Photon mass from gravitational time delay.

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Abstract.

Using a possible solution of the orbital theorem in UFT 111 of this series (www.aias.us), the delay due to the Sun´s gravitation is calculated in a radar beam grazing the sun and reflected from a planet. In this calculation the photon mass is the only unknown, so can be measured experimentally using contemporary high accuracy satellite data.

Keywords: ECE theory, orbital theorem, gravitational time delay, photon mass.

1. Introduction.

The mass of the photon is an important quantity to measure because the pathology or randomly repeated dogma of the old twentieth century "standard model" asserts incorrectly that the mass of the photon is identically zero. Despite its gross irrationality, this concept has become accepted uncritically, and is the mainstay of the U(1) sector symmetry of the standard model. In rational and scientific thought, the U(1) sector symmetry has been rejected in many ways [1-10] by many scientists. This means that only a small group of dogmatists still adhere to U(1) and related but obsolete concepts such as the Higgs boson. Recently ECE theory [1-10] has made this irrationality obsolete. It has also been shown in UFT 150 that the Einsteinian calculation of light deflection is riddled with errors, self inconsistencies and obscurities. This means that the derivative calculation of the gravitational time delay is also incorrect. The basic reason is that both calculations assert incorrectly that photon mass is identically zero. This is absurd, because without mass the photon cannot be attracted by the mass M of the Sun. If the photon mass m is correctly considered as in Section 2, the calculation becomes clear and simple to understand.

The photon mass is a concept that has been advocated for several hundred years, for example in the corpuscular theory of light of Newton, who obtained his ideas from his predecessors back to classical times. Similarly, the ideas of relativity began to crystallize with Heaviside and Fitzgerald in the late eighteen eighties, and were put into mathematical format by, for example, Voigt and by Lorentz independently. However, in classical times, beauty (or nature as we would say) was already thought to be geometry. The Lorentz transform was first inferred by considerations of electromagnetism and has become the mainstay of special relativity. The twentieth century concept of the photon was inferred in mathematical format by Planck, who defined it as the quantum of electromagnetic energy. The Planck theory defines the photon by its angular frequency ω in radians per second within a universal constant $\hbar$, in joules seconds, the S.I. units both of action and angular momentum. The constant $\hbar$ is known as the reduced Planck constant, it is the Planck constant h divided by 2π. The concept of photon mass, although natural to rational physics, profoundly changes the twentieth century dogma that masquerades as physics. This dogma can survive only because of its tremendous complexity and grotesque obscurity, and only because it cannot be compared with experimental data because of many unobservables and loose parameters. Rational physics on the other hand is well known to be based on the Ockham Razor and Bacon´s philosophy. This means that a theory of physics must strive to be as simple as possible, and that theory must be reduced to a format in which it can be tested against experimental data to give a clear result. Dogma survives only because an original paper is not studied, pathological science (as defined by Langmuir) survives because it is the lazy minded and uncritical repetition of dogma. In other words no one reads the original paper to see if it is right. The experimental data must be as precise as possible, and must be repeatable in one laboratory and reproducible in different laboratories.

The photon mass means for example that electromagnetism is not a gauge theory, because the Proca equation is not gauge invariant in the old dogma. The Proca equation is the d´Alembert equation with finite photon mass and has been derived straightforwardly [1-10] in a limit of ECE theory. There follows a domino effect in which the standard model collapses completely if the photon mass is finite, or identically non-zero. The electroweak theory cannot have a U(1) sector symmetry, because the latter is based on zero photon mass and the arbitrary and incorrect assertion that electromagnetism in the vacuum is somehow made up only of transverse components. This dogma defies the existence of spacetime, with four dimensions. Self inconsistently, the dogma is based on four dimensional Minkowski spacetime, asserting that only two out of four dimensions exist. The ancient and ultra obscure Gupta Bleuler procedure [11] is used to conveniently "remove" two dimensions. U(1) or O(2) is the Lie group of a plane, despite the fact that the everyday three dimensional world (or space) is O(3), and despite the fact that Lie group of special relativity is the Lorentz group of four dimensional and physical spacetime, extended by Wigner to the Poincaré group [1-11].

Photon mass means in rational thought that space has three dimensions, part of four dimensional spacetime. The mythical and hyper expensive Higgs boson is based on the irrationality of U(1). So the Higgs boson does not exist in nature. The search at CERN is doomed to failure and is a monument to blank-minded dogma and pathology in science, a folly of tremendous magnitude saturated with self-interest. The inverse Faraday effect and fundamental B(3) field [1-10] of electromagnetism show that there is photon mass, because the B(3) field is longitudinal. Within a factor, B(3) is simply the magnetism induced in the electron by the photon. In the standard dogma, B(3) cannot exist despite the fact that it is observed. This is because the dogma asserts that electromagnetism in the vacuum must be transverse because there is no photon mass. Thus dogma is the very opposite of experience, the former exists in the darkest recesses of Plato´s cave, and is the idol of the cave in Bacon´s adaptation of Plato. The B(3) field and photon mass are manifestations of a generally covariant unified field theory [1-10] which encompasses electromagnetism and gravitation using a relatively simple geometry due to Cartan, and using only four dimensions. The useless and derivative pathology of string theory is rejected as non-science. This is simply because string theory has produced nothing new because it cannot be tested experimentally.

Photon mass also means that there is no Big Bang, because the photon behaves as a relativistic particle of velocity v in a vacuum, and recently the Hubble telescope has shown that there is no Big Bang. ECE theory has shown that the Einstein equation upon which Big Bang pathology is based is incorrect. It is simple to show that the connection of geometry as defined by the commutator [12] must be antisymmetric and that spacetime torsion as well as curvature must always exist. In the old pathology there was only curvature. Einstein used a symmetric connection, neglected torsion, and that is incorrect. When the Einstein equation is tested against elementary Cartan geometry [1-10] the Einstein equation and all its thousands of derivative metrics fail. These metrics exist only because of pathology, they exist not in nature, but in the human mind. Some are grotesque, and so completely obscure that only their proponents use them.

Einstein advocated photon mass as soon as his form of special relativity appeared in 1905. Einstein contributed importantly to the old quantum theory, the theory of absorption and emission, the Brownian motion and the proof of the existence of molecules, and the photoelectric effect, a proof of the existence of photons. So he is an important figure in rational science. The ECE theory is named Einstein Cartan Evans theory because it is based on general relativity, the basic concept of which is due to Einstein. However, scholarship has proven many times over ninety years that the mathematical development of general relativity by Einstein is unfortunately incorrect. ECE is a proposal for the first mathematically correct theory of general relativity. As such, ECE has been accepted as rational science, and the old dogmatists of the standard model will gradually fade into well deserved obscurity. It is not rational to expect dogma to rush to accept new reason. Dogma and pathology are by definition unreasonable, which is why it took so long for science to emerge from the cave. It tends always to flee back into the cave at the sight of a new and rational theory.

Before embarking on Section 2 and the simple calculation of gravitational time delay in terms of photon mass, a short review is given of the difficulties that follow from the wholly irrational assumption of identically zero photon mass in the light deflection calculation of Einstein made probably in about 1916 or 1917. Despite having suggested photon mass himself, about twelve years earlier in 1905, Einstein in 1917 proceeded to ignore its existence by using the null geodesic condition, eq. (17) of UFT 150. This means that the infinitesimal of proper time vanishes, so basic quantities cannot be defined. These are the conserved hamiltonian H, and the conserved quantities E, p and L, respectively the total energy, linear and angular momentum. These are all defined in general relativity [1-10] by dividing by the infinitesimal of proper time, but the latter is zero identically if the photon mass is zero identically. Einstein also assumed that the photon orbit is a circle, Eq. (25) of UFT 150. This is an arbitrary assumption made only to simplify the calculation and not for any reason based on physics or observation. There is no experimental observation of a circular photon orbit. It leads to disaster, because the denominator vanishes in the integral that Einstein uses. The integral is singular, and can never produce a meaningful result. In the pathology the latter is always claimed to be "twice the Newtonian result". This cannot be true, and furthermore, there is no Newtonian result for a particle of no mass. Particles with no mass do not exist in Newtonian dynamics.

In his calculation, Einstein uses constants of motion a and b. These are by definition constants, and cannot be varied. Yet Einstein uses three different values of b during the course of the calculation, despite the fact that b is fixed at R_0, the distance of closest approach, by the fact that the theory must produce 180º by definition if there is no deflection. The constant a becomes identically infinite if the photon mass is identically zero, so $1 / a^2$ disappears from Einstein´s calculation. This means that the mass m is assumed to be attracted by the mass M even though the mass m does not exist and even though it is assumed thereby that there is no attraction. Such are the recesses of the human psyche, able to persuade itself of any irrationality. Einstein attempts to evaluate his infinite integral by varying the fixed M in calculus. This is analogous to trying to differentiate a function such as 2x by differentiating with respect to 2. The procedure is incorrect and has no meaning. It produces the mythology of twice Newton, as if one Newton was not enough already. It seems that Einstein already had this answer in his mind, and proceeded to force the mathematics to give it up. The familiar derivative errors of pathological science now apply. The same incorrect method was used in the time delay calculation corrected in Section 2 by use of finite photon mass. Eddington claimed to have "verified" this incorrect claim by Einstein, but the Eddington experiment was not repeatable, and not reproducible. We are left with the fact that NASA Cassini and other contemporary apparatus produce the precise result. The Einstein theory has become wholly irrelevant. In UFT 150, Einstein´s OWN integral was evaluated experimentally and shown by ordinary desktop computer to be incorrect. The numerical work was done with Maxima and Mathematica, and therefore self-checked to machine precision. Any amount of precision will not rectify the fact that Einstein used a singular integral to assert a precise and finite result. Looked at rationally, this is absurd.

In Section 2 we consider a radar signal sent from Earth, grazing the Sun, and reflected back to Earth by a planet. The Sun´s gravitation means that the time taken for this reflection is slightly longer than the time that would be taken if the gravitational field were absent (M = 0). This is defined as "the gravitational time delay". It is worked out straightforwardly in terms of an identically non-zero photon mass m, using the assumption that for one photon, the total energy of the photon is given by the Planck law.

2. Gravitational time delay.

The calculation is a simple extension of the light deflection calculation used in UFT 150, based on:

$$\frac{d\varphi}{dr} = \frac{1}{r^2}\left(\frac{1}{b^2} - \left(1 - \frac{r_0}{r}\right)\left(\frac{1}{a^2} + \frac{1}{r^2}\right)\right)^{-½} \tag{1}$$

where r and φ are the cylindrical polar coordinates in a plane, and where:

$$a = \frac{L}{mc} \quad , \quad b = \frac{cL}{E} \quad , \quad r_0 = \frac{2MG}{c^2} \quad . \tag{2}$$

Here G is Newton´s constant. From Eq. (1), light grazing the Sun is deflected by an amount:

$$\Delta\varphi = 2\int_{R_0}^{\infty} \frac{1}{r^2}\left(\frac{1}{b^2} - \left(1 - \frac{r_0}{r}\right)\left(\frac{1}{a^2} + \frac{1}{r^2}\right)\right)^{-½} dr - \pi \tag{3}$$

because it would carry on in a straight line represented by π radians or 180º if there were no M present. The angle π is the angle subtended by a straight line in a plane. In UFT 150 the constant b is defined by the need to produce 180º when M is zero, so:

$$b = R_0 \tag{4}$$

and because b is a constant of motion, it cannot change. It is always given by Eq. (4). The conserved orbital angular momentum of the photon is therefore:

$$L = R_0\frac{E}{c} \tag{5}$$

The conserved total energy of the photon is given by Planck´s theory as:

$$E = \hbar\,\omega \tag{6}$$

so the constant a is defined by:

$$a = \frac{\hbar\,\omega}{mc^2} \tag{7}$$

as used in UFT 150. This is the simplest possible developed using one photon. In general there is a Planck distribution of photons in the beam of light.

The time delay is derived by using:

$$\left.\begin{aligned} &\frac{dt}{dr} = \frac{dt}{d\tau}\frac{d\tau}{d\varphi}\frac{d\varphi}{dr} \quad , \qquad E = mc^2\left(1 - \frac{r_0}{r}\right)\frac{dt}{d\tau} \quad , \\ &\qquad\qquad\qquad\qquad\qquad L = mr^2\frac{d\varphi}{d\tau} \end{aligned}\right\} \tag{8}$$

where $d\tau$ is the infinitesimal of proper time. In this calculation it is identically non-zero as required. Therefore:

$$\frac{dt}{dr} = \frac{1}{c}\left(1 - \frac{r_0}{r}\right)^{-1}\left(1 - \left(1 - \frac{r_0}{r}\right)\left(\frac{1}{a^2} + \frac{1}{r^2}\right)R_0^{\,2}\right)^{-1/2} \tag{9}$$

The time taken for the radar beam to be reflected is obtained from the integral:

$$t = \frac{1}{c}\int\left(1 - \frac{r_0}{r}\right)^{-1}\left(1 - \left(1 - \frac{r_0}{r}\right)\left(\frac{1}{a^2} + \frac{1}{r^2}\right)R_0^{\,2}\right)^{-1/2} dr \tag{10}$$

with a and b defined as above, leaving the photon mass as the only unknown to be determined by the very precise experimental observation possible with contemporary satellite apparatus.

This integral can be evaluated analytically when M is zero, providing the baseline calculation. In the first approximation consider:

$$m \sim 0 \tag{11}$$

because m is very small in magnitude. The baseline integral is then:

$$t_0 = \frac{1}{c}\int\left(1 - \frac{R_0^{\,2}}{r^2}\right)^{-1/2} dr = \frac{1}{c}\left(r^2 - R_0^{\,2}\right)^{1/2} . \tag{12}$$

Consider the geometry of Fig. (1).

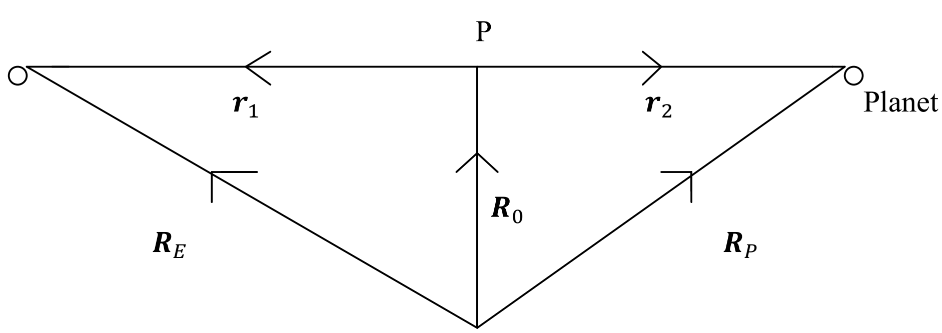

Fig. 1

The radar beam propagates in a straight line from earth to planet and back again. The origin of the coordinate system is at O. By vector analysis:

$$\left.\begin{aligned} \boldsymbol{R}_E &= \boldsymbol{R}_0 + \boldsymbol{r}_1 \quad , \quad \boldsymbol{R}_P = \boldsymbol{R}_0 + \boldsymbol{r}_2 \quad , \\ \boldsymbol{r}_1 &= \boldsymbol{R}_E - \boldsymbol{R}_0 \quad , \quad \boldsymbol{r}_2 = \boldsymbol{R}_P - \boldsymbol{R}_0 \quad , \end{aligned}\right\} \tag{13}$$

and the magnitudes are given by:

$$r_1^{\ 2} = R_E^{\ 2} - R_0^{\ 2} \quad , \quad r_2^{\ 2} = R_P^{\ 2} - R_0^{\ 2} \quad . \tag{14}$$

The time taken for the radar beam to go from the Earth to point P is:

$$t_1 = \frac{1}{c} \int_{R_0}^{R_E} \left(1 - \frac{R_0^{\ 2}}{r^2} \right)^{-½} dr = \frac{r_1}{c} \quad . \tag{15}$$

The time taken for the radar beam to go from point P to the planet is:

$$t_2 = \frac{1}{c} \int_{R_0}^{R_P} \left(1 - \frac{R_0^{\ 2}}{r^2} \right)^{-½} dr = \frac{r_2}{c} \quad . \tag{16}$$

The total time for a return trip from Earth to planet and back again is therefore:

$$t_0 = 2\,(\,t_1 + t_2) = \frac{2}{c}\,(r_1 + r_2)\,. \tag{17}$$

This is exactly the result expected if the radar beam were travelling at c directly from Earth to planet and back again. Therefore the method used in the baseline calculation is correct.

Consider now the same radar beam travelling from the Earth to the planet, but grazing the Sun with distance of closest approach R_0. This experiment is shown in Fig. (2), where the angle of deflection, θ, has been greatly exaggerated for illustrative purposes.

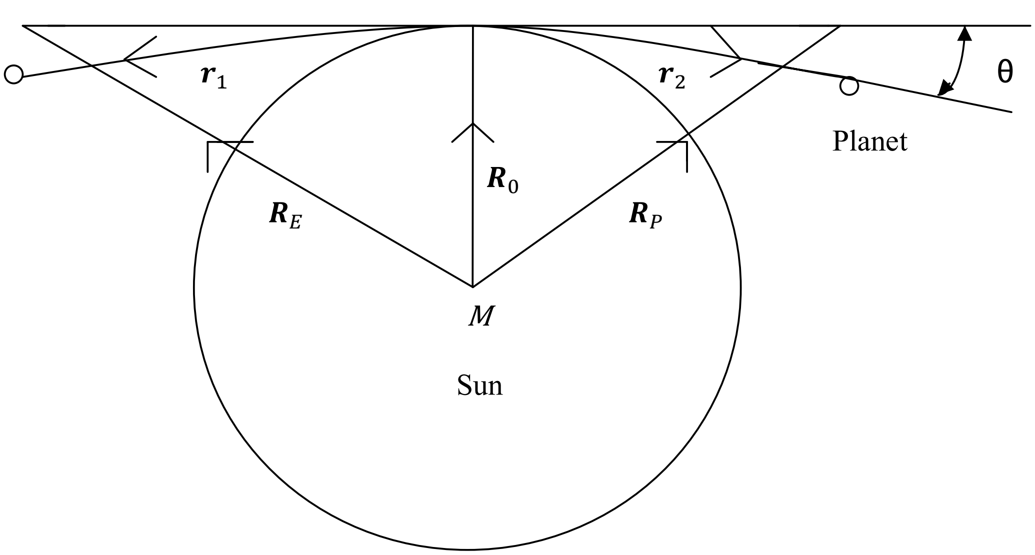

Fig. 2

Experimentally, it is only a few arc seconds, a few microradians. In Fig (2) the mass of the Sun M is non-zero, and the origin of coordinates is the centre of the Sun. To an excellent approximation, R_0 is the radius of the Sun. Using this geometry in Eq. (10), the time taken for the radar beam to propagate from the Earth to the planet and back again is:

$$t_3 = \frac{2}{c} \left(\int_{R_0}^{R_E} f(r)\ dr \ + \int_{R_0}^{R_P} f(r)\ dr \right) \quad , \tag{18}$$

$$f(r) = \left(1 - \frac{r_0}{r}\right)^{-1} \left(1 - \left(1 - \frac{r_0}{r}\right) \left(\frac{1}{a^2} + \frac{1}{r^2}\right) R_0^{\ 2}\right)^{-½} . \tag{19}$$

So the gravitational time delay is: $\left(\frac{1}{R_0^2} - (1 - r_0 u)\left(\frac{1}{a^2} + u^2\right)\right.$

$$\Delta t = t_3 - t_0 \ . \tag{20}$$

This is worked out to machine precision in Section 3, using Maxima and Mathematica, and the photon mass determined for a radio frequency of ω about 10^8 radians per second.

3. Numerical computation of light deflection and photon mass

In this section we analyze the integral (3) of light deflection numerically. The integration challenges numerical methods because the integrands are of order 10^{-19} while the integration range is from about 10^9 to infinity. Rewriting the integral in the u coordinates with $u = 1/r$ leads to

$$\Delta\varphi = 2 \int_0^{\frac{1}{R_0}} \left(\frac{1}{R_0^2} - (1 - r_0 u) \left(\frac{1}{a^2} + u^2 \right) \right)^{-1/2} du - \pi \ . \tag{21}$$

To get an impression of the nature of the integrand, we have first analyzed the argument of the square root in the original formulation (3) of the integral with r dependence. Negative values in the integration range $r \geq R_0$ lead to an imaginary square root so that the integral does not exist. From the graphical plot in Fig. 1 we see that the characteristic of the argument is defined by the parameter a. For $a = R_0$ the argument is always negative. When a is enlarged, there is a zero crossing, and for a about 3×10^{11} and above, this zero comes to lie outside the integration range. So there is a starting point for a from which upwards the integral exists.

The full integrand with u coordinate is shown in Fig. 2. There is a pole of the function graph for $u = 1/R_0$, the upper integration limit, up to which the integration has to pertain. For $a > 10^{11}$ there is no difference visible on the plotted scale. Observe that the u axis only shows the uppermost part of the integration range. The integral is determined by the behaviour near the singularity. This makes a numerical integration very sensitive.

We used two highly sophisticated integration procedures of the computer algebra system

Maxima: *quad_qags* and *quad_qag*, from the QUADPACK package. The results of the *quad_qags* procedure are reported in Figs. 3-5. According to Fig. 3, the integral exists for $a \geq 3.33217 \times 10^{11}$. The value of $\Delta\varphi$ obtained from the integral (8.489×10^{-6}) is very close to the experimental value of 8.484×10^{-6} . Curiously, there is the same result for a whole range of a, then the result jumps onto a logarithm-like curve. There are some points where no convergence could be reached. These have been omitted. Closer inspection of the beginning (Fig. 4) shows that there is a certain uncertainty, but only by about 0.2% of the absolute value. The apparent grouping on the y axis leads to the conclusion that the limit of numerical precision has been reached. An alternative plot in Fig. 5 shows that the absolute errors of the integration procedure are sufficiently small and the experimental value of $\Delta\varphi$ can be reproduced sufficiently well.

A more convincing result is obtained from the *quad_qag* procedure as shown in Figs. 6-8. Convergence is obtained in all cases beginning from $a = 3.37654 \times 10^{11}$ (Fig. 6). To find the onset of the integral requires a finer a mesh again as shown in Fig. 7. Fig. 8 looks identical to Fig. 5, with the exception that there is convergence at all points now. The *quad_qag* procedure allows for defining six degrees of quadrature formulae. The results for the first value of a are shown in Table 1. There is no significant deviation between the six options. Since the second, fifth and sixth give the closest result to the experimental value of $\Delta\varphi$, we prefer to take their common value $a = 3.37655447822 \times 10^{11}$ as the final result. This differs by 1% from the value of *quad_qags*. With the result of *quad_qag*, we can compute the photon mass according to Eq. (7):

$$m = \frac{\hbar\omega}{ac^2} \mathrm{R}_0 \ . \tag{22}$$

The result gives a photon mass of

$$\boxed{m = 2.4176 \times 10^{-38} \text{ kg.}} \tag{23}$$

For all calculations we used the parameters

$$\mathrm{R}_0 = 6.9569 \times 10^8 \text{ m}, \quad \mathrm{G} * \mathrm{M} = 1.327124971 \times 10^{20} \ \frac{\mathrm{m}^3}{\mathrm{s}^2}, \quad \mathrm{r}_0 = \frac{2\mathrm{GM}}{\mathrm{c}^2} = 2953.25134 \text{ m},$$
$$\omega = 1 \times 10^{16} \ \frac{1}{s}, \quad \hbar = 1.054571628 \times 10^{-34} \ Js, \quad \mathrm{c} = 2.99792458 \times 10^8 \text{ m/s}. \tag{24}$$

Since the light frequency ω is only an approximation for the range of visible light, there is an uncertainty in this value being greater than obtained from the two methods of calculation. The value is larger than that obtained from analytical methods in UFT paper 150, showing that approximations infer considerable errors due to the delicate form of the integrand.

Degree of inter-polation	Delta_phi	Estimated error	First value of a
1	8.3816963889482565*10^-6	1.3706304938049789*10^-8	3.3765447831*10^11
2	8.4554707955319941*10^-6	7.0560551207563817*10^-9	3.3765447822*10^11
3	8.4173461090131241*10^-6	9.3238675223672223*10^-9	3.3765447826*10^11
4	8.4254315178000638*10^-6	1.471603874159512*10^-8	3.3765447824*10^11
5	8.4433555302965146*10^-6	3.5415584499892262*10^-9	3.3765447822*10^11
6	8.4432219753516335*10^-6	8.2869157144624569*10^-9	3.3765447822*10^11
quad_qags	8.4890410230187285*10^-6	7.3393069399685373*10^-10	3.33217*10^11

Table 1. Integration results for different types of interpolation (*quad_qag*) and *quad_qags*

Finally we compare our results with that of the Einstein integral

$$\Delta\varphi_{E1} = 2\int_0^{\frac{1}{R_0}} \left(\frac{R_0 - r_0}{R_0^3} - u^2 + r_0 u^3\right)^{-1/2} du - \pi \tag{25}$$

and Einstein's analytical result

$$\Delta\varphi_{E2} = \frac{4GM}{c^2 R_0} - \pi \quad . \tag{26}$$

With improved parameters of (24) this gives

$$\Delta\varphi_{E1} = 8.490169 \text{ x } 10^{-6} \tag{27}$$

and

$$\Delta\varphi_{E2} = 8.490136 \text{ x } 10^{-6} \tag{28}$$

Our numerical result of 8.489041 x 10^{-6} radians is slightly nearer to the experimental value of (8.4848 ± 0.003) x 10^{-6}. Considering the experimental error and the fact that other more varying measurements exist, we conclude that our numerical method is in best agreement with experimental data.

4. Numerical computation of the Shapiro time delay

The time delay for a gamma ray grazing the sun is given by Eqs. (17-20). Because there is no factor of $1/r^2$ in the integral and the boundaries are finite, it is recommendable to stay at the *r* coordinate and not to transform the integral to the *u* coordinate. The same procedure as for the angle of light deflection leads to an onset of the integral value for a certain value of *a*. The results are plotted in Fig. 9. The time delay is 5.614 ms for Earth – Mars which is an order of magnitude larger than the experimental values, see Table 2.

Ref.	Time delay Δt [ms]	Planets	Frequency
Shapiro et al. [13]	0.200	Earth - Venus	Radar, 7.84 GHz
Shapiro et al. [14]	0.250	Earth - Mars	Radio frequency
Reasenberg et al. [15]	0.200	Earth - Mars	Radio frequency
Wald [16]	0.633	Earth - Mars	-

Table 2. Experimental (Shapiro, Reasenberg) and other theoretical (Wald) values of gravitational time delay.

Sun radius parameter	Time delay Δt [ms]	First value of a [m]
R_0	5.614	3.3765447808*10^11
1.25 R_0	0.266	4.029038339*10^11
3 R_0	-141.0	1.7545067*10^12

Table 3. Time delay integration results for *quad_qag*, Type 6, and comparison with calculation of Wald and experiment of Shapiro.

In order to estimate the influence of the parameters in the calculation, we have altered the effective sun radius From Table 3 can be seen that enlarging this radius by 1/8, the experimental value for the time delay is met. From experiments it is not fully clear how light and radar rays behave near to the sun surface (photosphere). It is possible that plasma effects play a role. Therefore an estimation of the effective sun radius is difficult.
We have also compared the time delay value with that of Wald [16]. He denotes by Δt what correctly is the total travelling time of the ray, i.e. the base time t_0 and the relativistic enlargement Δt. With reduction to the "true" Δt his formula reads:

$$\Delta t = \frac{2MG}{c^3}\left[2\,log\frac{R_E+\sqrt{R_E^2-R_0^2}}{R_0} + 2\,log\frac{R_P+\sqrt{R_P^2-R_0^2}}{R_0} + \sqrt{\frac{R_E-R_0}{R_E+R_0}} + \sqrt{\frac{R_P-R_0}{P+R_0}}\right] \tag{29}$$

with R_E being the orbital radius of the Earth and R_P being the respective radius of Mars. The result of this formula (0.633 ms, see Table 2) is more than twice the experimental one. This either shows that the method of Wald is erroneous or (more likely in this case) that the interpretation of the measurements of the Shapiro delay is unclear because the effective sun radius is not known. In the literature [14] it is reported that there is "agreement with the predictions to within the estimated uncertainty of 0.5%". We cannot confirm this by our evaluation of Wald's formula.

The calculation of the photon mass depends on the photon energy according to Eq. (22). With an estimated radio frequency of 100 MHz we obtain

$\hbar\omega \sim 6.6 \cdot 10^{-28}\,J$

which leads to a photon mass of

$$m = 1.5 \text{ x } 10^{-47} \text{ kg.} \tag{30}$$

This value is much smaller than that obtained from light deflection, Eq. (23). The reason probably is that no monochromatic photons were used, at least in the light deflection experiment. The Planck distribution of photon energy has to be taken into account. In Eq. (22) we have to replace the photon energy $\hbar\omega$ by the mean value of the Planck distribution $< \hbar\omega >$:

$$m = \frac{<\hbar\omega>}{ac^2} R_0 \tag{31}$$

with $$< \hbar\omega >= \frac{\hbar\omega\ e^{-x}}{1-e^{-x}} \tag{32}$$

and $$x = \frac{\hbar\omega}{kT} . \tag{33}$$

k is Boltzmann's constant and T the temperature of the photon ray. As can be seen from Table 4, finite temperatures significantly reduce the effective photon energy and, consequently, the calculated photon mass. For 2500 K we obtain a value of about 10^{-51} kg which is in the range of other experimental estimations. Between radar and radio waves there is no significant difference in the Planck distribution.

ω [rad/s]	**T** [K]	***m*** [kg]
1.0*10^16 (light)	No Planck distr.	2.417*10^-38
	500	1.094*10^-104
	1000	1.626*10^-71
	1500	1.856*10^-60
	2000	6.270*10^-55
	2500	1.301*10^-51
	3000	2.118*10^-49
	3500	8.046*10^-48
	4000	1.231*10^-46
4.9*10^10 (radar waves)	No Planck distr.	1.191 *10^-43
	500	1.581*10^-40
	1000	3.164*10^-40
	1500	4.747*10^-40
	2000	6.329*10^-40
	2500	7.912*10^-40
	3000	9.494*10^-40
	3500	1.107*10^-39
	4000	1.265*10^-39
6.3*10^6 (radio waves)	No Planck distr.	1.519 *10^-47
	T>0	Same results as for radar waves

Table 4. Photon mass calculation from Planck distribution for three photon frequencies.

5. Parameter study

The impact of the parameters R_0 (Sun radius) and r_0 (Schwarzschild radius) on the results has been studied. It has been shown already that the time delay is quite sensitive on the effective Sun radius R_0. This has been studied in detail in Fig. 10 where the a dependence of time delay Δt is plotted for different R_0 values. The maximum value decreases quickly and there is a nodal point where the curves cross over. There is no such crossing for the r_0 dependence of the time delay (Fig. 11). The maximum of the curves is highest again for the physical value of r_0.

Similar results are obtained for the dependence of the angle of deflection $\Delta\varphi$ (Figs. 12, 13). However there is no crossing of the curves for varying R_0. The maximum values are below zero because of reduced precision in the grid points on the abscissa axis. One can see that there is a considerable variance in the onset values of the curves as well as the ordinate values. Compared to the experimental value of $\Delta\varphi$, the variation is larger by several orders of magnitude, showing again that the result is very sensitive to the choice of parameters.

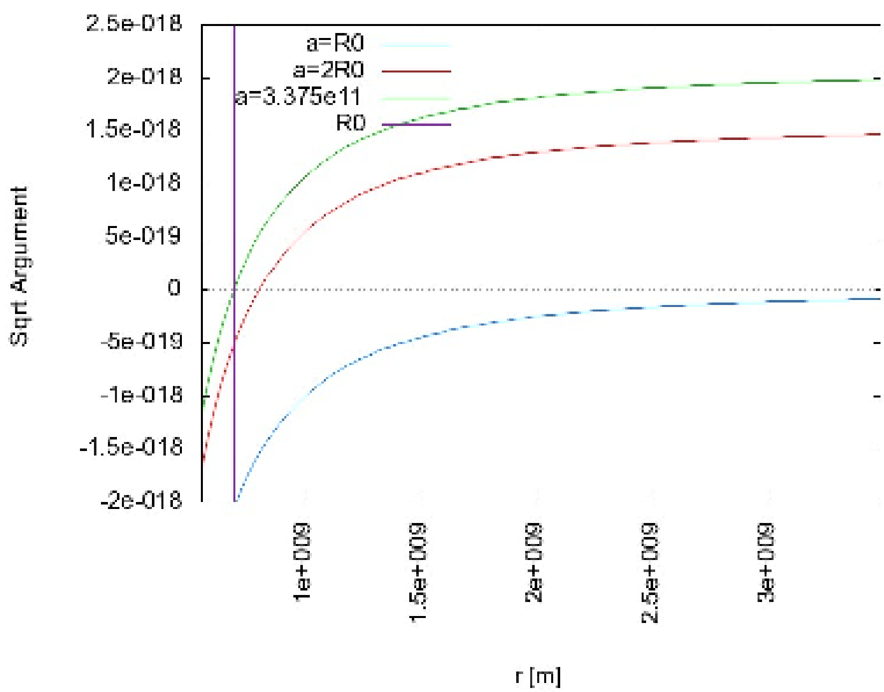

Fig. 1. Argument of square root in integral for different parameter values of a .

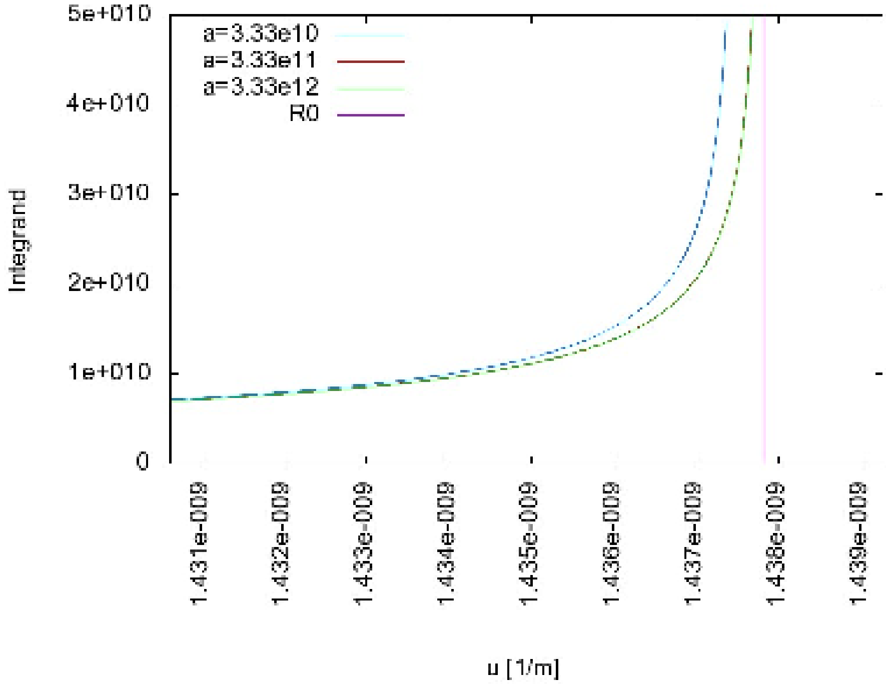

Fig. 2. Integrand for different parameter values of *a*.

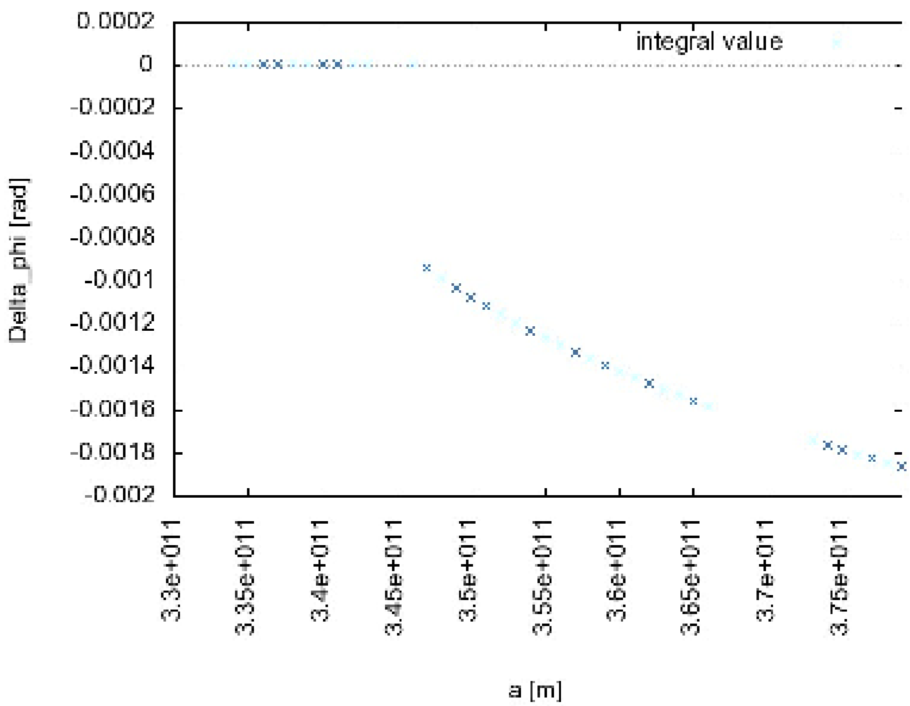

Fig. 3. Integral evaluated for different parameters of *a*, *quad_quags* method.

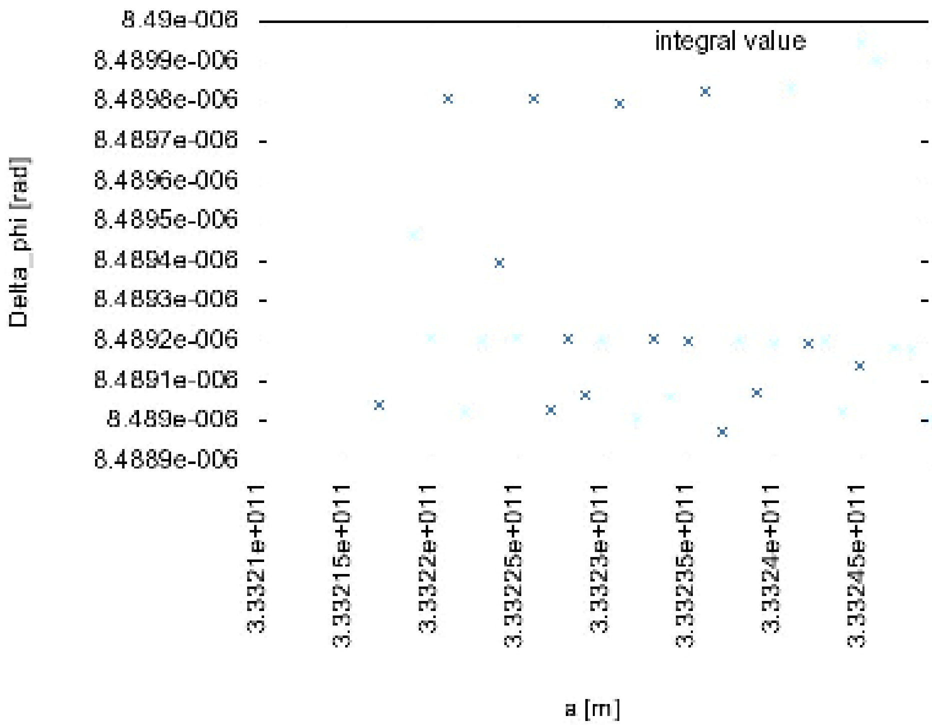

Fig. 4. Integral evaluated with *quad_quags* method, narrowed to relevant range of *a* , and with narrowed vertical scale.

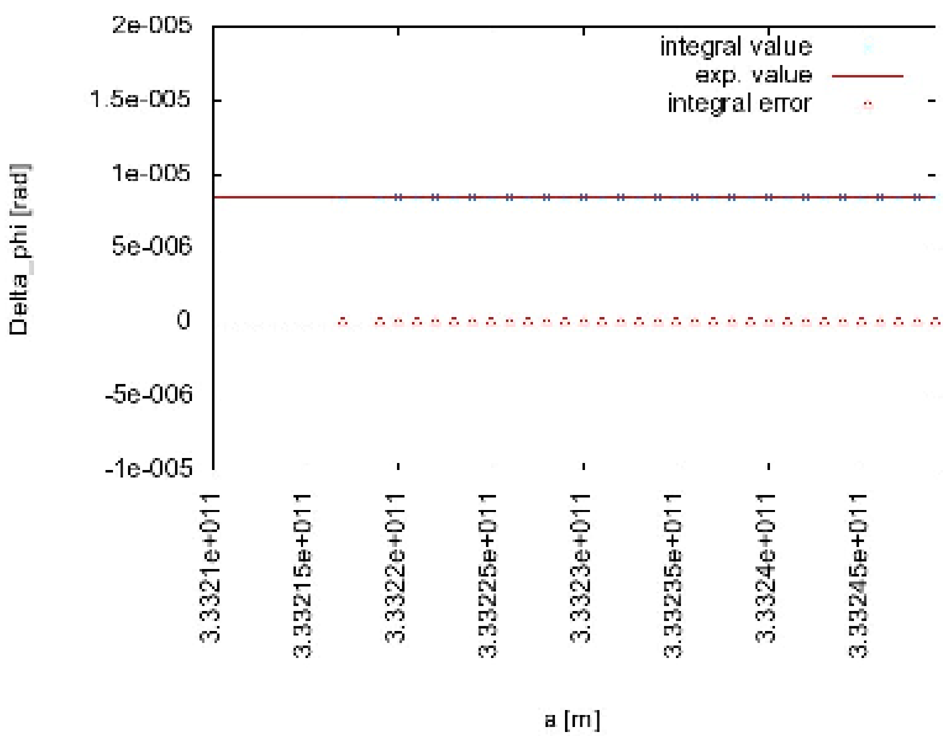

Fig. 5. Same as Fig. 4, with comparison to experimental value and integral precision.

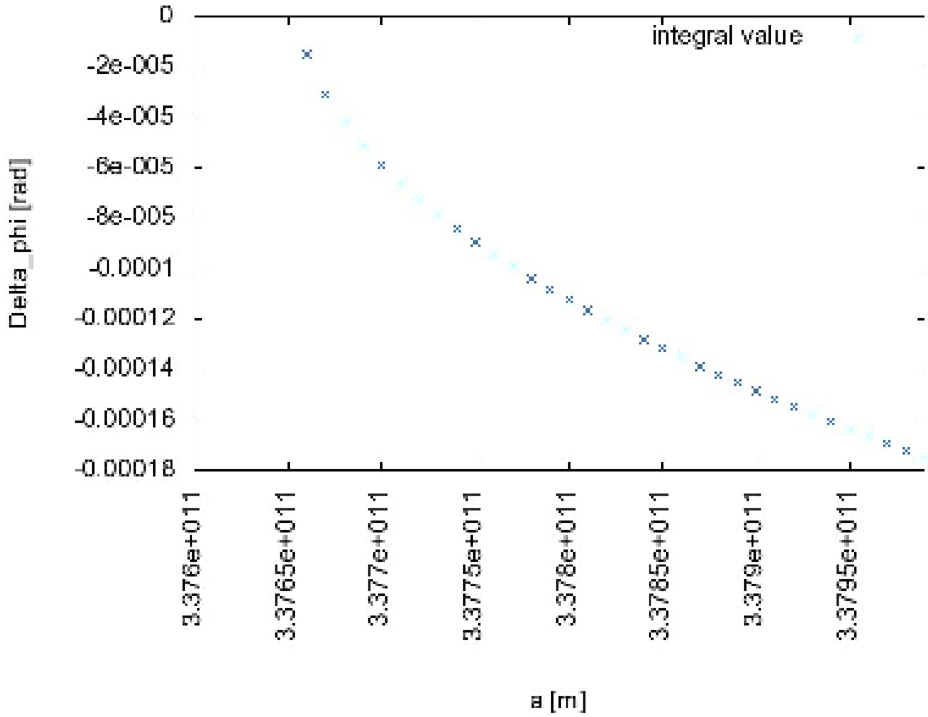

Fig. 6. Integral evaluated for different parameters of *a*, *quad_quag* method, type 6.

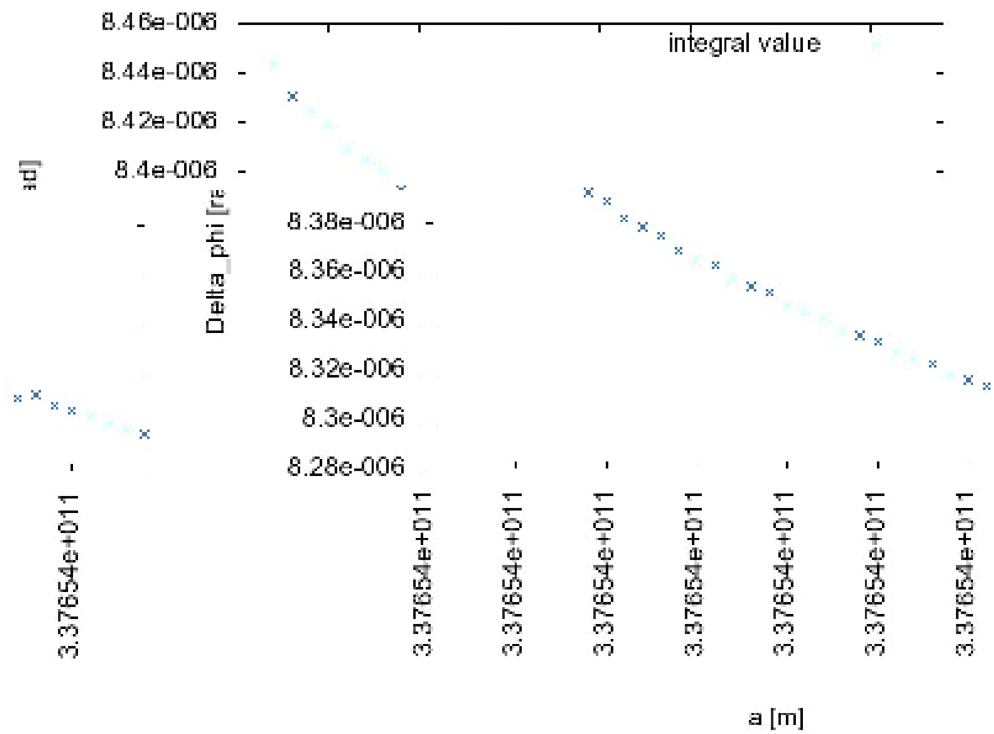

Fig. 7. Integral evaluated with *quad_quag* method, narrowed to relevant range of *a* , and with narrowed vertical scale. Difference between x tics is 50 m.

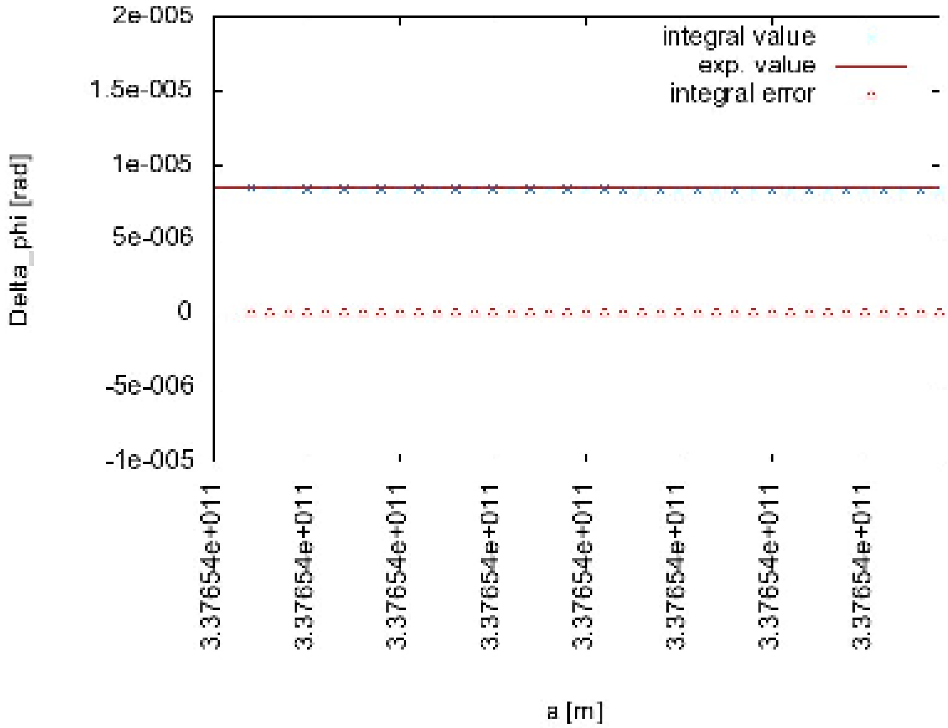

Fig. 8. Same as Fig. 7, with comparison to experimental value and integral precision.

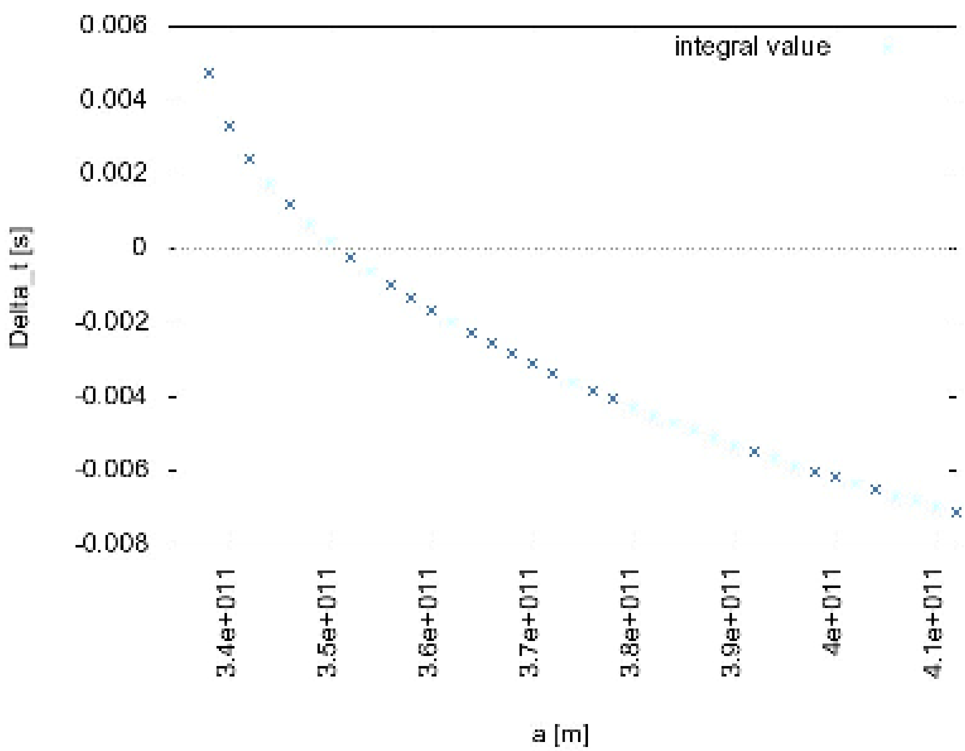

Fig. 9. Time delay for different parameters of *a, quad_quag* method, type 6.

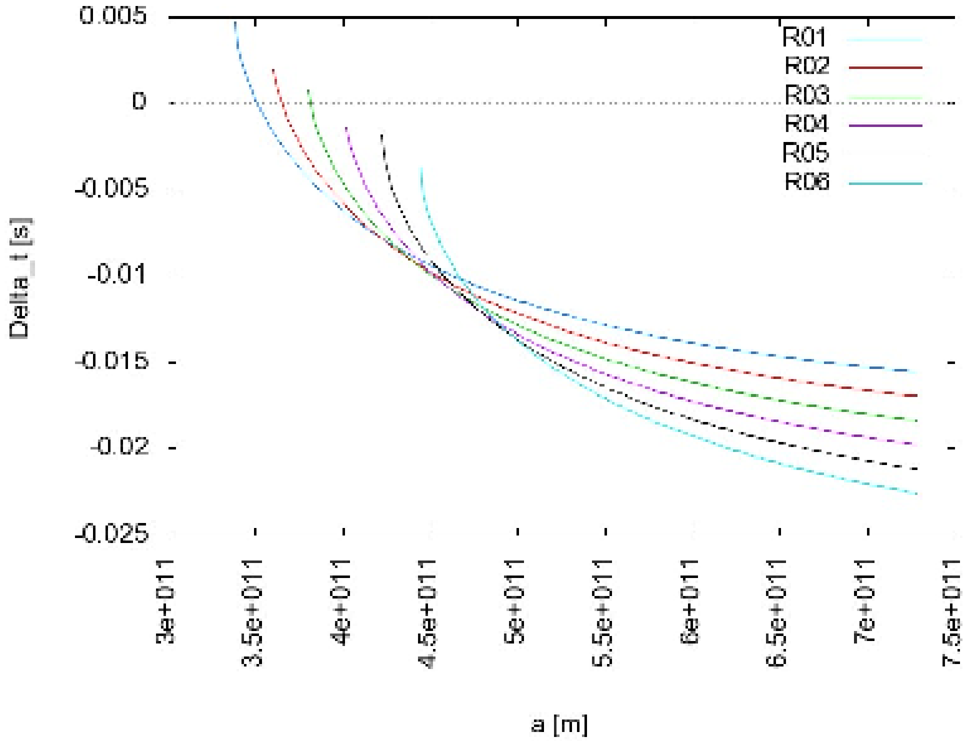

Fig. 10. Time delay Δt for R_0 values between 1 × Sun radius and 1.2 × Sun radius.

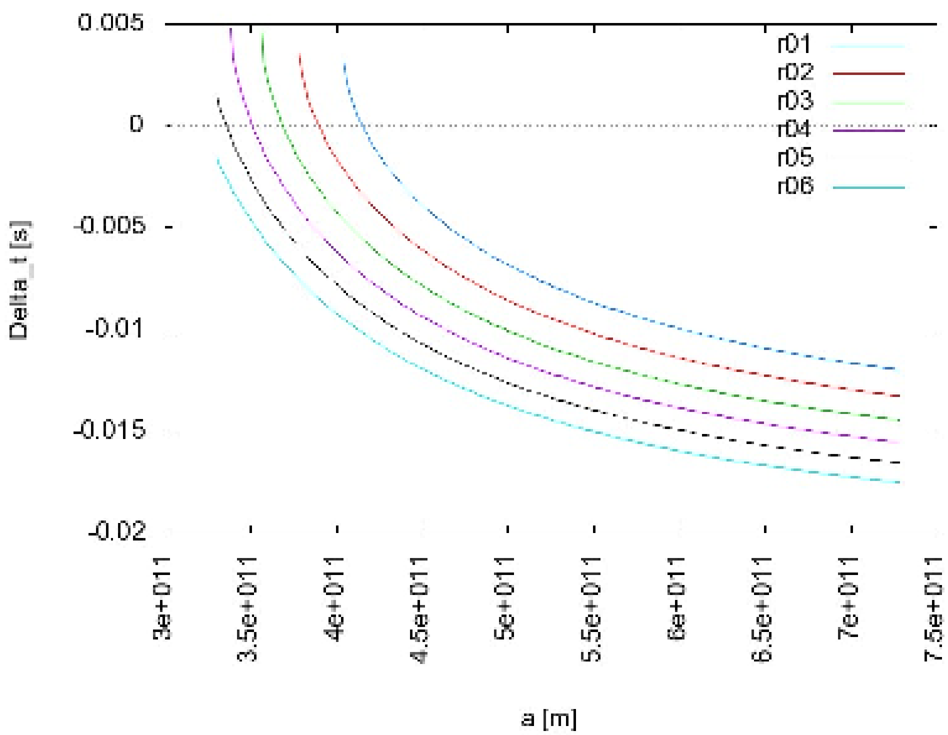

Fig. 11. Time delay Δt for r_0 values between 0.7 × and 1.2 × Schwarzschild radius.

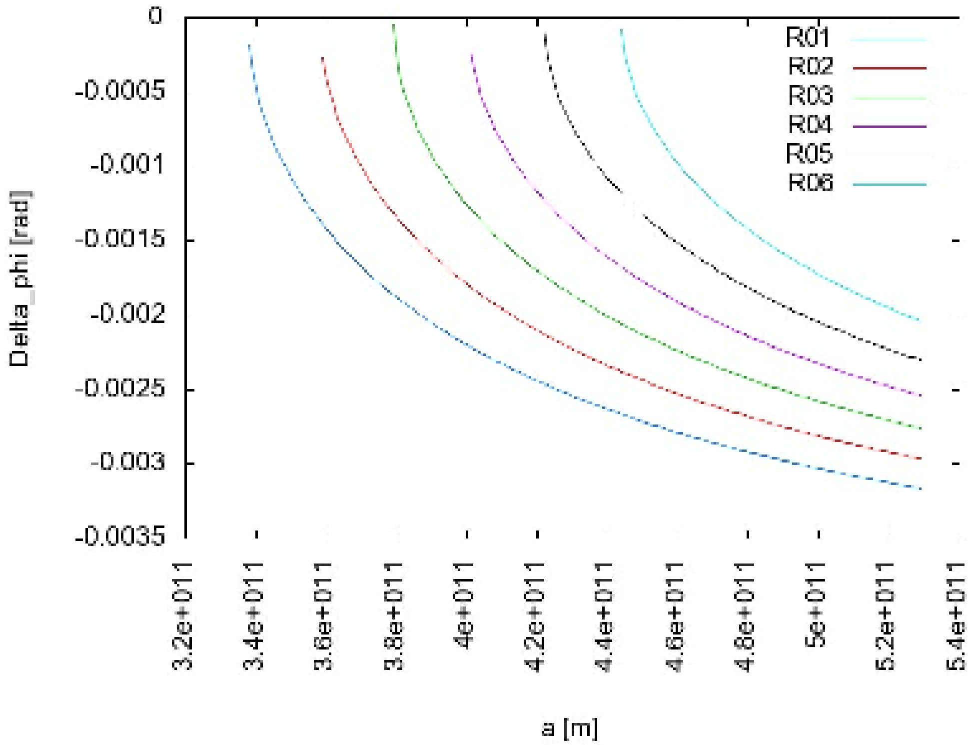

Fig. 12. Deflection angle $\Delta\varphi$ for R_0 values between 1 × Sun radius and 1.2 × Sun radius.

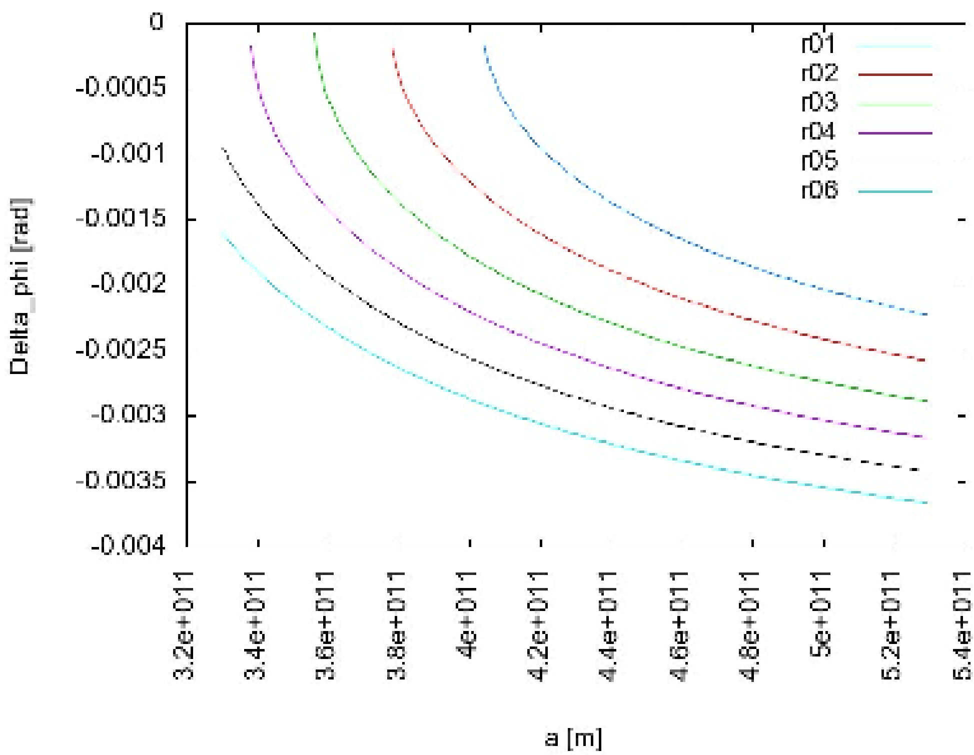

Fig. 13. Deflection angle $\Delta\varphi$ for r_0 values between 0.7 × and 1.2 × Schwarzschild radius.

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