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Celestial Mechanics: from the bases of the past to the challenges of the future

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Abstract: This special issue of Journal of Physics: Conference Series brings a set of 31 papers presented in the Brazilian Colloquium on Orbital Dynamics (CBDO), held on December 1 - 5, 2014, in the city of Águas de Lindoia (SP), Brazil. CBDO is a traditional and important scientific meeting in the areas of Theoretical and Applied Celestial Mechanics. The meeting takes place every two years, when researchers from South America and also guests from other continents present their works and discuss the paths trodden by the space sciences.

1. Introduction

Astronomy is considered the oldest of the sciences because of interest and, especially, the need to understand the celestial phenomena since the beginning of mankind. Celestial mechanics is a branch of astronomy which studies the dynamics of the bodies under the action of gravitational interaction. Its origin was motivated by administrative and often religious aspects of ancient civilizations. The observation of periodicities in the celestial bodies' motion allowed the Babylonians, Egyptians, Greeks, Arabs, Chinese, Incas, Aztecs, Mayas and others to build calendars and to develop agriculture. They were able to forecast phenomena such as eclipses, the seasons and the precession of the equinoxes.

2. Modern Celestial Mechanics

The start of modern celestial mechanics is rooted in the 16th and 17th centuries with works such as those of Nicolaus Copernicus (1473 - 1543), Tycho Brahe (1546 - 1601), Johannes Kepler (1572 - 1630), Galileo Galilei (1564 - 1642) - the first man to use a telescope to see the sky - and Isaac Newton (1642 - 1727). Newton presented the first formulation of gravitational force, which was published in his book entitled *Philosophiae Naturalis Principia Mathematica*, in 1687. In the following centuries, many scientists added important contributions to celestial mechanics, such as Leonhard Euler (1707 - 1783), Jean le Rond d'Alambert (1717 - 1783), Giuseppe Lagrange (1736 - 1813), Pierre Laplace (1749 - 1827), Adrien-Marie Legendre (1752 - 1833), Hamilton William (1805 - 1865), Henri Poincaré (1854 - 1912), Lyapunov Aleksandr (1857 - 1918), and many others. The works of these scientists have resulted in extraordinary advances in terms of understanding the origin and evolution of the Solar System. They have also paved the way for the dawn of the space age of the 20th century [1].



3. Celestial Mechanics in 20th and 21st centuries

The twentieth century brought new requirements for mankind. After wars, the consolidation of urban societies and population growth, regular activities like communication between people, governments, research institutions, banks and commercial and industrial corporations require high speed and accuracy. In addition, high speed and accuracy are also needed for weather forecasting to reduce the impact of natural disasters, support high-productivity agriculture, navigation, transportation of people and the trade of goods, public safety, natural resources exploitation, etc. In this environment and in order to respond to these new demands, astronautics (or astrodynamics) arose in the second half of the 20th century as a branch of celestial mechanics. The development of rockets allowed the placement and maintenance of thousands of satellites orbiting the Earth which carry out all sorts of missions in response to the requirements of the modern lifestyle. The astronautics of the 20th century also allowed the expansion of knowledge on the Solar System. Probes were sent to all planets, man walked on the Moon, robots explored the surface of Mars and the Hubble space telescope revealed new "old" objects of the Solar System and the Universe [2]. All of this has driven astronomy and celestial mechanics forward.

Now, in the 21st century, about 3,500 satellites are in operation around the Earth, probes and/or robots are exploring the Moon, Mars, Ceres, Saturn, Pluto, asteroids and comets. The Kepler telescope is right now in space finding exoplanets and new planetary systems, and thereby providing new challenges for celestial mechanics. Astronautics uses, and will keep using, the theories of celestial mechanics to send more and more probes and manned spacecrafts to the farthest corners of the Solar System, without forgetting, however, a problem it itself created: space debris. Because of this, one can glimpse years and years of hard work and development for celestial mechanics.

4. Brazilian Colloquium on Orbital Dynamics, CBDO

In order to discuss and develop celestial mechanics in Brazil, a group of Brazilian scientists formed by Sylvio Ferraz-Mello, Rodolpho V. de Moraes, Atair Rios Neto and Wagner Sessin (1946-1997) organized the first Brazilian Colloquium on Orbital Dynamics, CBDO, in 1982. At that time, Brazil was preparing the means to develop, build and launch its first satellites, while consolidating important research groups on celestial mechanics. Since then, the CBDO has taken place every two years, gathering scientists from South America as well as guests from other continents [3].

The main areas 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.

This special issue of Journal of Physics: Conference Series brings papers presented in the 17th CBDO, held on December 1-5, 2014, in Águas de Lindoia (SP), Brazil. The papers deal with areas of theoretical and applied celestial mechanics such as: planetary science, trajectory optimization, attitude control of spacecrafts, swing-by dynamics, flying formation, space propulsion, space robotic exploration and space debris.

The 31 papers selected 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. This issue presents papers discussing planetary formation, the optimization of lunar transfer trajectories, low-thrust maneuvers around the Earth and Mars, swing-by strategies, analysis of missions to Europa, a moon of Jupiter, and the triple asteroid (153591) 2001 SN263 - target of the first Brazilian mission to the deep space, called ASTER project [4]. This special issue also contains works regarding the development of continuous propulsion systems, attitude control of spacecraft, CubeSats, space debris, tethered space systems, space robots and chaos applied to space exploration. In the next section, the papers are presented one by one.

5. Introducing the papers

In this section, we present the 31 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 work. 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 "Preliminary Analysis of Optimal Round Trip Lunar Missions", by L. A. Gagg Filho and S. S. Fernandes, studies optimal bi impulsive transfer maneuvers considering the particular problem of sending a spacecraft to the Moon and back to the Earth with minimum fuel consumption [5-7].

The paper "Estimating the trajectory of a space vehicle passing by the Moon using Kalman Filter", by A. F. S. Ferreira, H. K. Kuga, A. F. B. A. Prado and O. C. Winter, uses the Kalman filter to try to estimate parameters of a swing-by maneuver [8] using the Moon as the celestial body for the close approach.

The paper "Multiple island chains in wave-particle interactions", by M. C. de Sousa, I. L. Caldas, A. M. Ozorio de Almeida, F. B. Rizzato and R. Pakter, presents an analysis of isochronous island chains in Poincaré sections near integrable twist perturbation systems [9,10].

The paper "Space Tether Systems – Stability Solutions of a Dumbbell-like System", by D. P. S. dos Santos, S. A. R. F. A. Morant, A. D. Guerman and A. A. Burov, searches for geometries that generate stable solutions for tethers [11] in astrodynamics.

The paper "Particle transport induced by electrostatic wave fluctuations", by K. C. Rosalen, M. Roberto and I. L. Caldas, is a study on the numerical investigation of particle transport driven by electrostatic waves at the plasma edge for a large ratio tokamaks, by considering a kinetic model derived from guiding-center equations of motion [12].

The paper "Nonlinear Least Squares Method for Gyros Bias and Attitude Estimation using Satellite Attitude and Orbit Toolbox for Matlab", by W. R. Silva, H. K. Kuga and M. C. Zanardi, considers the problem of estimating the attitude [13,14] and the gyro bias of a satellite using techniques based on least squares.

The paper "ALR – Laser altimeter for the ASTER deep space mission. Simulated operation above a surface with crater", by A. B. V. de Brum, F. C. da Cruz and A. Hetem Jr., considers details of a laser altimeter that is designed to study the surface of the three bodies of the asteroid 2001SN₂₆₃, which is the target of the ASTER mission [4,15].

The paper "Close Approach Maneuvers around an Oblate Planet", by G. M. C. Oliveira, A. F. B. A. Prado and D. M. Sanchez, studies the effects of the non-spherical form of a celestial body in a swing-by maneuver [8,16], by making numerical simulations of the restricted three-body problem with the additional force due to the J_2 term of the potential of the Earth.

The paper "Three-dimensional Two-Body Tether System – Equilibrium Solutions", by D. P. S. dos Santos and A. Ferreira, searches for equilibrium points in space where a tether [11,17] can be located and have a zero resultant force acting on it.

The paper "A study of optimal low-thrust limited-power transfers between coplanar orbits with small eccentricities", by F. C. Carvalho and S. S. Fernandes, studies the important problem of transferring a spacecraft between coplanar orbits with small eccentricities [7,18] using a propulsion system that is able to deliver a low thrust to the spacecraft.

The paper "Searching for less perturbed elliptical orbits around Europa", by J. C. dos Santos, J. P. S. Carvalho, A. F. B. A. Prado and R. V. de Moraes, uses the integral of the perturbing forces [19,20] to generate maps of orbits that can show their level of perturbation, indicating the ones that are less perturbed to be used by spacecraft.

The paper "Study of the influence of computational parameters on the formation of a giant gaseous planet", by R. A. Moraes and E. Vieira Neto, studies the problem of the formation of giant planets similar to Jupiter and Saturn [21,22] from a practical point of view of the computational parameters used in the simulations.

The paper "Experiment on signal filter combinations for the analysis of information from inertial measurement units in AOCS", by M. N. Pontuschka, I. M da Fonseca and M. A. A. Melo, introduces an investigation into an FDIR software subsystem that may be part of the attitude and orbit control subsystem, AOCS. An experiment encompassing an accelerometer and a wireless communication system so as to provide input signals to be filtered by the filtering algorithm is also shown [23,24].

The paper "Out-of-Plane Orbital Maneuvers Using Swing-bys with the Moon", by J. B. S. Neto, A. F. B. A. Prado and J. K. S. Formiga, verifies the conditions where a maneuver using a swing-by with the Moon is advantageous with respect to a standard one-impulsive maneuver to change the inclination of the orbit of a spacecraft around the Earth [7,25].

The paper "If there dissipation the particle can gain energy", by R. E. de Carvalho, describes two different mechanisms to gain energy from the presence of dissipation in a time-dependent non-linear system [26,27].

The paper "Permanent Magnet Hall Thrusters Development and Applications on Future Brazilian Space Missions", by J. L. Ferreira, A. A. Martins, R. Miranda, A. Schelling, L. Souza, E. G. Costa, H. O. Coelho, A. C. B. Serra and F. S. Nathan, studies several aspects of a low thrust engine, that can be used to maneuver a satellite, which is being developed in the Plasma Physics Laboratory of the National University of Brasilia [28].

The paper "Ball's motion, sliding friction, and internal load distribution in a high-speed ball bearing subjected to a combined radial, thrust, and moment load, applied to the inner rings center of mass: Mathematical model", by M. C. Ricci, develops set of non-linear algebraic equations, which must to be solved using a numerical procedure, for Ball's motion, sliding friction and internal loading distribution computation for a high-speed ball bearing [29,30].

The paper "Ball's motion, sliding friction, and internal load distribution in a high-speed ball bearing subjected to a combined radial, thrust, and moment load, applied to the inner ring's center of mass: Numerical Procedure", by M. C. Ricci, studies the same problem of the previous paper, but from a numerical point of view [31].

The paper "Attitude control system design using a flywheel suspended by gimbals", by, Raphael W. Peres and M. C. Ricci, studies different forms to keep the attitude of a satellite within specified values [32], in order to maintain the satellite in conditions to satisfy the mission requirements.

The paper "Ionosphere influence on success rate of GPS ambiguity resolution in a satellite formation flying" by, L. Baroni, considers the problem of how to deal with the ambiguity resolution of the GPS [33,34] sign in the case of satellite constellations.

The paper "Evasive Maneuvers in Route Collision With Space Debris Cloud", by A. D. C. Jesus, R. T. Sousa and E. Vieira-Neto, shows alternatives to maneuver [35,36] a satellite such that it can avoid collision with a cloud of space debris that is in its trajectory.

The paper "Influence of the external torques in the angle between the spin axis and the Sun direction Spin stabilized Satellite", by G. B. Motta and M. C. Zanardi, studies of the influence of the environmental torques in the angle between the spin axis and the Sun's direction (solar aspect angle) for a spin stabilized satellite [37].

The paper "Magnitude of Solar Radiation Torque and the Earth Shadow Region", by R. E. S. Cabette, M. C. Zanardi and I. Kolesnikov, describes the effects of the passage of a satellite in the shadow of the Earth using the magnitude of the torque generated by the solar radiation pressure [38,39].

The paper "Development of a Helicon Double Layer Thruster" by J. L. Ferreira, F. N. O. Lopes, H. O. Coelho Júnior, A. C. B. S. Serra and E. G. Costa, shows the evolution in the developments of a helicon double layer thruster [40,41], which is a propulsion system with a high potential to be used in space activities.

The paper "The State-of-art in Space Robotics", by I. M. da Fonseca and M. N. Pontuschka, is a survey indicating the latest results in the developments of robots made for space applications and it also includes a discussion of the applications of new concepts such as robonauts, space tugs and robots for future planetary exploration [42,43].

The paper “Study of the decay time of a CubeSat type Satellite considering Perturbations due to the Earth’s Oblateness and Atmospheric Drag”, by T. P. Brito, C. C. Celestino and R. V. Moraes, introduces a study of the best re-entry time for a CubeSat when it is affected by the Earth's oblateness and atmospheric drag [44].

The paper “Gravitational disturbances generated by the Sun, Phobos and Deimos in orbital maneuvers around Mars with automatic correction of the semi-major axis”, by E. M. Rocco, presents analyses into maneuvers of a spacecraft into orbit around Mars that is disturbed by the gravitational attraction of the Sun, Phobos and Deimos. Impulsive optimal maneuvers considering the Lambert’s Problem to reduce fuel consumption are also considered [45,46]

The paper “Analysis of the influence of perturbative forces in an artificial lunar satellite”, L. D. Gonçalves, E. M. Rocco and R. V. de Moraes, contains numerical models to study the influence of the orbital disturbance forces in trajectories of lunar satellites [47,48] such as the gravitational attraction of the Sun and Earth, lunar albedo and the solar radiation pressure.

The paper “simulations due to the lunar gravitational model uncertainty”, by L. D. Gonçalves, E M Rocco, R. V. de Moraes and H. K. Kuga, simulates part of the orbital trajectory of the Lunar Prospector mission in order to analyze the relevance of the Kalman filter to estimate the trajectory. Disturbance due to the lunar potential gravitational (LP100K model) was also considered [49].

The paper “H infinity controller design to a rigid-flexible satellite with two vibration modes”, by A. G. de Souza and L. C. G. de Souza, is a study into the rigid-flexible satellite ACS design using the H infinity method [50,51].

The last paper of this special issue is entitled “Navigation and control of an UVA quadrotor in search and surveillance missions”, by L. A. Frederico, L. S. Martins-Filho and A. L. da Silva, and it describes the studies into the application of specific random motion, known as Levy flights, to control the trajectory of an Unmanned Aerial Vehicle (UAV) quadrotor designed for surveillance [52,53].

6. Conclusions

Brazil has important groups researching theoretical and applied celestial mechanics. They are distributed in research institutes such as the National Observatory (Observatório Nacional, ON), the National Institute for Space Research (Instituto Nacional de Pesquisas Espaciais, INPE), the Department of Aerospace Science and Technology (Departamento de Ciência e Tecnologia Aeroespacial, DCTA), and the many departments of Mathematics, Physics and Engineering in public universities, such as the Federal Universities of Rio de Janeiro (UFRJ), São Paulo (UNIFESP), Minas Gerais (UFMG), and ABC (UFABC), and the São Paulo State Universities (USP and UNESP).

These research and education institutions work to conduct advanced scientific investigations into the many areas of celestial mechanics, and the papers presented here show the efforts in that direction.

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