Aerospace Science and Engineering - III Aerospace PhD-Days Materials Research Forum LLC
Materials Research Proceedings 33 (2023) 185-192 https://doi.org/10.21741/9781644902677-27

Interplanetary trajectory design in high-fidelity model: Application to deep-space CubeSats' cruises

Claudio Toquinho Campana[1,a] *

[1]Politecnico di Milano, Department of Aerospace Science and Technology, Via La Masa 34, 20156, Milan, Italy

[a]claudiotoquinho.campana@polimi.it

Keywords: Highly Nonlinear Astrodynamics, Phase Space Analysis, Autonomous Interplanetary Cubesats, High-Fidelity Trajectory Design

Abstract. This paper tackles the problem of first guess trajectory generation for interplanetary missions flying in chaotic environments. Simplified dynamical models are first exploited to perform the preliminary design of deep-space trajectories which leverage orbital perturbations. A real trajectory is then obtained by a refinement procedure in a high-fidelity model. A description of tools and methodologies which will be developed during this PhD research is provided.

Introduction

Just few decades ago, only big companies and international agencies owned the resources necessary to operate in the space sector. It is undoubtful that nowadays the space environment is, instead, getting always more and more accessible and affordable to everyone: the so-called phenomenon of new space economy [1]. This is the result of a slow process started with an increasing interest in space applications by the public, which brought to the spreading of accepted scientific knowledge and to the foundation of smaller businesses active in the space sector [2].

CubeSat technology is an emblematic by-product of this new paradigm. In fact, the competitivity in development and manufacturing costs of CubeSats, which are satellites of reduced size, is attracting an always wider sector of the space community. In particular, the option to adopt CubeSats for travelling interplanetary missions is nowadays extensively investigated. If successful, this research field would open to a world of possibilities.

Despite the relatively low development costs of a CubeSat mission, it is however true that the current paradigm of operating it, once in orbit, from ground, weakens the overall conveniency [3]. With the development of proper technologies, autonomous CubeSats will perform missions in the outer space with a small, if not absent, supervision from ground. CubeSats would be, therefore, an interesting alternative to traditional spacecrafts in the framework of interplanetary cruises. Nevertheless, current technological limits, such as limited on-board computational resources and propulsive capabilities, significantly constraint the possible applicative scenarios. The scientific community, space agencies, and industries are working to design missions and develop technologies which could enable stand-alone travels (e.g. M-ARGO mission [4]).

This PhD project is framed in the context of highly nonlinear astrodynamics applied to assist autonomous interplanetary CubeSat missions. Overall, the purpose is to develop new methodologies for trajectories design and optimization. Particularly, this research investigates how to consciously exploit the dynamics of a chaotic environment for the design of deep-space cruises. The techniques are expected to both improve the on-ground trajectory design phase and make the on-board autonomous generation of a reference trajectory more effective and efficient.

Statement of the problem and research questions

It is well known that the design of an interplanetary cruise is a challenging task because of the intrinsically chaotic dynamics that governs the motion of a spacecraft [5]. Multiple attractors and

Content from this work may be used under the terms of the Creative Commons Attribution 3.0 license. Any further distribution of this work must maintain attribution to the author(s) and the title of the work, journal citation and DOI. Published under license by Materials Research Forum LLC.

orbital perturbations, in fact, act together in a relevant way making the phase space highly nonlinear and rather complex to be well characterized. This causes the dynamics to be extremely sensitive to small variations in the states and, therefore, the generation of optimal trajectories in such environments is especially difficult. On the other hand, this intrinsic complexity, if properly managed and accounted for, enables to design trajectories which appear only in this framework [6, 7]. To mention some, dynamical structures like periodic orbits [8], and invariant manifolds [9] can be found and exploited only in autonomous multibody models. A trajectory designed in these simplified dynamical environments may enable for more fuel-efficient transfers, this usually at the expenses of a longer travel time [10].

The design of an interplanetary trajectory is a rather complex activity. Creativity and experience are essential to obtain efficient transfers which respect mission constraints and reach the objectives. When designing interplanetary trajectories in multibody dynamics, there are strategies and methodologies which are commonly used with the aim of simplifying the procedures and obtain better results. As it happens often in many scientific fields, it is useful to begin the analysis considering only simplified models which, nonetheless, try to retain all the important features of the complete phenomenon. Once the design has been accomplished in these reduced environments, it is of paramount importance to assess whether what achieved is reasonable even when contextualized in the real framework.

This procedure is at the base of what is usually done also in the perspective of interplanetary trajectory design [11]. In this regard, as previously mentioned, peculiar dynamical structures appear only in simplified models which try to provide a first approximation and an accurate description of what really happens. A preliminary design of the trajectory is therefore commonly performed in models of reduced complexity to exploit their intrinsic characteristics. In other words, at a first iteration of the design process, the trajectory is developed in models which account only for principal dynamics, while completely neglecting secondary ones. However, the mission will eventually be flown in the real scenario, thus the nominal trajectory is, by definition, the one that exists in the real solar system model [5], which accounts for all possible perturbations and dynamical contributors. The next step in the process, therefore, consists in refining the seeding orbit in the complete dynamical framework. At this aim, the trajectory is corrected using direct transcription and the related optimization problem is solved though a multiple shooting method [12]. The objective is to enforce the resulting trajectory to retain the characteristic features of the initial seed when moving to the real environment, which translates in minimizing the corrections applied by the multiple shooting optimization process [5]. This final step is usually executed using "brute force" since the real dynamics is simply corrected for and not accounted for in the first place. Since the dynamics in such environments is extremely sensitive, this very last step may lead to the loss of optimality and the effectiveness of the resulting trajectory may be compromised. As mentioned in [13], the transition from the Circular Restricted Three-Body Problem (CR3BP) [14] to a realistic model is usually very sharp. In that work the authors proposed a gradual refinement passing through intermediate models of increasing fidelity (for example the elliptic circular restricted three-body problem, and the restricted four-body problem). On the contrary, this project tries to identify methodologies to account for the presence of perturbations in advance, so to make the transition smoother. Techniques are foreseen to be developed facing the problem from different prospectives, so that to make the study more rigorous.

This premise brings to our research questions, here summarized for a better visualization.

RQ1. To what extent can the dynamic information be exploited to improve the refinement of trajectories initially designed in simplified models?

RQ2. How much more effective is a methodology that explicitly exploits this enhanced awareness of the dynamical environment, compared to traditional refinement methods?

RQ3. *To what extent can we beforehand account for and exploit perturbations to design more efficient trajectories, yet carrying out their preliminary design in simplified models?*

RQ4. *To what extent can the developed methodologies contribute to the stand-alone efficient and effective generation of first guess trajectories when an interplanetary CubeSat has to design its own journey on board?*

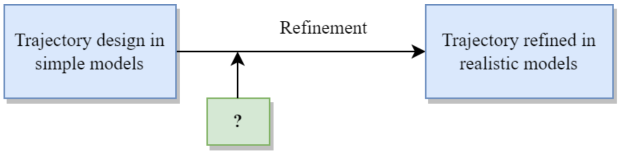

Fig. 1 - Downstream approach

RQ1 and *RQ2* are strictly related to each other. In this case, the problem is approached downstream, which means finding a way to smooth the "brute force" of the refinement process. Fig. 1 schematically represents this. The question mark identifies the contribution yielded by answering to *RQ1* and *RQ2*. We then ask ourselves if, instead, the problem could be faced upstream, as depicted in Fig. 2 following the same notation of before. This can be rigorously formulated by introducing *RQ3*, the answer of which may be even of more scientific interest and, possibly, bring to relevant technical outcomes. Finally, the analysis accomplished to give answers to all these questions will contribute during the investigation of the last one, which may be regarded as the technical application of this scientific research. The limited computational resources and propulsive capabilities of a CubeSat require specific solutions to make up for these problematics. It is clear, however, that these two technological constraints necessitate solutions which are in contrast each other since very fuel-efficient journeys can be calculated only at the expenses of a more extensive processing. If successful, the answer to *RQ4* would contribute to the design of more effective trajectories in a more efficient way.

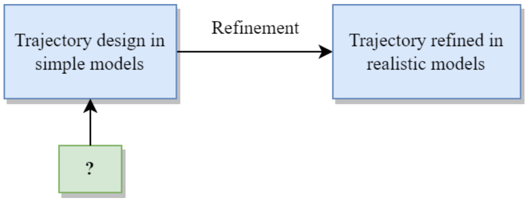

Fig. 2 - Upstream approach

Expected outcomes

The way it has been formulated makes this scientific research suitable for an incremental approach. In fact, the outcomes of each individual question pose the bases for the successive one. In general, the phases of the project can be subdivided respecting the order with which the research questions have been formulated. For each phase, therefore, some relevant outcomes are expected. In particular, the answers to *RQ1* and *RQ2* may be regarded as a preparatory work in view of *RQ3* and *RQ4*. In this section, each research question is associated to its related expected outcomes. In the next one, the methodologies adopted to tackle the problem will be explained.

Outcomes from RQ1

A deep understanding of the effects of relevant perturbative phenomena, such as, for example, third-body attractions, Solar Radiation Pressure (SRP), and bodies' oblateness, on the refinement of relevant interplanetary trajectories is sought after. This should allow to identify some regions in the dynamical phase space where these effects are more pronounced (sensitive regions) and how / how strongly they play a role in the refinement process. The effect of each individual perturbation relevant for the dynamical system under examination is expected to be better characterized. Furthermore, it is also investigated their impact on the refinement of important dynamical structures such as periodic orbits, manifolds, resonant orbits, etc.. In examining how these evolve, common behaviours may be identified. This preliminary analysis should enhance our overall confidence of the dynamics of notable environments. A modified refinement method is therefore developed with the aim of explicitly accounting for the different sensitivity regions of the phase space.

Outcomes from RQ2
Some real case scenarios will be used as playground to test and validate the developed refinement technique. Its effectiveness in the refinement process will be assessed by comparing the results against those obtained with traditional refinement methodologies.

Outcomes from RQ3
Exploiting the enhanced awareness of the dynamical environment, result of the previous points, a procedure is sought after which would allow to perform a more aware trajectory design. Still working with simplified models, the understanding of how perturbations would affect the designed trajectory is expected to produce positive effects on the results. Firstly, the awareness of how relevant dynamical structures would evolve in a real flyable model may suggest different design strategies. Secondly, a trajectory modelled following this approach is expected to be more robust and, therefore, deviate less during the successive refinement. This is foreseen to be beneficial for the convergency of the refinement process. Some relevant mission analyses will be re-computed to understand whether any improvement is obtained in terms of transfer efficiency if adopting the designed methodology.

Outcomes from RQ4
The outcomes of each previous points are eventually adapted and applied in a unified methodology. This one would enable an autonomous CubeSat to perform a more rigorous and efficient on-board interplanetary trajectory design. The developed technique will be tested to assess how much the computational performances and the effectiveness of the solutions are improved thanks to its adoption.

Methodology

This section describes how the project will be developed. Fig. 3 represents its summary.

Preliminary analysis
The project, expected to last three years, begin with a literature review of modern techniques for design of interplanetary trajectories in multibody environments. Because of the increasing interest on the topic for strategical applications (e.g. ARTEMIS mission [15]), many mission analysis for various kinds of transfers can be found in the literature. It is of paramount importance, therefore, to identify those dynamical environments that describe interesting scenarios for the purpose of this project. These should span a wide enough spectrum of representative cases, so that to make the analysis as complete as possible and applicable in different contexts. Following a preliminary study of the literature, some possible candidates have been identified and are here reported. Still, during the development of the study, this list is likely to be adapted.

- Cislunar environment
- Earth-to-Moon transfer by intersection of Sun–Earth and Earth–Moon manifolds
- Mars and Phobos system
- Jupiter and its moons
- Binary asteroid systems

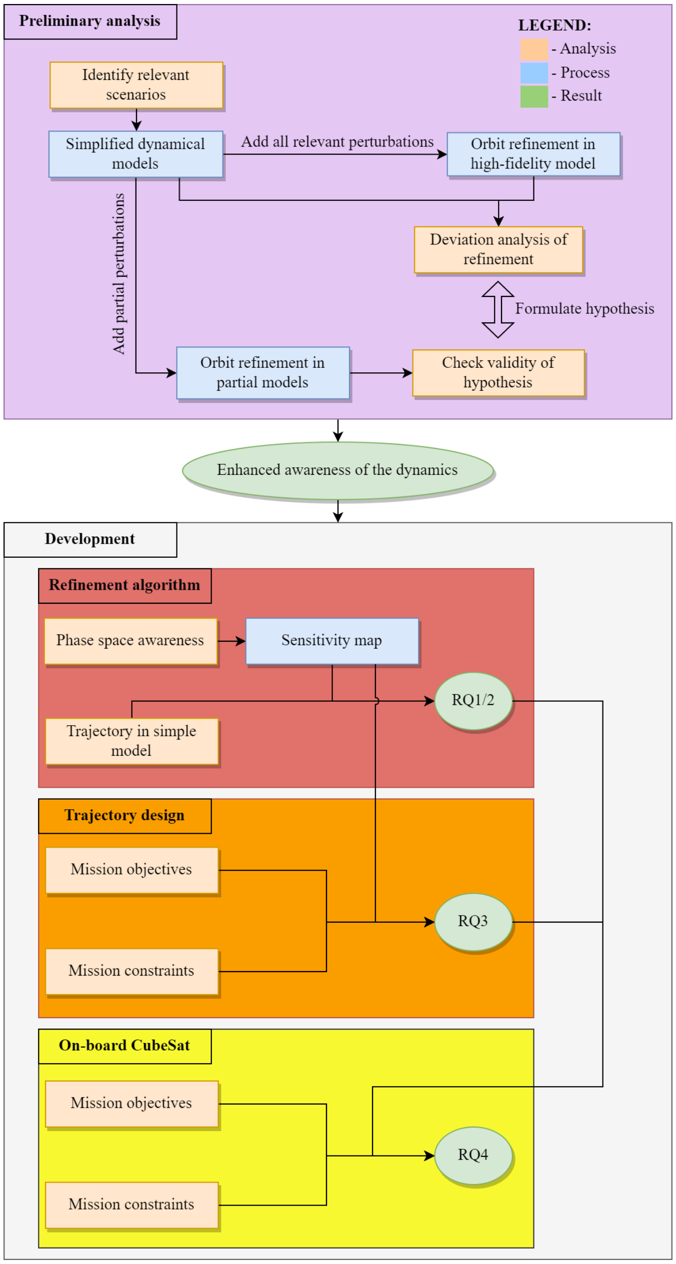

Fig. 3 - Methodology

Simplified multibody models are exploited to perform the preliminary design of trajectories. These are then refined in the real model. Nevertheless, the last two scenarios are much more challenging than the others; the dynamical environment is richer, so much that the simplified model themselves may not be suitable in these frameworks. In fact, in those cases, the effect of perturbations is much more prominent. Constraining the dynamics in a too simplistic model would neglect effects that cannot be anymore regarded as perturbations. It is planned, therefore, to begin the analysis considering more simple environments and then adapt and test the methodologies in those more critical.

The Earth–Moon system is firstly analysed in the CR3BP. Assuming that the design of transfer trajectories is done exploiting dynamical structures such as periodic orbits and manifolds, their refinement in a realistic model is investigated (purple box in Fig. 3). First of all, families of Lyapunov and Halo orbits, which are important structures in modern trajectory design, are refined in the high-fidelity Roto-Pulsating Restricted n-Body Problem (RPRnBP) [5]. This model includes the orbital eccentricity of the primaries, the attraction of all other planets, the Sun, the oblateness of celestial bodies, and the SRP in the description of the dynamics. In this high-fidelity system, periodicity properties are lost. After refinement, sections of the new orbits which most / least deviated from the seeding ones are identified. The analysis on the results should suggest relations between deviations and perturbations. Regions of the phase space more prone to changes are also identified. From this procedure, hypotheses are formulated about the effects that each individual perturbation has on the overall refinement process. To prove what predicted, the refinement process is repeated, this time injecting in the system single or a combination of more perturbations. Finally, the entire process is redone to study how homoclinic and heteroclinic trajectories evolve. In this regard, Poincaré sections are generated to investigate how manifolds change in this new non-autonomous dynamical framework. At this purpose, it may be interesting to introduce in the analysis chaos indicators to better characterize time-varying features of the phase space. This may ease in revealing correlations between natural flow structures and perturbations in the high-fidelity model. The procedure is repeated for all scenarios. A preliminary analysis of the results focuses on understanding, for each specific framework, the following points:

- recognize characteristic influence of individual perturbations in the refinement process;
- discretize the time-varying phase space in regions depending on the dynamical contribution introduced by each perturbation;
- perform a sensitivity analysis and identify sensitive regions;
- investigate the effects of perturbations in reference structures (e.g. understand how manifolds and Poincaré intersections evolve in the process);
- define parameters and methodologies that ease the understanding of the relations between perturbations and refinement (e.g. frequency analysis of the dynamical model [16], phase space regions discretization, selection of suitable chaos indicators).

Development

As a result of the previous analysis, the relation between orbital perturbations and the effects they have on the phase space is more intelligible. This enhanced awareness must be exploited to make practical improvements in the field of efficient low-energy transfers in multibody dynamics. First of all, time-dependent sensitivity maps are derived as consequence of the analysis of the previous part. Each applicative scenario will have its own map representing the correlation between perturbations and natural flows as function of time. To answer to *RQ1* and *RQ2*, a traditional multiple shooting technique is modified so that to use the information of the sensitivity map during trajectory refinement (red box in Fig. 3). This is supposed to be done by introducing a variable time step for the discretization of the seeding trajectory designed in simplified models. The time interval between discrete states is therefore adjusted to adapt for the rapidity with which the dynamical behaviour of the system changes. Thanks to the sensitivity map, we already know in advance where this would happen. The reference trajectory is then more densely discretized in the correspondence of sharp variations in the dynamical behaviour of the phase space. Furthermore, the objective function is modified such that diverse weights are introduced to allow different deviations in regions with different dynamical stability. The purpose of this is to take more advantage of the perturbative effects, thus exploiting the natural flow. As result of these two modifications to the standard multiple shooting method, the following benefits are expected:

- the algorithm is efficient since a finer discretization is introduced only where necessary;
- the algorithm is more likely to converge because the dynamics is indulged;
- the result better exploits perturbative phenomena, fostering more efficient transfers.

To test how well the algorithm perform, previous relevant mission analyses are recomputed. This should prove whether improvements are obtained in terms of convergency rate, efficiency of the process, and effectiveness of the obtained solutions.

The core part of the project is now discussed (orange box in Fig. 3). For each simulated scenario, some relevant deep-space missions are hypothesized. If available, some transfers already available in the literature may be adopted for comparison purposes. In any case, clear mission objectives and constraints are formulated to give a physical meaning to the problems. The sensitivity map plays now a fundamental role. From the mission objectives, we know indicatively which transfer we need to perform. Simplified models are adopted to formulate a first guess solution. This one has to be computed trying to exploit as much as possible the natural features enabled by the adoption of a reduced dynamics. At the same time, however, the knowledge of how perturbations will act on it in a high-fidelity representation shall not be overlooked. On the contrary, since we now have this kind of awareness, we need to exploit it. This can be done following two different approaches. Either we try to avoid all those regions, in the reduced phase space, whose counterpart in the sensitivity map would show strong deviations in the dynamical behaviour; or we explicitly try to use them. In the first case there is, therefore, the attempt to suppress perturbations, such that the dynamics of simplified models is preserved. The second approach is, instead, more interesting. In this case, the seeding trajectory, which is the one computed in the simplified model, will be designed such that perturbative regions are crossed with judicious. This increases somehow the uncertainty because, during refinement, the trajectory is expected to deviate more. However, this produces the beneficial effect that mission constraints can be relaxed more, hence increasing the freedom of the system. Many different seeding trajectories can then be designed since they will eventually adhere to the mission requirements after refinement. This process is foreseen to bring benefits in terms of transfer costs.

The last point introduces the developed techniques in the computing loop that allows a multi-mission autonomous CubeSat to perform its own trajectory design. The CubeSat is supposed to receive from ground both its mission requirements and a proper sensitivity map. It is now just a matter of connecting the answers to the previous research questions (yellow box in Fig. 3). In particular, the CubeSat will first generate preliminary trajectories following the procedure described in the previous paragraph. Then, the trajectories are refined thanks to the modified multiple shooting technique. For validation purposes, the algorithm will be tested in processor-in-the-loop simulations using hardware representative for a CubeSat interplanetary mission. The efficiency of the algorithm and its effectiveness, in terms of computing low-cost transfers, is evaluated by comparing the results with those obtained with traditional procedures.

Conclusions

This PhD project tries to give practical answers to the problem of designing interplanetary trajectories in highly nonlinear environments in autonomy. The contribution of perturbation in generating more effective trajectories in more efficient ways is investigated. Starting from an accurate analysis of how perturbations play a role in the dynamical description of the phase space, practical methodologies are then developed. A modified multiple shooting algorithm and a new trajectory design procedure are the outcomes of this research. Their efficiency and effectiveness are tested in relevant simulated scenarios.

Acknowledgments

The author desire to thank Prof. Francesco Topputo and Dr. Gianmario Merisio for their support in writing this abstract.

This research is funded by the Italian Ministry of University and Research, 38th PhD cycle.

References

[1] H. C. Alewine, «Space accounting,» Accounting, Auditing & Accountability Journal, vol. 33, p. 991-1018, 2020.https://doi.org/10.1108/AAAJ-06-2019-4040

[2] E. Kulu, «In-Space Economy in 2021 - Statistical overview and classification of commercial entities,» in 72nd International Astronautical Congress (IAC 2021), Dubai, United Arab Emirates, 2021.

[3] G. Di Domenico, E. Andreis, A. C. Morelli, G. Merisio, V. Franzese, C. Giordano, A. Morselli, P. Panicucci, F. Ferrari e F. Topputo, «Toward self-driving interplanetary CubeSats: the ERC-funded project EXTREMA,» in International Astronautical Congress: IAC proceedings, 2021.

[4] R. Walker, D. Koschny, C. Bramanti e I. Carnelli, «Miniaturised Asteroid Remote Geophysical Observer (M-ARGO): a stand-alone deep space CubeSat system for low-cost science and exploration missions,» in 6th Interplanetary CubeSat Workshop, Cambridge, UK, 2017.

[5] D. A. Dei Tos, «Trajectory optimization of limited control authority spacecraft in high-fidelity models,» 2018.

[6] F. Bernelli-Zazzera, F. Topputo e M. Massari, «Assessment of mission design including utilization of libration points and Weak Stability Boundaries,» 2004.

[7] W. S. Koon, M. W. Lo, J. E. Marsden e S. D. Ross, Dynamical systems, the three-body problem and space mission design, Marsden Books, 2011.

[8] E. J. Doedel, V. A. Romanov, R. C. Paffenroth, H. B. Keller, D. J. Dichmann, J. Galán-Vioque e A. Vanderbauwhede, «Elemental periodic orbits associated with the libration points in the circular restricted 3-body problem,» International Journal of Bifurcation and Chaos, vol. 17, p. 2625-2677, August 2007.https://doi.org/10.1142/S0218127407018671

[9] F. Topputo, M. Vasile e F. Bernelli-Zazzera, «Low energy interplanetary transfers exploiting invariant manifolds of the restricted three-body problem,» The Journal of the Astronautical Sciences, vol. 53, p. 353-372, December 2005.https://doi.org/10.1007/BF03546358

[10] F. Topputo, «On optimal two-impulse Earth-Moon transfers in a four-body model,» Celestial Mechanics and Dynamical Astronomy, vol. 117, p. 279-313, August 2013.https://doi.org/10.1007/s10569-013-9513-8

[11] D. A. Dei Tos, «Automated trajectory refinement of three body orbits in the real solar system model. Dynamical substitutes of Lagrangian points and quasi-periodic orbits about them,» 2014.

[12] K. Oshima, F. Topputo e T. Yanao, «Low-energy transfers to the Moon with long transfer time,» Celestial Mechanics and Dynamical Astronomy, vol. 131, January 2019.https://doi.org/10.1007/s10569-019-9883-7

[13] D. A. Dei Tos e F. Topputo, «On the advantages of exploiting the hierarchical structure of astrodynamical models,» Acta Astronautica, vol. 136, p. 236-247, July 2017.https://doi.org/10.1016/j.actaastro.2017.02.025

[14] V. G. Szebehely, Theory of orbit: the restricted problem of three bodies, Academic Press, 1967, p. 668.https://doi.org/10.1016/B978-0-12-395732-0.50007-6

[15] D. C. Folta, M. Woodard, K. C. Howell, C. Patterson e W. Schlei, «Applications of multi-body dynamical environments: The ARTEMIS transfer trajectory design,» Acta Astronautica, vol. 73, p. 237-249, April 2012.https://doi.org/10.1016/j.actaastro.2011.11.007

[16] G. Gómez, J. J. Masdemont e J. M. Mondelo, «Solar system models with a selected set of frequencies,» Astronomy & Astrophysics, vol. 390, p. 733-749, July 2002.https://doi.org/10.1051/0004-6361:20020625