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Possible oscillations in high-precision measurements of Newton's gravitational constant —A reassessment based on the generalized Lomb-Scargle periodogram

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Abstract – The presence of an oscillation with a period of 5.9 yr in measured values of Newton's gravitational constant G over more than three decades, and of a correlation with a 5.9 year oscillation in the length of day (LOD) variability, was recently reported by Anderson *et al.* (*EPL*, **110** (2015) 10002). A reanalysis based on an improved data set of measured G values was conducted by Schlamminger *et al.* (*Phys. Rev. D*, **91** (2015) 121101(R)) with the result of supporting the finding of a low-frequency oscillation present in the G measurements (with a period of ~ 6 yr). A subsequent reanalysis by Anderson *et al.* (arXiv:1505.01774 [gr-qc]) using the improved data set of Schlamminger *et al.* confirmed the presence of the oscillation. However, the phase relationship changed (G and LOD not in phase anymore). In an additional analysis, Pitkin showed by Bayesian model selection that the oscillation is most probably due to chance since the data can be modelled at best with the assumption that the scattering of values is caused by measurement errors and an additional Gaussian noise term overlaid. In order to add to the analysis of possible oscillation in G data sets the aim of our work was to reanalyze the data based on the data sets compiled by Schlamminger *et al.* using the generalized Lomb-Scargle (GLS) periodogram (and the Lomb-Scargle (LS) periodogram, as a control) with additional bootstrapping-based statistical testing. We found periods of ~ 6 yr and ~ 0.8 yr in all the investigated data sets; however, the corresponding peaks in the spectra did not reach statistical significance. We therefore conclude that there is not enough statistical evidence that these oscillations are not due to chance —a finding in agreement with the work of Pitkin.

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Introduction. – Values of Newton's gravitational constant G measured with high-precision setups over the last 35 years by different groups show a large variability (in the range of about 500 ppm), exceeding the experimental errors in the single experiments (< 50 ppm). The origin of the variability is not yet known. In general, it could be due to an overlooked systematic effect, *i.e.*, a disturbance of the measurement procedure, or it might be a real physical effect indicating that the theory of gravity by itself is incomplete at present. In both cases, new insights into the origin are of high importance and significance.

Recently, Anderson *et al.* [1] showed that the long-term variability in measured G values (*i.e.*, values reported by the 2010 CODATA report [2] and newer values obtained by Quinn [3] (BIMP-13) as well by Rosi [4] (LENS-14)) can be modelled by a sinusoidal function with a period length (T) of 5.899 ± 0.062 yr and an amplitude (A) of $(1.619 \pm 0.103) \times 10^{14}\,\mathrm{m^3kg^{-1}s^{-2}}$. In addition, Anderson *et al.* hypothesized that this oscillation of G values could be linked to a 5.9 yr oscillation present in the time series of the length of day (LOD) [5] since both oscillations shared approximately the same frequency and were in phase.

In a subsequent paper, Schlamminger *et al.* [6] pointed out that the data set used by Anderson *et al.* [1] was imprecise with respect to the timing of measured G values. Schlamminger *et al.* presented a novel collection of G values measured over the last 35 years (*i.e.*, the data also used by Anderson *et al.* but with corrected measurement times and additional data from another measurement [7]). Fitting sine functions (based on minimizing the L1 or L2 norms) to the novel data set revealed an oscillation with $T = 0.769$ yr (strongest oscillation) and one similar to that found by Anderson *et al.* with $T = 6.1$ yr (using the L1 norm minimization) and $T = 6.2$ yr (L2 norm), respectively. In addition, Schlamminger *et al.* listed and analyzed the measured values of Karagioz and Izmailov [8] (TR&D-96) (number of measurements: $n = 26$) by fitting a sine function with $T = 5.9$ yr to the data. The evaluation of the goodness of fit advised to reject the null hypothesis that the measured and predicted values are the same (degrees of freedom: 23, $\chi^2 = 14.3$, leading to $p = 0.917957$ with a significance level of $\alpha = 0.05$).

Anderson *et al.* updated their analysis by using the new data set provided by Schlamminer *et al.* (but without including the measurement results of Karagioz and Izmailov [8], *i.e.*, data set TR&D-96 containing data that were generated by averaging over a large time span) and published it as an appendix in the paper uploaded to arXiv [9]. Employing a model of two sine waves for the fitting revealed oscillations with $T_1 = 1.023087 \pm 0.000042$ and $T_2 = 5.911615 \pm 0.000028$. While the fitting with the new data set confirmed the presence of an oscillation with $T = 5.9$ yr, it was recognized that the newly fitted oscillation (with T_1 and T_2) is not in phase with the LOD anymore (phase shift: 174 days).

By reanalyzing the data sets used by Anderson *et al.* [1,9] and Schlamminger *et al.* [6] using the Bayesian model selection concerning possible oscillations, Pitkin [10] concluded that the best model is the one in which there is an additional unknown Gaussian noise term on top of the observed experimental errors and thus came to the conclusion that the oscillations observed by Anderson *et al.* and Schlamminger *et al.* were due to chance.

Anderson *et al.* [11] criticized the analysis and conclusion of Pitkin [10], and conjectured from a new reanalysis that they stood by their conclusions of potential periodic terms in the reported G measurements.

In a reply, Pitkin [10] pointed out that his result was misinterpreted and that the novel analysis by Anderson *et al.* did not take into account a penalty for overfitting (as was done by his analysis) which would lead to an erroneous conclusion about the best fit being that with two sinusoidal oscillations instead of a Gaussian noise term. Pitkin defended his conclusion that the possible oscillations in the data found were results of two factors: experimental errors and an additional unknown Gaussian noise term.

The present unsatisfying situation motivated us to reanalyze the data by means of an additional method, the generalized Lomb-Scargle periodogram (GLS) (a well-established spectral analysis method in astrophysics), and a statistical test in order to determine the statistical significance of possible peaks in the periodogram.

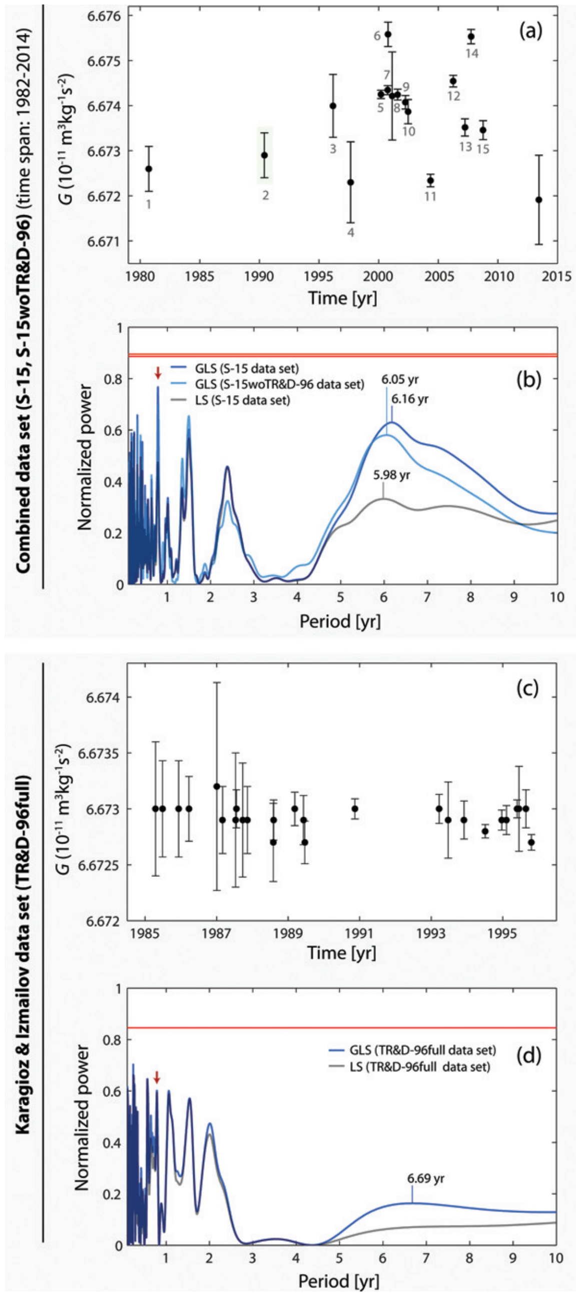

Fig. 1: (Colour online) (a) Data sets S-15 ($n = 16$) and S-15woTR&D-96 ($n = 15$), according to Schlamminger *et al.* [6]. The numbers near the single data points refer to the single data sets as mentioned in the section "Data and analysis methods" in the present paper. The single data set not used in data set S-15woTR&D-96 (*i.e.*, number 2) is highlighted in green. (b) LS and GLS periodograms of the data sets S-15 and S-15woTR&D-96. (c) Data set TR&D-96full according to [6]. (d) GLS and LS spectra of the TR&D-96full data set. The red arrows in (b) and (d) indicate the peak at ~ 0.8 yr. The red line indicates the false-alarm probability (FAP) of 5% for the spectra.

Data and analysis methods. – For the present analysis three data sets were used: the data set collected and published by Schlamminger in table II in [6] i) with (data set: S-15, $n = 16$) and ii) without (data set: S-15woTR&D-96, $n = 15$) the measurement results of Karagioz and Izmailov (data set: TR&D-96) [8], and iii) the single measurement of Karagioz and Izmailov by

Table 1: Listing of studies investigating possible oscillations in data sets of high-precision G measurements. LSSF: least-squares fitting of a sine wave; n: number of measurement values in the data set; T: period length; LS: Lomb-Scargle; GLS: generalized Lomb-Scargle.

Study, data set and analysis method	Detected high-frequency oscillations	Detected low-frequency oscillations
1) Anderson *et al.* [1]: $n = 13$ (CODATA 2010 table XVII, BIPM-13, LENS-14). Type of analysis: LSSF	not analyzed	$T = 5.899 \pm 0.062$ yr, no stat. analysis
2) Schlamminger *et al.* [6]: $n = 17$ (corrected data also used by Anderson *et al.* [1] and additional data). Type of analysis: LSSF	$T = 0.769$ yr (with L1 and L2 norm), no stat. analysis	$T = 6.1$ yr (L1 norm), $T = 6.2$ yr (T2 norm), no stat. analysis
3) Anderson *et al.* [9]: $n = 18$ (all data of table II of Schlamminger *et al.* [6] except the TR&D-96 data set. Type of analysis: LSSF (with two sinus functions)	$T = 1.023087$ yr, no stat. analysis	$T = 5.911615$ yr, no stat. analysis
4) Pitkin [10]: $n = 12$ (data set used by Anderson *et al.* [1], excluding TR&D-96) and alternatively $n = 17$ (data set used by Schlamminger *et al.* [6]. Type of analysis: LSSF and Bayesian model selection		$T \approx 5.9$ yr (not statistically significant)
5) This study: i) S-15 data set: $n = 16$ (Schlamminger *et al.* [6]; ii) S-15woTR&D-96 data set: $n = 15$ (S-15 data set except for the values of TR&D-96); iii) TR&D-96 data set: $n = 26$) (data of Karagioz and Izmailov as listed by Schlamminger [6]). Type of analysis: LS and GLS periodograms, and statistical analysis	S-15: $T = 0.77$ yr (GLS and LS); S-15woTR&D-96: $T = 0.79$ yr (GLS and LS) (all statistically not significant)	S-15: $T = 6.16$ yr (GLS), $T = 5.98$ yr (LS); S-15woTR&D-96: $T = 6.05$ yr (GLS); TR&D-96full: $T = 6.69$ yr (GLS) (all statistically not significant)

itself as published by Schlamminger *et al.* in table I in [6] (data set: TR&D-96full, $n = 26$).

Data set S-15 represents the data set analyzed by Schlamminger *et al.* [6], whereas data set S-15woTR&D-96 was initially used by Anderson *et al.* [9] in their updated analysis. Anderson explained not using the TR&D-96 data by arguing that this data set spans a time period of 3835 days, possibly introducing a bias in the fitting.

For data set S-15 the following single data sets were employed (for a description of the single data sets according to the identifiers see [6]): 1) NIRS-82, 2) TR&D-96, 3) LANL-97, 4) UW-00, 5) BIPM-01sc, 6) UWUP-02, 7) MSL-03, 8) HUST-05, 9) UZH-06, 10) HUST-091, 11) HUST-09b, 12) JILA-10, 13) BIPM-13sc, 14) UCI-14a, 15) UCI-14b, and 16) LENS-14.

In order to detect possible oscillations in the data sets S-15, S-15woTR&D-96 and TR&D-96full, the generalized Lomb-Scargle (GLS) periodogram [12] was applied. The GLS periodogram is a further development of the Lomb-Scargle (LS) periodogram [13,14] in that for the least-squares fitting the measurement errors (*i.e.*, the variability in the y-axis) are also taken into account, and that the input data do not need to have a mean value of zero. The function used in the GLS approach to fit the data is $y = a\cos(\omega t) + b\sin(\omega t) + c$, with ω the frequency (or period length $T = 2\pi/\omega$) and c a constant accounting for the offset of the data. Both methods, LS and GLS, are methods of least-squares spectral analysis (LSSA) enabling the detection of periodicities in non-equidistantly sampled data. GLS is widely applied in astrophysics, *e.g.*, to detect exoplanets (*e.g.*, [15]) or to analyze space maser signals [16]. In order to compare the GLS spectra with the less accurate LS spectra, both were calculated.

The GLS periodogram was calculated for data sets S-15, S-15woTR&D-96 and TR&D-96full, whereas the LS periodogram was calculated for data sets S-15 and TR&D-96full. For the calculation the astroML package in Phython [17,18] was employed. The period range investigated was [0.1, 10] yr.

The statistical significance of the detected peaks was evaluated by calculating the false-alarm probability (FAP) for the frequency range investigated based on bootstrapping significance testing. To this end, the data were shuffled while keeping the observational times fixed. Ten thousand bootstraps were calculated for the testing. A FAP value of 0.05 was chosen as a threshold value for evaluation of the statistical significance of the detected peak. FAP = 0.05 corresponds to a change of 5% that the peak in the spectrum is due to random, Gaussian, noise.

Results. – For data sets S-15 and S-15woTR&D-96 the largest peak in the GLS spectra is at $T = 0.77$ yr. The LS spectrum of data set S-15 exhibits the largest peak at $T = 0.77$ yr, too. For data set TR&D-96full a peak in the similar period range is present at $T = 0.79$ yr (for both the GLS and LS spectra). In the period range 3–10 yr the largest peak in the GLS spectra of data sets S-15 and S-15woTR&D-96 is at $T = 6.16$ yr and $T = 6.05$ yr, respectively. The LS spectrum of data set S-15 shows a corresponding peak at $T = 5.98$ yr. For data set TR&D-96full a peak is observable at $T = 6.69$ yr in the GLS spectrum.

Neither the peaks in the GLS and LS spectra of the data sets S-15 and S-15woTR&D-96 nor the peaks in the GLS spectra of data set TR&D-96full are statistically significantly different from Gaussian noise (*i.e.*, peak amplitudes do not cross the threshold of the FDR).

Discussion and conclusion. – Our results and how they related to the previous findings from the groups can be summarized as follows:

1) All three analyzed data sets exhibit an oscillation with a period length of $\sim$ 6 yr in the LS and GLS spectra.

2) The $\sim$ 6 yr peak is stronger in the GLS spectrum compared to the LS one indicating the importance of taking the measurement errors into account for the fitting. Also the period length is slightly increased in the GLS spectra ($T = 6.16$ yr (S-15) and $T = 6.05$ yr (S-15woTR&D-96) compared to the LS spectrum ($T = 5.98$ yr (S-15)).

3) The $\sim$ 6 yr oscillation detected is in agreement with the findings of Anderson *et al.* [1,9], Schlamminger *et al.* [6] and Pitkin [10] (see table 1).

4) The fit of a $\sim$ 6 yr oscillation to all of the data sets is not statistically significantly different from a fit of the time-shuffled data, *i.e.*, there is no evidence that the $\sim$ 6 yr oscillation is not due to chance. This is in agreement with the findings of Pitkin [10].

5) The strongest oscillation present in data sets S-15 and S-15woTR&D-96 has a period of $\sim$ 0.8 yr (based on the LS and GLS analyses), in agreement with the findings of Schlamminger *et al.* [6]. The period of the oscillation is similar to that (*i.e.*, $T = 1.023087$ yr) found by Anderson *et al.* [9].

6) Data set TR&D-96full also exhibits a $\sim$ 0.8 yr oscillation —a finding that was not reported yet.

7) An oscillation with a period of $\sim$ 1 yr in G data was discussed in some older papers; for example, Stephenson [19] mentioned an indication that an annual cyclical variation of G may be present by reanalyzing the temporal variability of the data sets of Heyl [20] and Heyl and Chrzanowski [21]. Theoretical predictions of an annual oscillation of G were published (*e.g.*, [22–24]). In addition, a possible annual oscillation in the fine structure constant alpha was reported [25]. It is unknown whether the observed $\sim$ 1 yr oscillation in the present analysis is related to these observations and works.

Based on our findings we conclude that both oscillations (with a period of $\sim$ 6 yr and $\sim$ 0.8 yr) could be found in the data. However, there is not enough statistical evidence that the findings are not due to chance implying that they are Gaussian noise. Our finding is in agreement with the finding of Pitkin. In addition, we agree with the conclusion of Pitkin that for evaluating the goodness of fit, the complexity of the fitted model has to be taken into account (as, unfortunately, was not done by Anderson *et al.* [11]).

Besides our conclusion, we support the initiative of Anderson *et al.* to investigate possible oscillations in G data measurements and to perform a correlation analysis with novel parameters (like the LOD time series) in order to find the origin of the inter-measurement variability.

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