XVIII Brazilian Colloquium on Orbital Dynamics (2016): the bases of Celestial Mechanics and its development in the research institutions in Brazil

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Abstract. The Brazilian Colloquium on Orbital Dynamics (CBDO) is the most important and traditional scientific meeting aimed at Theoretical and Applied Celestial Mechanics in Latin America context, and it is realized every two years. The last one, XVIII CBDO edition, took place from November 28 to December 02, 2016, in the city of Águas de Lindoia (SP) Brazil, and received more than two hundred researchers from Brazil, Argentina, Uruguay, Peru, Mexico, United States, Europe and Asia. For five days, current and high-level works in Celestial Mechanics were presented and discussed. This special issue of the Journal of Physics: Conference Series brings together a set of 27 papers presented in the CBDO distributed in the areas covered by the meeting.

1. Introduction

Celestial Mechanics is an area of Astronomy that studies the dynamics of the bodies under the action of gravitational interaction, including both spacecrafts and natural astronomical bodies such as star, planets, moons, comets, planetary rings, etc.

The beginnings of the Astronomy and Celestial Mechanics is related with the observation and description of the periodicities in the celestial bodies’ motion since the early days of mankind. As such, ancient astronomers learned the differences between stars and planets, as stars remain relatively fixed over the centuries while the planets have movement in comparatively short time, as well as many other phenomena. As a result, this science played an important role in determining the seasons, calendarizes and in the development of agriculture, navigation and religion, thus, contributing to the emergence of important ancient civilizations and their cultures [1].

Modern Celestial Mechanics started with the works of Nicolaus Copernicus (1473-1543), Tycho Brahe (1546-1601), Johannes Kepler (1572-1630), Galileo Galilei (1564-1642) and Isaac Newton (1642-1727). Kepler, for example, provided important contributions as a model for quantitative prediction of planetary position from geometrical and arithmetical techniques, and he was also the first to rise discussions on the physical causes of the motion of the planets [2]. In this historical context, Newton presented the first formulation of gravitational force, which was published in Phyllosophiae Naturalis Principia Mathematica, in 1687, describing the causes of the planetary motion and expanding the Kepler’s laws. However, the term “Celestial Mechanics” is more recent than that. It was introduced by Pierre-Simon Laplace (1749 - 1827) [2]. During the centuries XVIII and IXX, many other scientists
contributed to the bases and advances in Celestial Mechanics and for the understanding of the origin and evolution of the Solar System. Among them, we can cite Leonhard Euler (1707 - 1783), Jean le Rond d’Alambert (1717 - 1783), Giuseppe Lagrange (1736 - 1813), the Laplace himself, Adrien-Marie Legendre (1752 - 1833), Hamilton William (1805 - 1865), Lyapunov Aleksandr (1857 - 1918), and many others. But this list of honorable scientists would not be complete without Henri Poincaré (1854 - 1912), the most important contributor to Celestial Mechanics in the final years of the nineteenth and the early years of the twentieth centuries. Considering the circular restricted three-body problem, where two massive bodies move in circular orbits around their common center of mass, and a particle with negligible mass moves under the gravitational attraction of the other two, Poincaré established the concepts of nonintegrable dynamical system and deterministic chaos [3]. Although the circular restricted three-body problem is described by a set of deterministic equations, its behavior may become chaotic and unpredictable under certain conditions. However, taking account the mass hierarchy in the solar system, the work of Poincaré can be considered to describe many sub systems such as Sun-planet-particle, Earth-Moon-particle, etc. [3, 4], as well as countless strategies to space navigation in the context of modern Astronautics.

The works of these scientists form the bases of several current researches in theoretical and applied Celestial Mechanics, including the ones presented in this special issue.

2. Space age
In the twentieth century, after the end of Second World War, the space age began, firstly driven by a frenzied race between United States of America and the former Soviet Union. The milestone of this age was the launch of the Sputnik satellite [5]. So, a new and exciting branch of the Celestial Mechanics so-called Orbital Mechanics emerged with focus on the study on rocket and spacecraft trajectories, including orbital maneuvers such as orbital plane changes, lunar and interplanetary transfers as well as studies on propulsion systems and devices to control these space vehicles.

Thus, from the 50’s years the mankind began its adventure toward space, and soon in these first 60 years of this new age, powerful rockets have taken thousands of artificial satellites and space stations into space. Astronauts have walked on the Moon, more than 100 automatic probes have launched toward moon, all planets of the solar system and many asteroids and comets [5]; the space telescopes Hubble and Kepler are right now in orbit exploring the deep space and finding exoplanets and new planetary systems, thereby, providing new knowledges and challenges for Celestial Mechanics [1], and helping us to understanding better our place and mission in the Universe.

This demand for space navigation is clearly responsible for the recent progress in Celestial Mechanics, and it is strongly linked with the advent of high-performance digital computers. Indeed, the needed accuracy for spacecraft navigation would not be possible without the advances of the high-speed computers. For examples, to put the Pionner II probe (launched in April 1973) in a trajectory that reached Jupiter in December 1977 and Saturn in September 1979, it was required a navigation accuracy of better than one part in 10 million [3, 5]. Much more precision and intensive calculations were required on the Cassini-Huygens probe which studies Saturn and its natural satellites since 2004, including a landing on Titan and testing the Einstein’s theory of relativity [6]. Another fantastic adventure through the space was the Rosetta mission. Its journey started on 2 March 2004. The spacecraft performed fly-bys with the Earth (November 2005, 2007 and 2009) and Mars (February 2007), the asteroids 2867 Steins and 21 Lutetia on September 2008 and July 2010, respectively, before of reaching its target – the comet 67P/Churyumov-Gerasimenko – on August 2014, and becoming the first spacecraft to follow a comet. The Philae module was released by the spacecraft on December 12, 2014, and, in turn, it was the first human device to land on a comet’s surface [7]. Missions like these are only possible thanks to the accuracy, robustness and durability of the currently high-performance computers. Many other examples can be given, but exceed the purposes of this editorial.

Currently, the Orbital Mechanics has a very important role for modern society, since there are thousands of satellites in Earth’s orbit providing fast communication, entertainment and navigation
facilities, weather forecast and natural resource prospecting. If today we live the reality where large industrial or trade corporations, wars and homemade routines can work in a continent and to be managed from other ones; and whether it is possible to be with friends and relatives without known their exact location around the world, such as predicted by Sir Arthur Clarke in the early 1960’s, it is because the advances of the space exploration and the fantastic machines that are in space. However, the man still didn’t learn to live without pollutes and, for this reason, the space activities also spread debris around the Earth that threatening the space exploration. How to predict the motion of those debris and how to remove them are nowadays important topics in actual Orbital Mechanics.

Many challenges for the future of space exploration propel the current researches in Orbital Mechanics, for example, the control over the space debris, the resumption of space flights to the Moon and the dreamt colonization of the Solar System, and, why not, other systems. How? If we can evoke the romantic image of the majestic sailing ships that crossed the ocean with goods and settlers to the New World between the 16th and 19th centuries, we can also imagine big spaceships propelled by Solar sails cruising the depths of interplanetary space transporting goods and settlers to truly new worlds.

3. Orbital Mechanics in Brazil

Activities related to space area in Brazil began in the mid-1950s. At that time, the Brazilian Ministry of Aeronautics worked to build and entrench the Technical Center of Aeronautics (CTA – Centro Técnico da Aeronáutica) located in the city of São José dos Campos (SP). Currently, it is called Department of Aerospace Science and Technology (DCTA - Departamento de Ciência e Tecnologia Aeroespacial), and it is subordinated to the Brazilian Ministry of Defense [5,8]. DCTA has several institutes, among which we highlight:

- Institute of Aeronautics and Space (IAE – Instituto de Aeronáutica e Espaço), created in 1969 [5,9], is the main responsible for the development, production and launching of rockets in Brazil. During the course of its 37 years, it has developed the sounding rockets: Sonda I, II, III and IV, VS-30, VS-40, VSB30 and the VLS (satellite launch vehicle), among other projects [10].

- Technological Institute of Aeronautics (ITA – Instituto Tecnológico da Aeronáutica), created in 1950 [5], is aimed to the teaching and the research in Aeronautics, Mechanics, Electronic, Computation, Airport infrastructure and Aerospace Engineering. ITA had crucial importance in the development of the Brazilian aerospace industry, such as EMBRAER, for example, and also in Orbital Mechanics.

From 1960, the Brazilian government created several groups and committees to leverage researches in the space area. In 1971, these groups and committees gave origin to the National Institute for Space Research (INPE – Instituto Nacional de Pesquisas Espaciais), also located in the city of São José dos Campos (SP), and with the mission of conducting scientific researches, technological development and to provide qualified human resources in the space areas. Currently, INPE has sites located in 11 cities in the Brazilian territory [5,12], and it is subordinated to Brazilian Ministry of Science, Technology, Innovation and Communication.

INPE has already developed and launched 7 satellites, two of which are satellites for data collection (SCD 1 and 2) and 5 others for terrestrial resources in cooperation with China (CEBERS project). Currently, programs as the satellite Amazon 1 for Earth observation and of small scientific satellites as EQUARS for atmosphere monitoring and MIRAX for investigation of the galactic plan through X-rays, and a Multi Mission Platform for satellites are examples of projects in development in INPE [13].

The Institute has several divisions and laboratories to carry out its mission. In the field of applied Celestial Mechanics, there are the Space Mechanics and Control Division, the Laboratory for Integration and Testing of Satellites, the Combustion and Propulsion Division, as well as the postgraduate courses in the areas of Space Engineering and Technology with emphasis in Space Mechanics and Control, Combustion and Propulsion, Science and Technology of Materials and Sensors, and Space Systems Engineering and Management. INPE also offers postgraduate courses in other areas such as Astrophysics, Earth System Sciences, Space Geophysics, Meteorology and Remote Sensing and Applied Computing.
Teaching and research in Orbital Mechanics has made great advances since the foundation of the ITA and INPE. The training of human resources by these institutes is undoubtedly of great importance for the diffusion of research in Orbital Mechanics in Brazil. Researchers trained in INPE and ITA Postgraduate courses hold positions as professors and researchers in several public and private universities in the country, for example, in the Federal Universities of ABC (UFABC), São Paulo (UNIFESP), Paraná (UFPR), Brasília (UNB), Minas Gerais (UFMG), Recôncavo da Bahia (UFRBA), São Paulo State University (UNESP), Feira de Santana State University – Bahia (UEFS), State University of Campinas (UNICAMP), Pontifical Catolic University (PUC), etc. In this way, cooperation networks between these universities, the INPE and the ITA arise and are strengthened day-by-day. This special issue of the Journal of Physics: Conference Series is a good example of this mechanism.

Theoretical Celestial Mechanics, in turn, had its development in Brazil linked to the Institute of Astronomy, Geophysics and Atmospheric Sciences (IAG) of the University of São Paulo (USP) [14], National Observatory (ON) [15] and Federal University of Rio de Janeiro (UFRJ). Similarly, postgraduate courses at these institutions have formed many Professors and Researchers who work in several public and private universities in Brazil.

4. Brazilian Colloquium on Orbital Dynamics, CBDO

In the early 1980’s, a small group of Brazilian scientists organized the first edition of the Brazilian Colloquium on Orbital Dynamics [1]. Since then, the CBDO has taken place every two years, gathering scientists from South America as well as guests from other continents. The main areas of the CBDO deals with are: theoretical Celestial Mechanics, Dynamical and Planetary Astronomy, Planetary Science and Solar System dynamics, Astronautics and Dynamical Systems and Chaos applied to space research.

The 27 papers selected for this special issue have between six and nine pages and bring together the outcomes of research studies developed in Brazilian universities and research institutes. They represent the results of the strengthening of important research groups and the formation of new researchers and engineers who will work in Brazilian space activities in the coming decades. In the next section, the papers are presented one by one.

5. Introducing the papers

In this section, we present the 27 selected papers of this special issue. We also take this opportunity to thank all the authors for their valuable contributions, and for investing a lot of work and effort into the results of their research works. Special thanks go to reviewers who dedicated their precious time in providing numerous comments and suggestions, criticism and constant and enthusiastic support. The papers are presented one by one in sequence.

The paper “Searching for orbits around the triple system 45 Eugenia” searches for orbits to place a spacecraft around the triple asteroid 45 Eugenia [16]. It uses a semi-analytical mathematical model that represents the most important dynamical characteristics of that system [17]. The smaller bodies are assumed to be in elliptical orbits that are processing due to the flattening of the main body. Orbits with passages near both smaller bodies are considered. The simulations consider other dynamical aspects, such as close approaches [18] and gravitational captures [19].

The paper “Fractal boundaries in chaotic Hamiltonian systems” considers the motion of charge particles in a magnetized plasma subjected to electrostatic drift waves and identify the set of initial conditions that imply in trajectories that leave the interaction region through one of two different and complementary exits. They show that the initial conditions associated to those exists belongs to two sets that present a fractal basin boundary [20]. This behavior leads to a dynamics that phenomenon of final-state uncertainty [21], i.e., once the initial condition is determined within a certain uncertainty, it turns to be increasingly difficult to know for sure to which exit the trajectory will pass through.
The paper “Deviations in CBERS-4 Satellite Direction Components From The Electromagnetic Disturbance of Communication Antennas” brings a model for disturbance of electromagnetic origin [22,23] on the orbit of the CBERS-4 (China-Brazil Earth Resources Satellite 4) considering the antennas theory and the laws of the energy-momentum conservation [24].

The paper "Gamma radiation in ceramic capacitors: a study for space missions" investigates the effects of the cosmic radiation on ceramic capacitors [25]. The investigation uses a data logging system developed considering the open source Arduino platform and shows how the capacitance decreases with exposure to gamma radiation [26].

The effects on a spacecraft's electrical equipments during its passage through the Van Allen belts [27] are investigated in the paper "Analysis of the passage of a spacecraft between the Van Allen belts considering a low and high solar activity". The Van Allen belts are modeled using the data from the Van Allen probes mission to estimate the spacecraft's absorbed radiation dose [28,29].

A solar energy collector system that can operates 24 hours per day is the subject of the paper entitled “Solar Power Satellite system in formation on a common geostationary orbit”. The authors propose and analyze a system composed by a sunlight reflector and a microwave transmitting satellite (MTS) orbiting the Earth. The microwave transmitting satellite (MTS) is placed on a common geostationary orbit (GEO) in the Earth's equatorial plane, and the sunlight reuses the solar radiation pressure to achieve quasi-periodic orbits about the MTS, so that the sunlight is always redirected to the MTS, which converts the solar energy in electromagnetic power and transmits it by microwaves to an Earth-receiving antenna. A linear approximation found by Baig and McInnes [30] was used as an initial condition for the full equations of motion of the sunlight reflector about the GEO point in the Earth-satellite two-body problem, taking into account the effects solar radiation pressure.

The paper “Searching for orbits around the triple asteroid 2001SN263” searches for orbits for a spacecraft that needs to observe the smaller bodies of this triple asteroid system [31,32]. The orbits are classified using the criterion of minimum average distance between the spacecraft and the asteroid to be observed. Stable orbits around both smaller bodies were found with average distances below 1.5 km. The mathematical model takes into account the gravity of all the bodies and the solar radiation pressure.

The paper “On the use of a variable coefficient of reflectivity associated with an augmented area-to-mass ratio to de-orbit CubeSats” shows a new option to de-orbit small satellites from low Earth orbits. It uses a device for area augmentation and/or variation of the coefficient of reflectivity of the satellite [33-35]. Using this technique makes to de-orbit the satellite even in regions where the density of the atmosphere is small or almost zero not.

The evaluation of disturbance of the four Galilean moons (Io, Europa, Ganymede and Callisto) on a spacecraft’s trajectory orbiting Jupiter was the aim of the paper “Mapping the Galilean moon’s disturbance acting on a spacecraft’s trajectory”. The focus is on a short period of time, a few days, equivalent to the orbital period of the farthest Galilean moon from Jupiter, to evaluate the magnitude of the Galilean moons gravitational disturbance applied in the spacecraft trajectory during this period of time. The authors were able to show the disturbance velocity increments in the spacecraft trajectory caused by that four Galilean moons. The simulations were performed using the STRS (Spacecraft Trajectory Simulator), developed by [36, 37].

The dynamics of artificial satellites in Mercury's orbits when the effects due non-spherical shape of this planet [38] is considered and discussed in the paper "Analysis of the long and short-period terms due the nonsphericity of the central body: applications for Mercury". The investigation consists in an approach taking into account the single-averaged and unaveraged equations. Emphasis is given to analyze the effect of the $C_{22}$ term in the dynamics of the spacecraft in special in the variation of the spacecraft orbital elements [39,40].

The paper “Injection of a microsatellite in circular orbits using a three stage launch vehicle” develops a study to verify the capacity of the Brazilian Microsatellite Launch Vehicle (VLM) to inject payloads into Low Earth Orbits [41, 42]. The dynamical model used in the paper has three degrees of freedom associated with the translational motion of the rocket. It is shown the altitude reached in the separation of the second stage, the altitude and velocity of injection, the flight path angle at the moment of the
activation of the third stage and the duration of the ballistic flight. Numerical integrations are used to approach this problem [43].

A tetrahedral layout of four satellites in flying formation is presented in paper “Relative Positioning Evaluation of a Tetrahedral Flight Formation’s Satellites”. The formation is calculated considering a geometrical perspective and the adjust the orbital parameters of each satellite. Also, A detection algorithm is used as flag to signal the regular tetrahedron’s exact moments of occurrence. To do so, the volume calculated during the simulation is compared to the real volume, based on the initial conditions of the exact moment of formation and respecting a tolerance [44].

A study on the application of the Lambert's problem [45] of bi-impulsive orbital transfers with time constraint for the execution of minimum fuel maneuvers between coplanar and non-coplanar elliptical orbits is presented in paper “Study of orbital transfers with time constraint and fuel optimization”. A genetic search algorithm [46] is considered to determine the minimum fuel trajectory with an iterative variation of two Keplerian elements of the final orbit [47].

In the paper “Orbital and attitude evolution of SCD-1 and SCD-2 Brazilian satellites”, the authors present the time history of the SCD satellites orbit and attitude, and to present some discussions about the evolution of these parameters. The SCD-1 and SCD-2 satellites were launched in 1993 and 1998, respectively. For more than 20 and 16 years in service, they have shown reliable operation. The main objective of this work is to present the time history of the SCD satellites orbit and attitude, and to present some discussions about the evolution of these parameters. The rate of change of their orbital elements is small and the main dissipative orbit perturbations acting on the satellites are the sun radiation pressure and atmospheric drag in a less extent. The authors using estimation obtained by simulations show that the satellites will reach the highest decay around the year 2030. The satellites reentry is estimated to occur well after the year 2120. Considering that the maximum operational time was designed, at the launching time, to be around 2 years for each satellite, the conclusion is that the excellent Brazilian manufacturing and engineering made it possible for the satellites to be still operating and collecting data, and to the date there are no signs of any fatal malfunction which could decommission the satellites.

The laser rangefinder to be used in the ASTER deep space mission is the main subject of the paper entitled “Reviewed plan of the ALR, the laser rangefinder for the ASTER deep space mission to the triple asteroid 2001-SN263”. The Brazilian deep space mission ASTER plans to send a small spacecraft to investigate the triple asteroid 2001-SN263. The launch is expected to occur in June, 2020. In this work, the most important features for the laser rangefinder are defined and presented.

Studies on clouds of debris close a spacecraft [48,49] and test of maneuvers for propulsion systems with linear and exponential mass variation [50] is the subject of the paper “Collisional Cloud Debris and Test of maneuvers for propulsion systems”. These studies show that the propulsion system with linear mass variation model is more efficient.

The paper “Artificial satellites orbiting planetary satellites: critical inclination and sun-synchronous orbits” study the behavior of the critical inclination and sun-synchronous orbits for artificial satellites that are orbiting moons of planets. The study takes into account the effects of the harmonics $J_2$ and $C_{22}$. The moons considered in the simulations are the Moon [51-53] of the Earth, Io and Europa [54].

The asteroid 243 Ida is located in the asteroid belt, between Mars and Jupiter, belongs to the family of asteroids Koronis whose origin is supposed to be the result of the collision of two major bodies [55]. In the paper “Simulation of the trajectories described by a space vehicle around the asteroid 243 Ida and its natural satellite Dactyl” the authors study the dynamics of this system, orbital trajectories are simulated around Ida considering, besides the gravitational attraction of Dactyl, the non-central gravitational field of the asteroid, defined by a polyhedral model that defines the shape and the non-uniform mass distribution of the body. The simulations showed that due to the irregular shape of the asteroid an exploration spacecraft would approach the surface even when using an almost circular initial orbit. This is a characteristic of the orbits around asteroids, in which the gravitational perturbation can oscillates expressively as function of the altitude. The main disturbance in the trajectory of the spacecraft was due to the gravitational potential of Ida.
The paper “A 2-DOF model of an elastic rocket structure excited by a follower force” brings a model of an elastic rocket structure excited by the follower force given by the motor thrust tangent to the deformed shape [56,57]. This model has two degree of freedom and the results indicate possible occurrence of stable and unstable vibrations, such as limit cycles [58].

Electromagnetical propulsion is the main subject of the paper “Particle-in-cell numerical simulations of a cylindrical Hall thruster with permanent magnets”. Hall thrusters (HTs) are electromagnetic propulsion devices that apply a cross-field discharge in an annular channel to generate a plasma [59]. The cylindrical Hall thruster (CHT) is an alternative concept first developed at the Princeton Plasma Physics Laboratory [60]. The CHT presents higher propellant utilization and comparable performance with conventional HTs [61]. The magnetic field in this thruster can be set by using electromagnets or permanent magnets [62]. In this paper, the authors present first results of a numerical model of a CHT. This model solves particle and field dynamics self-consistently using a particle-in-cell approach. A number of techniques applied to reduce the execution time of the numerical simulations is also described. For this, a strategy is used in which a spacecraft orbits Mars, but with the same orbital period of Deimos and similar orbital elements.

In the paper “Orbital Trajectories in Deimos Vicinity Considering Perturbations of Gravitational Origin”, the authors study the possibility of maintaining an artificial satellite near to the Deimos surface, even when considering the intense Mars gravitational attraction. This approach of the spacecraft to Deimos, as well as to maintain the spacecraft in this region could be of great importance for observation, conducting experiments or even landing.

The paper “Equilibrium points in the asteroid 2001SN263” searches for the equilibrium points of the triple asteroid system 2001SN263. It takes into account the sizes and shapes of the bodies that constitute the system [63-66]. The study is made using the physical and orbital characteristics of the largest body. Nine equilibrium points are found, with five of them collinear. An analysis of the stability these points are also made, showing that only the equilibrium points L4 and L5 are linearly stable. The results can be used for the ASTER mission under planning [67].

Electromagnetical propulsion is also the main subject of the paper “Magnetic Field Design for a Strongly Improved PHALL Thruster”. Here, the focus is on the developing high efficiency Hall Effect Plasma Thrusters (PHALL) using permanent magnets [68]. The use of permanent magnets in these thrusters is mainly related to the decrease of used power for propulsion, especially important for low power thrusters as for micro-satellites. The authors show how each magnetic field configuration affects the generated plasma and consequently the generated propulsion force and efficiency.

The paper “Rendezvous and quasi-rendezvous maneuvers with space debris” studies the problem of rendezvous maneuvers between a spacecraft and a space debris [69-73]. This technique can be used to help to remove space debris and so to protect the Earth and other satellites against collisions. It is studied the distribution of these maneuvers in terms of the final relative velocities between the spacecraft and the debris. The results show that it is possible to use these maneuvers to approach the debris.

An investigation on the application of a flat Solar sail as method of propulsion [74-76] is considered in paper “Numerical analysis of orbital transfers to Mars using solar sails and attitude control”. A attitude control that allows a finite variation number in the orientation of the sailcraft along of its trajectory guarantees reduction of the final relative velocity with Mars without, however, a very larger increase in time of transfer.

The paper “Orbital migration and Resonance Offset of the Kepler-25 and K2-24 systems” presents analytical and numerical studies of the resonance capture under Type-I migration for the Kepler-25 [77] and K2-24 [78] Kepler systems. Those two systems are close to a 2/1 mean-motion resonance. The results show that the average values of the period-ratio between two consecutive planets have an important shift compared to the resonant nominal value. The results depend on the flare index and the distance to the central star. The results obtained are in agreement with the available observations.
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