nature portfolio

Peer Review File

Non-zero Yarkovsky acceleration for near-Earth asteroid (99942) Apophis

Web links to the author's journal account have been redacted from the decision letters as indicated to maintain confidentiality.

21st Sep 21

Dear Dr Pérez-Hernández,

Your manuscript titled "Non-zero Yarkovsky acceleration for (99942) Apophis" has now been seen by 3 reviewers, and I include their comments at the end of this message. They find your work of interest, but some important points are raised. We are interested in the possibility of publishing your study in Communications Earth & Environment, but would like to consider your responses to these concerns and assess a revised manuscript before we make a final decision on publication.

We therefore invite you to revise and resubmit your manuscript, along with a point-by-point response that takes into account the points raised. Please highlight all changes in the manuscript text file.

In particular please ensure the the revised manuscript meets the following editorial threshold:

Provide a compelling independent computation of a non-negligible Yarkovsky effect on Apophis and clearly outline how this result advances or refines our understanding of the orbital dynamics of Apophis

We are committed to providing a fair and constructive peer-review process. Please don't hesitate to contact us if you wish to discuss the revision in more detail.

Please use the following link to submit your revised manuscript, point-by-point response to the referees' comments (which should be in a separate document to any cover letter) and the completed checklist:

[link redacted]

** This url links to your confidential home page and associated information about manuscripts you may have submitted or be reviewing for us. If you wish to forward this email to co-authors, please delete the link to your homepage first **

We hope to receive your revised paper within six weeks; please let us know if you aren't able to submit it within this time so that we can discuss how best to proceed. If we don't hear from you, and the revision process takes significantly longer, we may close your file. In this event, we will still be happy to reconsider your paper at a later date, as long as nothing similar has been accepted for publication at Communications Earth & Environment or published elsewhere in the meantime.

We understand that due to the current global situation, the time required for revision may be longer than usual. We would appreciate it if you could keep us informed about an estimated timescale for resubmission, to facilitate our planning. Of course, if you are unable to estimate, we are happy to accommodate necessary extensions nevertheless.

Please do not hesitate to contact me if you have any questions or would like to discuss these revisions further. We look forward to seeing the revised manuscript and thank you for the opportunity to review your work.

Best regards,

Joe Aslin

Associate Editor,
Communications Earth & Environment
https://www.nature.com/commsenv/

Twitter: @CommsEarth

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REVIEWER COMMENTS:

Reviewer #1 (Remarks to the Author):

Comments on the manuscript "Non-zero Yarkovsky acceleration for (99942) Apophis" by Jorge A. P´erez-Hern´andez & Luis Benet.

* What are the major claims of the paper?

Authors have obtained an orbital solution and the value of an Yarkovsky transverse parameter A2 (A2 = −2.90±0.03) ×10-14 au/d2) for Apophis with optical and radar observations including 2021. In this case, original software was used. Shown, that this solution provides quantitatively better residuals than the one which includes only a gravitational interaction. The acceleration associated to Yarkovsky effect induces a semi-major axis drift equal to −199 ± 2 m/yr. Based on these data, estimates of the minimum distances and their errors in approaching the Earth in 2029, 2036, and 2068 were obtained, excluding the possibility of an asteroid colliding with the Earth.

* Are these claims novel, and will they be of interest to others in the community? If the conclusions are not original, it would be helpful if you could provide relevant references.

The results have been obtained on independent software created by the authors. In this sense, they are new ones.
Confirmed that the minimum distances in approaching the Earth in 2029, 2036, and 2068 exclude the possibility of Apophis' colliding with the Earth.

* Is the work convincing, and if not, what further evidence would be required to strengthen the conclusions?

The work is convincing:
As follows from 'Supplementary Information', all parts of the software have been tested and testing has shown their high accuracy.

Comparison of the results obtained with the results of other authors and their agreement suggests that there are no significant errors in the work of the authors.

Comments and questions
1. The authors "consider Apophis as a mass-less test-particle subject to the Newtonian gravitational attraction from the Sun, the eight planets, the Moon, Pluto and the 16 most massive main-belt asteroids..."
There is no explanation why 16, rather than 10 or 20, the most massive asteroids are selected. Have estimates been made of the gravitational influence of massive asteroids on the motion of Apophis before such a choice? Perhaps Apophis had close encounters with other asteroids. Such research would be interesting and useful.

2. As follows from the work, the authors did not include the effect of the solar light pressure on the motion of the asteroid. Have there been any preliminary estimates of the impact of this factor?

3.The authors do not report the value of the A2 obtained in JPL. Meanwhile, in JPL (https://ssd.jpl.nasa.gov/sbdb.cgi#top) was obtained A2=(−2.901±0.019) ×10-14 au/d2.
This value practically coincides with the result of the work under consideration. But isn't it a consequence of the same model of the motion?

4.The authors cite the paper
Tholen, D. & Farnocchia, D. Detection of Yarkovsky acceleration of (99942) Apophis. In AAS/Division for Planetary Sciences Meeting Abstracts, vol. 52, 214–06 (2020);

however, do not provide the value of the semi-major axis drift, which is equal to –170 m/yr. It would be interesting if the authors would comment on the reasons for the discrepancy between their and these values. This discrepancy is about 15 times greater than the corresponding error.

Resume.
The authors have created the software to improve an orbital parameters of any asteroid and estimate a magnitude of the non-gravitational acceleration.
These estimates were obtained for Apophis. Besides, it was shown that the minimum distances in approaching the Earth in 2029, 2036, and 2068 exclude the possibility of Apophis' colliding with the Earth. All estimates obtained are in good agreement with those previously obtained by other authors, using the same model of motion and the same set of observations (site of JPL).
These coincidences indicate the correct operation of the program; however, the results obtained can hardly be called new, rather confirming ones.

Therefore, I cannot recommend the manuscript "Non-zero Yarkovsky acceleration for (99942) Apophis" by Jorge A. P´erez-Hern´andez & Luis Benet as proposed for publication in Communications Earth & Environment.

Reviewer #2 (Remarks to the Author):

The paper summarizes an impressive amount of excellent work on the orbit of (99942) Apophis, and definitely deserves to be published in Communications Earth & Environment, essentially in its present form.

There are only a few minor points to address, listed hereafter; the authors can easily take care of them without the need, for me, to see the revised manuscript.

1) Reference 4 is incomplete; the book that contains Chesley's paper is: Asteroids, Comets, Meteors, Proceedings of IAU Symposium 229, Edited by D. Lazzaro, S. Ferraz-Mello & J.A. Fernández. Cambridge: Cambridge University Press, 2006.

2) At the top of page 8 the ζ coordinate on the 2029 be-plane is introduced, without explanation; the authors should either explain what it is, or perhaps mention the paper in which it is introduced in the context of NEA impacts, that is Valsecchi, Milani, Gronchi, Chesley, Astronomy and Astrophysics, v.408, p.1179-1196, 2003 (sorry for the self reference, as a referee it is for me a little embarrassing).

3) The systematic bias signature present in the observations from the observatory of MPC code 217 mentioned at the beginning of Section 4 of the supplementary material is also evident in the orbital solution of NEODyS, as evidenced in the webpage https://newton.spacedys.com/neodys/index.php?pc=2.1.2&o=217&ab=0; the authors do not need to modify the text, anyway.

Giovanni Valsecchi

Reviewer #3 (Remarks to the Author):

Please, see the attached report.

Manuscript. COMMSENV-21-0507-T

Title. Non-zero Yarkovsky acceleration for (99942) Apophis

Authors. Jorge A. Pérez-Hernández, Luis Benet

Referee. Alessio Del Vigna, Department of Mathematics, University of Pisa

In the present paper the authors describe how they independently computed the Yarkovsky acceleration for asteroid (99942) Apophis, by fitting the orbital elements and the Yarkovsky parameter A_2 to the currently available optical and radar astrometry.

The observational dataset of Apophis contains thousands of optical observations collected at various oppositions and also several high-precision radar measurements. As a consequence the orbit of Apophis is known at a very accurate level and thus also small perturbations become relevant to make reliable predictions. The leading source of uncertainty for Apophis is known to be the Yarkovsky effect, which causes a secular semi-major axis drift. An estimate of the magnitude of this effect is thus fundamental to understand the future motion of this asteroid.

The paper is clear and presents an important result. I thus recommend it for publication on Nature Communications Earth & Environment, after a revision. I also suggest a careful revision of the English writing and phrasing, as explained in some comments below.

Comments on the paper

(i) Pag. 2, first paragraph

Specify that r_{Sun} is the heliocentric distance expressed in au. Moreover, improve the phrasing of the sentence starting with "Our goal is" writing "Our goal is to determine the unknown proportionality constant A_2 which fits the optical and radar astrometry, using precise numerical integration of the equations of motion".

(ii) Pag. 2, second paragraph

It is stated that the equations of motion are solved using a 30-order Taylor integrator, whereas in the supplementary material I found that the order is 25. Is this correct or are these two the same integrator? In the latter case, please correct the wrong value of the order.

(iii) Pag. 3, beginning

In the sentence ending with "transported along the integration in time" I would cite again the supplementary material (Section 3) to point the reader to the details there contained.

(iv) Pag. 4, second paragraph

Can you explain in some way the bimodal distribution of the residuals of the purely gravitational solution?

(v) Page 8, beginning

I would place a reference to a paper explaining Öpik variables, for instance Valsecchi *et al.* (2003), *Resonant returns to close approaches: Analytical theory.*

(vi) Page 8, first paragraph

I would add a few words about how the authors computed the values of ζ for which Apophis would impact the Earth in 2036 and 2068. Did you obtained these values from the b-plane resonant circles?

(vii) Page 8, last sentence of first paragraph

The authors state that their results "must be revised in the future" because of the accumulation of the integration errors. This could be true if one considers just the nominal orbit to make predictions, since close approaches introduce a strong non-linearity in the propagation. But there are several techniques, *e.g.* the Line Of Variations method, invented extactly to overcome this kind of difficulties and perform a reliable impact monitoring, even with a time horizon well beyond a century in some case. Therefore this sentence, being it potentially misleading, has to be removed or changed to account for these methods.

(viii) Caption of Figure 2

I would change "residuals [...] contain zero" with "residuals are compatible with zero".

(ix) Table 1

There is a typo in the caption: "thee" should be "the". As for the content of the table, in the χ^2 row the values are expressed using a comma instead of a point as decimal separator.

Comments on the supplementary material

(i) Caption of Figure 1

I would change "The x coordinate of all panels" with "the horizontal axis of all panels", to avoid the use of x.

(ii) Caption of Table 1

For a better phrasing, do not use symbols at the beginning of sentences. For instance, I suggest to write "Value of Gm for the 16 main-belt asteroid perturbers" (avoid indexed variables if not necessary).

(iii) Pag. 7

The bold title should section 5.

General comments

(i) There are some points which deserves some English correction.

- Pag. 2: "allows to estimate" and "allows to consider" must have the complement like "allows one to estimate" and "allows one to consider".
- Pag. 8: "accumulation of numerical errors grow" has to be changed with "grows".

- Pag. 8: “this non-gravitational solution allow us” must be changed in “allows us”.

(ii) Check that all the units of measurement are separated from their numerical values with a blank.

(iii) Always use parenthesis to separate a measurement with its uncertainty from the related power of 10, as in Table 2 and 3 of the supplementary material.

Response to Referee 1

We thank the Referee for her/his time and commitment revising our work. We begin pointing out that in the revised version of the paper we have updated the observation dataset, and use it to update our calculations, which improves slightly the uncertainty obtained for A_2; we have updated Table 1 (main paper) and Tables 2 and 3 (Supplementary information) accordingly. Below we omit quoting the initial general comments on our paper, which are positive in all evaluated aspects, and respond all comments and questions raised by the Referee, and the final opinion (rejection) on our paper.

Referee comment/question:

1. The authors "consider Apophis as a mass-less test-particle subject to the Newtonian gravitational attraction from the Sun, the eight planets, the Moon, Pluto and the 16 most massive main-belt asteroids..."

There is no explanation why 16, rather than 10 or 20, the most massive asteroids are selected. Have estimates been made of the gravitational influence of massive asteroids on the motion of Apophis before such a choice? Perhaps Apophis had close encounters with other asteroids. Such research would be interesting and useful.

Author's Response:

The reason we used the 16 most massive main-belt asteroids is to have a fair comparison with other models which also estimate the value of A_2 for Apophis, though not all models use the 16 most massive asteroids. In the present version of the paper we mention this in the second paragraph of

the ‘Results and discussion’ section (page 3), including some relevant references.

Regarding previous estimates of the gravitational influence of massive asteroids, Giorgini et al [Icarus 193 (2008), 1-19] studied the combined influence of the 128 top-ranked perturbers, and checked the offset considering 8, 16, 32 and 64 main perturbers. They found that only small corrections arise when more than 32 perturbers are considered. In order to have a somewhat similar estimate on the influence of the asteroids in the value of A_2 for Apophis, besides our calculation using 16 asteroids we also considered 32, which is a test on the robustness of the model. We find that the value of A_2 changes in 0.002σ, where σ is the associate uncertainty to A_2 we obtained for 16 asteroids; other quantities of interest are also marginally affected. In the revised version of the paper we mention this result in a new paragraph in the ‘Results and discussion’ section (page 8 and 10).

Giorgini et al (2008) also studied the close approaches of their reference orbit for Apophis with other asteroids integrating up to 2036. We have not considered the close encounters with other asteroids, though we agree with the Referee that this is indeed an interesting topic.

Referee comment/question:

2. As follows from the work, the authors did not include the effect of the solar light pressure on the motion of the asteroid. Have there been any preliminary estimates of the impact of this factor?

Author’s Response:

The Referee is right, we did not include the solar radiation pressure in the calculations we reported

in the previous version of the paper. As for previous estimates of A_1 for Apophis, we are only aware of the value reported in the JPL page for Apophis (`https://ssd.jpl.nasa.gov/tools/sbdb_lookup.html#/?sstr=Apophis`).

As del Vigna et al. [A&A 617 (2018), A61] phrase it "Solar radiation pressure is a more complicated perturbation to detect". Our approach allows to obtain an estimate, but the results do not constrain properly the value for A_1, since its associated uncertainty is too large. This can be due to the dataset itself: as we observe with the computation of A_2, we require observations from 2021 to properly constrain the uncertainties. Perhaps the computation of A_1 requires even more observations of better quality. We do not know if the value reported by the JPL includes the high-quality observations reported by Tholen and Farnocchia (2020), which are not publicly available; in any case, the reported uncertainty by JPL is also about the size of A_1.

In the present version of the paper, we have included some of these remarks in a new paragraph in the 'Results and discussion' section (page 10), where we also quote the value reported by JPL. While we are unable to provide a meaningful value for A_1, the exercise allows to see that our approach is robust to include new unknown parameters.

Referee comment/question:

3. The authors do not report the value of the A_2 obtained in JPL. Meanwhile, in JPL (`https://ssd.jpl.nasa.gov/sbdb.cgi#top`) was obtained $A_2 = (-2.901 \pm 0.019) \times 10^{-14}$ au/d2. This value practically coincides with the result of the work under consideration. But isn't it a consequence of the same model of the motion?

Author's Response:

The Referee is correct, in the previous version of the paper we did not quote the value indicated in the JPL page nor cited it, and the JPL value practically coincides with the one we obtain. In the revised version of the paper (page 6), we used the words of the Referee (practically coincides) and quoted the JPL value, properly citing the web page. As pointed out above, we have also included other observations in the dataset (up to May 2021) and updated our results.

The coincidence of the values is not related to using the same model of the motion, though. The JPL calculation (performed the 2021-Jun-29 by D. Farnocchia) according to the web page uses JPL's DE441 planetary ephemeris (Ryan S. Park et al 2021 AJ 161 105) and the SB441-N16 model for the asteroid. Our calculation is also independent of the JPL in terms of the numerical integration: JPL integrations uses Adams integrator while we use a Taylor's method; the methods display distinct accumulation of the numerical errors. In addition, we exploit jet-transport techniques to obtain the fitting parameters. As far as we know, we use the same debiasing and weighting scheme as the JPL for the observations; for the computation of the uncertainties we exploit the derivatives provided by our integrations, which again differs from the methods used by the JPL. It is quite rewarding that we both obtain practically the same value for A_2; after all, while the methods differ, the underlying physics is the same.

Referee comment/question:

4. The authors cite the paper Tholen, D. & Farnocchia, D. Detection of Yarkovsky acceleration of (99942) Apophis. In AAS/Division for Planetary Sciences Meeting Abstracts, vol. 52, 214-06

(2020); however, do not provide the value of the semi-major axis drift, which is equal to –170 m/yr. It would be interesting if the authors would comment on the reasons for the discrepancy between their and these values. This discrepancy is about 15 times greater than the corresponding error.

Author's Response:

The Referee is again right, it is surprising that the difference of our value for A_2 and their value differ in $\sim 7\%$, but the semi-major axis drift differs in more than $\sim 15\%$. It is difficult to comment about that difference since there are no details in the abstract nor in the pdf of the talk (which can be found in `https://aas.org/sites/default/files/2020-10/David_Tholen_DPS52.pdf`).

The following remarks may clarify the difference. The last plot of the pdf (page 6) corresponds to Fig. 4 of Vokrouhlický et al. [Icarus 252 (2015) 277–283], which is obtained from the distribution for the semi-major axis drift (Fig. 3 of the paper). From this, our guess is that Tholen & Farnocchia reported the value corresponding to the peak of the distribution of Fig. 3 of Vokrouhlický et al. paper (-11.8×10^{-4} au/Myr). As discussed in Vokrouhlický et al, other representative values that characterize $\langle \dot{a} \rangle$ are the mean of the distribution (-12.8×10^{-4} au/Myr) or its median (-12.4×10^{-4} au/Myr). These values yield much better agreement with the value we report. Finally, we note that the uncertainty reported by Tholen & Farnocchia for A_2 is 10 times larger than the one we obtain; this may also be a reason for the apparent discrepancy.

Referee comment/question:

Resume.

The authors have created the software to improve an orbital parameters of any asteroid and estimate a magnitude of the non-gravitational acceleration. These estimates were obtained for Apophis. Besides, it was shown that the minimum distances in approaching the Earth in 2029, 2036, and 2068 exclude the possibility of Apophis' colliding with the Earth. All estimates obtained are in good agreement with those previously obtained by other authors, using the same model of motion and the same set of observations (site of JPL). These coincidences indicate the correct operation of the program; however, the results obtained can hardly be called new, rather confirming ones.

Therefore, I cannot recommend the manuscript "Non-zero Yarkovsky acceleration for (99942) Apophis" by Jorge A. Pérez-Hernández & Luis Benet as proposed for publication in Communications Earth & Environment.

Author's Response:

Referee 1 rejects our paper based on the opinion that our results are not new but confirming ones. As we responded in point 3 above, the "coincidence" of the obtained value of A_2 does not result from having the same models nor using the same methods to obtain the best fitting parameters. We emphasize that the code we have developed and used for the paper is publicly available, as well as the observations, and therefore it is open for inspection, review, and reproducibility. The physics is the same though, and therefore we must expect to have a confirming result. Yet, it was not our goal to validate the computations by the JPL, which indeed appeared earlier than our initial submission. Using our results and methods, as the Referee recognizes, we addressed the collision probability in 2029, 2036 and 2068, which exploits the smaller uncertainty computed; as far as

we know, these results are new and improve over previous estimates. The total independence of the methods to obtain the fitting values should not be reduced to validating results, specially for potentially hazardous objects, but should be rather encouraged. We believe we have contributed with new methods to estimate quantities which are difficult to obtain and whose uncertainty plays a major role for collision assessment. We hope the Referee finds these arguments convincing.

Response to Referee 2

We thank the Referee for her/his time and positive opinion on our work. We point out that in the revised version of the paper we have updated the astrometry dataset and use it to update our calculations. This improves slightly the uncertainty obtained for A_2.

Referee comment/question:

1) Reference 4 is incomplete; the book that contains Chesley's paper is: Asteroids, Comets, Meteors, Proceedings of IAU Symposium 229, Edited by D. Lazzaro, S. Ferraz-Mello & J.A. Fernández. Cambridge: Cambridge University Press, 2006.

Author's Response:

We have updated the reference following the suggestion by the Referee. Due to changes in the format of presentation of the paper, the reference numeration changed, and it is now Reference 2.

Referee comment/question:

2) At the top of page 8 the ζ coordinate on the 2029 be-plane is introduced, without explanation; the authors should either explain what it is, or perhaps mention the paper in which it is introduced in the context of NEA impacts, that is Valsecchi, Milani, Gronchi, Chesley, Astronomy and Astrophysics, v.408, p.1179-1196, 2003 (sorry for the self reference, as a referee it is for me a little embarrassing).

Author's Response:

Following the suggestion of the Referee, for the ζ coordinate we have added the wording "which is related to the arrival times of the NEA", and cited the paper suggested by the Referee (page 7).

Referee comment/question:

3) The systematic bias signature present in the observations from the observatory of MPC code 217 mentioned at the beginning of Section 4 of the supplementary material is also evident in the orbital solution of NEODyS, as evidenced in the webpage `https://newton.spacedys.com/neodys/index.php?pc=2.1.2&o=217&ab=0`*; the authors do not need to modify the text, anyway.*

Author's Response:

We thank the Referee for this comment. As we understand it, he refers to the bias in the residuals, where all appear to have the same sign. Yet, since we are not so familiar with NEODyS, we have left the text unmodified.

Response to Referee 3

We thank the Referee for her/his time, careful reading and positive opinion on our work. In the revised version we have updated the astrometry dataset and use it to update our calculations, which improves slightly the uncertainty of A_2.

A. Comments on the paper

Referee comment/question:

(i) Pag. 2, first paragraph.

Specify that r_{Sun} is the heliocentric distance expressed in au. Moreover, improve the phrasing of the sentence starting with "Our goal is" writing "Our goal is to determine the unknown proportionality constant A_2 which fits the optical and radar astrometry, using precise numerical integration of the equations of motion".

Author's Response:

We have amended the text as suggested (page 3).

Referee comment/question:

(ii) Pag. 2, second paragraph

It is stated that the equations of motion are solved using a 30-order Taylor integrator, whereas in the supplementary material I found that the order is 25. Is this correct or are these two the same integrator? In the latter case, please correct the wrong value of the order.

Author's Response:

We thank the Referee for noting this issue. We have used order 25 for computing the planetary ephemeris and Apophis orbit. We have clarified this in the text of the main paper (in the 'Methods' section, page 11) as well as in the Supplementary Information (page 3 and page 6).

Referee comment/question:

(iii) Pag. 3, beginning

In the sentence ending with "transported along the integration in time" I would cite again the supplementary material (Section 3) to point the reader to the details there contained.

Author's Response:

We have amended the text as suggested, which is now included in the 'Methods' section (page 11).

Referee comment/question:

(iv) Pag. 4, second paragraph

Can you explain in some way the bimodal distribution of the residuals of the purely gravitational solution?

Author's Response:

The two-mode (bimodal) distributions for the right ascension and declination residuals are a consequence of the two clusters of purple points that can be observed in the main panel of Fig. 1. We simply interpret them as an indication that there is some inconsistency in the gravity-only model; this statement assumes implicitly that the errors are Gaussian distributed. In the revised version of

the paper, this has been made explicit (page 6, in the 'Results and discussion' section).

Referee comment/question:

(v) Page 8, beginning

I would place a reference to a paper explaining Öpik variables, for instance Valsecchi et al. (2003), Resonant returns to close approaches: Analytical theory.

Author's Response:

We have added the reference to Valsecchi et al (2003) paper (reference 25), as suggested.

Referee comment/question:

(vi) Page 8, first paragraph

I would add a few words about how the authors computed the values of ζ for which Apophis would impact the Earth in 2036 and 2068. Did you obtained these values from the b-plane resonant circles?

Author's Response:

The Referee is right, we computed the ζ values based on the resonant circles in the 2029 b-plane. This is now indicated in the text (page 8), with more details explained in the Supplementary information (new section 6).

Referee comment/question:

(vii) Page 8, last sentence of first paragraph

The authors state that their results "must be revised in the future" because of the accumulation of the integration errors. This could be true if one considers just the nominal orbit to make predictions, since close approaches introduce a strong non-linearity in the propagation. But there are several techniques, e.g. the Line Of Variations method, invented extactly to overcome this kind of difficulties and perform a reliable impact monitoring, even with a time horizon well beyond a century in some case. Therefore this sentence, being it potentially misleading, has to be removed or changed to account for these methods.

Author's Response:

We are thankful for the criticism on this point and agree that the sentence was potentially misleading. We have clarified in the present version of the paper that future observations contribute to refine the nominal orbit and hence the collision assessment (page 8).

Referee comment/question:

(viii) Caption of Figure 2

I would change "residuals [...] contain zero" with "residuals are compatible with zero".

Author's Response:

We followed the suggestion of the Referee and changed the text accordingly (page 7).

Referee comment/question:

(ix) Table 1

There is a typo in the caption: "thee" should be "the". As for the content of the table, in the χ^2

row the values are expressed using a comma instead of a point as decimal separator.

Author's Response:

We have corrected the typo in the caption of Table 1. Regarding the χ^2 value, the numbers included were correct, and we used the comma to separate the thousands. To avoid confusions, we use now the decimal point and report $\chi^2(\times 10^{-3})$. We note that since we updated the observational dataset (which includes more observations than in the previous version), the quantities reported in Table 1 have been slightly corrected.

B. Comments on the supplementary material

Referee comment/question:

(i) Caption of Figure 1

I would change "The x coordinate of all panels" with "the horizontal axis of all panels", to avoid the use of x.

Author's Response:

We followed the advice of the Referee and changed the caption as suggested.

Referee comment/question:

(ii) Caption of Table 1

For a better phrasing, do not use symbols at the beginning of sentences. For instance, I suggest

to write "Value of Gm for the 16 main-belt asteroid perturbers" (avoid indexed variables if not necessary).

Author's Response:

We followed the advice of the Referee and changed the Table caption as suggested.

Referee comment/question:

(iii) Pag. 7

The bold title should section 5.

Author's Response:

Thanks for spotting this; this has been corrected in the present version of the paper.

C. General comments Referee comment/question:

(i) There are some points which deserves some English correction.

- *Pag. 2: "allows to estimate" and "allows to consider" must have the complement like "allows one to estimate" and "allows one to consider".*
- *Pag. 8: "accumulation of numerical errors grow" has to be changed with "grows". 2*
- *Pag. 8: "this non-gravitational solution allow us" must be changed in "allows us".*

Author's Response:

We have amended the text as suggested. We also asked a native English speaker colleague to proofread our paper.

Referee comment/question:

(ii) Check that all the units of measurement are separated from their numerical values with a blank.

Author's Response:

We have carefully checked this and acted accordingly.

Referee comment/question:

(iii) Always use parenthesis to separate a measurement with its uncertainty from the related power of 10, as in Table 2 and 3 of the supplementary material.

Author's Response:

We thank the Referee for his suggestion; we have thoroughly checked that the values that have been included with its uncertainty are separated from the common power of 10.

19th Nov 21

Dear Dr Pérez-Hernández,

Your manuscript titled "Non-zero Yarkovsky acceleration for (99942) Apophis" has now been seen by our reviewers, whose comments appear below. In light of their advice I am delighted to say that we are happy, in principle, to publish a suitably revised version in Communications Earth & Environment under the open access CC BY license (Creative Commons Attribution v4.0 International License).

We therefore invite you edit your manuscript one last time to comply with our format requirements and to maximise the accessibility and therefore the impact of your work.

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We hope to hear from you within two weeks; please let us know if you need more time.

Best regards,

Joe Aslin

Associate Editor,
Communications Earth & Environment
https://www.nature.com/commsenv/
Twitter: @CommsEarth

REVIEWERS' COMMENTS:

Reviewer #1 (Remarks to the Author):

I read new manuscript by Dr Pérez-Hernández and co-workers entitled "Non-zero Yarkovsky acceleration for (99942) Apophis"
and would like to say, that authors took into account all my comments and suggestions. I have no new questions or comments.

I believe that in the proposed form the article can be recommended for publication in Communications Earth & Environment.

Reviewer #3 (Remarks to the Author):

The authors carefully revised the paper, improving its quality. I do not have any further comment on it, thus it is now ready for publication.

We thank all referees for their time and commitment in the revision of our work. Since there are no further remarks or suggestions from the referees, we do not add any more replies to them.

Reviewer #1 (Remarks to the Author):

I read new manuscript by Dr Pérez-Hernández and co-workers entitled "Non-zero Yarkovsky acceleration for (99942) Apophis"
and would like to say, that authors took into account all my comments and suggestions. I have no new questions or comments.

I believe that in the proposed form the article can be recommended for publication in Communications Earth & Environment.

Reviewer #2 (Remarks to the Author):
[No further remarks]

Reviewer #3 (Remarks to the Author):

The authors carefully revised the paper, improving its quality. I do not have any further comment on it, thus it is now ready for publication.