval, in which the estimated true value of G can be placed, shows the excellent agreement between the proposed approach and CODATA recommendations in terms of the desired relative uncertainty of 1.4 x 10^{-5}.

Keywords: - Physical-mathematical model, information theory, theory of similarity, gravitational constant measurement, relative and comparative uncertainties

I. INTRODUCTION

People perceive the world through the senses, which are embodied in their minds in the form of feelings, emotions and images that are close or far from reality. In turn, the images are transformed into models of phenomena and processes in the power of the human desire to know the structure of the universe. Currently there are various and perfectly developed mathematical methods and test benches, along with powerful computers, to address physical, technical, chemical and biological problems, including the measurement of Newton's gravitational constant (NGC) *G*.

The importance of the high precision of *G* not only stems from pure metrological interest; it has a key role in different theories including gravitation, cosmology, particle physics and astrophysics. At the same time, the current spread of values of *G* considered as a fundamental constant of nature, at present, is very poor compared with other physical fundamental constants, many of which have uncertainties of the order of parts in 108. The constant determining the electronic structure of atoms, the Rydberg, has an uncertainty of only four parts in 1012 [1].

When measuring G, it is desirable to identify and assess all relevant variables chosen by the conscious observer, based on his/her knowledge, experience and intuition. There can be pitfalls: objective and subjective uncertainties of the physical-mathematical model and the methods of calculation associated with it. Many inferences and assumptions can be justified on the basis of experience (and sometimes uncertainties can be estimated), but the degree to which our assumptions correspond to the study of NGC is never established.

The aim of this paper is an introduction of possible estimates of the expedient level of accuracy for the calculation of NGC that is based on a realization of three conditions: a. there is a pre-specified list of recorded variables; b. the possible range of variation of G is defined or declared *before* the realization of experiments or computational simulations; and c. any factors that are ignored in making predictions have actually been taken into account to calculate the uncertainty of the physical-mathematical model that is applied to verify the exact value of NGC. For this purpose, the principles of the information and similarity theories are applied in order to formulate a fundamentally novel metric called comparative uncertainty, which limits any future accuracy of NGC measurements. This "first-born" uncertainty is connected only to a finite number of recorded variables taken into account during the development of experimental schemes or physical-mathematical models. In other words, a certain uncertainty exists *before* starting a field experiment or computer simulation due only to the limited dimensions of the model. It is independent of any possible activities of the modeler. All subsequent arguments and calculations are presented in the manifest/background paper [2]. However, for a more complete and clear understanding of the stated approach, here are all the necessary definitions, calculations and explanations.

II. FORMULATING THE APPLIED TECHNIQUES

What value of accuracy can be achieved, or what is the smallest achievable uncertainty of NGC measurements?

Fundamental limits on the maximum accuracy with which we can determine the physical variables are defined by the principle of Heisenberg's uncertainty. However, Planck's constant is infinitesimally small with respect to macro bodies. This is why this uncertainty in macroscopic measurements cannot be used for practical applications. Uncertainties of position and momentum, calculated in accordance with the Heisenberg's principle, do not manifest themselves in practice, and lie far beyond the achievable accuracy of experiments.

In [2], the approach for calculating the lowest uncertainty of the researched variable (in our case, NGC), based on principles of information and similarity theories, is formulated. Following it, a certain uncertainty exists before starting experiments due only to the known recorded number of variables. In turn, the dimensionless (DS) comparative uncertainty ε of the DS variable $\boldsymbol{u}$, which varies in a predetermined DS interval $\boldsymbol{S}$, for a given number of selected physical dimensional (DL) variables $\boldsymbol{z}''$, and β'' (the number of the recorded primary physical variables) can be determined from the following relation:

$$\varepsilon = \square \boldsymbol{u}_G / \boldsymbol{S} \le [(\boldsymbol{z}' - \boldsymbol{\beta}')/(\boldsymbol{\Psi} - \xi) + (\boldsymbol{z}'' - \boldsymbol{\beta}'')/(\boldsymbol{z}' - \boldsymbol{\beta}')] \quad (1)$$

where $\square \boldsymbol{u}_G$ is the DS uncertainty of the physical-mathematical model describing the experiment of the measurement of G; □ is the number of primary physical variables with independent dimensions; SI (International system of units) includes the following seven (ξ = 7) basic primary variables: **L**–length, **M**–mass, □–time, **I**–electrical current, **Θ**–thermodynamic temperature, **J**– luminous intensity, **F**–number of substances. The dimension of any secondary variable **q** can only express a unique combination of dimensions of the main primary variables in different degrees [3]:

$$\mathbf{q} \supset \mathbf{L}^{l} \cdot \mathbf{M}^{m} \cdot \mathbf{T}^{t} \cdot \mathbf{I}^{i} \cdot \mathbf{\Theta}^{\Theta} \cdot \mathbf{J}^{j} \cdot \mathbf{F}^{f} \quad (2)$$

l, *m*... *f* are exponents of variables, the range of which has a maximum and minimum value; according to [4], integers are as follows:

$$-3 \le l \le +3,\ -1 \le m \le +1,\ -4 \le t \le +4,\ -2 \le i \le +2$$
$$-4 \le \Theta \le +4,\quad -1 \le j \le +1,\quad -1 \le f \le +1 \quad (3)$$

the exponents of variables take only integer values [4], so the number of choices of dimensions for each variable $\boldsymbol{e}_k$, $\boldsymbol{k} = \{ l, m... f \}$ according to (3) is as follows:

$$\boldsymbol{e}_l = 7;\ \boldsymbol{e}_m = 3;\ \boldsymbol{e}_t = 9;\ \boldsymbol{e}_i = 5;\ \boldsymbol{e}_\theta = 9;\ \boldsymbol{e}_j = 3;\ \boldsymbol{e}_f = 3; \quad (4)$$

the total number of dimensional options of physical variables equals $\boldsymbol{K^*} = \prod_l^f \boldsymbol{e}_i - 1$

$$\boldsymbol{K^*} = \boldsymbol{e}_l \cdot \boldsymbol{e}_m \cdot \boldsymbol{e}_t \cdot \boldsymbol{e}_i \cdot \boldsymbol{e}_\theta \cdot \boldsymbol{e}_j \cdot \boldsymbol{e}_f - 1 = 7 \cdot 3 \cdot 9 \cdot 5 \cdot 9 \cdot 3 \cdot 3 - 1 = 76{,}544 \quad (5)$$

where "-1" corresponds to the occasion when all exponents of variables of primary variables in Eq. (5) are treated to zero dimensions; □ is a product of $\boldsymbol{e}_k$; $\boldsymbol{K^*}$ includes both required, and inverse variables (for example, L^1 – length, L^{-1} – running length). The object can be judged knowing only one of its symmetrical parts, while others structurally duplicating this part may be regarded as information-empty. Therefore, the number of options of dimensions may be reduced by □ = 2 times. This means that the total number of dimensional physical variables without inverse variables for SI is:

$$\boldsymbol{\Psi} = \boldsymbol{K^*} / 2 = 38{,}272 \quad (6)$$

$\boldsymbol{z}'$ is the total number of DL physical variables in the chosen class of phenomena (COP); in the SI frame, every researcher selects a particular COP to study a material object. COP is a set of physical phenomena and processes described by a finite number of primary and secondary variables that characterize certain features of MO from the position with qualitative and quantitative aspects [3]. In studying mechanics, which is widely applied for NGC measurements with a torsion balance, the base SI units are typically used: *L*, ***M***, ***T*** (***LMT***). There are publications [5] that study NGC with electromagnetism. In this case, the basic set often includes *L*, *M*, *T* and ***I*** (***LMTI***);

$\boldsymbol{\beta}'$ is the number of primary physical variables in the chosen COP.

Equation (1) quantifies $\square \boldsymbol{u}_G/\boldsymbol{S}$ caused by the limited number of variables taken into account in the theoretical or experimental analysis of NGC value. On the other hand, it also sets a limit on the increasing of the measurement accuracy in conducting experimental studies. In turn, $\square \boldsymbol{u}_G/\boldsymbol{S}$ is not a purely mathematical abstraction. It has a physical meaning, consisting of the fact that in nature, there is a fundamental limit to the accuracy of displaying any observed material object, which cannot be surpassed by any improvement of instruments and methods of measurement.

Equating the derivative of $\Delta u_G/S$ (1) to zero, we obtain the condition to achieve the minimum comparative uncertainty for a particular COP:

$$(z'-\beta')^2/(\Psi-\xi) = (z''-\beta'') \quad (7)$$

Two remarks should be noted here.

1. For mechanics processes ($COP_{SI} \equiv LMT$), the lowest comparative uncertainty can be reached at the following conditions:

$$(z'-\beta') = (e_l \cdot e_m \cdot e_t - 1)/2 = (7 \cdot 3 \cdot 9 - 1)/2 = 94 \quad (8)$$

$$(z''-\beta'') = (z'-\beta')^2/(\Psi-\xi) = 94^2/38{,}265 = 0.2309 < 1 \quad (9)$$

This equals

$$\varepsilon_{LMT} = (\Delta_{pmm}/S)_{LMT} = 94/38{,}265 + 0.2309/94 = 0.0049 \quad (10)$$

In other words, according to (9), even one DS main variable does not allow one to reach the lowest comparative uncertainty. Therefore, in the frame of the suggested approach, nobody can realize the original first-born comparative uncertainty by using any mechanistic model ($COP_{SI} \equiv LMT$). Moreover, the greater the number of mechanical parameters, the greater the first-born embedded uncertainty. In other words, the Cavendish method, into the frame of the suggested approach, is not recommended for NGC measurement.

Such statements appear to be highly controversial, and one might even say, very unprofessional; not credible and far from current reality. However, as we shall see below, the proposed approach allows one not to make the obvious conclusions, consistent with practice.

2. For electromagnetism processes ($COP_{SI} \equiv LMTI$), the lowest comparative uncertainty can be reached at the following conditions:

$$(z'-\beta') = (e_l \cdot e_m \cdot e_t \cdot e_i - 1)/2 = (7 \cdot 3 \cdot 9 \cdot 5 - 1)/2 = 472 \quad (11)$$

$$(z''-\beta'') = (z'-\beta')^2/(\Psi-\xi) = 472^2/38{,}265 = 5.822135 \quad (12)$$

Then, one can calculate the minimum achievable comparative uncertainty ε_{LMTI}

$$\varepsilon_{LMTI} = (\Delta_{pmm}/S)_{LMTI} = 472/38{,}265 + 5.822135/472 = 0.0123 + 0.0123 = 0.0246 \quad (13)$$

Let us speculate on further applications of Equations (1), (10) and (13) for NGC measurements.

III. ANALYSIS OF G MEASUREMENTS

The present analysis of data of the NGC variations is associated with both the latest observations and with the impending reform in fundamental metrology: the introduction of new definitions of basic SI units. For the following comparison of results of G measurements using the suggested approach, we note that the comparative uncertainties of the DL variable U and the DS variable u equal:

$$(\Delta u/S) = (\Delta U/r^*)/(S^*/r^*) = (\Delta U/S^*) \quad (14)$$

where S, Δu – DS variables, respectively, range of variations and total uncertainty in determining the DS variable u; S^*, ΔU – DL variables, respectively, range of variations and total uncertainty in determining the DL variable **U**; r^* - DL scale parameter with the same dimensions as **U** and S^*.

In none of the current experiments of the calculation of NGC value has the prospective interval been *declared*, in which its true value can be placed. In other words, the exact trace of the placement of G is lost somewhere. Therefore, in order to apply our stated approach, as a possible measurement interval of NGC, we choose the difference of its value reached by the experimental results of two projects: $G_{min} = 6.6719199 \cdot 10^{-11}$ $m^3\ kg^{-1}\ s^{-2}$ [6] and $G_{max} = 6.6755927 \cdot 10^{-11}$ $m^3\ kg^{-1}\ s^{-2}$ [7]. Then, the possible observed range S* of G variations equals

$$S^* = G_{max} - G_{min} = 6.6755927 \cdot 10^{-11} - 6.6719199 \cdot 10^{-11} = 3.6728 \cdot 10^{-7}\ m^3\ kg^{-1}\ s^{-2} \qquad (15)$$

Taking into account (15), we analyzed several publications and CODATA (Committee on Data for Science and Technology) recommendations over the past 15 years (2000–2016) from the position of the reached relative and comparative uncertainty values. These data are summarized in Table 1 and Figures 1–3.

Table 1. Summary of partial history of Newtonian gravitational constant measurements in terms of its value, and absolute, relative and comparative uncertainties

Figure 1. Graph summarizing the partial history of measurement of the Newtonian gravitational constant G

Figure 2. Graph summarizing the partial history of Newtonian gravitational constant determinations in terms of the decrease of relative uncertainty

Figure 3. Graph summarizing the partial history of Newtonian gravitational constant determinations in terms of the decrease of the comparative uncertainty

As a rule, when considering the accuracy of the achieved results during the NGC measurement, the concept of relative uncertainty is used. However, this method for identifying the measurement accuracy does not indicate the direction in which one can find the true value of NGC. In addition, it involves an element of subjective judgment [20]. This is why we apply an additional criterion: the comparative uncertainty.

It is seen from the data given in Table 1 and Figures 1–3 that the affirmations presented in [1, 21] are fully confirmed. The fact is that there was not a dramatic improvement of the accuracy of the measurement of NGC during the last 15 years. This is true when based on the calculation of the relative uncertainty, the possible achievable lowest value of which was not mentioned. In addition, judging the data by the comparative uncertainty according to the proposed approach, one can see that the measurement accuracy had not significantly changed either. Perhaps this situation has arisen as a result of unaccounted systematic errors in these experiments [1, 21]. At the same time, it must be mentioned that, most likely, the exactness of NGC as other fundamental physical constants, cannot be infinite, and, in principle, must be calculable. Therefore, the development of a larger number of designs and an improvement of the various experimental facilities for the measurement of NGC by using schemes combining a torsion balance and electromagnetic equipment (electrostatic servo control) [21] is absolutely necessary in order to obtain closer results to the minimum comparative error $(\square_{min})_{LMTI}$.

The analyzed publications fall into two classes of phenomena: $COP_{SI} \equiv$ ***LMT*** and $COP_{SI} \equiv$ ***LMTI*** for which the comparative uncertainties, respectively, equal 0.0049 (10) and 0.0246 (13). It should be mentioned that within the proposed approach, to achieve the equal comparative uncertainties of mathematical models describing the same material object, but with different COP, a distinctive number of dimensionless complexes used in a mathematical model or during field experiments is required. For further discussion, we will use 0.0246 as a stronger constraint.

Applying the present approach, we can argue about the order of the desired value of the relative uncertainty $(r_{min})_{LMTI}$. For this purpose, we take into account the following variables: $(\square_{min})_{LMT} = 0.0246$ (13), $S_G = 3.6728 \cdot 10^{-11}$ (15). Then, the lowest possible absolute uncertainty for $COP_{SI} \equiv$ ***LMTI*** equals

$$(\Delta_{min})_{LMTI} = (\square_{min})_{LMTI} \cdot S^* = 0.0246 \cdot 3.6728 \cdot 10^{-11} = 9.035088 \cdot 10^{-16}\ m^3\ kg^{-1}\ s^{-2}$$

(16)

In this case, the lowest possible relative uncertainty $(r_{min})_{LMTI}$ for $COP_{SI} \equiv$ ***LMTI*** is as follows:

$$(r_{min})_{LMTI} = (\Delta_{min})_{LMTI} / ((G_{max} + G_{min})/2) = 9.035088 \cdot 10^{-16} / 6.673756 \cdot 10^{-11} = 1.353823 \cdot 10^{-5} \approx 1.4 \cdot 10^{-5} \qquad (17)$$

This value is in excellent agreement with the recommendations mentioned in [14] of $1.4 \cdot 10^{-5}$ and could be particularly relevant in the run-up to the adoption of new definitions of SI units.

IV. DISCUSSION

The strength and the special value of the suggested approach is that it, in revealing features of the distribution of variables in the model and pattern of the numerical calculation of the comparative uncertainty of the model of G measurement, not only allows the results to be understood, but can also predict the future. In other words, can the proposed method augment the study of G? The analysis of scientific data, in our opinion, can give this question quite a clear answer.

Like any other method, the proposed hypothesis has contradictory provisions and assumptions that are difficult to be perceived by the reader. Moreover, we have to be very careful with the results. At the same time, the universe in which we live is a unique object, and therefore it is not clear that it is an accident or natural [22]. Therefore, the approach does not give any recommendations on the selection of specific physical variables, but limits only their number; the information-based slant requires the equiprobable appearance of variables chosen by the modeler; it fully ignores developer knowledge, intuition and experience; the approach requires the knowledge or declaration of changes in the range of G values. Factually, its value has not been declared in any serious experimental research regarding NGC. The possible range of G is regularly viewed in the review articles only in terms of confirmation of the convergence of experimental data to a certain value or reducing the spread of the results.

For obvious practical results, this method gives an integral metric of the influence of a number of chosen variables on the model discrepancy. Such integral characteristics are not of a physical nature. To determine them, we needed to calculate the total number of dimensionless criteria in SI, and to declare a specific interval of G changes. Moreover, this metric has an inherent duality, as follows. On the one hand, it is obvious that the choice of the class of phenomena and quantity of chosen variables are entirely determined by the researcher. On the other hand, before the beginning of the experiments, and regardless of the particular implementation of the assembled test stand, against the will of the researcher, the magnitude of the lowest achievable comparative uncertainty is already known, provided that the changes in the interval of the NGC are defined.

Many attempts have been made to verify a true-target value of G by using perfect experimental schemes and different modern technologies. It has been shown that only by combining torsion balance and electromagnetic equipment is there a chance to verify the real G value. In other words, “seeing the light at the end of the tunnel”. From the present investigations, one can conclude that the fundamentally novel analysis determines the most simple and reliable way to select the measurement model with the optimal number of selected variables.

This the first time that comparative uncertainty was used instead of relative uncertainty in order to compare the measurement results of NGC. A direct way to obtain reliable results has always been open, i.e. to assume that the NGC value lies within the chosen interval. However, this idea cannot be proven because of the difficulty of specifying the possible range of G. Of course, the choice of the value of the variation of NGC is controversial because of its apparent subjectivity. With all this, the use of the $\aleph_{SI}$-hypothesis and the concept of comparative uncertainty allow us to give recommendations on which direction to carry out experimental investigations and identify achievable minimum relative uncertainty in the calculations of the gravitational law in classical mechanics.

V. CONCLUSION

Unfortunately, We have used information and similarity theories to formulate general principles and derived effects, which are amenable to rigorous experimental verification of measurements of Newton’s gravitational constant.

A measure of evaluation of the achievable accuracy of measurement of Newton’s gravitational constant is suggested, and we formulated the method of calculating the comparative uncertainty realized during the experiment.

The present analysis of published studies on the measurement of the Newton’s gravitational constant allows us to hope that our approach will be used to compare the accuracy achieved in various experimental settings and by applying methods that differ from each other.

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Table 1. A table summarizing the partial history of Newtonian gravitational constant measurements by view of the reached its value, and absolute, relative and comparative uncertainties

No	Year	Gravitational constant	Relative uncertainty	Absolute uncertainty	G changes range	Reached comparative uncertainty	Ref.
		$G \times 10^{11}$	$r_G \times 10^5$	$\Delta_G \times 10^{15}$	$S_G \times 10^{14}$	$\varepsilon = \Delta_G/S_G \times 10^2$	
		$m^3\ kg^{-1}\ s^{-2}$		$m^3\ kg^{-1}\ s^{-2}$	$m^3\ kg^{-1}\ s^{-2}$		
1	2000	6.674256	1.4	0.934396	3.6728	2.5441	[8]
2	2001	6.675593	4.0	2.670237		7.2703	[7]
3	2002	6.674230	15	10.01134		27.2581	[9]
4	2002	6.674072	3.3	2.202444		5.9966	[10]
5	2002	6.674210	15	10.01132		27.2580	[11]
6	2003	6.673873	4.0	2.669549		7.2684	[12]
7	2006	6.674251	1.9	1.268108		3.4527	[13]
8	2008	6.674287	10	6.674287		18.1722	[14]
9	2009	6.673492	2.7	1.801843		4.9059	[15]
10	2010	6.672341	2.1	1.401192		3.8150	[16]
11	2010	6.673848	12	8.008618		21.8052	[17]
12	2014	6.675542	2.5	1.668886		4.5439	[18]
13	2014	6.674083	4.7	3.136819		8.5408	[19]
14	2014	6.671920	15	10.00788		27.2486	[6]

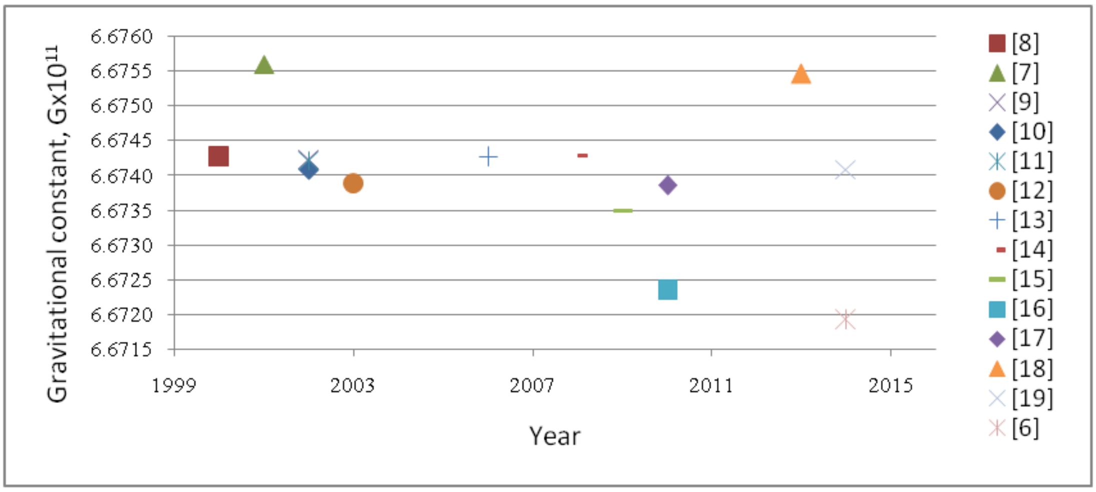

Figure 1. A graph summarizing the partial history of Newtonian gravitational constant measurements by view of the reached its value

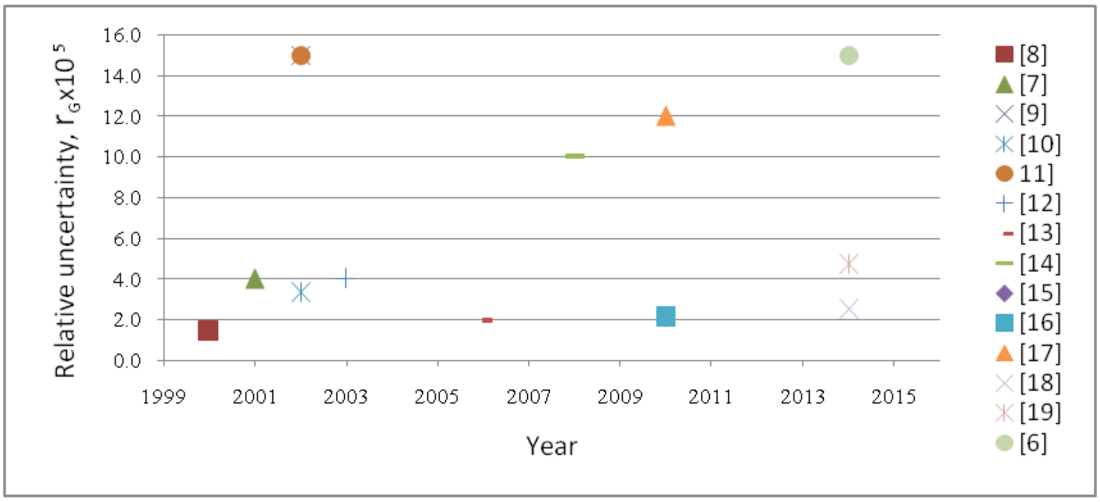

Figure 2. A graph summarizing the partial history of measurement of Newtonian gravitational constant measurements by view of the reached relative uncertainty r_G

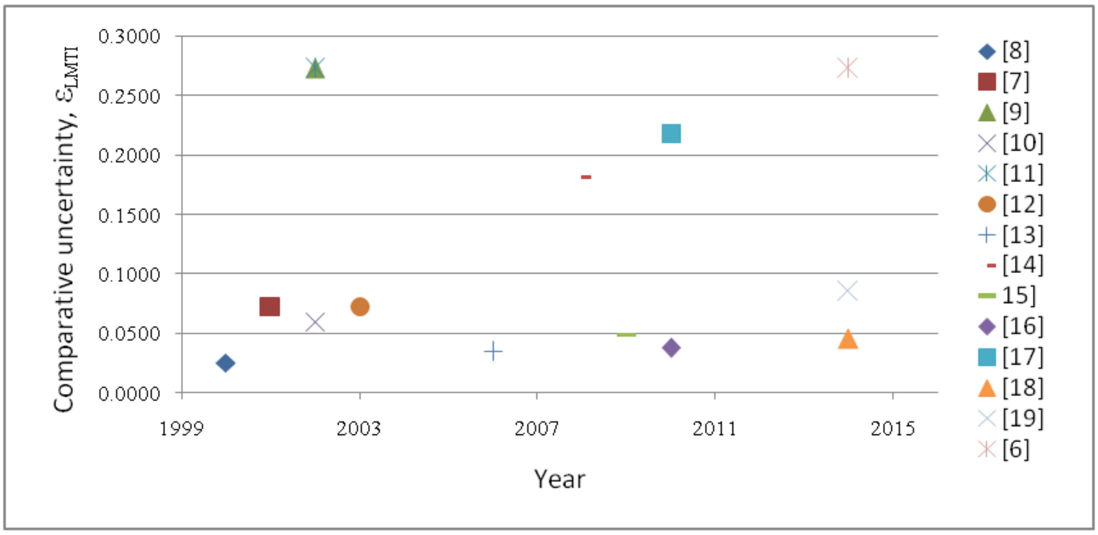

Figure 3. A graph summarizing the partial history of measurement of Newtonian gravitational constant measurements by view of the reached comparative uncertainty ε_{LMTI}