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LUCAS DOS SANTOS FERREIRA

Planning and maintenance of small satellite constellations for planetology studies

Guaratinguetá
2025

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Planning and maintenance of small satellite constellations for planetology studies

Doctoral Thesis presented to the Graduate Program in Physics and Astronomy of the São Paulo State University "Júlio de Mesquita Filho" as a partial requirement to obtain the degree of Doctor in Physics.

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LUCAS DOS SANTOS FERREIRA

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***DEZEMBRO* de 2025**

Dedico este trabalho a minhas avós maternas Perola, Nize e Amelita *(In Memoriam)* e meus avós paternos Valdelice e Euclides *(In Memoriam)*.

This work is dedicated to my maternal grandmothers, Perola, Nize, and Amelita *(In Memoriam)*, and to my paternal grandparents, Valdelice and Euclides *(In Memoriam)*.

CURRICULAR DATA

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"In their hearts human beings plan their course, but the Lord establishes their steps" ***Proverbs 16:9***

Resumo

O objetivo deste trabalho foi contribuir para as pesquisas em planetologia, propondo estudos para a exploração de satélites naturais no Sistema Solar com futuras aplicações para a implementação de pequenas constelações de satélites em torno desses satélites naturais. Nesse sentido, foram investigados métodos visando localizar configurações orbitais favoráveis para o posicionamento das espaçonaves, em particular, órbitas com altas inclinações e quase-circulares. Critérios de desempenho e performance também foram estabelecidos para avaliar a produtividade e o funcionamento dessas órbitas e, posteriormente, das futuras constelações. Como objetivo específico, os satélites naturais de Saturno, particularmente, Jápeto e Titã, foram escolhidos como alvos para as investigações realizadas. Para o estudo das órbitas das espaçonaves, em torno de Jápeto investigamos, inicialmente, a dinâmica de uma espaçonave em torno de Jápeto, levando em conta as perturbações gravitacionais devidas a Saturno e Titã com foco em determinar condições orbitais que sejam mais adequadas para a futura implementação dessas constelações de pequenos satélites. Estudos iniciais determinaram as regiões de fronteira que delimitam as órbitas que sobrevivem em um intervalo de $5,0$ anos dentro do intervalo da esfera de influência de Jápeto para órbitas circulares e excêntricas. Através dessas investigações, os critérios de desempenho criados foram analisados e as condições admissíveis foram determinadas. Com base nas investigações realizadas, três propostas o estudo de futuras constelações foram apresentadas. Inicialmente, as propostas visaram incluir 1 satélite em 2 planos orbitais com altitudes diferente. Outra proposta baseava-se na implantação de novos satélites que poderiam ser distribuídos pelos dois planos orbitais, de modo a apresentar uma diferença de fase de 90 graus em relação ao mesmo plano e uma diferença de fase de 45 graus em relação aos satélites no outro plano orbital, a uma altitude de $6,0R_{Jpeto}$. Finalmente, a terceira proposta inicial sugeriu duas constelações em altitudes diferentes ($a_{S_{11}} = 4,0\ R_{Jpeto}$ e $a_{S_{21}} = 6,0\ R_{Jpeto}$), do tipo Walker, com 8 satélites distribuídos em dois planos orbitais equidistantes, com uma separação em termos de longitude do nó ascendente de 180 graus. Posteriormente, considerando uma espaçonave em torno do satélite natural Titã, foram realizados estudos para avaliar os efeitos perturbativos de Saturno e a não uniformidade de massa de Titã. Especificadamente, os coeficientes harmônicos zonais J_2, J_3, J_4 e o setorial C_{22} foram assumidos, assim como, um modelo simplificado de arrasto atmosférico também foi considerado. Mapas de tempo de vida foram obtidos considerando diversas configurações orbitais iniciais, as quais foram analisadas em diferentes cenários de perturbações orbitais. Os resultados mostram as regiões limitantes para órbitas com tempos de vida de ao menos 5.0 anos. Além disso, foram aplicados os coeficientes de performance relacionados aos elementos orbitais determinando as regiões com órbitas mais adequadas para a implementação de futuras constelações. Para introduzir o estudo de constelações de satélites os formalismos gerais relacionados aos critérios de perda (inoperabilidade) dos satélites foram apresentados, bem como, critérios de desempenho visando estabelecer a qualidade das órbitas também foram determinados. Algumas definições para o planejamento e análise das constelações foram discutidas e com base em trabalhos anteriores um modelo de cobertura utilizando cones de visibilidade híbridos foi apresentado. Um estudo colaborativo foi realizado no qual foram utilizados conhecimentos relacionados à Teoria Flower Constellation e à Necklace Flower Constellation. Juntamente com as metodologias propostas para o projeto de constelações, o estudo buscou determinar órbitas que conservassem a propriedade de repetidos Ground-traces, relacionada à escolha do semieixo maior inicial a, órbitas congeladas, vinculadas aos valores de e e ω, e compartilhamento de trajetória entre todos os satélites envolvidos na constelação. Essas propriedades foram avaliadas em um sistema dinâmico, utilizando cálculos de média e utilizando o pacote Rebound, assumindo os coeficientes har-

mônicos J_2 e J_3 de Titã. Nos estudos em torno do satélite natural Titã, foram geradas uma série de configurações para diferentes designs, sendo avaliadas as constelações compostas por dois planos orbitais, 6 satélites distribuídos nas duas órbitas e as configurações orbitais: Design I: $a = 5.3482\ R_{Titan}$, $e = 4.946302 \times 10^{-4}$, $i = 73.3572°$, $\Omega_{S_{11}} = 63.92°$, $M_{S_{11}} = 186.96°$, Design II: $a = 7.5952\ R_{Titan}$, $e = 7.5 \times 10^{-5}$, $i = 11.24°$, $\Omega_{S_{11}} = 57.49°$, $M_{S_{11}} = 199.81°$ e Design III: $a = 5.3495\ R_{Titan}$, $e = 0.000112$, $i = 11.74°$, $\Omega_{S_{11}} = 51.49°$, $M_{S_{11}} = 205.70°$.
Palavras Chaves: Constelações, Titã, Jápeto, Satélites artificiais, Astrodinâmica, Órbitas,Perturbações.

Abstract

The objective of this work was to contribute to research in planetology, proposing studies for the exploration of natural satellites in the Solar System with future applications for the implementation of small satellite constellations around these natural satellites. In this sense, methods were investigated to locate favorable orbital configurations for the positioning of spacecraft, in particular, orbits with high inclinations and quasi-circular orbits. Performance criteria were also established to evaluate the productivity and functioning of these orbits and, subsequently, of future constellations. As a specific objective, the natural satellites of Saturn, particularly Iapetus and Titan, were chosen as targets for the investigations carried out.

For the study of spacecraft orbits around Iapetus, we initially investigated the dynamics of a spacecraft around Iapetus, taking into account the gravitational perturbations due to Saturn and Titan, focusing on determining orbital conditions that are more suitable for the future implementation of these small satellite constellations. Initial studies determined the boundary regions that delimit the orbits that survive in a range of 5.0 years within the sphere of influence of Iapetus for circular and eccentric orbits. Through these investigations, the performance criteria created were analyzed and the admissible conditions were determined. Based on the investigations carried out, three proposals for the study of future constellations were presented. Initially, the proposals aimed to include 1 satellite in 2 orbital planes with different altitudes. Another proposal was based on the deployment of new satellites that could be distributed across the two orbital planes, so as to present a phase difference of 90 degrees in relation to the same plane and a phase difference of 45 degrees in relation to the satellites in the other orbital plane, at an altitude of $6.0R_{Iapetus}$. Finally, the third initial proposal suggested two Walker-type constellations at different altitudes ($a_{S_{11}} = 4.0\ R_{Iapetus}$ and $a_{S_{21}} = 6.0\ R_{Iapetus}$, with 8 satellites distributed in two equidistant orbital planes, with a separation in terms of longitude from the ascending node of 180 degrees. Subsequently, considering a spacecraft around the natural satellite Titan, studies were carried out to evaluate the perturbative effects of Saturn and the non-uniformity of Titan's mass. Specifically, the zonal harmonic coefficients J_2, J_3, J_4, and the sectoral C_{22} were assumed, as well as a simplified atmospheric drag model. Lifetime maps were obtained considering various initial orbital configurations, which were analyzed under different orbital perturbation scenarios.

The results present the limiting regions for orbits with lifetimes of at least 5.0 years. In addition, performance coefficients related to orbital elements were applied, determining the regions with the most suitable orbits for the implementation of future constellations. To introduce the study of satellite constellations, the general formalisms related to satellite loss (inoperability) criteria were presented, as well as performance criteria aimed at establishing the quality of the orbits. Some definitions for the planning and analysis of constellations were discussed, and based on previous work, a coverage model using hybrid visibility cones was presented. A collaborative study was carried out in which knowledge related to Flower Constellation Theory and Necklace Flower Constellation was used.

Along with the proposed methodologies for constellation design, the study sought to determine orbits that preserved the property of repeated Ground-traces, related to the choice of the initial semi-major axis a, frozen orbits, linked to the values of e and ω, and trajectory sharing among all satellites involved in the constellation. These properties were evaluated in a dynamical system, using averaging calculations and the Rebound package, assuming the harmonic coefficients J_2 and J_3 of Titan. In studies of the natural satellite Titan, a series of configurations for different designs were generated, evaluating constellations composed of two orbital planes, 6 satellites distributed in the two orbits, and the following orbital configurations: Design I: $a = 5.3482\ R_{Titan}$, $e = 4.946302 \times 10^{-4}$, $i = 73.3572°$, $\Omega_{S_{11}} = 63.92°$, $M_{S_{11}} = 186.96°$, Design II: $a = 7.5952\ R_{Titan}$, $e = 7.5 \times 10^{-5}$, $i = 11.24°$, $\Omega_{S_{11}} = 57.49°$, $M_{S_{11}} = 199.81°$ and Design III: $a = 5.3495\ R_{Titan}$, $e = 0.000112$, $i = 11.74°$, $\Omega_{S_{11}} = 51.49°$, $M_{S_{11}} = 205.70°$.

Keywords: Constellations, Titan, Iapetus, Artificial satellites, Astrodynamics, Orbits, Perturbations.

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List of Acronyms

$r_{\mathbf{H}}$ Hill's radius. i, 46, 47, 75, 104

2BP Two-Body Problem. 28, 32

2D-LFC 2D Lattice Flower Constellation. 13, 165–168, 171, 174

2D-NFC 2D Necklace Flower Constellation. 13, 165, 171, 174, 185, 186, 188, 189

ANOrbit appropriate natural orbits. 70

CR3BP circular restricted three-body problem. 39, 42

CollAlt collision due to contact with the atmosphere. i, 48, 49, 115, 116

CollAtm collision due to contact with the denser atmosphere. i, 48, 49, 106–108, 110, 115, 177

CollSur collision with the surface. i, iii, 48, 75, 114, 116

Collecc collision by eccentricity. 49, 197

EJHill ejection by Hill sphere. 47, 106, 114, 116, 227

FCT Flower Constellation Theory. 13

NFC Necklace Flower Constellation. 13, 171

SOI sphere of Influence. i, 46, 47, 104, 177

Contents

1 Introduction

This initial chapter provides a general introduction to the motivations behind the development of this research. To this purpose, an introduction to the ideas and concepts of small satellite constellations will be presented. Subsequently, an overview of the natural satellites of the Saturn system will be provided, with a particular focus on the natural satellites Titan and Iapetus. Following this, the general and specific objectives of this study will be discussed. Finally, the structure of the document will be presented.

1.1 Constellation of satellites and small satellites

In response to the challenges and applications emerging in space research environments, the use of satellite constellations has developed as one of the proposals to meet this demand (Abashidze et al., 2022). In general terms, a satellite constellation can be defined as a set of satellites coordinated to orbit a given body in a pre-established configuration, aiming to preserve characteristics such as formation, synchronization between satellites, and predictability in the face of perturbative scenarios. Thus, these configurations dynamically seek to promote the performance of one or multiple activities by assuming satellites in different orbital configurations, but which generally work together to perform these proposed activities. In this sense, it is expected that the satellites in these constellations will be able to function both collectively and individually, thus highlighting the autonomous navigation conditions of each spacecraft (Curzi et al., 2020; Arnas & Casanova, 2020; Abashidze et al., 2022). Several studies have demonstrated the advantages of using small satellites and constellations of these objects in various space applications, including budget projections for sectors such as satellite production and launch. These advantages can be found in sectors in which these small satellites can be produced on a larger scale, tested more quickly, and transported via launch clusters (Sweeting, 1992; Kopacz et al., 2020). In addition, in terms of satellite production, replacing a large satellite, which is often more expensive and involves greater complexity in its construction, with several small satellites that are less costly to produce is an interesting idea (Shiroma et al., 2011). Therefore, the benefits related to launch issues lie in the possibility of transporting a considerable number of these small satellites with just a few launches. In addition, the advantages in terms of fuel costs are also taken into account, since smaller satellites require less propellant for maneuvers and less fuel storage (Sweeting, 1992; Crisp et al., 2019). The proposal to utilize satellite constellations also serves as a means to prevent potential failures and provide enhanced support for the mission, since possible failures in one of the constellation components can be resolved by replacing the object or restructuring the constellation distribution. In contrast, this option wouldn't be possible when carrying out the mission with only one large artificial satellite (Shiroma et al., 2011). Among other characteristics presented in the literature, Shiroma et al. (2011) describes the function of these satellites arranged in constellations, since through a constellation, any member of the system can replace or assume a new function within the set. It is also possible to distribute mission activities to sets of satellites present in the constellations, reducing the time required to perform the activities and thus enhancing the objectives.

The areas of interest for the use of these satellite constellations are found in academia, as well as in the military and commercial sectors (Curzi et al., 2020). Within the scientific fields, studies conducted with biological experiments and climate research have provided incentives for the implementation of these constellations. Several private companies also intend to launch many satellite systems in the coming years and are considering operating in areas mainly focused on the Internet of Things and mass media , in the case of Earth (Qu et al., 2017; Curzi et al., 2020).

Several studies are presented considering the feasibility of launching several small satellites in a single launch, among them, Crisp et al. (2015) presents two strategies to reinforce studies in this regard, by researching the implementation of a constellation of satellites that would be launched together and later separated into their respective orbits through natural perturbations due to Earth's gravitational field. To do this, the launch vehicle would take these satellites to an orbit around a Lagrangian point of the system Earth-Moon, from where they would be launched into their final orbits around the Earth. Other works, such as Babuscia et al. (2016), also apply studies considering the insertion of constellations of small satellites of the "CubeSats" type around the Moon.

Given the challenges involved in managing these constellations, Curzi et al. (2020) present aspects related to the management of these systems, highlighting that, due to the high volume of objects in many constellation projects, optimization, preferably automated, is important for tracking these objects. Systems that assess the useful life of these small satellites allow for early detection of potential problems that could compromise the formation's operation. In this sense, work has been proposed and developed to promote algorithms to manage the traffic of these satellites, a sector of high importance, since poor satellite flight formation tends to compromise the constellation and thus the mission. Among the areas of research in this field, the dangers posed by space debris are also a topic of interest, as presented by Curzi et al. (2020).

In view of that one of the scenarios envisaged for the use of these small satellites is the construction and use of constellations, resulting in a large number of these small objects in a wide variety of orbital conditions, systems aimed at controlling the location of each of these objects and managing the geometry of the constellation need to be developed and constantly improved, considering possible increases, failure, and various effects to which the satellite cluster is subject (Curzi et al., 2020).

In this respect, there are geolocation systems in space that seek to locate these objects spatially, considering, in some cases, terrestrial transmitters, which can promote a better overall configuration for the satellites that are part of the constellations. Among the vast array of direct or passive positioning methods is the Time Difference of Arrival (TDOA) method, as e.g presented by (CaJacob et al., 2016), which takes into account the delay in the transmission and reception of signals between objects and, in some cases, a terrestrial transmitter. Examples of the use of the TDOA can be found both for underwater acoustic positioning and for locating interplanetary spacecraft (Gurfil et al., 2012). In light of a minimum required grid of three satellites in flight, these geolocation methods seek to keep errors associated with the location of objects and receivers on the ground within an acceptable margin (Shiroma et al., 2011).

In this context, studies related to the geographic location of a source through multiple emitters have been, over the years, one of the topics present in several works. Among these works, Foy (1976) used a method known as Taylor series estimation or Gauss-Newton interpolation as a first proposal to use and encourage the use of already known methods to solve systems composed of simultaneous equations. His methods had some advantages, although some points, such as the determination of an initial estimate, were among the restrictions present. Other authors, such as Friedlander (1987) and Smith & Abel (1987), also followed similar works. Research such as Li & Wei (2005) presents a method using genetic algorithms to determine position coordinates considering the intersection of hyperbolic curves that are determined by the different arrival times of signals emitted and received by various sensors. Aiming to improve performance in determining these positions, Gurfil et al. (2012) presents theoretical bases using the *Time Difference of Arrival* method, taking into account ambiguities that it proposes to resolve through filtering techniques. Even considering that nearly planar satellite flight configurations are geometrically simpler, it uses this formation to help preserve the flight formation over the long term.

The frequency difference of arrival (FDOA) technique is also used among other geolocation methods. In this context, Kim et al. (2011) displayed that the use of both methods, the difference in arrival and frequency of arrival of the signal, was efficient in geolocating transmitters, proposing in their research studies considering algorithms for tracking moving targets through the combined use of the two methods presented. Among the reasons for using this approach is the fact that TDOA measurements are not accurate enough to determine the position of the target, thus, the combination of methods aims to determine the position and speed of targets with greater accuracy. In their studies, Kim et al. (2011) displayed a reduction in the error in determining the position, demonstrating the accuracy of the tracking method. In addition to the studies on this approach, the work of Gustafsson & Gunnarsson (2003) presents and analyzes an algorithm for determining position coordinates by seeking to determine a gradient through nonlinear least squares calculations, highlighting the importance of studies related to possible sources of interference in sending and receiving the signal, using hybrid geolocation methods for this purpose.

These and other geolocation concepts have been widely used on Earth and are already very common in applications based on constellations GPS, GLONASS, Galileo. They allow users to accurately determine their position and plan more efficient routes to reach a given location. Given these investigations and the growing interest in establishing permanent colonies on the Moon and Mars, these same concepts of location can be applied to these celestial bodies, because once these small constellations of satellites are positioned around these bodies can greatly assist in establishing these human bases in terms of location, as well as communication, weather forecasting, and scientific studies.

In light of the advances in various sectors, particularly academic, technological, and economic, proposals and implementations of satellite constellations have increased, a factor that haIn that regard, s enabled proposals including studies of various bodies in the Solar System, , such as planets, asteroids, and the natural satellites of many planets, where some scientists believe there are great opportunities for research and new knowledge about these objects, as well as the formation of the Systems themselves. Among the target bodies in the Solar System, natural satellites such as Titan, Enceladus, Europa, Ganymede, and Callisto have been seen as nearby destinations for exploration (Konstantinidis et al., 2015; Waite et al., 2017; Hofstadter et al., 2017). Other systems, such as Dione and asteroids, are also particularly interesting targets (Gonçalves et al., 2019; Oliveira & Prado, 2020). In this context, studies related to the viability of implementing small constellations satellite around these natural satellites have proven to be of great importance. because such investigations tend to promote tools and systems that contribute to the design, development, and maintenance of these constellations. This will enhance the realization of future missions and enable the exploration of new systems. In that regard, the investigations carried out in this research focused on the natural satellites present in the Saturn system.

1.2 Natural Satellites of Saturn

The natural satellites of Saturn are among the most interesting celestial bodies in our Solar System, each exhibiting unique characteristics that have attracted significant scientific interest. Research on these celestial bodies covers fields related to geology, atmospheric sciences, and astrobiology as evidenced in works such as Schoenfeld et al. (2023b); Peter et al. (2024) and Gopalchetty & Coates (2025) . These investigations have been providing insights into the formation, evolution, and potential for harboring life forms on these natural satellites. Thus, research conducted on natural satellites of Saturn has transformed our understanding of these distant celestial bodies, in addition to promoting advances in a wide range of areas related to both planetary studies and life on Earth. For the studies conducted in this work, two natural satellites of the Saturn system were considered: Titan and Iapetus. In the following sections, some characteristics of these bodies will be presented.

Titan

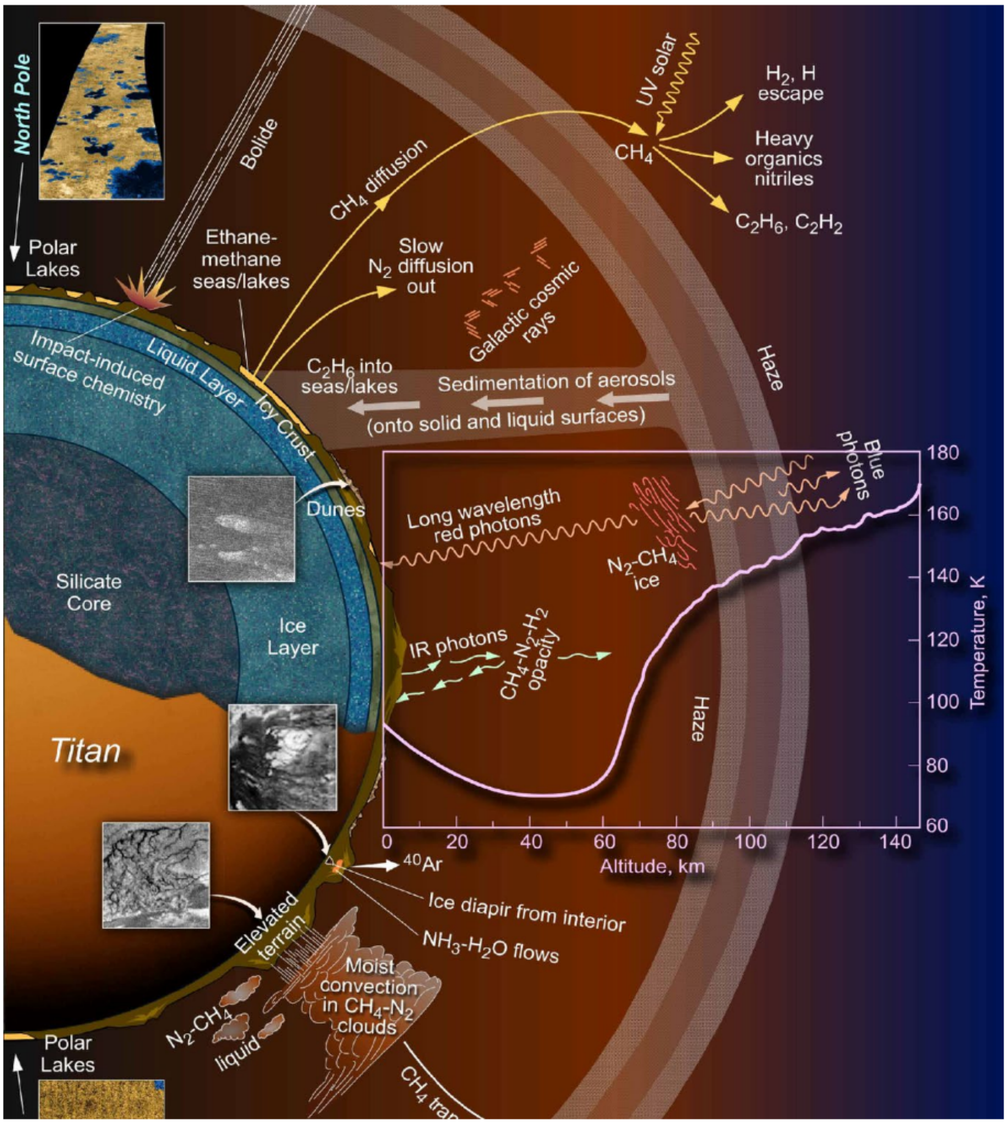
As one of the largest natural satellites in the Solar System and the largest natural satellite around Saturn, Titan is an incredible celestial body due to its characteristics and peculiarities. Discovered in the 17th century, its first characteristics were presented some time later by Kuiper (1944), when the first ideas about the presence of an atmosphere on this natural satellite emerged. With advances in space exploration through the Voyager 1 and 2 missions, some of the hypotheses related to the presence and atmospheric composition of Titan were confirmed e.g., the results presented in the investigations of West et al. (1983); Lindal et al. (1983); Richardson et al. (2004) and Vervack Jr et al. (2004). However, due to its dense and opaque form, there was still discoveries and investigations to be made. Through the Cassini-Huygens mission, in which the Huygens probe entered the atmosphere and landed on the surface of the natural satellite, in addition to the various flybys performed, new horizons of investigation were discovered (Elachi et al., 2002; Tomasko et al., 2005). Since the information about the rich atmosphere of Titan, as well as the biochemical processes present in this body, presented the possibility of investigating processes related to the formation of life, habitability, among others (Solomonidou et al., 2024).

The data collected by the missions, as well as the images and signals detected by ground-based and space telescopes, have led to a wide range of knowledge and discoveries about this natural satellite. Among these studies, analyses were carried out during the descent of Huygens, producing material for investigations of haze, clouds, and atmospheric composition (Tomasko et al., 2005). Studies have demonstrated the rich composition of hydrogen and methane present in the dense atmosphere of this natural satellite, resembling the atmosphere of Earth. The chemical-organic processes present in its atmosphere demonstrate a favorable scenario for studies of atmospheric chemistry in prebiotic conditions that resemble the atmosphere of Earth in a primitive period. Considering its distance from the Sun, Titan is among the few bodies in the Solar System where a stable liquid is found on its surface. In addition, studies demonstrate how the atmosphere of this natural satellite contributes to this active complex methane cycle. This actively and constantly influences the dynamics and composition of both the atmosphere and the ground of this natural satellite, since it is one of the factors responsible for the entire hydrological process on Titan.

Results also indicate a strong influence on climate dynamics, since its composition is capable of producing a greenhouse effect on this natural satellite. Several studies have also demonstrated how the relief formations of Titan are influenced by atmospheric actions (Lunine, 1997; Müller-Wodarg et al., 2014; Hörst, 2017). Through these and other investigations, the interaction processes, which demonstrate a unique characteristic, are demonstrated through transport or deposits that are carried out by fluvial, pluvial, or eolian processes in various regions of the natural satellite (Elachi et al., 2006; Domingos et al., 2006; Nixon et al., 2020). This demonstrates the constant dynamics present both on the surface and in the atmospheric regions of Titan. Previous studies also investigate the internal composition of this satellite, tectonic processes, and possibly cryovolcanism processes (Wall et al., 2009; Lopes et al., 2010, 2013).

Another interesting feature of Titan is related to the relative speed of its atmospheric mass in relation to the average rotational speed of the natural satellite. In the case of Titan, its average atmospheric speed has a rotation rate higher than the average rotation rate of the surface of the body. Previous investigations have demonstrated the high rate of atmospheric super-rotation, which is 10^2 greater than that of Earth and second only to that of Venus and Saturn (Read & Lebonnois, 2018). In this regard, several studies have proposed models for the dynamics of the winds present on Titan (Tomasko et al., 2005; Mitchell et al., 2006). Due to the opacity present in the atmospheric region of Titan, but more precisely in the region of atmospheric haze, which extends to an altitude of 300 km, until recently, the measurements and studies on wind dynamics present on the natural satellite were limited, since not all wavelengths can cross into this region. This is because its configuration tends to make it difficult to obtain high-resolution images due to light scattering and absorption (Schaller et al., 2009; Hörst, 2017; Rianço-Silva et al., 2024; Gopalchetty & Coates, 2025). However, the atmospheric dynamics of Titan promote the so-called atmospheric windows, which are a combination of regions and time intervals where certain wavelengths can cross the denser atmospheric regions of Titan (Barnes et al., 2007; Wye et al., 2007; Barnes et al., 2020). Figure 1.1 illustrates a diagram of the dynamics of the natural satellite Titan.

Figure 1.1: Diagram of the dynamics in Titan

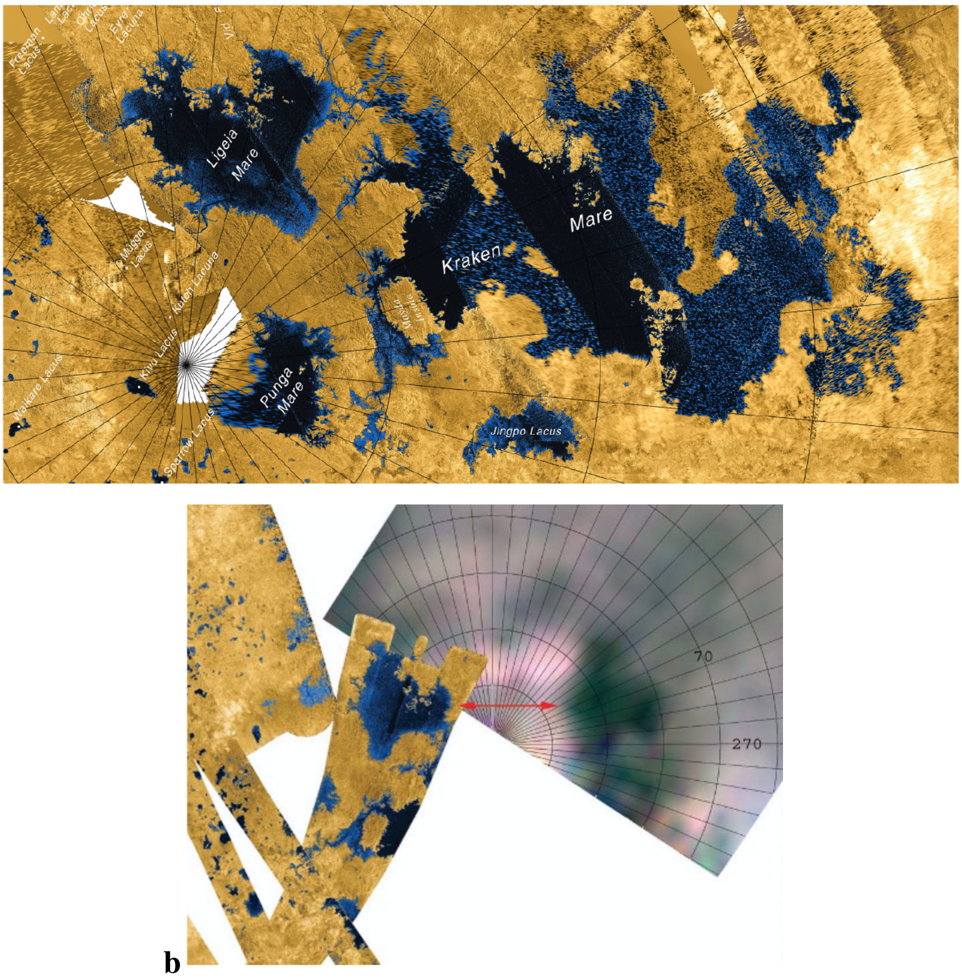


From: Gopalchetty & Coates (2025)

With the arrival of the Cassini/Huygens mission, knowledge about these atmospheric windows and better results on the dynamics of winds on Titan could be obtained. Results demonstrate the presence of strong zonal winds in its stratospheric regions (Read & Lebonnois, 2018). More results related to wind dynamics and cloud formations around Titan, as well as investigations into dynamic models for analyzing atmospheric windows, can be found in papers such as e.g. Tomasko et al. (2005); Schaller et al. (2009); Lorenz et al. (2012) and Barnes et al. (2020).

Another important aspect of Titan is the presence of lakes and reservoirs composed of methane and hydrocarbons in liquid form (Mitchell et al., 2006; Brown et al., 2008; Turtle et al., 2018; Poggiali et al., 2024). Studies demonstrate that the cycles present on Titan may resemble the current water cycle on Earth (Hayes et al., 2018). Related to this cycle are cloud formation processes, wind dynamics, and precipitation. Several studies indicate that methane lakes on Titan are located near the poles, covering a surface area of no more than 3% of the total area of the Titan. Its main regions of lakes and seas can be located in the north by Kraken Mare, Ligeia Mare, and Punga Mare, Figure 1.2(a), and in the south by Lake Ontario, Figure 1.2(b).

Figure 1.2: Images of lakes in the northern and southern polar regions of Titan.



a

b

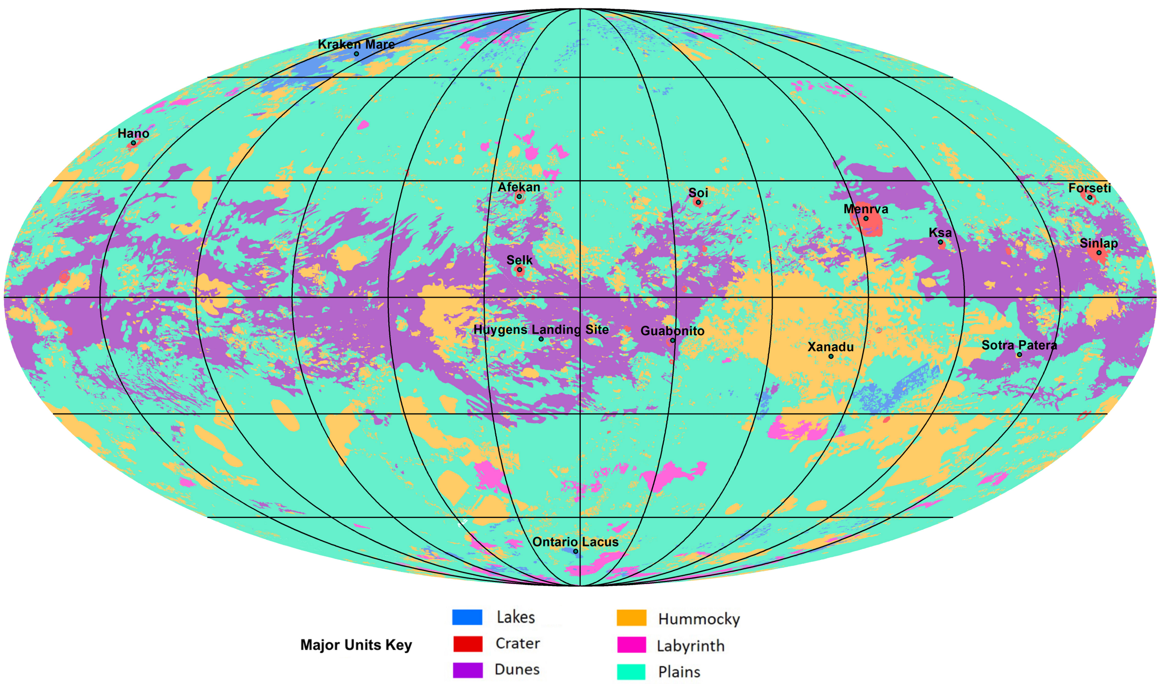
From: **(a):** Nixon et al. (2020) and **(b):** Brown et al. (2008)

Several other smaller regions, which are part of these lake units, are classified as dry or wet regions. Studies also propose scenarios for investigating erosion processes and craters generated by impacts, although these craters are found to a lesser extent as examples, those presented in investigations of Lopes et al. (2020) and Poggiali et al. (2024).

Just like the atmospheric regions, the surface of this natural satellite has also been the subject of several investigations related to geological formation and surface modifications. Among these investigations are studies related to the geomorphological formations of this natural satellite. Many of these geomorphological studies considered the data available from the Cassini mission, using sources such as Cassini's Synthetic Aperture Radar (SAR) mode, microwave data, infrared data, and the Imaging Science Subsystem (ISS), in addition to images from the Infrared Mapping Spectrometer (VIMS) and altimetry and topography results derived from the Synthetic Aperture Radar (SAR) (Lopes et al., 2010).

Previous studies as e.g. Malaska et al. (2016); Birch et al. (2019); Lopes et al. (2020); Schoenfeld et al. (2021) and Schoenfeld et al. (2023a), contributed to the development of geological maps for Titan, which presented catalogs of the surface of this natural satellite highlighting the presence of main units such as hydrological regions, where lakes and seas are found, dune regions, plains, Hummocky regions, mountainous regions, and crater regions, as demonstrated by Figure 1.3.

Figure 1.3: Geological map of Titan.



From: Wood & Radebaugh (2020)

Through these studies, as e.g. Lopes et al. (2020); Schoenfeld et al. (2021) and Schoenfeld et al. (2023a), it has been demonstrated that Titan has a predominance of flat regions, corresponding to approximately 65 % of its surface. These regions are concentrated in the equatorial regions and at mid-latitudes, with an amplitude not exceeding 30 degrees. Investigations have also shown that these regions are the most prevalent for dune formation. This factor is related to strong atmosphere-surface interactions, evidenced by the fact that many very similar organic compositions are found at different latitudes (Lunine, 1997; Müller-Wodarg et al., 2014). Studies have also indicated that the lakes and dunes of Titan are regions with younger formations.

Iapetus

Just as Titan, Iapetus is an intriguing natural satellite in the system of Saturn. Having been discovered by Giovanni Cassini during observations of Saturn around 1671, it is the most distant regular natural satellite of Saturn (Ćuk et al., 2024). Its scientific discovery was made together with the satellites Rhea, Dione and Tethys, as well as some structures of the rings of Saturn (Matson et al., 2002). Given a decreasing analysis in terms of mass and radius of the bodies, this natural satellite occupies the 11th position among natural satellites present in the Solar System. As with other celestial bodies in the system of Saturn, such as Enceladus, Dione, and Rhea, Iapetus has interesting characteristics that attract researchers from various fields of knowledge, placing him as a possible candidate for future missions (Peter et al., 2024). As opposed to Titan, these natural satellites of Saturn can be considered to have no atmospheric structures (Le Gall et al., 2019). In addition, among the points of interest for research on Iapetus are studies related to the different reflectivity of its hemispheres, which have a remarkable albedo dichotomy, resulting in one hemisphere, known as Cassini Regio, having a lower albedo, while the other hemisphere is more reflective. Investigations related to the reflection factors of these hemispheres indicate an approximate difference of (1/10) between their magnitudes (Morrison et al., 1975; Squyres et al., 1984; Buratti & Mosher, 1995; Spencer & Denk, 2010; Clark et al., 2012; Ćuk et al., 2024).

Among its orbital characteristics, Iapetus has a slightly eccentric orbit that is inclined relative to the equator of Saturn. Previous studies, e.g. Squyres et al. (1984); Spencer & Denk (2010); Nesvornỳ et al. (2014); Polycarpe et al. (2018) and Ćuk et al. (2024), discuss the orbital state of this satellite, because when comparing the dynamics of Iapetus with other regular satellites, it has a considerable inclination when compared to the other regular natural satellites of Saturn. Among the points of discussion are the past resonant effects between the orbits of Iapetus and Titan, which, due to its gravitational influence, would have altered the orbit of Iapetus, causing it to gain a little orbital eccentricity and inclination, but this did not result in the ejection of this natural satellite from the system of Saturn. Previous studies also demonstrate the low obliquity present in Iapetus, which implies a rotation axis that is almost perpendicular to its orbital plane (Davies & Katayama, 1984). Studies also demonstrate that, due to its orbital configurations, Iapetus is outside the region of influence of the magnetosphere of Saturn for most of its orbital revolution. Although this natural satellite has a rotation period of 73.98 days, studies seek the causes of its long rotation period, since its density, shape, and orbital parameters could favor a faster rotation (Thomas, 2010).

Through initial analysis of images from flybys of the regions of the natural satellites of Saturn, mountainous formations were observed on Iapetus. Over the years, new analyses carried out by the Cassini mission revealed a large mountain range in the regions near the equator of Iapetus (Denk et al., 2000). Previous studies have also shown that this extensive mountain range, which covers more than 70% of the equatorial diameter of the natural satellite, has regions with altitudes close to 20 km, in addition to an width of approximately 70 km. Several studies have been conducted in an attempt to understand the factors that led to the formation of these mountain ranges, where some investigations propose endogenous factors, such as global contraction processes, convection, as well as changes in the satellite's rotation due to tidal effects (Group et al., 1979; Castillo-Rogez et al., 2007; Sandwell & Schubert, 2010). Other investigations seek external factors, such as the accumulation of material due to a primary ring present in the natural satellite, among others (Detelich et al., 2021). Previous investigations also demonstrate the non-uniformity present in the distribution of these mountain ranges in the eastern and western hemispheres, as well as the different slopes present in these regions (Detelich et al., 2021). Several studies also propose the analysis and cataloging of the elevations and slopes present on the surface of Iapetus, highlighting crater regions in order to investigate their origins and their relationship with the composition of these natural satellites. Given these investigative scenarios, observation missions, mainly with equatorial and quasi-polar orbits, can contribute to the observation of the mountain ranges surrounding the satellite's equator, as well as the study of quasi-polar crater regions.

Orbital Characteristics

The orbital dynamics of the natural satellites of Saturn provide an interesting scenario for studies related to gravitational dynamics and dissipative forces acting on different timescales. The orbital configurations of its natural satellites reflect the superposition of the proposed initial conditions combined with the various effects experienced during their formation, such as tidal interactions, secular perturbations, and possible resonant crossings. In this context, knowledge of the orbital characteristics of these natural satellites is important for the dynamic study of spacecraft in nearby regions. The Table 1 until Table 3 present the main physical properties, mean orbital properties and orbital properties, assuming the plane of the equator of Saturn as reference plane, of these natural satellites, respectively.

Table 1: Physical Parameters of Saturn, Titan, and Iapetus.

Body	$mass\ (kg)$	$R(km)$	$\rho\ (g/cm^3)$	J_2	J_3	J_4	C_{22}
Saturn	5.6834×10^{26}	60268	0.687	1.629×10^{-2}	-	2.38×10^{-6}	3.202×10^{-7}
Iapetus	1.8059×10^{21}	734.5	1.0887	-	-	-	-
Titan	1.34553×10^{23}	2575.5	1.880	33.089×10^{-6}	-0.179×10^{-6}	-1.077×10^{-6}	10.385×10^{-6}

Source: Porco et al. (2004), Denk et al. (2010), and NASA/JPL. (NASA/JPL)

Table 2: Mean orbital properties of Iapetus and Titan.

Body	a (km)	e	I (Degrees)	ω (Degrees)	Ω (Degrees)	M (Degrees)	Orbital Period (Days)
Titã	1221900.	0.029	0.3	78.3	78.6	11.7	15.94
Iapetus	3561700.	0.028	7.6	254.5	86.5	74.8	79.32

Source: NASA/JPL. (NASA/JPL). Access: 17/01/2026.

Table 3: Orbital properties of Iapetus and Titan assuming the plane of the equator of Saturn as reference plane.

Body	a (km)	e	I (Degrees)	ω (Degrees)	Ω (Degrees)	f (Degrees)
Titã	1221947.6	0.029	0.4	327.7	254.7	19.7
Iapetus	3561700.	0.029	15.9	359.7	253.2	331.9

Source: NASA/JPL. (NASA/JPL). Access: 25/01/2026.

Related to the natural satellite Titan, studies conducted over the years indicate that the natural satellite has an almost circular orbit with low inclination relative to the equator of Saturn, located in the region of Saturn's rings. In terms of its rotation, Titan exhibits synchronous behavior in relation to its orbital period and rotation around its own axis. This behavior may be a response to the type of regular formation within the circumplanetary disk from which the satellite was generated. On the other hand, Iapetus has a considerably different orbital configuration, since this natural satellite has moderate eccentricity and an inclination greater than 15 degrees when analyzed in terms of Saturn's equator. These characteristics make Iapetus the subject of investigation, since they cannot be explained by assuming a purely dissipative formation and evolution scenario. Its properties suggest a more complex dynamic history, with the presence of orbital excitation processes and mean motion resonance mechanisms with Titan (Denk et al., 2010; Thomas, 2010; Detelich et al., 2021; Ćuk et al., 2024).

1.3 Objectives

The objective of this work was to contribute to research related to planetology, by proposing studies for the exploration of natural satellites in the Solar System , conducting studies of orbits and models of small satellite constellations around these celestial bodies. To do this, studies were initially conducted to structure the determination and validation of orbits. Criteria were also established for evaluating the productivity and functioning of these orbits and, subsequently, of the constellations.

Afterwards, investigations were conducted to map possible orbital configurations, both natural and with pre-established properties, for the allocation of individual satellites. The aim was to map the most appropriate regions around these natural satellites , to subsequently expand such conditions for the allocation of satellite constellations at a subsequent stage. In this way, the study aimed to contribute to the field of astrodynamics linked to the development of space missions around bodies with dynamics different from those found on Earth. This opens up new possibilities for studies of more distant celestial bodies with economical resource management and maximization of activities, since small satellite constellations generate more optimized space missions. The use of these constellations seeks to promote a greater impact on research development, as they allow celestial bodies of scientific interest, such as planets or natural satellites, to be observed for long periods of time and in a collaborative and multitasking manner. As a specific objective, the natural satellites of Saturn, Iapetus and Titan, were chosen as the target bodies for the investigations aimed at implementing small constellations.

1.4 Methodology

Based on the objective of this study, which was to plan designs for small satellite constellations for various applications in studies related to planetology, and knowing the various processes related to modeling, validation, and performance of these constellations, this study considered a simplified methodology, dividing the study processes into theoretical and computational stages. Initially, bibliographic studies were conducted on the dynamics of the celestial bodies Titan and Iapetus to learn in detail about the dynamics in the systems containing these natural satellites, as well as the forces and perturbative interactions present. In these stages, computational resources were developed to contribute to the analysis of disturbed environments, with computational routines being developed to simulate dynamic evolutions, including the main perturbing forces involved in each dynamic system. For this stage, some of the codes developed were built using the REBOUND package and the IAS15 integrator, due to the consideration of non-conservative forces in the dynamics.

Once the environment in which the constellations would be inserted was known, a bibliographic study was also conducted to obtain knowledge about the art of constellation planning. Subsequently, computational routines were developed to calculate the orbital conditions for the distribution of satellites belonging to the constellations. In conjunction with this stage, criteria and constraints were also developed to test and adjust the satellites individually and in the constellation arrangement.

Thus, studies of various orbital regions for the constellation were carried out for each of a bodies considered, with the aim of finding those in which the relative positions of the satellites remain least affected by unmodeled perturbations, as well as analyzing how the perturbative effects caused changes in the individual and relative orbits of each satellite in each orbital region and in each celestial body. The results were analyzed using tables and graphs in which the behaviors of the main variables of the problem, among other relevant variables obtained during the research, were shown. To support these studies, the computational tools developed used Python and C programming languages in addition to, computational tools such as Wolfram Mathematica, MATLAB, and R.

1.5 Organization of the manuscript

This research is organized to present a literature review in Chapter 2. Subsequently, Chapter 3 presents the theoretical foundations, beginning with a summary analysis of the Two-Body Problem, developed under two approaches: the first assuming an undisturbed system and the second one in the presence of possible external perturbations affecting orbital dynamics. In addition, considering the non-homogeneity of the mass of the central body, the mathematical deductions and physical considerations regarding the zonal and sectorial harmonic coefficients will be presented. Following this, the formalism of the N-body problem will be introduced. Emphasis will also be placed on the particular case of the Restricted Circular Three-Body Problem.

Subsequently, the formalism on perturbing potentials and the Lagrange planetary equations will also be discussed. Because of the presence of dissipative effects in the system under study, the formalism related to atmospheric drag force will also be discussed. In addition to the theoretical basis present in Chapter 3, mathematical formalism for the studies of frozen orbit, ground-track repetition orbits, Flower Constellation Theory (**FCT**) and Necklace Flower Constellation (**NFC**); and methodologies 2D Lattice Flower Constellation (**2D-LFC**) and 2D Necklace Flower Constellation (**2D-NFC**) will be presented in the introduction on the Chapter 7.

The results of the investigations conducted were compiled in Chapters 4 to 7. Initially, in Chapter 4, aiming to provide a basis for the following chapters on results, the criteria used in the dynamics of individual orbits are presented, as well as an overview of the problem proposed for satellite constellations around natural satellites. Thus, the theoretical foundations and criteria were established regarding the inoperability of the artificial satellites involved in the dynamics, as well as performance criteria and analyses of revisit time and coverage, ground-track maps, and coverage maps. In addition, the Rebound Integrator, a computational tool employed in the numerical simulations, will be introduced. First, a brief overview of the integrator will be provided, followed by a description of the implementations made in the program to construct the systems analyzed in this work. Finally, the simulator's validation process will be presented.

Chapters 5 and 6 present and discuss the results obtained in investigations conducted to catalog natural orbits and with pre-established initial properties around natural satellites of Saturn. The investigations around Iapetus are presented in Chapter 5, and those around Titan in Chapter 6. The studies were conducted considering different perturbative scenarios. For the system of the Iapetus, the investigations focused on the dynamics with two perturbing bodies, Saturn and its natural satellite Titan, assuming one perturbing body planar and one inclined case. The investigations around Titan focused on gravitational perturbations from Saturn, and also due to the non-homogeneous mass of Titan. The evolutions of some orbital conditions were presented, as well as the criteria presented in Chapter 4 were tested. Initial proposals for constellation designs were also propagated.

In Chapter 7, a stage of the research project will be presented, where a new approach to the design of satellite constellations around Titan was developed, combining advanced theoretical structures and practical orbital strategies. A preliminary theoretical foundation on the repetition properties of ground-track and frozen orbits will be presented, along with theories and methodologies on Flower Constellation and Necklace Flower Constellation. Subsequently, using the natural satellite Titan, the results obtained and cataloged are presented, as well as the propagation and some constellation models. A summary of the model on different perturbative systems will also be presented. Finally, Chapter 8 will present some conclusions and future projects will be in the Chapter 9. The supplementary materials for the theoretical chapters and the results chapters are presented in the Appendix A and Appendix B, respectively.

8 Conclusion

In this document, studies were conducted to contribute to research related to planetology, proposing studies for the exploration of natural satellites in the Solar System through the implementation of small satellite constellations. For the investigations assumed, the natural satellites of Saturn, Titan, and Iapetus were chosen as the target bodies for the studies. The investigation processes used a simplified methodology divided into theoretical and computational stages. After a literature review and the stages of computational modeling, the most suitable regions for the implementation of spacecraft on the target bodies were mapped, assuming different perturbative dynamics. Criteria were also established to evaluate the productivity and functioning of these orbits and, subsequently, of the constellations. The results obtained were analyzed using tables and graphs with the support of computational tools developed using Python and C programming languages. In addition to computational tools such as Wolfram Mathematica, MATLAB, R, and the REBOUND package.

The results of the investigations were presented in Chapters 4 to 7. To introduce the study of satellite constellations, Chapter 4 presented the general formalisms related to the loss (inoperability) criteria of the individual satellites involved in the dynamics. The criteria determined the correlation between satellite altitudes and the radius of influence of the natural satellite in orbit. In this context, assuming structures with atmospheric dynamics, additional criteria were included. Related to investigations on orbit quality, performance criteria $\delta_{E_{ij}}$ and $\Delta_{E_{ij}}$ were also presented, as well as requirements for analyzing the revisit time and terrestrial coverage of satellites in orbit. Finally, a proposal for allocating additional satellites to a constellation was presented, including two coverage systems. Contributions to the analysis of the magnitude of the perturbing forces present in the various parameter systems were determined for the harmonic coefficients J_3, J_4, J_5, J_6, and the sectorial coefficient C_{22}.

In Ch. 5, an investigation was carried out considering the dynamics of a spacecraft around a central body in the presence of two perturbators, one planar and the other inclined and eccentric. For this study, the satellite Iapetus was assumed, accounting for the gravitational perturbations from Saturn and Titan. The simulations were conducted to determine the most appropriate orbits for the future implementation of small satellite constellations. For this purpose, lifetime maps assuming a 5-year orbital interval were generated for an interval covering the full region of Iapetus' sphere of influence. Progressed and retrograded orbits were considered with eccentricity in the range $[10^{-4}, 0.3]$. The boundaries of the surviving orbit regions were determined assuming only perturbations of Saturn and, subsequently, with the addition of the perturbations of Titan. Regions external to the survival regions were also investigated, and the results indicate that, in general, lifetime maps for orbital conditions external to the survival regions maintain a strong influence on the duration of the orbits, in relation to the selection of the initial semi-major axis and the selection of the inclination, thus demonstrating an influence on the initial altitude of these orbits. It was also observed that there is an extensive region in the center of the initial conditions grid, between the vicinity of 60 degrees of inclination for prograde orbits and 120 degrees for retrograde orbits, where orbital conditions did not survive the 5-year simulation. It was observed that, for an increasing order of eccentricity, these regions begin at a semi-major axis of 7.0 $R_{Iapetus}$, tending toward smaller semi-major axes as the initial eccentricity of the orbit increases, eventually reaching the entire range for more eccentric cases.

When including the gravity effects of Titan, it was observed that its influence does not change the overall behavior of the maps. On the other hand, conditions with losses of up to 55 months were observed in the range of 15.0 to 18.0 radii of Iapetus, along the simulated orbital eccentricities. It was also seen that such conditions stand out in the maps and decrease as the initial eccentricity of the orbits increases. Although these are isolated conditions, orbital conditions were also found in which the time intervals increased by around 43 months, also for semi-major axis values between 10.0 and 15.0 radii of Iapetus. The performance coefficients δ were also analyzed, and the admissible orbits were determined using the most appropriate associated parameters. Analysis of these parameters showed that for the dynamics around Iapetus, the conditions with the lowest coefficients were found for semi-major axes less than 11.8 $R_{Iapetus}$, assuming that these regions decrease by the value of the eccentricity to a range of approximately 9.0 $R_{Iapetus}$ for the case of $e_{S_{ij}} = 0.1$, with the results related to the greater influence of the perturbators. The results also showed that when analyzing two eccentricity values, $e_{S_{ij}} = 0.001$ and $e_{S_{ij}} = 0.1$, the maps of the coefficients δ_a have a difference in coefficients that can be considered minimal, even though the eccentricities have a difference of 10^2. The analysis of the parameter δ_e allowed us to determine orbits with acceptable values in the range of 5.5 $R_{Iapetus}$ to 6.5 $R_{Iapetus}$ for $e_{S_{ij}} = 1.0 \times 10^{-3}$ and in the range of 1.5 $R_{Iapetus}$ to 2.5 $R_{Iapetus}$ for $e_{S_{ij}} = 0.3$. In addition, a region of coefficients with maximum values for the analysis was determined in regions above the admissible coefficients. Orbits with large semi-major axes, such as the interval from 24.0 $R_{Iapetus}$ to 31.0 $R_{Iapetus}$, also showed the presence of orbital conditions with small δ_e, indicating the possibility of spacecraft in these regions. Finally, based on the orbital conditions identified, three constellation proposals were presented. Initially, the proposals aimed to include one satellite in each of two orbital planes, for a total of two satellites in the project, to achieve shared coverage. These satellites were initially positioned over the same point on the surface of Iapetus, with only their initial altitudes differing. Another proposal was based on the deployment of new satellites that could be distributed across the two orbital planes to have a phase difference of 90 degrees relative to the same plane and a phase difference of 45 degrees relative to the satellites in the other orbital plane at an altitude of $6.0 R_{Iapetus}$. Finally, a third initial proposal, based on Walker (1984), proposed two constellations at different altitudes ($a_{S_{11}} = 4.0$ $R_{Iapetus}$ and $a_{S_{21}} = 6.0$ $R_{Iapetus}$), of the Walker type, with 8 satellites distributed across two equally spaced orbital planes, with a separation in terms of ascending node longitude of 180 degrees. The satellites in the constellations were distributed in the first orbital plane with a spacing of 90 degrees, and the second, based on a phase number F=1, has a 45-degree offset relative to the spacecraft in the first orbital plane.

In Ch. 6, studies were developed considering a natural satellite in the presence of a disturbing body assuming contributions due to the non-uniformity of the central satellite's mass. For these investigations, the natural satellite Titan was considered, assuming Saturn as the main perturbator and Titan's zonal and sectorial harmonics J_2, J_3, J_4, and C_{22}. The evaluation of perturbations in the dynamic environment allowed the determination of the altitude regions where each perturbing effect had a higher magnitude in the dynamics. The results showed that there is a small region near Titan's surface where the effects of J_2 have a magnitude above Saturn's perturbation. Although, it is a region below $1.2\ R_{Titan}$, the effects due to atmospheric drag are also present in these regions. For regions with altitudes higher than $1.5\ R_{Titan}$, the results indicate that Saturn's perturbations are dominant for the entire region of analysis, which involves Titan's sphere of influence, followed by the perturbation due to Titan's flattening up to an altitude higher than $3.3\ R_{Titan}$, because above this altitude, the perturbing effects due to Saturn's other natural satellites become dominant in the dynamics. The same behavior can be observed for harmonics C_{22} and J_4, which have the highest magnitude after coefficient J_2. These harmonics are present in the upper part of the range, while the lower part is dominated by C_{22} and J_4 harmonics, which have the highest magnitude after the J_2 coefficient. The dominance of C_{22} extends to an altitude of $2.5\ R_{Titan}$, while that of J_4 extends to an altitude of approximately $1.6\ R_{Titan}$. The results also showed that the inner natural satellites have a greater influence than those outside Titan. The results of the lifetime maps were initially evaluated assuming a dynamic with only Saturn in a planar scenario. Under these conditions, the lifetimes of orbits around Titan were investigated, assuming an initial semi-major axis range of up to approximately 6.0 Titan radii, an initial inclination for prograde and retrograde orbits in the range [0.0-180], and an initial eccentricity range of [0.0 – 0.5]. The simulations allowed us to catalog the delimiting regions for orbits surviving a period of 20.0 years. The investigations also evaluated the regions of non-survival, obtaining orbits with longer lifetimes in the regions closest to the natural satellite. A dynamic assuming an atmospheric drag model and the harmonic coefficient J_2 was also simulated, assessing its effects on the dynamics of spacecraft orbits. Results for a parameter evaluating the lifetime of orbits after entering the atmospheric region showed intervals of up to 12 days. With different criteria for spacecraft inoperability being determined, the studies showed the validity and influence of performing simulations assuming the possibility of spacecraft loss upon first contact with the atmospheric region. In addition, the altitude evaluation criterion Δ was evaluated for different dynamics, highlighting the regions with the lowest values for the coefficients determined. Subsequently, these investigations evaluated the effects of the other assumed harmonics on the limits of the orbit survival regions, assuming, for these investigations, an interval of 5.0 years of orbits. The results showed that the harmonic effects do not remodel the limits of the survival regions, but affect the orbits that did not survive the total integration time.

In Ch. 7, a study conducted in collaboration with researchers from the Institute of Mathematics and Applications (IUMA) at the University of Zaragoza was presented. In this study, knowledges related to Flower Constellation Theory and Necklace Flower Constellation were used. Along with the methodologies proposed for the design of constellations, the study sought to determine orbits that would conserve the Ground-track repetition property, related to the choice of the initial semi-major axis a, frozen orbits, linked to the values of e and ω, and trajectory sharing among all satellites involved in the constellation. For these investigations, the harmonic coefficients J_2 and J_3 of the orbited body were considered.

To contribute to research on exploration around natural satellites, the natural satellite Titan was considered as the target body for applying the proposed methodology. Based on previous work, flyover regions were pre-established, focusing on the regions of Titan's lakes and seas and points over quasi-equatorial regions. Assuming an altitude range of 1400 km to 20000 km and establishing the number of orbits per sidereal day, the initial semi-major axis values that preserve the ground-track repetition properties were found as a function of N_p and N_d. The orbital configurations obtained and the admissible parameters for the designs were cataloged. Three examples of constellations were considered, and their propagation in both an inertial and rotating system was presented.

Through the study of the phase diagram $e\sin(\omega) \times e\cos(\omega)$ and the orbital evolution of the eccentricity of the orbits of the satellites involved in the constellations, studies were carried out on two scenarios for the evolution of the constellations. Considering the orbital properties required in both scenarios, initially, the orbits were propagated assuming only harmonic perturbations due to the coefficients J_2 and J_3 and, subsequently, perturbations due to Saturn and the sectorial harmonic C_{22} were included. The results demonstrated the conservation of frozen orbit properties in the first scenario and allowed us to observe the duration intervals of the satellites present in the constellations. These analyses motivate future investigations related to the damping of other perturbative effects, as well as the planning of corrective orbital maneuvers, studies on coverage and revisit regions.

Thus, the research presented here offers a new approach to the design of satellite constellations around Titan, combining advanced theoretical frameworks and practical orbital strategies. Specifically, it leverages the 2D-Necklace Flower Constellation methodology to systematically organize multiple satellites, ensuring uniform coverage and efficient phasing. Furthermore, the proposed constellations are based on orbits with repetitive ground trajectories and frozen orbit characteristics, which are particularly advantageous for long-duration missions in disturbed environments, such as Titan's gravitational field. These choices enable sustained observation capabilities over specific regions of interest, reduced station maintenance requirements, and greater mission resilience. This integrated approach represents a significant advancement over conventional constellation architectures and is particularly well-suited to the unique challenges presented by Titan's orbital dynamics and scientific exploration needs. Therefore, the constellations designed in these investigations using the presented methodology demonstrate efficiency over other methods by reducing the number of satellites required or increasing coverage. Based on the parameters identified for the various designs investigated for the natural satellite Titan, this study evaluated three constellation designs consisting of two orbital planes and six satellites distributed across the two orbits. The orbital configurations considered were: Design I: $a = 5.3482\ R_{Titan}$, $e = 4.946302 \times 10^{-4}$, $i = 73.3572°$, $Omega_{S_{11}} = 63.92°$, $M_{S_{11}} = 186.96°$, Design II: $a = 7.5952\ R_{Titan}$, $e = 7.5 \times 10^{-5}$, $i = 11.24°$, $Omega_{S_{11}} = 57.49°$, $M_{S_{11}} = 199.81°$, and Design III: $a = 5.3495\ R_{Titan}$, $e = 0.000112$, $i = 11.74°$, $Omega_{S_{11}} = 51.49°$, $M_{S_{11}} = 205.70°$.

9 Future Projects

In view of the theories and methodologies presented in conjunction with the results obtained in this study, the following lines of future studies are been suggested as a continuation of the proposed investigations:

- Research related to planning corrective orbital maneuvers aimed at keeping satellites within the desired formation criteria or relocating these spacecraft to new orbital configurations when necessary.

- Studies aimed at assisting the implementation of small satellite constellations around the natural satellite, conducting combined investigations of swing-by maneuvers using two-by-two anchored satellites with and without the use of impulsive systems.

- Improvements in the study of revisit time and coverage of satellites involved in constellations.

- Studies of the attitude of satellites and the formation of constellations.

- Investigations for the development of tools to obtain periodic orbits, in addition to studying the evolution of these orbits due to the contributions from perturbations present when studying these small bodies.

- Investigations assuming dissipative forces not modeled using the current methodology of 2D Necklace Flower Constellations and the orbital properties proposed in this work.

- Based on the orbital conditions cataloged as having been ejected from the region of interest, we will investigate the evolution and dynamics of these orbits after they leave that region.

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