Preface

When the contract between Springer and the author was signed in 2007, the expected deadline for finishing the manuscript was March 31, 2010. In the Fall of 2009, when it appeared clearly to this author that a strong delay in writing the book was building up, he could not foresee that 2010 would have been a fundamental year for solar-photon sailing. As a point of fact, after many decades of waiting for the first experimental *full* missions with *proper* sailcraft, JAXA launched IKAROS (May 21, 2010) and NASA followed with NanoSail-D2 (December 19, 2010, with ejection on January 1, 2011). IKAROS' sail (about 200 square meters) consists of an aluminized polyimide, the commercially available APICAL-AH and the new material named ISAS-TPH, 7.5 μm in thickness. Although such a sailcraft is not a sail-ship capable to fly much faster than a chemical propulsion spacecraft, it however is of *basic importance* to solar sailing through all the technical items experimented with in space. In July 2010, JAXA announced two significant events: (1) using Doppler measurements, the orbit determination process indicated that the trajectory of IKAROS (after the second-stage sail deployment) was being perturbed by a solar-radiation thrust of about 1.12 mN, and (2) a slow attitude control maneuver was carried out on the spinning sail by using close-to-rim strips of voltage-driven liquid crystals, which can change their reflectance levels. Thus, thrust and sail attitude control torques were produced without any propellant consumption. Such things excited the international solar-sailing community, including this author. The historical IKAROS mission has affected this book in some notable points.

This book is a monograph on a branch of astrodynamics of solar sailing: *fast sailing*. This is the leading theme. This book has been arranged to be multidisciplinary to a certain extent. This was chosen for the following reasons: (1) *feasibility*: not always what in principle seems to exhibit no problem is realizable; (2) *challenge*: fast sailing is really a challenging endeavor, which could offer amazing potential to spaceflight; one should view sailcraft more generally than what may be got through the sole mathematical description of its trajectories; (3) *projection* to the future: building a future high-tech sail system could represent the realization key for systematically exploring the Kuiper belt, the "boundaries" of the solar system, the solar gravitational lens, and for going notably far beyond this. A fast sailcraft may be the core of an interstellar precursor mission.

Solar-Photon Sailing (SPS) is an old *in-space* propulsion concept that aims at getting thrust from the solar radiation pressure via a sufficiently large and light surface called *the solar sail*. This emphasizes the role of sunlight with respect to other propulsion concepts, which would utilize the momentum flux of the solar wind, namely the tenuous plasma consisting (mainly) of protons, electrons, and helium nuclei that the Sun ejects from its upper atmosphere. Both solar light and solar wind are omnidirectional and permanent, though variable, streams.

SPS, well beyond the denser zones of any planetary atmosphere, is one of the best candidates to fully become the 21st century in-space propulsion. One may wonder why future astronautics needs new propulsive systems, other than rockets and gravity assist via planetary flybys. After more than 50 years of space flight, they continue to do an excellent job indeed. Although very briefly, something has to be clarified in order to better understand this key-point. First of all, any gravity assist is not a real propulsion method, but actually a celestial-mechanics technique applied to space flight (very successfully). Many important historical missions would have been simply impossible without (multiple) planetary flybys. Second, rocket systems do not appear replaceable with regard to utmost-importance tasks such as launching, achieving some special orbits, and also soft landing on some massive celestial body.

Nevertheless, both rocket and gravity assist have their own bounds with respect to the future needs of robotic and/or human space exploration and expansion. Even though we shall expand this aspect in this book, we like to briefly mention some considerable drawbacks of them. By definition, any rocket system has to have a power source *onboard*; therefore, it is forced to eject a fraction of its mass-energy *directionally* for getting accelerated. There are quasi-rocket systems that could exhaust matter energized by some external power source via onboard photon collectors. Since the kinetic energy of such an ejection beam is normally very small compared with the beam's rest-mass, one can deal with the related energetics and dynamics as those ones of a rocket. A typical example is the solar-thermal engine where sunlight is used to heat some inert mass to be exhausted. Although rockets and quasi-rockets encompass as energy-limited as power-limited engines, they all obey the basic need to transport the propellant necessary to every trajectory and attitude maneuver. Many design features depend on this need; besides the complexity of a rocket vehicle, we highlight the fact that the vehicle's mass at departure may be really very high. This restricts the realizable space-mission classes very strongly.

Gravity-assist technique has aided spacecraft considerably, in general, and rockets, in particular. Without it, many significant space missions neither would have been accomplished in the past nor designed for the near term. Nevertheless, gravity assist relies on the relative positions of celestial bodies, because it is from their motions that the spacecraft will have to tap some (really tiny) amount of energy. This entails two important items: (a) missions have generally *narrow* launch windows, and the launch opportunities decrease with increasing the number of planetary flybys; (b) the transfer times to the final destinations are significantly long simply because the spacecraft have to follow (perturbed) Keplerian orbits between two consecutive flybys; if many flybys are required, then the ensuing long transfer time implies to use high-reliability technology and high cost. It is plain that the current or near-term status of in-space propulsion is no longer bearable because future highly desirable scientific, utilitarian, and even (some) commercial mission concepts have been increasing in number and payload mass. In addition, user communities normally request payloads with very long operational lives.

Although it is true that space-borne rocket engines will continue to be precious in normal and special situations entailing maneuver simplicity and rapidity, nevertheless a real revolution in space propulsion is mandatory for exploring the solar system and going beyond, but avoiding tremendous costs and the high risks of losing or strongly degrading high-return missions. We need not wait for a new frontier of fundamental physics. The point that should be grasped now is that hopefully we are approaching a long era where robotic/human exploration/expansion in space could be not only possible, but also systematic, reliable and cost-affordable. We are talking about something similar to what happened on the Earth oceans and seas for millennia *via* sails, which ultimately utilize solar energy through atmospheric winds. SPS could allow us to explore and utilize, widely and systematically, the Earth–Moon space, the Solar System and move our probes beyond the heliosphere in times acceptable and compliant with the human lifetime. Particularly interesting distant targets, which should be explored, are the many objects of the outer solar system known as the Edgeworth–Kuiper belt, the near and far heliopause, the near interstellar medium, the solar gravitational lens regions, and so on, in order of increasing distance from the Sun, from some tens to many hundreds of Astronomical Units. One will be aware that the technology developed for fast sailing could aid in accomplishing many missions—in the solar system—extremely expensive or practically unmanageable even via advanced rockets.

We are dealing with a special class of sailcraft and their related trajectories that should be capable to accomplish the deep-space exploration just mentioned. We will define *fast* solar sailing and study peculiar properties. Astrodynamics of fast solar sailing is relatively recent. The first technical paper on fast sailing was published in 1992, whereas a very preliminary quantitative investigation on nanotechnology-based SPS appeared in the specialized literature in 2008. An important step towards fast sailing missions has been the concept of Interstellar Probe by NASA (1999–2001, essentially). As said above, the era of space sailing has been opened very recently by IKAROS and NanoSail-D2; however, we are still far from missions systematically using sails for space exploration/utilization. Many space-ware countries should participate in such enterprise.

This book is organized as follows:

- Part I contains an introductory chapter on rocket dynamics in the context of very deep space missions. This chapter has a twofold purpose. The first one aims at strictly proving some basic rocket's properties that are not easy to find in the literature, especially for university students. The second objective is to show the considerable limitations a rocket has with respect to the growing needs of future spaceflight. For such combined reasons, some sections of Chap. 1 resort to basic concepts of special relativity. Although not recommended, skipping this chapter on a first reading does not affect the comprehension of the other chapters.

- Part II contains three chapters. For going beyond rockets, for instance by means of solar sails, one has to analyze the power sources in space.

  Chapter 2 describes and emphasizes the Sun's features the solar sailing relies on.

  Chapter 3 focuses on the concepts of sail-based spacecraft, or *sailcraft*, and which aspects of the complicated space environment may ultimately affect sailcraft design and trajectories.

  Chapter 4, in particular, deals with the problems related to an object such as a metallic sail moving inside the solar wind and the solar ultraviolet flow.
- Part III is the theoretical core of this monograph and consists of three chapters.

  Chapter 5 introduces the reader to the fundamentals of sailcraft trajectories, and a jerk-based analysis for finding all admissible types of thrust maneuvering, a set that includes sail axis changes.

  Chapter 6 describes in detail the very complicated problem of how radiation-pressure thrust can be modeled. One can see that, in addition to the first necessary condition from physics (i.e. the radiation pressure) for space sailing, there is a second necessary condition: optical diffraction, without which the control of the sail thrust would be quite limited.

  In Chap. 7, the theory of *fast* space sailing is explained in the framework of both two-dimensional and three-dimensional trajectories. The reader can also find how the 3D fast sailing is not a mere extension of the properties of 2D fast trajectories.
- Part IV will finally treat examples of fast missions through two chapters.

  Chapter 8 is devoted to the optimization and numerical calculation of sailcraft's fast trajectories. Two methods are discussed: (i) the variational approach, and (ii) the non-linear programming approach.

  Chapter 9 regards effects that should be considered in real designs of sailcraft and missions. It deals with (1) the influence of the variable solar irradiance on sailcraft trajectories, and (2) the problem of how sailcraft motion equations might be generalized *formally* for taking into account modifications of the sail's optical quantities caused by solar-wind ions and ultraviolet light.

References are included at the end of each chapter. The whole book has been designed by the author in $\LaTeX\,2_\varepsilon$ with the document class provided by Springer, and other packages common to this language version. Most of the figures and tables, and almost all of the numerical examples have been prepared by the author expressly for this monograph by using a set of sophisticated (large) computer codes for astrodynamics and space mission flight design.

International System of Units (SI) is used throughout this monograph in general, a due choice not only for the sake of standardization, but also in order to make the different scientific areas related to solar sailing easily understandable in their own scales. A few exceptions are some well-known expressive units from Particle Physics and Astronomy, and the "solar units" for expressing distance, speed, energy, and angular momentum for heliocentric trajectories.

Book prerequisites. The chapters of this book have been tailored for graduate students in Physics, Mathematics, or Engineering, especially the ones aimed at getting a Ph.D. in Astrodynamics and/or Space Propulsion. The book content is self-explanatory, in general. However, a limited understanding of the basic principles of Special/General Relativity is advisable for reading Chap. 1, and a few sections of Chaps. 5 and 6. The other sections use classical dynamics.

A few final words about the cut given to this book. The author strove to write a monograph containing *also* new aspects of solar-photon sailing not dealt with before in the specialized literature; also, he revised/enlarged heavily what he published in the past years, including computation codes. Of course, where applicable, results from very recent specialistic international journals and symposia are discussed and inserted in a wider context. Although the bibliography is always non-exhaustive in general, and the topic of this monograph is relatively recent in particular, many efforts have been made for indicating over four hundred references from various disciplines of Mathematics, Physics, and Engineering (until May 2012).

Rome, Italy Giovanni Vulpetti

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Vulpetti, G.
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