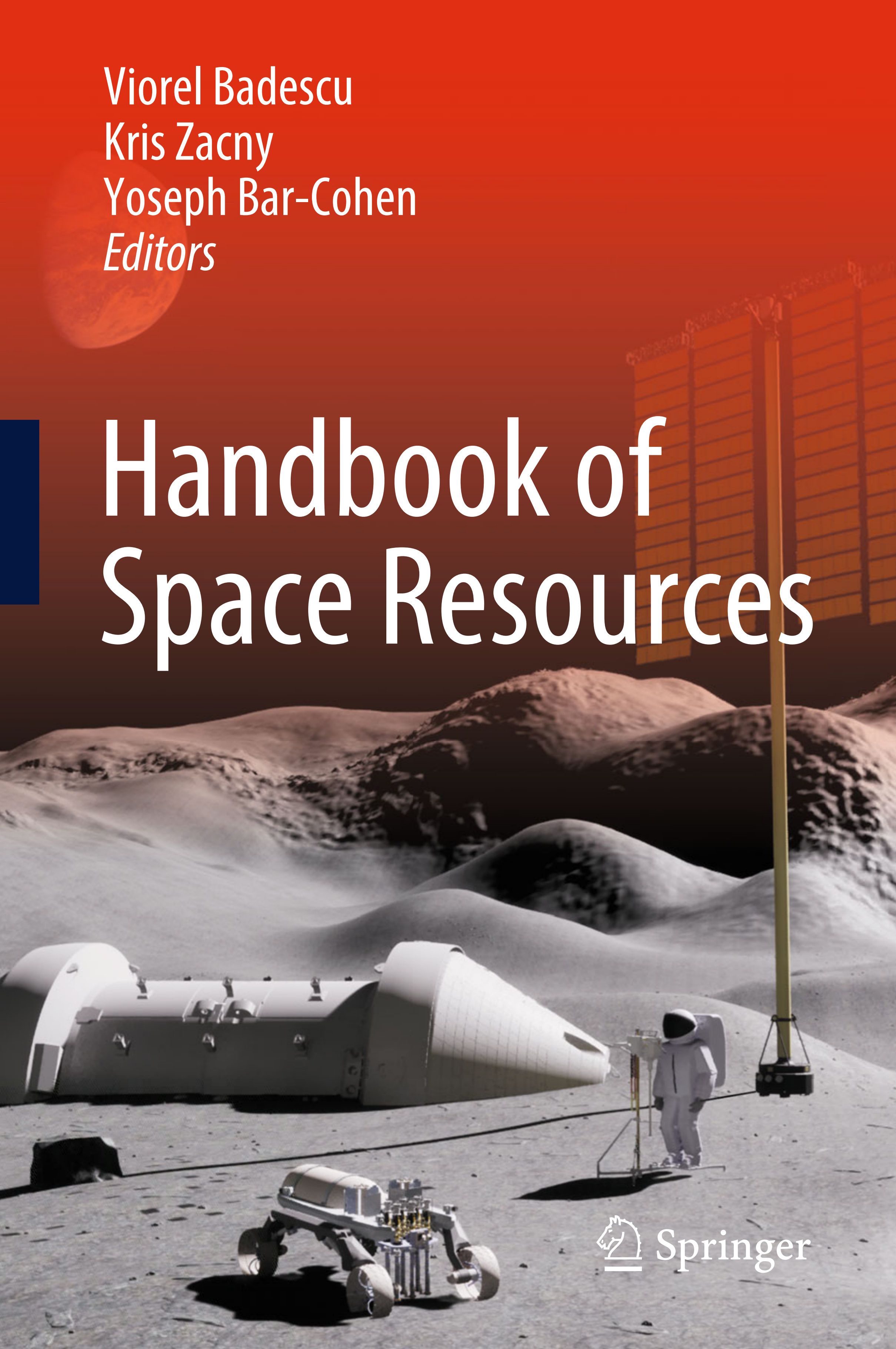
Viorel Badescu
Kris Zacny
Yoseph Bar-Cohen
*Editors*

# Handbook of Space Resources



Springer

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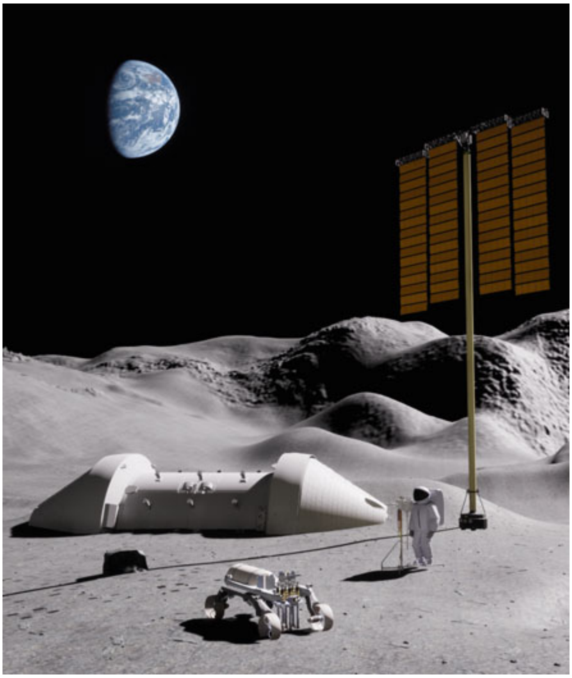

Viorel Badescu · Kris Zacny · Yoseph Bar-Cohen
Editors

# Handbook of Space Resources

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*This book is dedicated to all space miners*

# Preface

This book contains the latest perspectives on the space energy and material resources for human and robotic exploration and exploitation of the Solar System. It covers the latest advances as well as advantages and limitations of various space related systems and their potential applications to other fields. The book reviews various concepts and innovative options. It is a good resource for readers who are seeking background on various aspects of space-related activities.

The book is structured along logical lines of progressive thought and is divided into seven sections.

The first section deals with Technologies for Planetary Exploration and contains seven chapters. Chapter 1 is dealing with displaced non-Keplerian orbits for Sun and inner planet observation. Chapter 2 focuses on Dynamics and Control of Electrostatic Flight. Chapter 3 focuses on Tracking and thrust vectoring of E-sail-based spacecraft for solar activity monitoring. Chapter 4 deals with space elevators for space resource mining. Chapter 5 describes the orbital hub providing a LEO-infrastructure for multi-disciplinary science and commercial use cases. Chapter 6 covers instrumentation for planetary exploration. Finally, Chap. 7 covers space debris recycling by electromagnetic melting.

The second section of the book deals with Mercury and Venus and contains two chapters. Chapter 8 covers details about planetary exploration of Mercury with Bepi-Colombo and prospects of studying Venus during its cruise phase. Chapter 9 reports on the analysis of Smart Dust-based frozen orbits around Mercury.

The third section of the book, deals with the Moon, as a Steppingstone for In Situ Resource Utilization (ISRU) and it consists of six chapters. Chapter 10 deals with simulants in ISRU Technology Development. Chapter 11 focuses on regolith processing. Chapter 12 covers details on sintering as a method for construction of off-Earth infrastructure from off-Earth Materials. In Chap. 13 one can find information about the effects of mineral variations on the basalt sintering process and implications for ISRU. Chapter 14 proposes rocket mining for Lunar and Mars ISRU and Chap. 15 covers results about penetration investigations in Lunar regolith & simulants.

The fourth section of the book covers Mars, and it contains six chapters. Ice resource mapping of Mars is presented in Chap. 16 while Chap. 17 presents the design and modeling of an electrochemical device producing methane/oxygen and polyethylene from in-situ resources on Mars. Chapter 18 covers details about mobile Mars habitation and Chap. 19 proposes local resource creation on Mars. The planetary exploration of Mars is covered in Chaps. 20 and 21 and deal with robotic deployment and installation of payloads on planetary surface.

The fifth section of the book refers to Asteroids and Comets and it consists of three chapters. In Chap. 22 the reader can find information about asteroid habitats and how one can live inside a hollow celestial body. Chapters 23 and 24 deals with resources from asteroids and comets and the asteroids as small bodies with big potential, respectively, while Chap. 25 focuses on the exploration of asteroids and comets with innovative propulsion systems.

The sixth section of the book deals with Ocean Worlds and it contains four chapters. Chapter 26 presents the Ocean Worlds and their interior processes and physical environments. Robotic mobility and sampling systems for Ocean World bodies are described in Chap. 27 while Chap. 28 focuses on the communication and obstacles detection using piezoelectric transducers in melting penetrator of deep ice at ocean worlds. Ice Melting Probes are covered in Chap. 29.

Finally, the seventh section of the book deals with economics and policies, and it contains five chapters. The Lunar Ore Reserves Standards 101 (LORS-101) are presented in Chap. 30. Chapter 31 presents the economics of space resources with details about future markets and value chains. In Chap. 32 the reader can find details about the lifetime embodied energy and a theory about the value of new space economy. Policy and legal processes and precedent for space mining are covered in Chap. 33 while Chap. 34 presents legal considerations for space resources.

The book allows the reader to acquire a clear understanding of the scientific, legal and policy fundamentals behind specific technologies to be used for the exploration and exploitation of space resources. The principal audience may consist of researchers and engineers who are involved or are interested in space exploration in general and in specific bodies exploration in specific. Also, the book may be useful for industry developers interested in taking advantage of national or international space programs towards implementing space related technologies. Finally, it may be used for undergraduates, graduates and postgraduates as well as doctoral studies and teaching.

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The editors, furthermore, owe a debt of gratitude to all authors. Collaborating with these stimulating colleagues has been a privilege and a very satisfying experience.

Viorel Badescu
Kris Zacny
Yoseph Bar-Cohen

# About This Book

Earth has limited material and energy resources while these resources in space are virtually unlimited. Moreover, further development of humanity will require going beyond our planet and this requires utilization of extra terrestrial resources.

This book covers present-day perspectives on the space energy and material resources for potential human use. It reviews the latest advances as well as advantages and limitations of various space related systems and their potential applications to other fields. The book reviews proposed concepts and innovative options as well as solutions. It is a good resource for readers who are seeking background on various aspects of space-related activities.

Written for researchers, engineers, students and businessmen who are interested in space resources exploration and exploitation.

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# About the Editors

**Viorel Badescu** is Professor of Engineering Thermodynamics and affiliated with Candida Oancea Institute at Polytechnic University of Bucharest. His mainstream scientific contributions consist of more than 300 papers and forty books related to various fields in science and engineering. Most of his research areas refer to terrestrial and space solar energy applications, including research on photo-thermal energy conversion and solar power plants, the physics of radiation, photovoltaic conversion of solar energy, solar radiation properties and solar radiation distribution and forecasting. Other fields of interest are statistical physics and thermodynamics, the physics of semiconductors, optimal control of thermal engineering processes, terraforming and macro-engineering. He is Associate Editor and Member of the editorial board of several international journals including *Space Power, Energy, Renewable Energy and Journal of Energy Engineering* and Reviewer for more than fifty international journals. He is also Member of several scientific societies including the International Solar Energy Society and the European Astronomical Society and Member of the Romanian Academy.

**Dr. Kris Zacny** is Vice President and Senior Research Scientist at Honeybee Robotics. His focus is on developing space mining robots for In Situ Resource Utilization (ISRU) and space exploration. Prior to joining Honeybee Robotics, Dr. Zacny worked in South African underground gold, diamond and coal mines. Dr. Zacny received his Ph.D. from UC Berkeley in Extraterrestrial Drilling and Mining. He participated in several Antarctic, Arctic, Atacama and Greenland expeditions. Dr. Zacny has over 200 publications, including several co-edited books, and multiple NASA Group Achievement Awards. Dr. Zacny is Principal Investigator of TRIDENT ice mining drill scheduled to launch to the Moon in 2023 and 2024, as part of PRIME1 lander and VIPER rover, respectively. He is also Principal Investigator of PlanetVac pneumatic mining systems scheduled to launch to the Moon in 2024.

**Dr. Yoseph Bar-Cohen** is Senior Research Scientist and Group Supervisor at Jet Propulsion Laboratory (JPL). He received his Ph.D. in Physics from the Hebrew University, Jerusalem, Israel, in 1979. His research is focused on electroactive mechanisms, biomimetics and NDE. He has edited and co-authored 12 books (including this one), co-authored over 460 publications and co-chaired 56 international conferences. He documented his co-conceived inventions in 134 New Technology Reports (NTR) and 42 registered patents. His notable initiatives include the SPIE conference on electroactive polymers (EAP) and the EAP-in-Action Session that he chaired for 21 years as well as his challenging engineers and scientists worldwide to develop a robotic arm driven by artificial muscles to wrestle with human and win. For his contributions to the field of artificial muscles, *Business Week* named him in April 2003 one of five technology gurus who are ‘Pushing Tech’s Boundaries’. His scientific and engineering accomplishments earned him two NASA Honor Award Medals, two SPIE’s Lifetime Achievement Awards, Fellow of two technical societies: ASNT and SPIE, as well as many other honors and awards.

# Part I
# Technologies for Planetary Exploration

# Chapter 1
# Displaced Non-Keplerian Orbits for Sun and Inner Planet Observation

**Lorenzo Niccolai, Alessandro A. Quarta, and Giovanni Mengali**

**Abstract** A displaced non-Keplerian orbit is a trajectory whose orbital plane does not contain the center of mass of the primary body, so that its orbital maintenance requires the application of a suitable continuous thrust. Although the latter could be provided, in principle, by a low-thrust electric propulsion system, innovative propellantless propulsive technologies are well suited to such a mission scenario, due to their ability to generate thrust without requiring any propellant, thus significantly extending mission lifetime. This chapter focuses on the possibility of maintaining a displaced non-Keplerian orbit by means of both solar sails and electric solar wind sails (or E-sails). In fact, these advanced propulsion systems are both capable of generating a propulsive acceleration without consuming any propellant, by exploiting the solar radiation pressure (in case of solar sails) or the solar wind dynamic pressure (E-sails). This analysis uses recent models to provide a mathematical description of the propulsive acceleration generated by both propulsion systems, and different scenarios involving non-Keplerian orbits are analyzed. Particular focus is given to Type II displaced orbits, non-Keplerian orbits lying on the ecliptic plane, and heliostationary positions. Performance and attitude requirements are provided for each scenario. A linear stability analysis is also performed, in order to identify the combination of orbital parameters that characterize stable non-Keplerian orbits. The results suggest the feasibility of the mission scenarios discussed, but for most of them performance requirements are very demanding. A possible exception is non-Keplerian orbits lying on the ecliptic, which represent a very promising near-term scenario.

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## List of Acronyms

| | |
|---|---|
| **CR3BP** | Circular restricted three-body problem |
| **DNKO** | Displaced non-Keplerian orbit |
| **E-sail** | Electric solar wind sail |
| $L_1$ | First collinear Lagrangian point |
| **PDFO** | Planet following displaced orbit |

## 1.1 Introduction

A displaced non-Keplerian orbit (DNKO) is a closed spacecraft trajectory characterized by the fact that the primary body does not lie on the orbital plane, so that its orbital maintenance must be guaranteed by the application of a suitable continuous thrust. The first mission concept involving DNKOs was proposed by Forward (1984), who suggested the utilization of a classical (photonic) solar sail to generate a geosynchronous orbit whose orbital plane was either above or below the Earth's equatorial plane. The DNKO concept has been extensively investigated in the literature, and is surveyed in detail by McKay et al. (2011).

Although the generation of a DNKO is, in principle, obtainable with a generic low-thrust electric propulsion systems (Macdonald et al. 2011; Pan et al. 2019), the scientific investigation focused on DNKOs has recently received a significant impulse, mainly due to the renewed interest in propellantless propulsive systems, with special attention to solar sails and electric solar wind sails (or E-sails). These advanced propulsion systems are both capable of generating a propulsive acceleration without consuming any propellant, by exploiting the solar radiation pressure (in the case of solar sails) or the solar wind dynamic pressure (E-sails). A detailed description of such propellantless propulsive systems is given in Sect. 1.1.2, while a short review of possible applications of DNKOs is discussed in Sect. 1.1.1.

### *1.1.1 Mission Applications*

An extensive literature exists on DNKO maintained by different propulsion means (McInnes 1998; McKay et al. 2011), including solar sails (Bookless et al. 2006; Gong et al. 2014a, b; Song et al. 2016), E-sails (Mengali et al. 2009; Niccolai et al. 2017a, 2018; Pan et al. 2020), and hybrid propulsion systems (Ceriotti et al. 2014; Mengali et al. 2007b, c). In particular, a number of possible DNKO-based mission scenarios have been proposed. Among them, some of the most important and promising options are described below. Ceriotti et al. (2011, 2014) discuss the possibility of observing the planetary polar regions (providing a continuous coverage) by means of a hybrid propulsive system composed of a solar sail and an electric thruster. In their analysis, the Sun's and planet's gravitational attractions and the propulsive accelerations generated by the sail and by the electric thruster are all taken into account. Heiligers et al. (2011) analyze the maintenance of an out-of-equatorial plane geostationary orbit, a special case of circular DNKO which is synchronous with the Earth's rotation. Heiligers et al. (2014) propose the observation of high-latitude solar regions through DNKOs oscillating above and below the ecliptic plane, thus relaxing the constraint that requires the spacecraft to be constantly positioned at high heliocentric latitudes. Macdonald et al. (2011) discuss the creation of a communication relay for (near) future Mars exploration. They propose the utilization of highly non-Keplerian orbits to guarantee continuous communications between the Earth and Mars during solar conjunctions. Such orbits could be generated with an electric thruster or (more efficiently) with a hybrid system composed of an electric thruster and a solar sail.

A special application of the DNKO concept is the generation of a non-Keplerian orbit without displacement, that is, a closed trajectory whose orbital plane contains the primary body. These in-plane non-Keplerian orbits have the same shape as a classical conic section, but an orbital period different from that given by Kepler's third law. In a heliocentric scenario, such a particular closed orbit could have interesting scientific outcomes if designed to be circular with a radius not far from 1 au. In fact, in that case the planetary gravitational attraction should also be accounted for, so that the mission scenario would correspond to the maintenance of an artificial equilibrium point in the Sun-[Earth + Moon] circular restricted three-body problem (Aliasi et al. 2011, 2013a). An interesting potential application of such a scenario would be a solar warning mission placed at an $L_1$-type artificial equilibrium point, closer to the Sun than the natural $L_1$ point, in order to increase the feasible warning time in case of dangerous solar flares (Aliasi et al. 2015; Vulpetti et al. 2017).

### *1.1.2 Propellantless System Options*

The non-Keplerian nature of DNKOs implies that their generation requires a continuous thrust. Even though a quasi-DNKO could in principle be obtained with a succession of impulsive maneuvers (Caruso et al. 2019; McInnes 2011; Simo 2017), this analysis focuses on actual DNKOs. The requirement of a constantly acting thrust makes such a mission scenario well suited for propellantless propulsion systems, while DNKOs would be difficult to maintain with more conventional (chemical or electrical) thrusters. Accordingly, our analysis will be confined to solar sails and E-sails.

#### **1.1.2.1** *Solar Sail*

A solar sail (see Fig. 1.1) is a thin reflective membrane that exchanges momentum with the impinging photons, that is, it exploits the solar radiation pressure as its

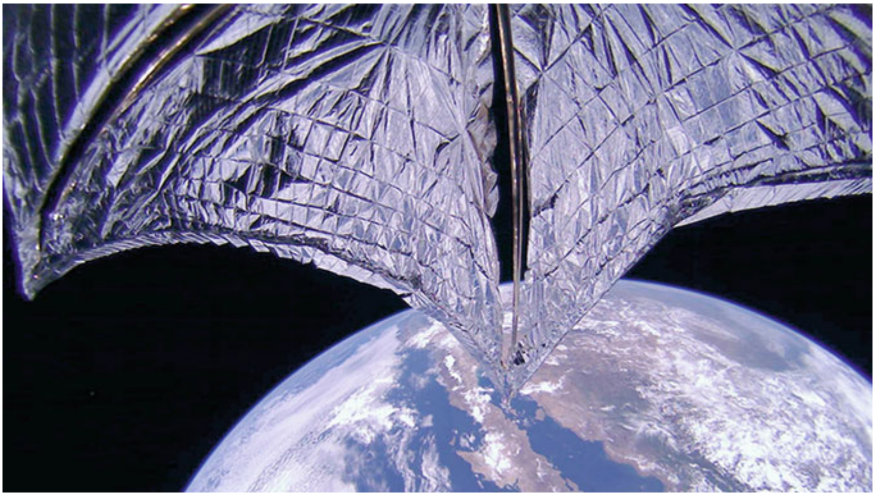


**Fig. 1.1** In-space picture of the deployed solar sail of LightSail-2 mission. *Credits* The Planetary Society

propulsive source. A comprehensive review of solar sailing may be found in many references, including Fu et al. (2016), McInnes (1999), Vulpetti et al. (2015), and Wright (1992).

The solar sail working principle is based on solar radiation pressure, which has been well known for more than 50 years, as is confirmed by its use for attitude control purposes in the Mariner 10 mission. However, the possibility of using a solar sail as a primary propulsion system has long been called into question.

Indeed, before the last passage of Halley's comet in 1986, NASA was planning to perform a cometary rendezvous by means of a spacecraft propelled by a solar sail, but the project was eventually discarded due to the high associated risks. The solar sail concept received a renewed impulse at the end of the last century, mainly thanks to the progress in material sciences, which led to the first flight of a solar sail-based spacecraft, JAXA's Interplanetary Kitecraft Accelerated by Radiation Of the Sun (IKAROS) (Mori et al. 2010; Tsuda et al. 2011). IKAROS, which was launched in May 2010, successfully performed a Venus flyby, demonstrating the solar sail deployment capability and the effectiveness of an attitude control system based on reflectivity control devices (Funase et al. 2011). More recently, in January 2011, the NanoSail-D2 mission by NASA tested the deployment of a small square solar sail (with a side-length of 3.2 m) in a LEO (Johnson et al. 2011). The Planetary Society, a private company, launched the first private solar sail satellite, the LightSail-1 (Nye et al. 2016), equipped with a 32 $m^2$ square sail, which performed a fast deorbiting from a LEO thanks to the augmented atmospheric drag. Recently, the LightSail-2 mission (Betts et al. 2019) was the first to be capable of effectively modifying the spacecraft orbital parameters by means of a solar sail. The recent success of solar sails is also demonstrated by future space missions that will be equipped with such a propulsion system, including JAXA's OKEANOS mission (currently still not financed) towards the Trojan asteroids (Funase et al. 2012; Mori et al. 2019), which should make use of a solar sail combined with an ion thruster powered by the solar cells placed on the sail surface, and NASA's Near Earth Asteroid Scout (NEA Scout), launched in November 2022, which should perform a flyby with a near-earth asteroid (Russell Lockett et al. 2019) by using a solar sail as primary propulsion system during the cruise phase (McNutt et al. 2014).

Modeling the propulsive acceleration generated by a solar sail is, in general, a complex task. A simple and effective tool is the so-called ideal thrust model, which assumes the sail shape to be a perfectly flat plane (referred to as nominal plane), and all of the photons impinging on the sail membrane to be specularly reflected. These hypotheses imply that the propulsive acceleration magnitude is overestimated, and its direction is considered parallel to the normal to the sail nominal plane in the direction opposite to the Sun. These results are neither realistic nor conservative, so that Dachwald (2004) proposed the use of a non-perfect specular reflection model, which accounts for the reduction of the propulsive acceleration magnitude by introducing a reflection efficiency, but leaves the direction unaffected and still assumes a flat shape. A further improvement in solar sail thrust modeling is constituted by the optical force model, in which the optical characteristics of the sail reflective surface are considered in the calculation of the propulsive acceleration. The optical force model will be used in our analysis, since it represents a good compromise between simplicity and accuracy, as implied by its use in the preliminary mission design phase of NASA's NEA-Scout mission. Other more complex models should also account for the variations of the optical properties with temperature (Ancona et al. 2017; Kezerashvili, 2008, 2014; Mengali et al. 2007a), or the influences of the light polarization and the features of the sail surface on the thrust generated. In this regard, the interested reader may refer to work by Vulpetti (2013) and Zola et al. (2018), where Fresnel reflection laws are taken into account to model the solar sail-generated thrust. Finally, the (small) thrust fluctuations associated with the variations of solar radiation pressure are also neglected. Further information may be found in the papers by Caruso et al. (2020) and Niccolai et al. (2019), where the use of reflectivity control devices is suggested to compensate for these environmental variations.

When the solar sail propulsive acceleration is described by an optical force model, the contributions of the absorbed, specularly reflected, scattered, and emitted photons are all taken into account, and the following expression for the propulsive acceleration vector a (Heaton et al. 2015; McInnes 1999) is obtained

$$\boldsymbol{a} = \beta\left(\frac{\mu_\odot}{r^2}\right)\frac{\hat{\boldsymbol{r}}\cdot\hat{\boldsymbol{n}}}{b_1+b_2+b_3}\left\{b_1\hat{\boldsymbol{r}} + [b_2(\hat{\boldsymbol{r}}\cdot\hat{\boldsymbol{n}}) + b_3]\hat{\boldsymbol{n}}\right\} \tag{1.1}$$

where $\beta$ is the (dimensionless) lightness number of the solar sail-based spacecraft, that is, the ratio of the maximum propulsive acceleration magnitude that the sail can generate at a given Sun–spacecraft distance to the local Sun's gravitational acceleration magnitude, $r$ is the Sun–spacecraft distance, $\mu_\odot$ is the Sun's gravitational

**Table 1.1** Optical and force coefficients for a solar sail with an optical force model (Heaton et al. 2015, 2017)

| Parameter | $c_r$ | $c_f$ | $B_f$ | $B_b$ | $\varepsilon_f$ | $\varepsilon_b$ | $b_1$ | $b_2$ | $b_3$ |
|---|---|---|---|---|---|---|---|---|---|
| Value | 0.91 | 0.89 | 0.79 | 0.67 | 0.025 | 0.27 | 0.095 | 0.8099 | 0.0151 |

parameter, $\hat{\boldsymbol{r}}$ is the Sun—spacecraft unit vector, and $\hat{\boldsymbol{n}}$ is the unit vector normal to the sail plane in the direction opposite to the Sun. Finally, the terms $b_1$, $b_2$ and $b_3$, referred to as force coefficients, may be obtained from the sail film optical properties as (Mengali et al. 2005)

$$b_1 = \frac{1 - c_r c_s}{2} \tag{1.2}$$

$$b_2 = c_r c_s \tag{1.3}$$

$$b_3 = \frac{B_f c_r (1 - c_s)}{2} + \frac{(1 - c_r)(\varepsilon_f B_f - \varepsilon_b B_b)}{2(\varepsilon_f + \varepsilon_b)} \tag{1.4}$$

where $c_r$ is the reflection coefficient, $c_s$ is the fraction of reflected photons that are specularly reflected, $B_f$ (or $B_b$) is the front (or back) sail surface non-Lambertian coefficient, and $\varepsilon_f$ (or $\varepsilon_b$) is the front (or back) sail surface emissivity coefficient. A recent estimation of the sail optical parameters in Eqs. (1.2)–(1.4) has been obtained during the preliminary design of the NEA-Scout mission. The experimental campaign has updated previous measurements (Heaton et al. 2015) and has relaxed the assumption of flat sail by accounting for the presence of millimeter-scale wrinkles that reduce the specular reflection fraction. The nominal values of the optical properties estimated by Heaton et al. (2017) are reported in Table 1.1.

An equivalent version of Eq. (1.1) is

$$\boldsymbol{a} = a_c \left(\frac{r_\oplus}{r}\right)^2 \frac{\hat{\boldsymbol{r}} \cdot \hat{\boldsymbol{n}}}{b_1 + b_2 + b_3} \left\{ b_1 \hat{\boldsymbol{r}} + [b_2 (\hat{\boldsymbol{r}} \cdot \hat{\boldsymbol{n}}) + b_3] \hat{\boldsymbol{n}} \right\} \tag{1.5}$$

where the characteristic acceleration $a_c$ is used as a performance parameter, that is, the maximum propulsive acceleration magnitude that the sail can generate at a Sun–Earth distance $r = r_\oplus \triangleq 1$ au. The characteristic acceleration of a solar sail-based spacecraft is

$$a_c = \beta \left( \frac{\mu_\odot}{r_\oplus^2} \right) \simeq \beta \times 5.93 \text{ mm/s}^2 \tag{1.6}$$

According to the thrust model of Eq. (1.5), the solar sail propulsive acceleration $\boldsymbol{a}$ lies in the plane spanned by the normal unit vector $\hat{\boldsymbol{n}}$ and the radial direction defined by $\hat{\boldsymbol{r}}$, and its orientation can be controlled by suitably adjusting the attitude of the sail nominal plane. Let $\alpha \in [-\pi/2, \ \pi/2]$ rad be the sail pitch angle, that is, the angle

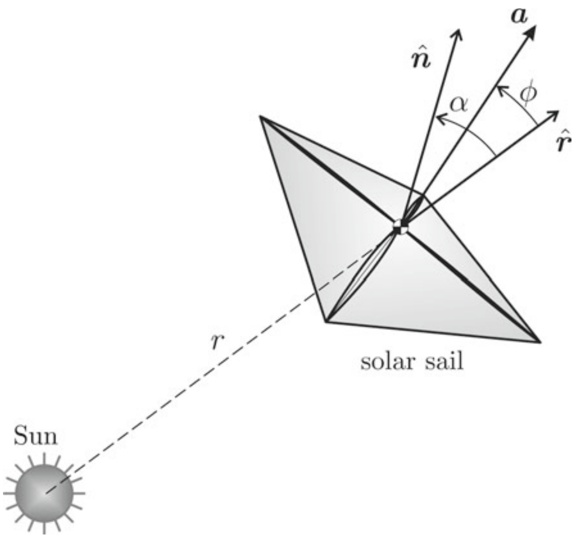


**Fig. 1.2** Solar sail thrust vector characteristics

between the direction of $\hat{\boldsymbol{r}}$ and that of $\hat{\boldsymbol{n}}$; see Fig. 1.2. Positive (or negative) values of the pitch angle correspond to positive (or negative) values of the projection of $\hat{\boldsymbol{n}}$ along the specific angular momentum vector $\boldsymbol{h} \triangleq \boldsymbol{r} \times \boldsymbol{v}$, where $\boldsymbol{v}$ is the spacecraft velocity vector. The sail pitch angle $\alpha$ is therefore given by

$$\alpha \triangleq \operatorname{sign}(\boldsymbol{h} \cdot \hat{\boldsymbol{n}}) \arccos(\hat{\boldsymbol{r}} \cdot \hat{\boldsymbol{n}}) \tag{1.7}$$

so that the propulsive acceleration vector can be rewritten by introducing the radial ($a_r$) and transverse ($a_\theta$) components, defined as

$$a_r \triangleq \boldsymbol{a} \cdot \hat{\boldsymbol{r}} = a_c \left(\frac{r_\oplus}{r}\right)^2 \frac{b_1 \cos\alpha + b_2 \cos^3\alpha + b_3 \cos^2\alpha}{b_1 + b_2 + b_3} \tag{1.8}$$

$$a_\theta \triangleq \left\| \boldsymbol{a} - a_r \hat{\boldsymbol{r}} \right\| = a_c \left(\frac{r_\oplus}{r}\right)^2 \frac{b_2 \cos^2\alpha \sin\alpha + b_3 \cos\alpha \sin\alpha}{b_1 + b_2 + b_3} \tag{1.9}$$

while the propulsive acceleration magnitude $a \triangleq \|\boldsymbol{a}\|$ is

$$a = \sqrt{a_r^2 + a_\theta^2} \tag{1.10}$$

The sail attitude modifies the thrust direction, as can be observed from Eq. (1.5). To quantify this effect, let $\phi \in [-\pi/2,\ \pi/2]$ rad be the sail cone angle, that is, the angle between the propulsive acceleration direction and the radial direction, viz.

$$\phi \triangleq \operatorname{sign}(\alpha) \arccos\left(\frac{\hat{\boldsymbol{r}} \cdot \boldsymbol{a}}{\|\boldsymbol{a}\|}\right) \equiv \operatorname{sign}(\alpha) \arccos\left(\frac{a_r}{a}\right) \tag{1.11}$$

where $a_r$ and $a$ are given by Eqs. (1.8) and (1.10), respectively. The variation of $\phi$ with $\alpha$ is illustrated in Fig. 1.3a, from which it is clear that the same thrust angle can be obtained with two different sail pitch angles (that is, with two different sail attitudes). A further interesting consequence of Eq. (1.11) is that a solar sail can generate a maximum thrust angle less than 55°. Finally, note that an attitude variation (i.e., an orientation change of $\hat{\boldsymbol{n}}$) also modifies the magnitude of $\boldsymbol{a}$; see Eq. (1.5). To account for this effect, a sort of "efficiency" parameter $\gamma \in [0, 1]$ is now introduced, defined as the ratio of the effective magnitude of the propulsive acceleration vector $\|\boldsymbol{a}\|$ to the maximum value of $\|\boldsymbol{a}\|$ (obtained when $\alpha = 0$, , that is, in a Sun-facing condition), viz.

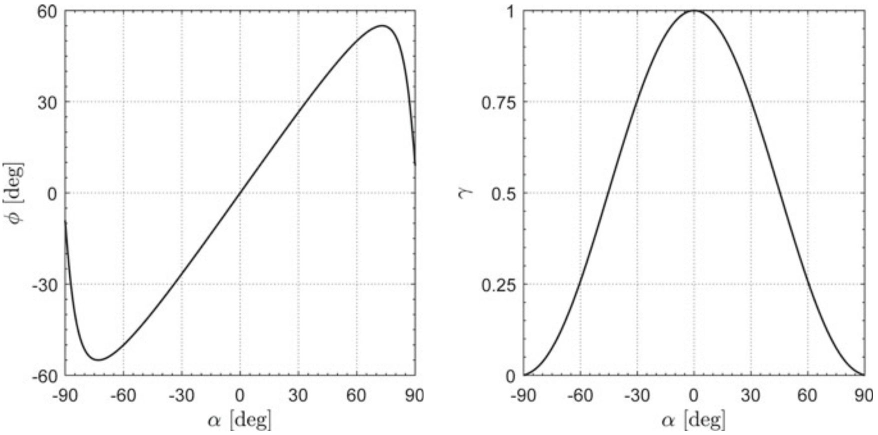
$$\gamma \triangleq \frac{\|\boldsymbol{a}\|}{\|\boldsymbol{a}\|_{\alpha=0}} \tag{1.12}$$

Clearly, $\gamma$ gives the effective dimensionless magnitude of the propulsive acceleration. Equation (1.12) can be specialized to the solar sail case as

$$\gamma = \frac{a}{a_c \left(\frac{r_\oplus}{r}\right)^2} \tag{1.13}$$

The variation of $\gamma$ as a function of the pitch angle α with an optical force model is shown in Fig. 1.3b, which highlights that smaller values of $\alpha$ correspond to larger propulsive acceleration magnitudes.

Therefore, to minimize the required sail performance, the pitch angle to be chosen for a given thrust angle is the minimum between the two possible values. Under such



(a) $\phi(\alpha)$ (b) $\gamma(\alpha)$

**Fig. 1.3** Variation of the cone angle $\phi$ and the dimensionless acceleration $\gamma$ as functions of the pitch angle $\alpha$ for a solar sail with an optical force model

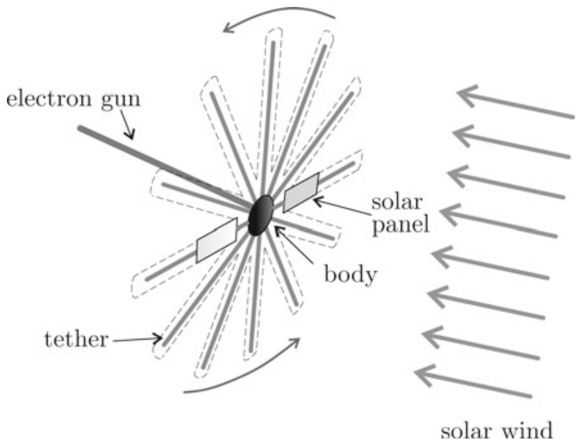


**Fig. 1.4** Basic sketch of an E-sail typical structure

an assumption, the function $\phi = \phi(\alpha)$ becomes invertible, see Fig. 1.3a, so that the value of $\alpha$ necessary for generating a thrust angle $\phi$ may be obtained with standard numerical methods.

#### 1.1.2.2 *E-Sail*

The E-sail propulsion concept consists of a spinning grid of tethers, kept at a high (usually positive) potential by means of an electron gun (Janhunen 2004; Mengali et al. 2008). When the E-sail is immersed in a surrounding plasma, such as the solar wind, the electrostatic interaction between the charged grid and the incoming ions generates a momentum exchange and thus a net propulsive acceleration. A sketch of the basic structure of an E-sail is shown in Fig. 1.4, while Fig. 1.5 an artistic rendering.

A first validation test of the E-sail working principle was attempted with the Estonian satellite EstCube-1 (Lätt et al. 2014), whose aim was to test the plasma brake concept (Janhunen 2010), a derivation of the E-sail working principle useful for spacecraft deorbiting from LEO (Bassetto et al. 2018; Niccolai et al. 2017b; Orsini et al. 2018). Unfortunately, the tether unreel mechanism failed, probably due to vibrational loads during the launch phase (Slavinskis et al. 2015). The first experimental in-situ data on the E-sail principle should therefore be provided by the Finnish satellite Aalto-1 (Kestilä et al. 2013), which was launched in June 2018 and is equipped with a 100 m-long plasma brake tether to perform an end-of-life deorbiting phase (Khurshid et al. 2014).

The most recent tool for describing the thrust generated by an E-sail is the model proposed by Huo et al. (2018), according to which the propulsive acceleration vector $\boldsymbol{a}$ is given by

$$\boldsymbol{a} = \tau \frac{a_c}{2} \left(\frac{r_\oplus}{r}\right) \left[\hat{\boldsymbol{r}} + (\hat{\boldsymbol{r}} \cdot \hat{\boldsymbol{n}})\hat{\boldsymbol{n}}\right] \tag{1.14}$$

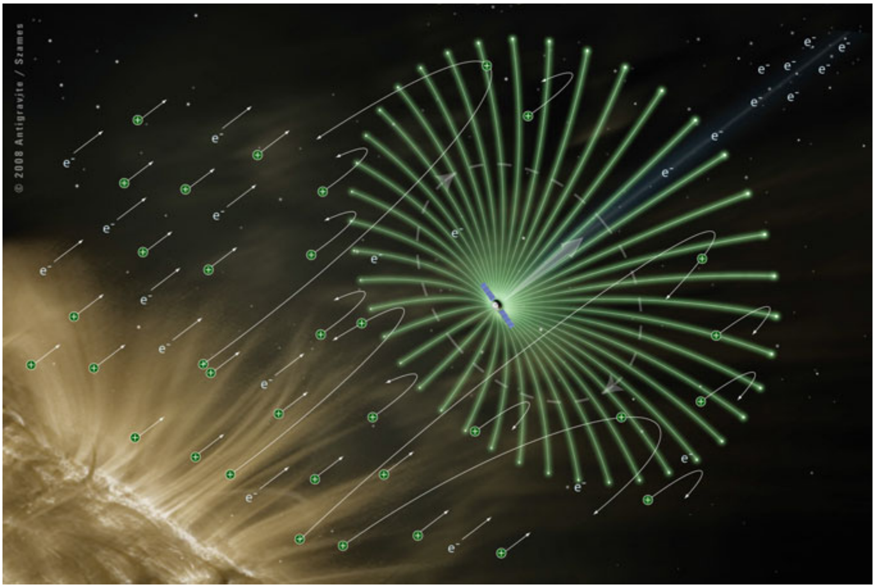


**Fig. 1.5** E-sail artistic rendering by Alexandre Szames, Antigravité (Paris)

where the same nomenclature as that of Eq. (1.1) is adopted. In Eq. (1.14), $\tau \in \{0, 1\}$ is a switching dimensionless parameter that accounts for the possibility of switching the electron gun either on ($\tau = 1$) or off ($\tau = 0$), while $a_c$ is the characteristic acceleration, with the same definition as that used for a solar sail.

Similarly to the solar sail case, Eq. (1.14) implies that the E-sail propulsive acceleration $\boldsymbol{a}$ belongs to the plane defined by the normal unit vector $\hat{\boldsymbol{n}}$ and the radial unit vector $\hat{\boldsymbol{r}}$; see Fig. 1.6.

Using the same definitions for the pitch angle $\alpha$, see Eq. (1.7), and the cone angle $\phi$, see Eq. (1.11), the following relation $\phi = \phi(\alpha)$ can be derived from Eq. (1.14)

$$\phi = \arccos\left(\frac{1 + \cos^2\alpha}{\sqrt{1 + 3\cos^2\alpha}}\right) \tag{1.15}$$

which is illustrated in Fig. 1.7a. The latter highlights that the maximum thrust angle is about 20° and, as such, an E-sail has a limited capability of generating a transverse thrust component (Quarta et al. 2016).

Moreover, similarly to the solar sail case, the same value of $\phi$ can be obtained with two different values of $\alpha$. Indeed, Eq. (1.15) can be analytically inverted to obtain

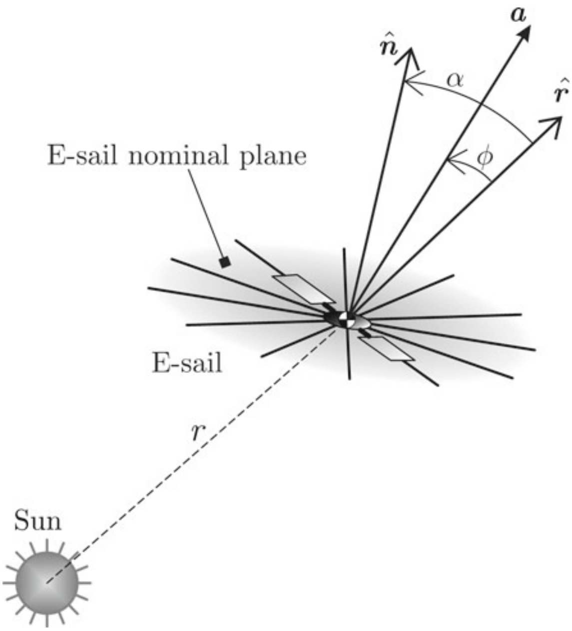
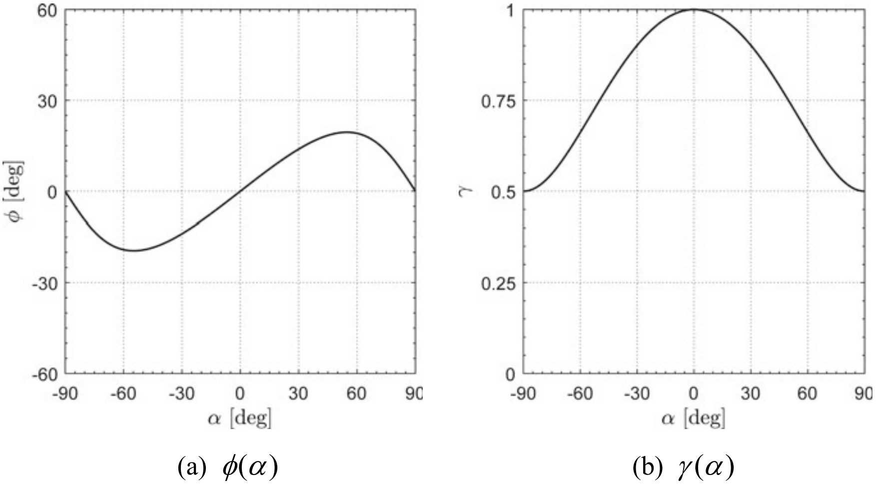


**Fig. 1.6** E-sail thrust vector characteristics



(a) $\phi(\alpha)$ (b) $\gamma(\alpha)$

**Fig. 1.7** Variation of cone angle φ and dimensionless acceleration $\gamma$ as a function of the pitch angle $\alpha$ for an E-sail

$$\alpha = \begin{cases} \operatorname{sign}(\phi) \arccos\left[\dfrac{\sqrt{2\left(3\cos^2\phi + \cos\phi\sqrt{9\cos^2\phi - 8} - 2\right)}}{2}\right] \\ \operatorname{sign}(\phi) \arccos\left[\dfrac{\sqrt{2\left(3\cos^2\phi - \cos\phi\sqrt{9\cos^2\phi - 8} - 2\right)}}{2}\right] \end{cases} \tag{1.16}$$

where the first expression gives the smaller value of $\alpha$ for a given value of $\phi$. The magnitude of $\boldsymbol{a}$ can be expressed from Eq. (1.14) as

$$a = \tau \frac{a_c}{2}\left(\frac{r_\oplus}{r}\right)\sqrt{1 + 3\cos^2\alpha} \tag{1.17}$$

and the dimensionless parameter $\gamma$ defined in Eq. (1.12) can be adapted to the E-sail case as

$$\gamma = \frac{\|\boldsymbol{a}\|}{\tau a_c\left(\frac{r_\oplus}{r}\right)} = \frac{\sqrt{1 + 3\cos^2\alpha}}{2} \tag{1.18}$$

which gives the results shown in Fig. 1.7b. Again, smaller pitch angles correspond to larger values of $\gamma$, so that, when a specific thrust angle must be reached, the smaller value of pitch angle is preferable in terms of performance requirements. Accordingly, only the first expression reported in Eq. (1.16) will be used in this analysis. A further consideration that may be derived from Fig. 1.7b is that an E-sail generates a nonzero thrust even when $\alpha = \pm\pi/2$ rad, and the only way to track a Keplerian arc is therefore to switch the electron gun off, which amounts to setting $\tau = 0$ in Eq. (1.14).

## 1.2 Displaced Non-Keplerian Orbits in a Heliocentric Scenario

This chapter is focused on the analysis of a heliocentric DNKO scenario maintained with a solar sail or an E-sail. Circular and elliptic DNKO cases are considered in Sects. 1.2.1 and 1.2.2, respectively. Examples of possible applications are given in Sect. 1.2.3, while a linear stability analysis of circular DNKOs is provided in Sect. 1.2.4.

Let $S$ be the center of mass of a spacecraft equipped with a propellantless propulsion system, which moves under the gravitational attraction of the Sun only and generates a propulsive acceleration $\boldsymbol{a}$. The spacecraft is tracking a DNKO with angular velocity $\boldsymbol{\omega}$ and, without loss of generality, we assume that its orbital plane is parallel to the ecliptic plane. The Sun's center of mass is located at point $O$, whose projection