Speed Of Light In FG5 gravimeter

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The absolute gravimeter measures the gravitational constant by dropping a corner cube retro-reflector in a vacuum. The light reflected by the corner cube interferes with another light from the same emission. The interference pattern can not be explained by the theory if the speed of light remains constant upon reflection. Two research teams were obliged to propose new definition of acceleration to match their test data. Neither team understands that the speed of light actually changes upon reflection by a moving mirror. The definition of acceleration should remain intact. The speed of reflected light should increase to match the observed fringe pattern from the gravimeter.

I. INTRODUCTION

Various types of gravimeters are used to measure the gravitational constant. One variation, absolute gravimeter, drops a corner cube retro-reflector in a vacuum to create interference pattern. The light from the laser is divided by a beam splitter into two beams. One beam aims at the falling corner cube and continues to the photo detector. The other beam aims directly at the photo detector. The combination of two light beams creates a fringe pattern that varies with time.

Many research teams attempted to apply the Doppler effect with constant speed of light to data of the gravimeter. They found minor discrepancy between the equation and the data. By assuming the speed of light to remain constant, they choose to add extra term to the definition of acceleration. One research team names the extra term as "speed of light perturbation" by stating that "the perturbation due to the finite speed of light was among the most inconsistent in corner-cube absolute gravimeters"[1].

No team understands that the speed of light can change upon reflection off a mirror in motion. The new speed after reflection produces a new phase shift corresponding to the interference pattern. The definition of acceleration should always stay intact.

II. PROOF

A. FG5 Gravimeter

Van Camp, M., Camelbeeck, T. and Richard, P. published a paper in 2003, "The FG5 absolute gravimeter: metrology and geophysics"[2]. The original equations in this paper are restated with modification on the name of one variable, T_i.

$$x_i = x_0 + v_0 T_i + \frac{g_0}{2}(T_i^2 + \frac{1}{12}\gamma T_i^4) \quad (1)$$

$$T_i = t_i - \frac{x_i - x_0}{c} \quad (2)$$

The original statement from the team is:

"Where the three unknowns are x_0, v_0 and g_0 are the initial position, velocity and acceleration at $t = 0$, γ is the vertical gravity gradient and c is the speed of light. Methods to extract the gravity gradient and trajectory parameters simultaneously have proved difficult to implement as signal-to-noise levels are low."

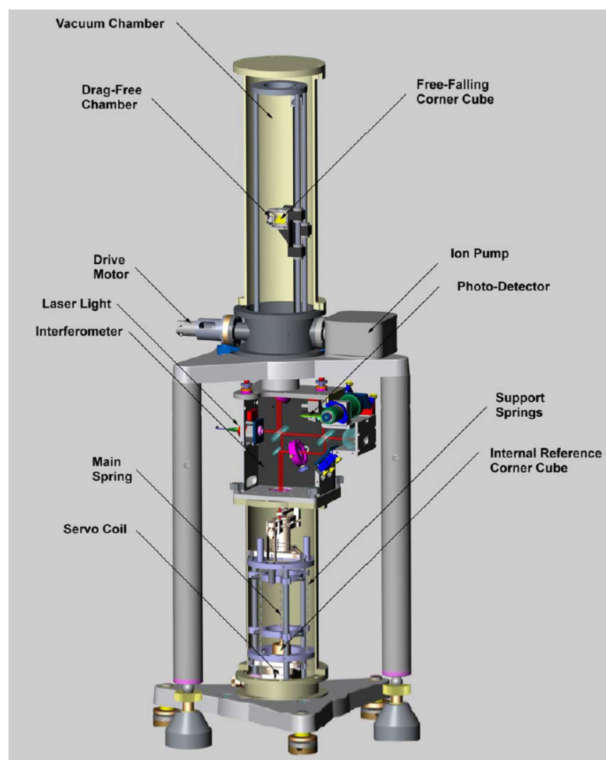

FIG. 1. FG5 gravimeter

Van Camp and the team decided to alter the definition of acceleration with equation (1) instead of considering the possibility that the speed of light can become different upon reflection.

B. IMGC02 Gravimeter

G D'Agostino, A Germak, S Desogus, C Origlia and G Barbato published a paper in 2005, "A method to estimate the time-position coordinates of a free-falling test-mass in absolute gravimetry"[3]. The equation (2) in the original paper is restated below with a different derivative convention as

$$\frac{d^2}{dt^2}z = g_0 + \gamma(z - z_0) - \phi\frac{d}{dt}z \tag{3}$$

with original comment as: "where g_0 is the acceleration at the level z_0, γ is the vertical linearized gradient and ϕ is the friction coefficient of residual air."

Based on the simulation results, the original conclusion from G D'Agostino and the team is:

"The results are strictly correlated to the algorithm that estimates the falling object acceleration from the trajectory. In particular, the total least-squares algorithm used by the IMGC02 was tested, which includes the vertical gradient γ and the friction coefficient of residual air ϕ as estimating parameters.

G D'Agostino's team also decided to alter the definition of acceleration with equation (3) instead of considering the possibility that the speed of light can become different upon reflection.

C. Micro-g LaCoste FG5 Gravimeter

Neither team understands that the speed of light changes upon reflection off a mirror in motion. The speed of light can be altered by the speed of the mirror[4,5].

Let C_1 be the speed of light before reflection. C_2 is the speed of light after reflection off a mirror approaching at the speed of v.

$$C_2 = C_1 + 2v \tag{4}$$

The FG5 gravimeter works by releasing a corner cube retro-reflector in the vacuum. The reference beam passes

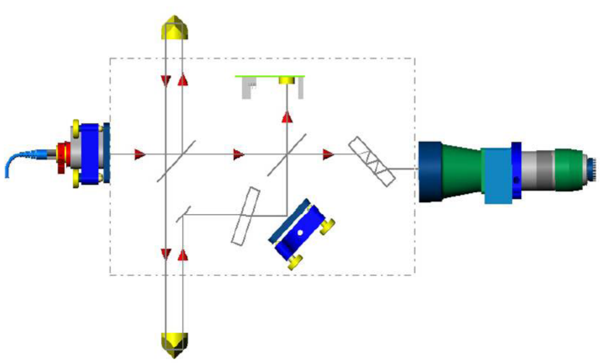

FIG. 2. Beam Path in FG5 interferometer

straight through the first splitter and is then split again to enter the detector and the optical devices for alignment. The test beam leaves vertically from the first splitter, travels through the dropper and Superspring, and is recombined with the reference beam at splitter #2.

D. Speed Of Light in FG5 Gravimeter

The light path in FG5 gravimeter can be summarized with a simplified diagram in figure 3.

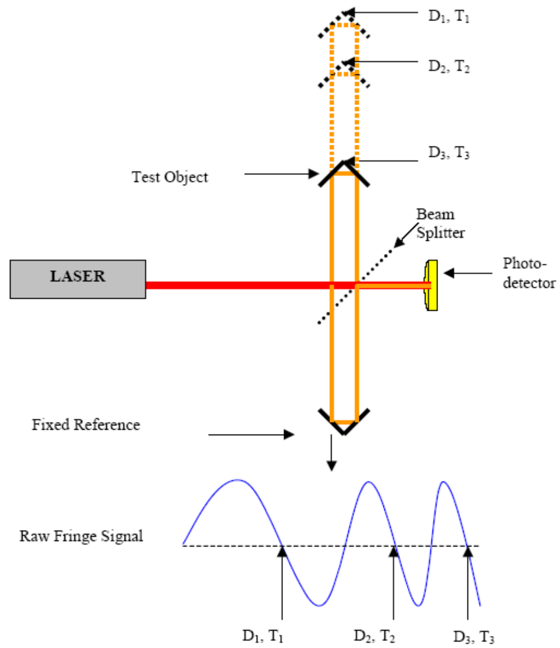

FIG. 3. Direct Measurement of g

As the optical fringes go through zero, the precise time is recorded by an atomic clock. A least-squares fit to the time and distance pairs is used to determine g.

let t_1 be the time the corner cube is released. The following table shows a list of the subsequent events of one divided beam based on figure 3.

TABLE I. Time and Event

Time	Event
t_1	corner cube is released
t_2	light leaves the laser
t_3	light is reflected by the splitter
t_4	light is reflected off the corner cube
t_5	light is reflected off the reference cube
t_6	light is reflected by the splitter
t_7	light reaches the photo detector

The distance travelled by the light is shown together with the speed of light in the next table.

L_1 is the distance between the splitter and the laser.

L_2 is the distance between the splitter and the photo detector.

TABLE II. Distance and Speed

Elapsed Time	**Distance**	**Light Speed**
$t_3 - t_2$	L_1	C_1
$t_4 - t_3$	Z_1-x	C_1
$t_5 - t_4$	Z_1-x+Z_2	C_2
$t_6 - t_5$	Z_2	C_2
$t_7 - t_6$	L_2	C_2

x is the distance moved by the corner cube.

C_1 is the speed of light at the time of emission.

C_2 is the speed of light after reflection off the corner cube.

Z_1 is the distance between the splitter and the initial position of the corner cube.

Z_2 is the distance between the splitter and the reference cube.

The other divided beam that passes through the splitter travels the distance of $L_1 + L_2$ to reach the photo detector at t_8.

The phase of each beam is ϕ_0 initially from the laser. The phase of a beam depends on the elapsed time and distance.

$$\phi = \phi_0 + \omega\delta t - k\delta L \tag{5}$$

Let ϕ_2 be the phase of the beam that is redirected toward the falling corner cube. Let ϕ_1 be the phase of the beam that goes directly to the photo detector.

$$\phi_1(t_8) = \phi_0 + \omega_1(t_8 - t_2) - k_1(L_1 + L_2) = \phi_0 \tag{6}$$

ω_1 is the angular frequency of beam 1 that goes directly to the photo detector. k_1 is the wave number of beam 1.

From the table 2,

$$t_7 = \frac{L_2}{C_2} + t_6 \tag{7}$$

$$t_6 = \frac{Z_2}{C_2} + t_5 \tag{8}$$

$$t_5 = \frac{Z_1 - x + Z_2}{C_2} + t_4 \tag{9}$$

$$t_4 = \frac{Z_1 - x}{C_1} + t_3 \tag{10}$$

$$t_3 = \frac{L_1}{C_1} + t_2 \tag{11}$$

The phase of beam 2 that is redirected toward the falling corner cube is ϕ_2. ω_2 is the angular frequency of beam 2 after reflection from the corner cube. k_2 is the wave number of beam 2 after reflection from the corner cube.

$$\phi_2 = \phi_0 + (\omega_1(t_3 - t_2) - k_1 L_1) + (\omega_1(t_4 - t_3) \tag{12}$$

$$-k_1(Z_1 - x)) + (\omega_2(t_5 - t_4) - k_2(Z_1 - x + Z_2)) \tag{13}$$

$$+(\omega_2(t_6 - t_5) - k_2(Z_2)) + (\omega_2(t_7 - t_6) - k_2 L_2) \tag{14}$$

$$= \phi_0 \tag{15}$$

From equations (7,8,9,10,11),

$$t_7 = \frac{L_2}{C_2} + \frac{Z_2}{C_2} + \frac{Z_1 - x + Z_2}{C_2} + \frac{Z_1 - x}{C_1} + \frac{L_1}{C_1} + t_2 \tag{16}$$

Beam 2 reaches the photo detector at t_7 which is later than t_8. Therefore, the interference takes place at t_7.

$$\phi_1(t_7) = \phi_0 + \omega_1(t_7 - t_2) - k_1(L_1 + L_2) \tag{17}$$

The phase shift between two beams at the time of t_7 is

$$\delta\phi = \phi_2(t_7) - \phi_1(t_7) \tag{18}$$

The FG5 gravimeter counts and times the fringes when the fringe signal becomes zero. From equations (15,17,18),

$$2(n + A)\pi = \delta\phi = \omega_1(t_7 - t_2) - k_1(L_1 + L_2) \tag{19}$$

$n = n(t)$ is an integer function of time. A is a constant.

$$t_7 - t_2 = \frac{L_1 + L_2}{C_1} + (n + A)\frac{\lambda_1}{C_1} \tag{20}$$

λ_1 is the wavelength of beam 1. From equations (16,20),

$$\frac{L_2}{C_2} + \frac{Z_2}{C_2} + \frac{Z_1 - x + Z_2}{C_2} + \frac{Z_1 - x}{C_1} = \frac{L_2}{C_1} + (n+A)\frac{\lambda_1}{C_1} \tag{21}$$

From equations (4,21),

$$x = Z_1 + \frac{Z_2 C_1 - L_2 v - \frac{\lambda_1}{2}(n + A)(C_1 + 2v)}{C_1 + v} \tag{22}$$

$$= Z_1 + Z_2 - \frac{\lambda_1}{2}(n + A) - v\frac{Z_2 + L_2 + \frac{\lambda_1}{2}(n + A)}{C_1 + v} \tag{23}$$

From initial condition, x=0=v at t=0,

$$n(0) + A = 2\frac{Z_1 + Z_2}{\lambda_1} \tag{24}$$

As x increases, the phase shift decreases. n decreases by an integer i.

$$n + A = 2\frac{Z_1 + Z_2}{\lambda_1} - i \tag{25}$$

From equations (23,25),

$$x_i = i\frac{\lambda_1}{2} - \frac{v_i}{C_1 + v_i}(Z_1 + 2Z_2 + L_2 - i\frac{\lambda_1}{2}) \tag{26}$$

As the corner cube falls, both x_i and v_i increase. i also increases as a positive integer.

E. Experimental Data

The manufacturer of Micro-g LaCroste FG5 gravimeter provides an equation[6] to calculate the gravitational acceleration with the consideration of the gravity gradient.

$$x_i = x_0 + v_0 t_i + \frac{1}{2} g_0 t_i^2 + \gamma(x_0 + v_0 \frac{t_i}{3} + g_0 \frac{t_i^2}{12}) \frac{t_i^2}{2} \quad (27)$$

The reason for the gradient is: "The finite value of the Earth's gravity gradient, $\gamma\ approximately - 3\mu Gal/cm$ causes a measurable change in g over the small length of the drop, and this complicates the 'standard' equation." The "standard" equation is

$$x_i = x_0 + v_0 t_i + \frac{1}{2} g_0 t_i^2 \quad (28)$$

The user's manual of Micro-g LaCoste FG5 states[6]: "The interferometer generates an optical interference fringe each time the test mass falls 1/2 the wavelength of the laser light. These fringes are counted and timed with an atomic clock to obtain precise time and distance pairs. A least-squares fit to these data are used to determine the value of g."

$$i \frac{\lambda_1}{2} = \iint^{t_i} g\, dt \quad (29)$$

Theoretically, the data will generate a constant for g to fit the "standard" equation.

$$i \frac{\lambda_1}{2} = x_0 + v_0 t_i + \frac{1}{2} g_0 t_i^2 \quad (30)$$

However, the least-squares fit to the data shows

$$x_i = x_0 + v_0 t_i + \frac{1}{2} g_0 t_i^2 + \gamma(x_0 + v_0 \frac{t_i}{3} + g_0 \frac{t_i^2}{12}) \frac{t_i^2}{2} \quad (31)$$

There is a minor difference between the theory and the actual data. From equations (30,31),

$$x_i \neq i \frac{\lambda_1}{2} \quad (32)$$

This discrepancy is the source of puzzle and difficulty experienced by most researchers on absolute gravimeter.

F. Experimental Verification

The common mistake by most research teams is to assume that the speed of light remains constant upon reflection off a moving object.

$$C_2 = C_1 \quad (33)$$

From equation (21,33),

$$Z_2 + Z_1 - x + Z_2 + Z_1 - x = (n + A)\lambda_1 \quad (34)$$

$$Z_2 + Z_1 - x = (n + A)\frac{\lambda_1}{2} \quad (35)$$

From initial condition $x = 0$ at $t = 0$,

$$n(0) + A = 2\frac{Z_2 + Z_1}{\lambda_1} \quad (36)$$

As x increases, the phase shift decreases. n decreases by an integer i.

$$n + A = 2\frac{Z_2 + Z_1}{\lambda_1} - i \quad (37)$$

From equations (35,37),

$$x_i = i\frac{\lambda_1}{2} \quad (38)$$

Equation (38) contradicts equation (32).

Most research teams recognize that equation (38) does not match the data collected by FG5 gravimeter. Few realize that the assumption of constant speed of light upon reflection from a moving mirror is invalid and is the source of problem.

The manufacturer of FG5 gravimeter applies least-squares fit to the data and proposes a more realistic equation (31).

Under the initial condition $x_0 = 0 = v_0$ at t=0, the non-standard equation (31) becomes

$$x_i = \frac{1}{2} g_0 t_i^2 (1 + \gamma \frac{t_i^2}{12}) \quad (39)$$

From equations (30,39),

$$x_i = i\frac{\lambda_1}{2}(1 + \gamma \frac{t_i^2}{12}) \quad (40)$$

In better agreement with equation (26) under the fact that the speed of light increases upon reflection.

$$C_2 = C_1 + 2v \quad (41)$$

The fringe pattern serves as an excellent experimental evidence that the speed of light increases upon reflection off the falling corner cube retro-reflector.

III. CONCLUSION

The FG5 gravimeter provides experimental evidence that the speed of light changes upon reflection off a moving mirror. Several researchers reported great puzzlement on the data from the absolute gravimeter while assuming that the speed of light remains constant.

Instead of looking for the correct speed of light, most researchers choose to augment the definition of acceleration. Without any theoretical proof, many physicists speculate that the velocity of light remains the same in different inertial reference frame. The speculation surely leads to incorrect conclusion.

The theoretical proof that the speed of light depends on reference frame finally became available in 2019[4,5]. The proof states that the speed of light is not conserved in reference frame while the wavelength of the light is conserved. The experimental proof was available from the FG5 gravimeter for decades. However, the data has not been understood correctly due to the lack of the theoretical proof.

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