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Recent measurements of the gravitational constant as a function of time

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A recent publication (J.D. Anderson *et. al.*, *EPL* **110**, 1002) presented a strong correlation between the measured values of the gravitational constant G and the 5.9-year oscillation of the length of day. Here, we provide a compilation of all published measurements of G taken over the last 35 years. A least squares regression to a sinusoid with a period of 5.9 years still yields a better fit than a straight line. However, our additions and corrections to the G data reported by Anderson *et al.* significantly weaken the correlation.

INTRODUCTION

The authors of a recent article [1] suggest a correlation between the results of measurements of the gravitational constant, G, and the length of day. Figure 1 in the referenced article shows the result of 13 measurements of G plotted as a function of time. Superimposed to the measurement is a sinusoidal fit with an offset of $\bar{G} = 6.673\,90 \times 10^{-11}\,\mathrm{m}^3\,\mathrm{kg}^{-1}\,\mathrm{s}^{-2}$, a period of $T = 5.9$ years at an amplitude of $A = 0.0016 \times 10^{-11}\,\mathrm{m}^3\,\mathrm{kg}^{-1}\,\mathrm{s}^{-2}$. The ratio of the amplitude to the offset is 2.43×10^{-4}. In addition to the fit a second trace shows a scaled version of the change in the length of day. This second curve is almost indistinguishable from the fit. The graph suggests a strong correlation of the result obtained by various experimenters around the world and the observed change in the length of day.

A closer look at the plotted G values reveals that several points are not plotted at the right time and one experiment published in 2014 [2] has been omitted. Here, we provide an updated and comprehensive set of measured values of G as a function of the date of measurement. From this data set we generate a new plot, shown in Fig. 1. Before discussing the plot, we briefly summarize the origin of the data.

DATA SOURCES

It is not always easy to find the exact time when data for a certain experiment were taken. Below we describe our attempts to narrow down the time for data taking for the most precise G experiments conducted in the last 35 years. We also give the most recent reference and some rationale for assigning a time to the measurement. The assigned time is our best estimate of the weighted average of the times when data was taken. In some occasions, this date is the mean of start and end date of the data acquisition period, in others, it is an average of individual dates when data was taken. For a number of reasons this may not always be the best measure of the effective time of a G measurement; in fitting data we suggest assigning an uncertainty in our tabulated times equal to 20 % of the time span in each case.

Typically, while the experiments are active, several articles are published as progress reports. Here we focus on the last published article, i.e., we ignore previous published numbers from the same experiment. At the time of the final publication the understanding of the experiment is most mature and the final, often most precise, number is presented.

NIST-82: This experiment was performed at the National Institute of Standards and Technology (then the National Bureau of Standards) in Gaithersburg, Maryland. A torsion balance in the so-called time-of-swing method was used. In this method the period of a torsional oscillator is measured in at least two different source mass configurations. The period differs because a change in mass distribution alters the gravitational potential of the oscillator, which provides one part of the restoring torque; the other being provided by the torsion spring. G can be calculated from the difference in the squares of the periods and the known mass distributions. The final result of the measurement of G is $(6.672\,5 \pm 0.000\,5) \times 10^{-11}\,\mathrm{m}^3\,\mathrm{kg}^{-1}\,\mathrm{s}^{-2}$. It was published in 1982 [4]. The dates when the measurements were performed can be inferred from Table 1 in [5]. The first measurement was carried out on August 29 and the last on October 10 1980. We use the average value, September 19 1980, as the time coordinate for this measurement.

TR&D-96: This measurement, performed in Moscow by researchers at Tribotech Research and Development Company, was obtained using a torsion balance in the time-of-swing mode. A value for $G = (6.672\,9 \pm 0.000\,5) \times$

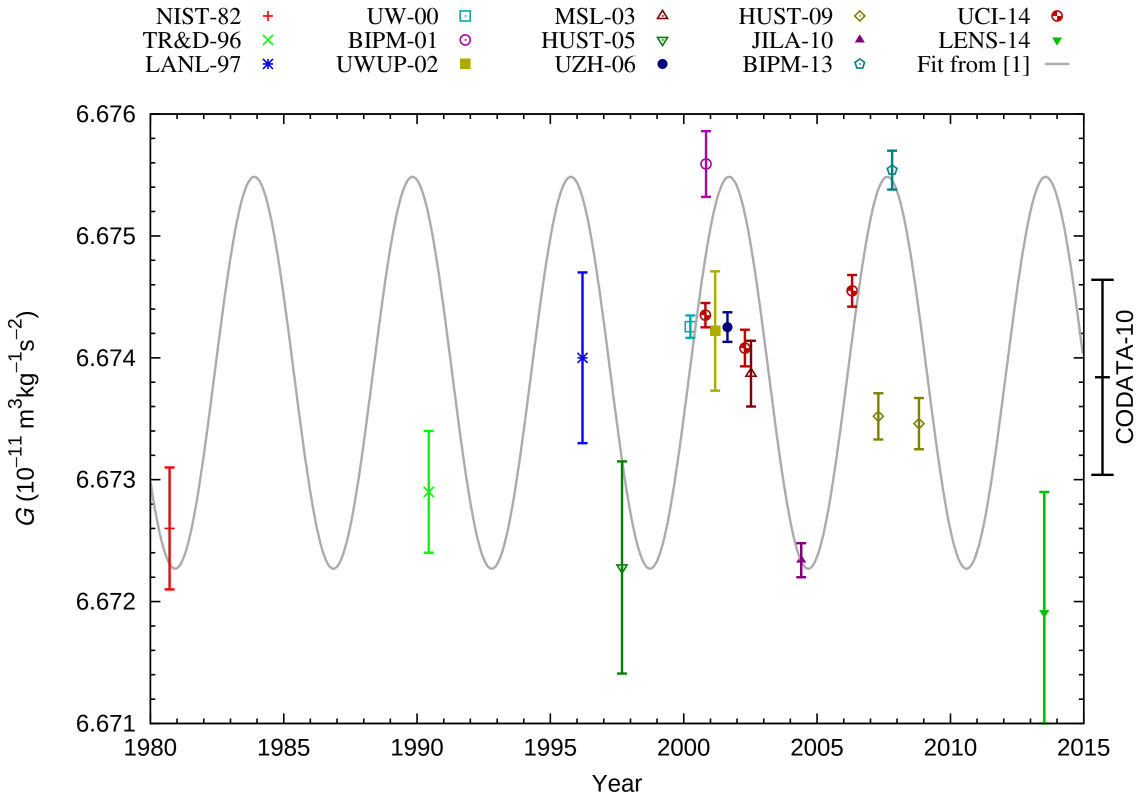

FIG. 1. Measurements of the gravitational constant, G as a function of time. The TR&D-96 data were taken over ten years; for this plot the final TR&D-96 result is shown at the average of their measurement dates. The solid gray sinusoidal curve is the fit to the data as it appears in [1]; it is indistinguishable from the scaled length-of-day-variation in the same reference. The point outside the frame gives 2010 recommended value of G with 1-sigma uncertainties according to the Task Group on Fundamental Constants of CODATA [3].

$10^{-11}\,\mathrm{m}^3\,\mathrm{kg}^{-1}\,\mathrm{s}^{-2}$ is published in [6]. The results of measurements that span 10 years are given in Table 3 of [6]. Unfortunately the data is limited in resolution with only four decimal places given. We reproduce the raw data with type A uncertainties in Table 1.

The TR&D-96 data alone can provide a very powerful test of the hypothesis that the measurements of G depend on the length of day. Figure 2 shows the data (again with only type A uncertainties) as a function of time. The best fit to a sinusoid with a period of 5.9 years yields an offset of $\bar{G} = 6.672\,93 \times 10^{-11}\,\mathrm{m}^3\,\mathrm{kg}^{-1}\,\mathrm{s}^{-2}$ and an amplitude of $A = 0.000\,083 \times 10^{-11}\,\mathrm{m}^3\,\mathrm{kg}^{-1}\,\mathrm{s}^{-2}$ with an uncertainty $\sigma_A = 0.000\,042 \times 10^{-11}\,\mathrm{m}^3\,\mathrm{kg}^{-1}\,\mathrm{s}^{-2}$. There are 23 degrees of freedom and the χ^2 is 14.3. Compared to the fit to a full G data set in [1], this fit yields an amplitude smaller by a factor of 19 and a phase differing by about 140 degrees.

In 2009, an analysis of various correlations of the TR&D measurements to solar activity and other cosmic periods was published [7]. Correlations were found, but it was reasoned that these correlations were mediated by terrestrial effects — most probably variations in temperature and the microseismic environment. In [7] data are shown ranging from 1985 to 2003. Unfortunately the data from 1995 to 2003 is not available to us.

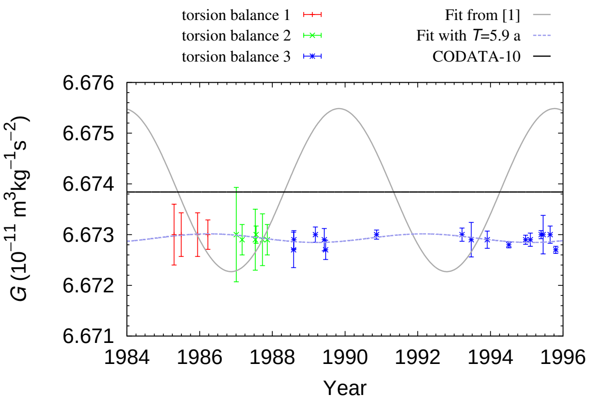

FIG. 2. Data from [6]. Karagioz and Izmailov measured over a decade using three different torsion balances. This figure shows the values obtained as a function of time. The plotted uncertainties are type-A only. According to Ref. [6] the type B uncertainty associated with this experiment is $0.000\,52 \times 10^{-11}\,\mathrm{m}^3\,\mathrm{kg}^{-1}\,\mathrm{s}^{-2}$.

The TR&D-96 data can be averaged to yield a single

Date mm/dd/yyyy	$G \times 10^{11}$ $(\mathrm{m^3\,kg^{-1}\,s^{-2}})$	$\sigma_G \times 10^{11}$ $(\mathrm{m^3\,kg^{-1}\,s^{-2}})$
04/19/1985	6.673 0	0.000 60
06/29/1985	6.673 0	0.000 43
12/11/1985	6.673 0	0.000 43
03/25/1986	6.673 0	0.000 29
01/04/1987	6.673 0	0.000 93
03/03/1987	6.672 9	0.000 30
07/14/1987	6.672 9	0.000 60
07/22/1987	6.673 0	0.000 17
09/24/1987	6.672 9	0.000 51
11/11/1987	6.672 9	0.000 30
08/02/1988	6.672 7	0.000 35
08/05/1988	6.672 9	0.000 18
03/09/1989	6.673 0	0.000 15
06/06/1989	6.672 9	0.000 22
06/20/1989	6.672 7	0.000 19
11/13/1990	6.673 0	0.000 09
03/21/1993	6.673 0	0.000 13
06/22/1993	6.672 9	0.000 34
11/30/1993	6.672 9	0.000 17
07/05/1994	6.672 8	0.000 06
12/20/1994	6.672 9	0.000 09
02/06/1995	6.672 9	0.000 13
05/25/1995	6.673 0	0.000 08
06/14/1995	6.673 0	0.000 38
08/24/1995	6.673 0	0.000 17
10/19/1995	6.672 7	0.000 07

TABLE I. The individual measurements and type A uncertainties as published in Table 3 of Ref. [6]. In the reference the relative type A uncertainties of G were given; we converted these into absolute uncertainties to keep all numbers in this article consistent.

data point as displayed in Fig. 1. The average of the individual dates listed in table I is June 9th 1990.

LANL-97: A time-of-swing experiment was performed at the Los Alamos National Laboratory in Los Alamos, New Mexico. This measurement is published in [8]. A value $G = (6.674\,0 \pm 0.000\,7) \times 10^{-11}\,\mathrm{m^3\,kg^{-1}\,s^{-2}}$ was obtained. The article gives no indication of when the data were taken. However, the thesis of C.H. Bagley [9] gives some information. Written on page 15 is "In January of 1996, I attempted a trial Heyl-type determination with this arrangement, hoping for a percent number or better". Later it is described how this measurement was much more precise, yielding the final value. On page 71 the reader learns that certain disturbances in the experiment became more frequent as the ambient temperature rose in April and May, until the data became unusable. The doctoral thesis was signed by the supervisors on July 8 1996. Thus we take March 15 1996 as a time stamp for this data point.

UW-00: The measurement with the smallest uncertainty to date was performed at the University of Washington in Seattle, Washington. It was published in 2001 [10]. The rotation rate of a turntable supporting a torsion balance was varied such that the torsion fiber did not twist. In this angular-acceleration-feedback-mode the gravitational acceleration of a torsion pendulum towards source masses is fed back to the turntable, leaving the torsion balance motionless with respect to the turntable and adding the gravitational acceleration to the turntable motion. The gravitational constant is inferred from the second derivative of the angle readout of the turntable with respect to time. The value published in 2001 must be corrected by a small amount due to an originally unconsidered effect of a small mass at the top of the torsion fiber which was also subject to the angular acceleration. This correction has been described in [11]. After applying this correction the final result is $G = (6.674\,255 \pm 0.000\,092) \times 10^{-11}\,\mathrm{m^3\,kg^{-1}\,s^{-2}}$. The measurement times are documented in [11]. Two sets of data were taken, one from March 10 2000 to April 1 2000, the other from April 3 2000 to April 18 2000. We use March 31 2000 to locate this G value.

BIPM-01: These measurements were performed with the first torsion pendulum built at the Bureau International des Poids et Mesures (BIPM) located in Sèvres, near Paris. The intent of this experiment was to measure G with the same torison balance operated in different methods. The final publication reports two measurement methods, the Cavendish method and the electrostatic-servo method. In the Cavendish method, the excursion of a torsion pendulum is measured for two different source mass positions. To convert the measured angles into torque, a measurement of the torsional spring constant of the pendulum suspension is required. Therefore, the free angular frequency of the torsion balance is measured. By combining this frequency measurement with a calculated number of the moment of inertia of the torsion pendulum, the spring constant is obtained. In the electrostatic servo method, the gravitational torque on the pendulum is compensated by an electrostatic torque produced by an electric potential applied to a capacitor, where one plate is on the pendulum bob and the other is fixed. In this phase, the applied voltage is measured. To calibrate the electrostatic transducer, the capacitance as a function of angle of the pendulum must be measured in a calibration measurement.

Combining the results of both methods yielded a result of $G = (6.675\,59 \pm 0.000\,27) \times 10^{-11}\,\mathrm{m^3\,kg^{-1}\,s^{-2}}$. It is published in [12]. The result of the Cavendish mode and the servo mode are in close agreement. The values $G = (6.675\,65 \pm 0.000\,44) \times 10^{-11}\,\mathrm{m^3\,kg^{-1}\,s^{-2}}$ and $G = (6.675\,53 \pm 0.000\,40) \times 10^{-11}\,\mathrm{m^3\,kg^{-1}\,s^{-2}}$ were obtained for the Cavendish mode and the servo mode, respectively. According to the authors [13] the servo mode data were obtained from September 29 to November 2

2000 and the Cavendish mode data from November 25 to December 13 2000. The average of the dates is November 2 2000, which we assign to be the time at which the combined G value was taken.

UWUP-02: This experiment was located at the University of Wuppertal in Germany. The separation of two simple pendulums was measured with microwave interferometry. The forces on the pendulums and, hence, their separation was modulated by moving source masses outside the apparatus. The final value of this measurement is published in a PhD thesis [14]. It is $G = (6.674\,22 \pm 0.000\,98) \times 10^{-11}\,\mathrm{m}^3\,\mathrm{kg}^{-1}\,\mathrm{s}^{-2}$. The appendix C of the thesis contains a table listing the data sets used for the final value. The first data set started on January 12 2001 and the last ended on June 29 2001. Twelve data sets ranging in duration from 1 to 6 days were taken. Most sets were taken within a week of each other. A longer break occurred between March 7 and May 11 and between May 18 and June 25. Averaging the dates of the sets yields March 6.

MSL-03: This measurement performed at the Measurement Standards Laboratory (MSL) of New Zealand, is the only recent measurement that has been carried out in the southern hemisphere. This measurement employs a torsion balance in the electrostatic servo mode with one difference: The calibration of the capacitance gradient is performed in an angular-acceleration experiment. The final value $G = (6.673\,87 \pm 0.000\,27) \times 10^{-11}\,\mathrm{m}^3\,\mathrm{kg}^{-1}\,\mathrm{s}^{-2}$ is published in [15]. One author [16] informed us that the data was gathered between March 21 2002 and November 1 2002. The average of these two dates is July 11 2002.

HUST-05: This is the first measurement of G performed at the Huazhong University of Science and Technology in Wuhan, China. A torsion balance in the time-of-swing mode was used for this measurement. A value was originally published in 1999 [17]. However, the original authors discovered two small errors in the mass distribution of their source masses. In 2005, a manuscript providing a small correction was published. Including the correction, a value of $G = (6.672\,3 \pm 0.000\,9) \times 10^{-11}\,\mathrm{m}^3\,\mathrm{kg}^{-1}\,\mathrm{s}^{-2}$ was obtained. The dates when the data were taken is given in Table 2 of the 1999 publication. Seven sets of measurements were taken, the first starting on August 4 and the last ending on October 15. No year is given. Since the manuscript was submitted on April 1998, we assume that the data were taken in 1997. This has been confirmed by the authors [18]. September 9 is equidistant in time from the start and the end of the set and we associate this date with the HUST-05 measurement.

UZH-06: The experiment was performed by researchers at the University of Zürich. The experiment was located at the Paul Scherrer Institute near Villigen Switzerland. The gravitational force of a large mercury mass on two copper cylinders was measured with a modified commercial mass comparator. The gravitational constant was measured to be $G = (6.674\,252 \pm 0.000\,12) \times 10^{-11}\,\mathrm{m}^3\,\mathrm{kg}^{-1}\,\mathrm{s}^{-2}$. this result was published in 2006 [19]. Figure 8 in this publication shows 43 days of data with a 6 day break. The first day of data was July 31 2001 and the last September 9 2001. The average of the two is August 21 2001, which we take as the time stamp for this measurement.

HUST-09: A second apparatus was constructed at HUST. Two measurements were performed with this torsion balance in the time-of-swing method. The averaged value of the two separate measurements was first published in 2009 [21]. It is $G = (6.673\,49 \pm 0.000\,18) \times 10^{-11}\,\mathrm{m}^3\,\mathrm{kg}^{-1}\,\mathrm{s}^{-2}$. A long article on the same measurements was published in 2010 [22]. Tables six and seven of the latter publication show the dates of the data sets used in the first and second experiment. The first experiment consisted of ten sets taken between March 21 2007 and May 20 2007. The second experiment started on October 8 2008 and ended on November 16 2008. The results for the first and second experiments are $G = (6.673\,52 \pm 0.000\,19) \times 10^{-11}\,\mathrm{m}^3\,\mathrm{kg}^{-1}\,\mathrm{s}^{-2}$ and $G = (6.673\,46 \pm 0.000\,21) \times 10^{-11}\,\mathrm{m}^3\,\mathrm{kg}^{-1}\,\mathrm{s}^{-2}$, respectively. Averaging the start and end dates of the sets, we obtain April 20 2007 and October 27 2008, respectively.

JILA-10: This experiment was performed at the Joint Institute for Laboratory Astrophysics in Boulder, Colorado. Similar to UWUP-02, two simple pendulums were used to measure the gravitational constant. Here, the pendulum separation was measured with a laser interferometer. The final result of the measurement, published in 2010 [23], is $G = (6.672\,34 \pm 0.000\,14) \times 10^{-11}\,\mathrm{m}^3\,\mathrm{kg}^{-1}\,\mathrm{s}^{-2}$. Figure 2 in this report shows the obtained values of G as a function of time. In [24], the same data is shown as a table. A total of thirteen numbers were obtained in the time ranging from May 12 to June 6 2004. Averaging the 13 dates yields May 28 2004.

BIPM-13: At the BIPM, a second torsion balance was constructed with the aim to measure G with two different methods. The results were published in 2013 [25]. Combining the results of both methods, the researchers obtained $G = (6.675\,54 \pm 0.000\,16) \times 10^{-11}\,\mathrm{m}^3\,\mathrm{kg}^{-1}\,\mathrm{s}^{-2}$. The Cavendish and the servo method yielded $G = (6.675\,86 \pm 0.000\,36) \times 10^{-11}\,\mathrm{m}^3\,\mathrm{kg}^{-1}\,\mathrm{s}^{-2}$ and $G = (6.675\,15 \pm 0.000\,41) \times 10^{-11}\,\mathrm{m}^3\,\mathrm{kg}^{-1}\,\mathrm{s}^{-2}$, respectively. These numbers included a small correction published in an erratum in 2014. Per one of the authors [13], the Cavendish data were obtained from August 31 to September 10 2007 and the servo mode data were measured in two campaigns. In the first campaign, measurement were performed on November 8, 13, 14, and 16 in 2007. The remaining measurements were taken on January 11, 12, 13, 15, and 16 in 2008. We average the provided dates and obtain October 25 2007 as an effective time stamp for the BIPM-13 data.

UCI-14: These measurements were performed using a torsion balance at cryogenic temperatures in the time-of-

Identifier	$G \times 10^{11}$	$\sigma_G \times 10^{11}$	Data acquisition			$e - s$	Device	Mode
	$(\mathrm{m^3\,kg^{-1}\,s^{-2}})$	$(\mathrm{m^3\,kg^{-1}\,s^{-2}})$	Start	End	Average	(Days)	(days)	
NIST-82	6.672 5	0.000 5	08/29/1980	10/10/1980	09/19/1980	42	torsion balance	time-of-swing
TR&D-96	6.672 9	0.000 5	04/19/1985	10/19/1995	06/09/1990	3835	torsion balance	time-of-swing
LANL-97	6.674 0	0.000 7	01/01/1996	04/15/1996	03/15/1996	105	torsion balance	time-of-swing
UW-00	6.674 255	0.000 092	04/03/2000	04/18/2000	03/31/2000	15	torsion balance	acceleration servo
BIPM-01s	6.675 53	0.000 40	09/29/2000	11/02/2000	10/16/2000	34	torsion balance	electrostatic servo
BIPM-01c	6.675 65	0.000 44	11/25/2000	12/13/2000	12/04/2000	18	torsion balance	Cavendish
BIPM-01sc	6.675 59	0.000 27	09/29/2000	12/13/2000	10/02/2000	75	torsion balance	Cavendish & servo
UWUP-02	6.674 22	0.000 98	01/12/2001	06/29/2001	03/06/2001	168	two pendulums	
MSL-03	6.673 87	0.000 27	03/21/2002	11/01/2002	07/11/2002	225	torsion balance	electrostatic servo
HUST-05	6.672 3	0.000 9	08/04/1997	10/15/1997	09/09/1997	72	torsion balance	time-of-swing
UZH-06	6.674 25	0.000 12	07/31/2001	08/21/2001	08/21/2001	21	beam balance	
HUST-09a	6.673 52	0.000 19	03/21/2007	05/20/2007	04/20/2007	60	torsion balance	time-of-swing
HUST-09b	6.673 46	0.000 21	10/08/2008	11/16/2008	10/27/2008	39	torsion balance	time-of-swing
JILA-10	6.672 34	0.000 14	05/12/2004	06/06/2004	05/28/2004	25	two pendulums	
BIPM-13s	6.675 15	0.000 42	11/08/2007	01/16/2008	12/15/2007	69	torsion balance	electrostatic servo
BIPM-13c	6.675 86	0.000 36	08/31/2007	09/10/2007	09/05/2007	10	torsion balance	Cavendish
BIPM-13sc	6.675 54	0.000 16	08/31/2007	01/16/2008	10/25/2007	138	torsion balance	Cavendish & servo
UCI-14a	6.674 35	0.000 10	10/04/2000	11/11/2000	10/23/2000	38	torsion balance	time-of-swing
UCI-14b	6.674 08	0.000 15	03/25/2002	05/12/2002	04/18/2002	48	torsion balance	time-of-swing
UCI-14c	6.674 55	0.000 13	04/08/2006	05/14/2006	04/26/2006	36	torsion balance	time-of-swing
LENS-14	6.671 91	0.000 99	07/05/2013	07/12/2013	07/08/2013	7	atom interferometer	

TABLE II. Summary of the most precise measurements of G carried out in the last 35 years. The "Start" and "End" columns indicate our best estimate of the dates when data acquisition began and ended.The "Average" column shows our best estimate for the mean date of data acquisition. The "$t - e$" column gives the difference between the end and start date of each data acquisition period in days. This column is important to estimate how much a periodic signal is averaged by the respective experiment. The data in this column can also be used to estimate an uncertainty on the average date. We suggest 20 % of the $t - e$ number to be a meaningful estimate of this uncertainty. For the table we separate the two BIPM measurements into four measurements to emphasize that two different methods were used, and include data labeled BIPM-01sc and BIPM-13sc for the best G and dates combining the two methods. Particularly for the 2013 BIPM data, the results with the two methods had strongly anti-correlated uncertainties, so that a $G(t)$ fit using the combined G value can give a significantly different result from a fit treating results from the two methods separately. The data represented in Figure 1 shows the combined G data BIPM-01sc and BIPM-13sc.

swing mode. The experiment was located near Hanford, Washington. Three different types of fibers with different mechanical properties, especially the amplitude dependence of the mechanical losses, were used. In the end, a result for each fiber was published in 2014 [2]. The numbers are $G = (6.674\,35 \pm 0.000\,10) \times 10^{-11}\,\mathrm{m^3\,kg^{-1}\,s^{-2}}$, $G = (6.674\,08 \pm 0.000\,15) \times 10^{-11}\,\mathrm{m^3\,kg^{-1}\,s^{-2}}$, and $G = (6.674\,55 \pm 0.000\,13) \times 10^{-11}\,\mathrm{m^3\,kg^{-1}\,s^{-2}}$. The principal investigator provided the following time intervals for the three measurements: Data with the first fiber was first was obtained from October 4 2000 to November 11 2000. The average of these dates is October 23 2000. Data with the second fiber was obtained during two disjoint intervals. About 14 % of the data was obtained between December 8 and December 14 2000. The remaining fraction of the data was obtained between March 25 and May 12 2002. For simplicity we assign the average of the dates in 2002, i.e, April 18 2002 to the result with the second fiber. The true average of all dates would be roughly January 30 2002. Measurements with the third fiber were collected from April 8 to May 15 2006. The mean of this interval is April 26 2006.

LENS-14: Following pioneering work at Stanford University [27], a precision measurement of G using an atom interferometer was performed at the University of Florence, Italy. The interferometer is oriented vertical. The phase shift between two paths is measured in one source mass configuration and then in a second source mass configuration. From the difference of the two phase shifts and the known mass distributions the gravitational constant can be calculated. The latest result was published in 2014 [28]. The published number is $G = (6.671\,91 \pm 0.000\,99) \times 10^{-11}\,\mathrm{m^3\,kg^{-1}\,s^{-2}}$. A longer account of the experiment can be found in [29]. The latter reference states that data was taken between July 5 and July 12 2013. The average of start and end date is July 8 2013. The experiment is still on-going and the group is working on an improved measurement of G.

In Table II we summarize the precision measurements of big G in the last 35 years.

Discussion

The main purpose of this article is to provide an as complete as possible list of G values obtained in measurements since 1980, along with an attempt to assign an as accurate as possible effective date for each measurement. The goal is to provide data for further investigations similar to that of Anderson and collaborators.

We caution the users of this data set that it is very possible that much or all of the apparent time variation of these G values may simply reflect overlooked systematic error in the individual measurements, with underestimated systematic uncertainty.

However, we have ventured to make our own data fits as follows, fitting to the G values and dates presented in this article. For all these fits the combined numbers for the two BIPM experiments were used:

1. A sinusoidal function with the parameters found in reference [1].
2. A sinusoidal function with free amplitude and phase but period fixed at 5.9 years.
3. A sinusoidal function with free amplitude, phase and period.
4. A single time-independent parameter, $\bar{G}$.

Results of the least squares adjustment of the data to the respective fit functions, with their corresponding χ^2 values, are presented in Table III. For these fits the uncertainty in the date was ignored. We also performed fits with uncertainties in both coordinates to these data. The outcome of these fits do not differ significantly from the results presented here.

Figure 3 displays the goodness of fit using two different norms for sinusoidal fits to these data as T is varied. The upper and lower graph show the best fits obtained by minimizing the sum of the absolute residual (L1-norm), $\sum_i |r_i|$, and the sum of the squared residual (L2-norm), $\sum_i r_i^2$, respectively. Here, r_i is the residual of the i'th data point, given by $r_i = \left(G_i - \bar{G} - C\cos\left(2\pi t_i/T\right) - S\sin\left(2\pi t_i/T\right)\right)/\sigma_i$, where G_i and σ_i is the measurement and its uncertainty performed at time t_i. Fits using the L1-norm are less sensitive to outliers [30] and may, hence, be more appropriate for the G data set.

Of note in this plot are:

1. There are a number of local minima.
2. The lowest L1 and L2-norm are both located at $T = 0.769$ years.

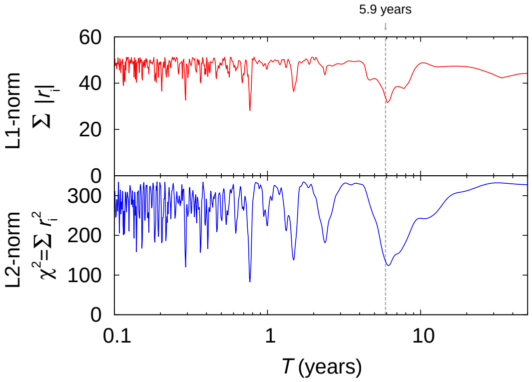

FIG. 3. The goodness of fit as a function of the period T. The upper graph shows the sum of the absolute residual, i.e., $\sum_i |r_i|$. The lower graph shows the sum of the squared residual given by $\sum_i r_i^2$. The individual residual is given in both cases by $r_i = \left(G_i - \bar{G} - C\cos\left(2\pi t_i/T\right) - S\sin\left(2\pi t_i/T\right)\right)/\sigma_i$, where G_i and σ_i is the measurement and its uncertainty performed at time t_i.

3. A local minimum is found at 6.1 years and 6.2 years for the L1- and L2-norm, respectively; not very different from the value of 5.9 years found by Anderson *et al.*.
4. There is a tantalizing local minimum in the L2-norm at 0.995 year – almost exactly one year.

In addition, we made a least squares regression to the data taken over a period of more than ten years by Karagioz and Izmailov [6], as discussed in the Data Sources section of this paper.

The situation is disturbing — clearly either some strange influence is affecting most G measurements or, probably more likely, measurements of G since 1980 have unrecognized large systematic errors. The need for new and fresh measurements is clear. Particularly valuable would be an apparatus run continuously over a period of some ten years without any alteration of the instrument properties. The metrology requirement for such an instrument would be minimal, since a constant absolute error in G would not preclude a stringent test for time variation of the measured G value.

Scientific exchange between different groups measuring G is necessary. The newly established working group on big G under the auspices of International Union of Pure and Applied Physics (IUPAP) was formed to assist experimenters who are interested in these challenging measurements. It can also provide a platform to discuss and understand each other's experiments.

Acknowledgment

We thank D.B. Newell and B.N. Taylor for assistance in locating some of the dates of the big G experiments,

Fit function	T (years)	$A \times 10^{15}$ $(\mathrm{m^3\,kg^{-1}\,s^{-2}})$	$\bar{G} \times 10^{11}$ $(\mathrm{m^3\,kg^{-1}\,s^{-2}})$	Maximum	χ_f^2	NDF	$P(\chi^2 \geq \chi_f^2)$	Remarks
from Fig. 1 in [1]	5.93	16.1	6.673 88	09/13/01	381	14	10^{-72}	
sine, fixed T	5.93	10.7	6.673 59	03/14/01	132	14	10^{-21}	
sine, T free	0.77	11.1	6.673 61	02/23/00	81	13	10^{-11}	global χ^2 minimum
sine, T free	6.17	11.0	6.673 54	02/14/01	124	13	10^{-19}	local χ^2 minimum
straight line	n.a.	n.a.	6.674 13	n.a.	335	16	10^{-61}	

TABLE III. Fit results for various scenarios on the data sets of big G measurements. For this table the L2-norm is used exclusively. The "Maximum" column gives the date of the first maximum after 01/01/2000. The "NDF" column shows the number of degrees of freedom for each fit.

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