Refining Lunar Trajectory Design: Software enhancement in the 'To The Moon' module of the CTK Platform

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Degree internship report as requirement to obtain the Title of Aerospace Engineer

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Dedication

To women who, through knowledge,
have decided to transform their environments
into more pleasant places to grow and live.

*"Lo que da verdadero sentido al encuentro
es la búsqueda y… es preciso andar mucho
para alcanzar lo que está cerca."*

José Saramago

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TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

ACRONYMS AND ABBREVIATIONS

AOP	Argument of Periapsis
COE	Classical Orbital Elements
CSV	Comma-Separated Values (File format)
CTK	Continuum Toolkit
DC1	Differential Corrector 1
DEC	Declination
DV	Delta-V
GMAT	General Mission Analysis Tool
GTO	Geostationary Transfer Orbit
INC	Inclination
JSON	JavaScript Object Notation
LEO	Low Earth Orbit
LOI	Lunar Orbit Insertion
NASA	National Aeronautics and Space Administration
P2M	Planet to Moon
P2P	Planet to Planet
RA	Right Ascension
RAAN	Right Ascension of the Ascending Node
RMAG	Magnitude of satellite's position vector
SC	Spacecraft
SOI	Sphere of Influence
STK	Systems Toolkit
TCM	Trajectory Correction Maneuver
TLE	Two-Line Element
TLI	Trans Lunar Injection
TOF	Time of Flight
UTC	Coordinated Universal Time
V	Velocity
VS code	Visual Studio Code

RESUMEN

En el contexto actual, marcado por un creciente interés de nuevos países en misiones espaciales y una mayor participación tanto de instituciones públicas como privadas, Continuum Space Systems es una compañía que brinda herramientas de navegación espacial para entidades del sector aeroespacial. En respuesta a este panorama dinámico, donde se observa un interés en ascenso por parte de nuevos actores en la realización de misiones espaciales, especialmente dirigidas hacia la Luna, este trabajo se enfoca en la transferencia lunar directa, un método ampliamente usado para alcanzar la Luna desde la Tierra, centrándose específicamente en las salidas donde el satélite ya tiene un impulso inicial de transferencia lunar, proporcionado por una fuente externa como un lanzador. Se describe el desarrollo y la metodología para integrar esta capacidad en la plataforma CTK de Continuum. Empleando GMAT, se generó un modelo inicial de prototipo de misión, empleando estrategias como el apuntamiento usando el B-plane y la optimización del delta-V total en la maniobra de inyección lunar. Los resultados muestran consistencia con datos de referencia utilizando el mismo método de salida (entre 0.6 - 1 km/s de delta-V), y revelan una correlación entre la fecha de salida y la inclinación de llegada respecto al ecuador lunar, donde ángulos de inclinación mayores implican menor delta V requerido, lo que refleja un comportamiento adecuado de los resultados. Además, se realizaron mejoras en el módulo "To The Moon" de CTK, proporcionando mensajes informativos para una mejor comprensión y análisis de los resultados, en beneficio de los usuarios de la plataforma. Este estudio contribuye al avance en el módulo "To The Moon" y amplía las posibilidades de uso de CTK, siendo la transferencia lunar directa un método convencional utilizado para alcanzar la Luna ampliamente.

***Palabras clave* — Trayectorias lunares, transferencia lunar directa, GMAT, diseño de misiones, delta-V.**

ABSTRACT

In the current context, marked by a growing interest from new countries in space missions and increased participation from both public and private institutions, Continuum Space Systems is a company that provides space navigation tools for entities in the aerospace sector. In response to this dynamic landscape, which sees a rising interest from new players in conducting space missions, particularly directed towards the Moon, this work focuses on direct lunar transfer, which has been used so frequently in lunar missions from Earth, specifically concentrating on departures where the satellite already has an initial lunar transfer impulse provided by an external source such as a launcher. The development and methodology for integrating this capability into Continuum's CTK platform are described. Using GMAT, an initial prototype mission model was generated, employing strategies such as pointing using the B-plane and optimizing the total delta-V in the lunar injection maneuver. The results show consistency with reference data using the same departure method (between 0.6 - 1 km/s of delta-V), and reveal a correlation between the departure date and the arrival inclination with respect to the lunar equator, where higher inclination angles imply lower required delta-V, reflecting appropriate behavior of the results. Additionally, improvements were made to the "To The Moon" module of CTK, providing informative messages for better understanding and analysis of the results, benefiting the platform's users. This study contributes to the advancement of the "To The Moon" module and expands the possibilities of CTK usage, with direct lunar transfer being a conventional method widely used to reach the Moon.

***Keywords* — Lunar trajectories, direct lunar transfer, GMAT, mission design, delta-V.**

I. INTRODUCTION

A. Motivation

Traditionally, the design and execution of space trajectories were managed internally by companies responsible for specific missions. However, this approach has shifted, and mission design and trajectory optimization have become essential services. With the renewed interest in the Moon as a scientific target, the 'To The Moon' module, created by Continuum, is motivated to design optimized trajectories to the Moon through software.

The project developed in this report contributes to aerospace engineering by improving and extending the "To The Moon" module on the CTK platform, enabling emerging companies and the aerospace industry as a whole to access efficient and precise tools for the design of orbital trajectories to the Moon. Furthermore, by expanding the module's capabilities to include departure from a translunar injection state, a significant limitation would be overcome, offering a more complete and versatile solution for space mission design. Ultimately, this project strengthens the capability to plan and execute lunar missions using one of the most common methods for lunar missions: direct orbit launch.

B. Problem Statement

In the current aerospace industry landscape, characterized by significant growth and increased involvement of both public and private entities, there is a recognized need to design trajectories for various space missions. This increase in demand motivates the mission of this internship: to contribute to the development of the backend of Continuum Space Systems, a company that provides space navigation tools for companies in the aerospace sector.

Considering the company's objectives, this academic internship is mainly focused on improving the "To The Moon" module, hosted on the CTK platform created by Continuum. This module is in charge of the design of trajectories for spacecraft to the Moon. Accordingly, this final report presents the progress in the improvements of the module, besides the addition of a new capability to depart from a translunar injection state, overcoming the current limitation of departing from low Earth orbits (LEO) or geostationary transfer orbits (GTO).

As a background to address this challenge, the work done by the previous intern in this module was taken into account, which was useful to understand the implementation of new capabilities in the platform and to analyze the expected results.

The improvement of this module by this project will encompass both theoretical research and the use of simulation models and graph generation to evaluate the consistency and optimization of the trajectories obtained. A fundamental consideration in any new platform capability is to enable users to determine launch periods and windows, presenting Delta V results in graphical and tabular formats. Consequently, one of the challenges addressed was always the comfort of the customer, ensuring that the platform is user-friendly for data input and clear with the results presented.

C. Paper Structure

This document is organized into a series of chapters that address different aspects of the final report of this academic internship. Chapter II establishes the general and specific objectives of the study, outlining the development trajectory and expected results. Next, in Chapter III, the necessary theoretical framework is presented, addressing key concepts on which the report is based, such as orbital mechanics and space trajectory design. Chapter IV details the methodology used to address the problem, including work strategies and procedures for the implementation of new capabilities in the CTK software. The development of the tasks executed within the company, the results obtained and their analysis are presented in Chapter V, which leads directly to Chapter VI, where the conclusions and recommendations derived from this report are discussed.

II. OBJECTIVES

A. General Objective

The goal of this internship is to analyze, augment and extend the "To The Moon" module of the CTK platform, aimed at orbital trajectory planning to the Moon. This objective closely aligns with Continuum's current roadmap, driving the development of essential capabilities for lunar and space exploration.

B. Specific Objectives

- Validate the current performance of the module, identifying areas for improvement in terms of accuracy and efficiency in the generation of trajectories to the Moon.
- Enhance the functionality of the module by optimizing the code and implementing more efficient algorithms for orbital trajectory design, with the goal of increasing reliability and accuracy in planning missions to the Moon.
- Expand the module's capability to enable departure from a translunar injection state, overcoming the current limitations of departure only from parking orbits, and thus providing greater flexibility in lunar mission planning.
- Develop enhancements for the "To The Moon" module interface to enable users to better understand and analyze planned trajectories to the Moon.

III. THEORETICAL FRAMEWORK

Lunar orbit optimization is considered an essential element for the exploration and study of the Moon. Its importance is linked to its critical role in reducing costs, maximizing mission efficiency and achieving scientific objectives. From the scientific point of view, the Moon acts as a true historical archive of the solar system, preserving traces of past events and offering valuable clues about its formation and evolution. Orbit optimization allows missions to access specific locations of scientific interest, such as craters, polar regions and unique geological features, where fundamental research into the history of our solar system and Earth can be conducted.

Space agencies are designing future crewed and crewless missions to the Moon [1], as well as the possible creation of a space station in lunar orbit. Orbit optimization increases the safety of lunar missions by minimizing the risk of collisions with obstacles and optimizes fuel consumption, which in turn contributes to the sustainability of lunar exploration in the long term. Theoretical trajectory models are necessary at the beginning of a mission design to ensure that a spacecraft will be able to arrive at their destination successfully.

A. Orbital Mechanics

Orbital mechanics is the foundation of any space mission. Newton's Law of Universal Gravitation and Kepler's laws are essential to understand how celestial bodies interact and how orbits can be planned. Newton, in his book Principia I [2], provides a complete explanation of the irregularities of the moon's motion, which is also part of the basis for his theory of universal gravitation. For the application of orbital mechanics, it is necessary to understand how bodies interact, this work focuses on the two-body Earth-Moon system, which orbit around their common center of mass once every 27.3 days. The mean distance between the center of the Earth and the center of the Moon is 384,400 km and the mass of the Moon is 1/80 of the mass of the Earth [3].

This work is based on the premise that, ideally, there are no perturbing forces affecting the spacecraft and that the orbital motion can be modeled using the two-body equation, as shown in eq. (1) [3]. The value of μ in this equation depends on the central body of attraction. For example, if the spacecraft is in orbit around the Earth, then μ would be the gravitational parameter of the

Earth. The GMAT software typically employs this model, where the force models acting on the spacecraft are changed throughout the mission as the central body of attraction changes.

$$\ddot{\mathbf{r}} = -\frac{\mu}{r^3}\mathbf{r} \tag{1}$$

There are multiple forces acting on a spacecraft in orbit, including perturbing forces such as solar radiation pressure, n-body effects, oblateness effects, magnetic torque, and gravity gradient torque [4][5]. These forces can be simplified in works of this nature because their magnitude is considerably smaller than the gravitational force of the primary body, and it is possible to obtain a precise and nearly optimal solution without considering these factors [5]. However, it is worth noting that GMAT allows for the incorporation of new force models that can be integrated into the mission.

Two approaches can be employed in the definition of a standard orbit: the use of position and velocity vectors, or the use of classical orbital elements (COE) [5]. In the case of three-dimensional orbits, the Keplerian orbital elements are the main parameters to describe mathematically the propagation of the orbit [6]. These elements are described in a set of two lines, known as Two Line Elements (TLE), which is a standardized format used to describe the orbit of a satellite. The visual representation of these COEs in three-dimensional space is shown in Fig. 1.

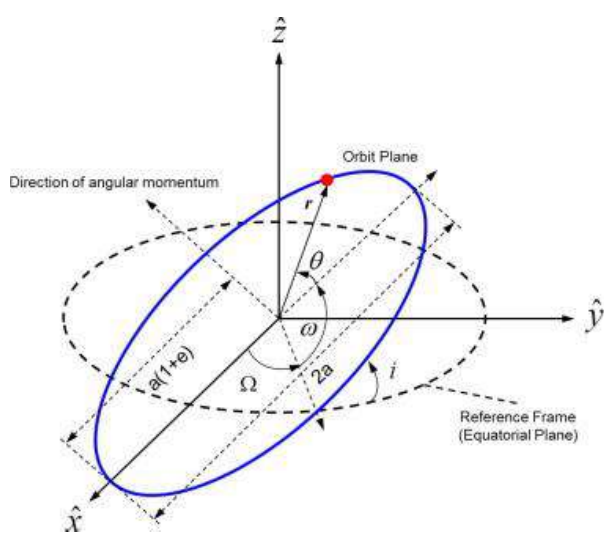

Fig. 1. Classical Orbital Elements for 3-dimensional orbits.

Source: [7].

Where Keplerian elements are scalars and they are described as:

- a: semi-major axis [m]
- e: eccentricity [dimensionless]
- i: inclination angle [rad]
- Ω: longitude of Ascending Node [rad]
- ω: Argument of Periapsis [rad]
- M: Mean anomaly [rad] / θ: True Anomaly [rad]

1) *Impulsive Maneuvers*

Orbital maneuvers transfer a spacecraft from one orbit to another, which can involve drastic changes such as transitioning from a low Earth orbit (LEO) to an interplanetary trajectory, or more subtle adjustments in the final stages of a spacecraft encounter. Within these maneuvers, impulsive maneuvers are brief engine burns that instantaneously change both the magnitude and direction of the velocity vector. During these maneuvers, the spacecraft's position is considered fixed, with velocity being the only parameter altered [6]. This idealization is useful in cases where the spacecraft's position barely varies during the brief duration of the maneuver, classifying them as "high-thrust" maneuvers.

On the other hand, non-impulsive maneuvers, also known as low-thrust maneuvers, involve a gradual change in the spacecraft's velocity over a significant period of time. High-thrust maneuvers typically have burn durations of less than 1% of the total trajectory time, while low-thrust maneuvers can have burn durations exceeding 50% of the trajectory time [8].

In the context of this work, impulsive burns are chosen for the missions developed, since these maneuvers are mainly focused on injection and orbit insertion. Impulsive burns are considered suitable for high-thrust engines with short burn times compared to the vehicle's inertia time. Each of these impulsive maneuvers results in a change delta-v in the velocity of the spacecraft, which may involve a change in magnitude (referred to as a "pumping maneuver"), direction (a "cranking maneuver"), or both characteristics of the velocity vector [6].

The relationship between the magnitude of $\Delta\mathbf{v}$ velocity increase and the mass of propellant consumed (Δm), as represented by eq. (2), is calculated using the initial mass of the spacecraft (m), the standard acceleration of gravity at sea level (g_o) and the specific impulse of the propellants

(I_{sp}), as defined in the literature [6]. Specific impulse, measured in seconds, is a metric of rocket propulsion system performance. The graph of Equation 2, presented in Fig. 1, illustrates this relationship for different values of specific impulse.

$$\frac{\Delta m}{m} = 1 - e^{-\frac{\Delta v}{I_{sp} g_0}} \tag{2}$$

The required propellant mass exceeds 25% of the initial spacecraft mass when dealing with delta-vs of around 100 m/s, Highlighting the importance of careful mission delta-v planning to minimize the propellant mass carried for the payload's benefit. This delta-v optimization is considered one of the main aspects in the realization of this work.

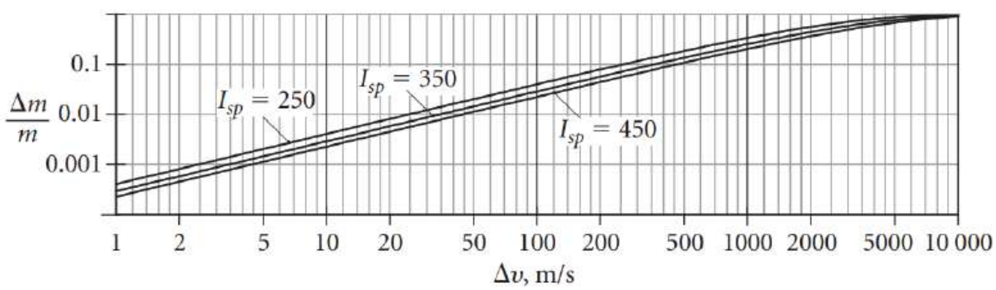

Fig. 2. Propellant mass fraction versus Δv for typical specific impulses.

Source: [6].

B. Space Trajectories Design

Numerous methods have been developed to model interplanetary trajectories, with various approaches focusing on the spacecraft's destination. In this study, the focus is on Earth-Moon transfers using B-plane targeting. The design of orbits to the Moon is mostly constrained by the orbital plane of this celestial body, which has led to diverse departure strategies, tailored to the specific conditions of the spacecraft and the mission [9]. To calculate the arrival at the destination, a B-plane targeting approach is employed, an imaginary plane defined by the spacecraft's trajectory and the position of the target body.

1) The Lunar Transfer Problem

There are multiple design methods to solve trajectories targeted to the Moon, through computation it is possible to compute accurate trajectories, which perform numerical integration of the equations of motion [3]. Due to the complexity of lunar motions, mission planning is highly dependent on the available lunar ephemerides. The general procedure involves defining initial conditions, $\bar{r}_0$ and $\bar{v}_0$, at the injection point (Fig. 3) and then applying a numerical integration method, such as the Runge-Kutta method [3], to compute the resulting trajectory. This trajectory, influenced by the initial conditions, may lead the spacecraft to impact the Moon or pass it completely. The objective is to adjust the injection conditions iteratively until a lunar trajectory is obtained that satisfies the mission objectives, seeking an arrival at the Moon with the minimum energy required for a given epoch.

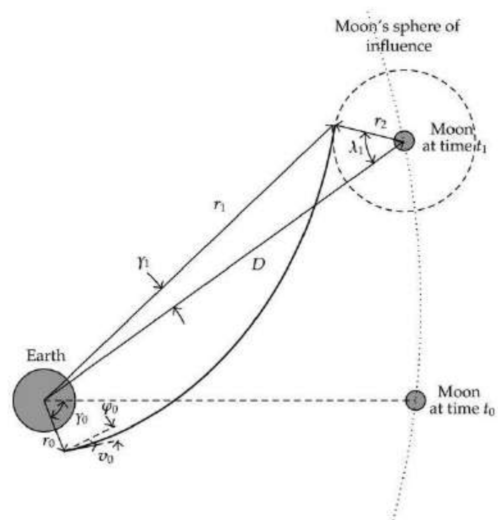

Fig. 3. Geometry of the geocentric phase Earth-Moon trajectory.
Source: [10].

The standard way to reach the Moon from the Earth is to use lunar transfer orbits. These orbits include the Earth parking orbit, the transfer orbit, and the lunar orbit [11]. The optimization of these orbits is crucial to minimize fuel consumption and maximize mission efficiency.

1. Earth parking orbit: This is the orbit around the Earth in which a spacecraft waits before starting a trip to the Moon. The altitude and inclination of this orbit can be optimized to reduce the energy required for the transfer.

2. Transfer Orbit: This orbit is used to carry the spacecraft from the Earth parking orbit to the lunar orbit. Optimization consists of choosing the appropriate launch window and determining the injection velocity.

3. Lunar orbit: Once in lunar orbit, the orbit can be adjusted to achieve precise insertion into the desired lunar orbit. This is essential for lunar landing missions or for a lunar orbiter.

However, the conventional and widely used method to achieve the Moon is the direct lunar transfer, which has been frequently employed since the first space missions directed towards our satellite, such as Luna 1, and has become a benchmark for numerous subsequent missions [12]. This means that to reach the moon there are two common ways of departure, from a parking orbit or from a direct transfer. This work focuses on the direct transfer method, because of its relevance to space missions and its importance within the capabilities of the software to be worked on.

Direct lunar transfers are defined as trajectories that depend exclusively on the gravitational influence of the Earth and the Moon. Although the Sun's gravity is considered, it is only taken into account as a perturbation in the transfer. A short-duration direct transfer involves a hyperbolic trajectory from Earth intersecting with the Moon, where the launcher provides the necessary delta-V for a Trans-Lunar Injection (TLI) maneuver into the transfer orbit [11]. This implies that the mission would start from step two, according to the general sequence described above. The most efficient direct transfers typically take 4-5 days, depending on the position of the Moon in its elliptical orbit, and resemble Hohmann transfers.

2) Trajectory Correction Maneuvers

In the mission context, after defining the departure method, trajectory correction maneuvers are contemplated, which is a maneuver performed by a spacecraft to correct or adjust its trajectory, usually in order to reach a specific target, such as the Moon. Trajectories can be perturbed by disturbing forces, or they may deviate from the intended path due to a targeting error during engine ignition. These errors are usually compensated for by the use of one or more TCMs, which is why these types of maneuvers were considered for the trajectories in this work, as it was desired to ensure that the spacecraft would achieve its destination accurately. These maneuvers may involve small adjustments in the spacecraft's velocity or direction, so in the case of direct transfer orbits it could be very useful to use these maneuvers after the TLI provided by the launcher, ensuring that the initial transfer parameters are adequate to initiate the course.

3) B-plane Targeting

The B-Plane, also known as the Body Plane, is an essential tool in space navigation that allows accurate and efficient planning of maneuvers near a target celestial body, such as the Moon or a planet, particularly useful for flybys, orbit insertion, or entry into a planetary landing module. In general, a spacecraft approaching a target planet will be in a hyperbolic orbit with its periapse as an insertion point near the opposite side of, in this case, the Moon [5]. This plane is an imaginary geometric concept in space that contains the target body and is orthogonal to the incoming asymptote of the spacecraft's trajectory, meaning it is perpendicular to the direction of the spacecraft's relative velocity as it approaches the celestial body (Fig. 4).

The utility of the B-plane lies in its ability to convert mission-relevant arrival parameters, such as altitude, inclination, and time of flight, into linear and easily manipulable values. Suppose the spacecraft is targeted for insertion into an orbit on the Moon, where the mission requires the spacecraft to arrive at a given time at an altitude of 100 km and an inclination of 40° relative to the lunar equator. The relationship between the insertion point (periapsis) and the spacecraft's velocity is not linear. However, the formulation of the B-plane allows for a linear relationship to be modeled between the B-vector of the target and the current velocity vector of the spacecraft.[13].

The B-vector is a fundamental component of the B-plane and represents the direction from the center of the target body to the point where the spacecraft would intersect the B-plane if there were no gravitational influence from the target body. This vector is defined by three-unit vectors: $\hat{S}$, $\hat{T}$ and $\hat{R}$, which represent the direction of the trajectory asymptote, the direction of the ecliptic plane of the target body, and the direction perpendicular to the previous two, respectively (see Fig. 4).

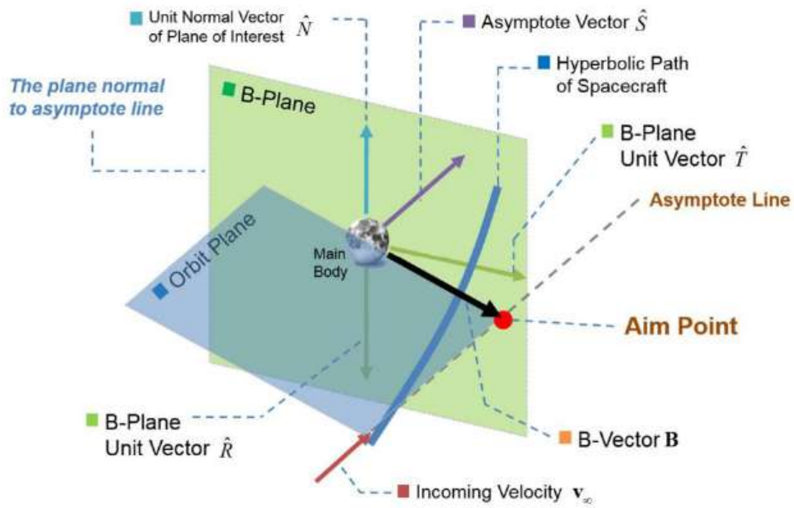

Fig. 4. Definition of target or arrival B-plane coordinates and B-plane vector.

Source: [14].

When utilizing B-plane Targeting to steer a spacecraft towards a target, it is important to consider the sphere of influence (SOI) of the target celestial body. This is because orbital insertion and trajectory correction maneuvers are planned taking into account the radius of gravitational influence of the celestial body, in this case the Moon, eq. (3) [6]. Therefore, when determining the maneuvers required to reach a specific point on the B-plane, it is crucial to consider how the sphere of influence affects the spacecraft's trajectory and maneuvers.

$$r_{\mathrm{SOI}} = R\left(\frac{m_{\mathrm{moon}}}{m_{\mathrm{earth}}}\right)^{\frac{2}{5}} \tag{3}$$

Where:

- r_{SOI} : Radio de la esfera de influencia de la Luna
- R : Distance from Earth to the Moon
- m_{earth} : Masa de la tierra
- m_{moon} : Masa Lunar

After modeling this approach to the target body, through a Lunar Orbit Injection (LOI) maneuver, the initial arrival parameters could be maintained, either by circularizing the orbit or following an orbit around the target with a required eccentricity. For the transfers worked, the LOI maneuver may become the only impulsive maneuver executed directly by the spacecraft's engines.

4) Delta-Vs Used for Earth-Moon Trajectories

In this section are presented some delta-vs used for direct trajectories to the moon, which served as a reference for the verification and validation of the results obtained in this work. Fig. 5 illustrates how the ΔV cost of a direct transfer increases moving away from the optimal transfer duration. However, the cost does not increase very rapidly until the transfer duration has changed by several days. Recent spacecrafts have taken advantage of optimal transfer durations to maximize the amount of payload sent to the Moon.

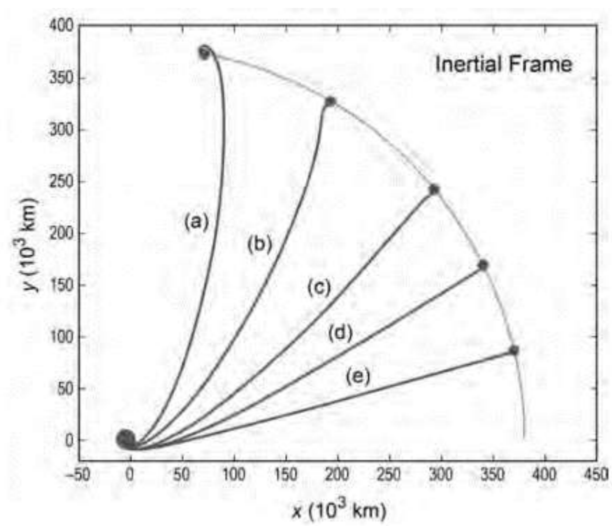

Fig. 5. Five example direct transfers shown in an inertial frame.

Source: [12].

The five examples in the graph show direct transfers from Earth to 100 km lunar orbits. These trajectories have been generated in the circular restricted three-body system. The following table (TABLE I) [12] applies to the labeled trajectories, showing the required delta-vs for each one:

TABLE I
DELTA VS OF EACH TRAJECTORY IN FIG. 5

	Direct Lunar Transfers			
Traj.	Duration (days)	ΔV_{TLI} (km/s)	ΔV_{LOI} (km/s)	Total ΔV (km/s)
(a)	6.0	3.138	0.829	3.966
(b)	4.5	3.134	0.813	3.948
(c)	3.0	3.152	0.893	4.045
(d)	2.0	3.240	1.248	4.488
(e)	1.0	3.831	3.024	6.854

Since the missions addressed in this project are based on direct injection, the delta V of the TLI will be provided by the launcher's boost. Therefore, for the missions in this study, the total delta V will be assumed as the delta Vs for the LOI maneuver. Consequently, the results obtained from the simulations should closely match those established in the reference table.

C. Orbital Trajectory Optimization

In the context of space navigation, optimization refers to the process of determining a trajectory for a spacecraft that meets specific initial and final conditions [15]. In general calculus, an optimal solution is found by taking the derivative of a known function and determining the minimums or maximums of this derivative [16]. Optimizing the trajectory of a spacecraft poses a considerable challenge, given that the dynamic system is nonlinear and many trajectories have points of discontinuity, either due to gravitational assists, thruster adjustments, thrust maneuvers, or coordinate transformations. Additionally, the initial and final conditions may not be explicitly known, as is the case in interplanetary missions whose conditions depend on the location of the planets at the time of departure and arrival, which are often optimized variables [15]. Due to the aforementioned difficulties, the design of optimal trajectories is performed computationally, which allows the iteration of different simulations, which means obtaining multiple results for the trajectory function.

There is no single variable selected to optimize all orbital trajectories, as the choice of the optimal variable depends on the specific mission parameters. Typically, a mission might require a trajectory that minimizes fuel consumption, power usage, flight time, or improvements in arrival or departure positions. Therefore, it is crucial to understand the objectives of a particular mission to select the optimization variables.

D. Optimization Software's for Space Trajectories

Several software packages are available to model missions and optimize orbital trajectories, including open source and non-public options. NASA has developed several of these software tools, although most are restricted to use by NASA centers or for U.S. government purposes. Among the open-source packages available from NASA are GMAT (General Mission Analysis Tool) [17] and the Trajectory Browser, with GMAT being the most widely used due to its higher fidelity and fewer limitations.

GMAT is used for the planning, analysis, and simulation of space missions, offering a wide range of capabilities for modeling orbital trajectories, calculating orbits around celestial bodies, planning space maneuvers, and optimizing interplanetary missions. This software is used in support of real-world missions, engineering studies, as an educational tool, and for public engagement. In addition, GMAT features models of real-world objects, such as spacecraft and thrusters, as well as analysis tools, such as propagators, graphs and reports. It is worth noting that GMAT is one of the software used in the development of this academic practice.

Outside of the tools developed by NASA, there are other software packages for orbital optimization, most notably System Tool Kit (STK), which is used globally by public and private sector organizations to model terrestrial, maritime, airborne, and space systems. However, the high cost and complexity of STK may limit its accessibility and comprehension for some users [8].

IV. METHODOLOGY

In this section, the methods and procedures employed to address the research objectives outlined in this internship project are presented. It describes the strategy used to collect, analyze and interpret the data necessary to answer the research questions and achieve the established objectives. The strategy is organized into sections covering how the internship was developed and the application of procedures for integrating capabilities and improvements in the "To The Moon" module.

The type of approach of this internship is fundamentally practical and applied, with a combination of theoretical research and practical work. The utilization of digital tools and specialized software, such as Visual Studio Code [18] and GMAT, is emphasized for carrying out the tasks. Additionally, a quantitative approach is adopted due to the collection of numerical data and simulation results, which are used to analyze the performance of orbital trajectories to the Moon. This method involves the use of statistical analysis and numerical data to evaluate and quantify the impact of the various strategies and improvements implemented on the trajectories.

A. Work Strategy

The academic internship was developed remotely, which involved an initial adaptation to the working environments under the mentorship of Emily Doughty and Dr. Sonia Hernandez during the first two months. During this familiarization period, a solid framework of guidance and support was established for the intern. Weekly or bi-weekly tasks were defined, outlined in a structured schedule (see TABLE II), designed to effectively achieve the project's objectives. To maintain fluid communication and progress monitoring, regular meetings were held, scheduled two to three times a week. In these sessions, the progress made on each of the assigned tasks was presented, allowing for constant feedback and continuous alignment with the goals of the academic internship.

TABLE II
TIMELINE OF ACTIVITIES

WBS NUMBER	TASK TITLE	START DATE	EXPECTED END DATE	DURATION (WEEKS)
1	**Earth to Moon Upgrades**			
1.1	**Review and Small Upgrades To The Moon**			
	Docstrings P2M.jl impulsiveP2M.jl	10/10/2023	10/23/23	2.0
	Outline similarities in P2M and P2P functions	10/16/23	10/23/23	1.0
	Add table to terminal with results	10/10/2023	10/16/23	1.0
	Add warning message if launch date varies from input in CONTROLLER	10/03/2023	10/10/2023	1.0
	Add warning message if launch date varies from input in VIEW	10/23/23	11/06/2023	2.0
	Output file updates	11/06/2023	11/20/23	2.0
	Generate plots if flag is true	11/20/23	12/04/2023	2.0
1.2	**Trade Analysis / Launch Window (1 month)**			
	Decide inputs for trade analysis (launch date, arrival conditions, etc.)			1.0
	Develop prototype			2.0
	Blueprint outputs (pork chop plot, DV, TOF)			2.0
	Add capability in Ctk			3.0
	Blueprint inputs/outputs in controller and view			2.0
1.3	**Translunar Injection**			
	Review code in P2M.jl for tranlunar injection	10/23/23	10/30/23	1.0
	Write GMAT prototype assuming a given state at epoch (get rid of TLI)	10/23/23	11/06/2023	2.0
	Infuse into CTK	11/06/2023	11/20/23	3.0
	Blueprint inputs/outputs in controller and view	11/20/23	12/04/2023	2.0

B. Implementation of New Capabilities in CTK

The review of the code hosted in the lunar injection module proved to be a valuable and insightful starting point for understanding the functioning of the capabilities already integrated into CTK. The diagram (Fig. 6), prepared by the previous intern, was especially helpful in understanding the code steps followed during a mission in the "To the Moon" module. Building on the understanding of this function scheme and with Emily's guidance, the following procedures were initiated to add a new capability to the module, focused on a direct transfer orbit to the Moon.

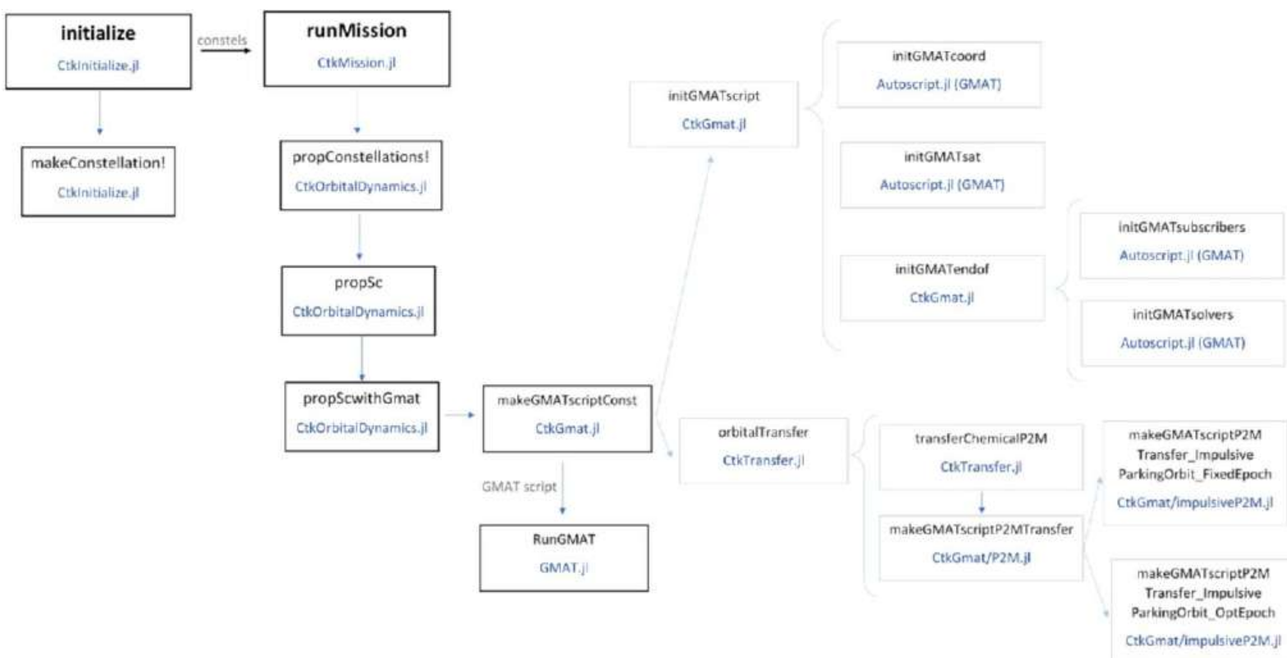

Fig. 6. Earth to Moon impulsive parking orbit transfer functions outline.
Source: Continuum documentation [19].

1) GMAT Mission

Before implementing a capability in CTK, a prototype is created using the software developed by NASA for space orbit simulation, GMAT. This open-source tool has been widely used in successful missions, highlighting its relevance and acceptance in the industry. To carry out the mission, a script is used to provide instructions to the software, guiding the spacecraft from an initial state to a final state, using the surrounding planetary dynamics.

The success achieved by this direct lunar orbit transfer mission prototype is crucial for its subsequent integration into CTK. For this reason, several iterative versions were elaborated until reaching the final version, following the methodology detailed in the following image (see Fig. 7):

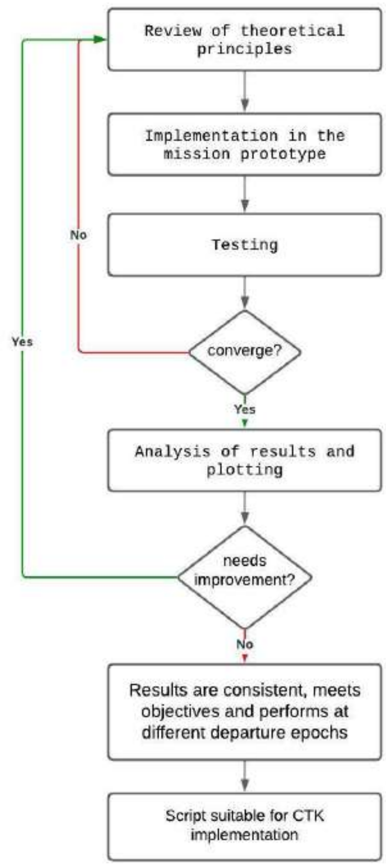

Fig. 7. flowchart for creation of the initial script.

2) *Embed script to CTK*

After obtaining a functional prototype to serve as the basis for the new capability, the next step is to integrate the script into the virtual machine hosting the CTK codes. In this case, the Visual Studio Code environment is used, which acts as the code editor accessing a shared repository on GitHub. This platform facilitates collaboration and version control of the CTK software, allowing different groups within the company to work on the project simultaneously. It also enables efficient tracking of code changes and management of issues and suggestions.

The VS Code editor supports a wide variety of programming languages. The primary language used in implementing the new capability in the backend is Julia, specifically designed to address tasks in the field of technical and scientific computing. Julia provides an optimal balance between productivity and computational performance, making it an ideal choice for this project.

Furthermore, to store mission-specific data, text files with a ".JSON" extension are used. These files adhere to the JSON (JavaScript Object Notation) format, known for being a lightweight data interchange format. In this context, JSON is used for communication between the server and the web application, specifically the main CTK software, facilitating interaction with the frontend of the system.

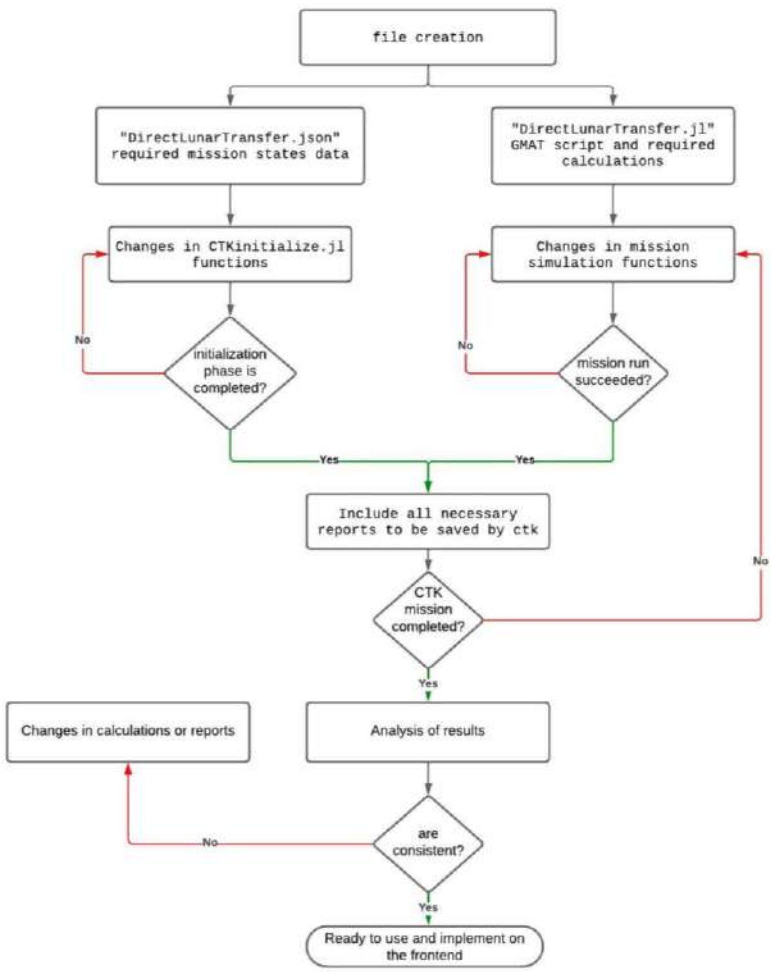

Fig. 8. flowchart used for CTK backend implementation.

To complete the implementation of the new capability, adjustments are made to various functions stored in files with ".jl" extension, following the flow outlined in Fig. 6. This flow begins with an initialization sequence, then proceeds through relevant functions to establish the necessary features for running the mission, including the execution of GMAT, and concludes with the function containing the script mentioned in item 1 of this subsection. To describe the methodology of integrating the script as a new capability, the flowchart in Fig. 8 is presented.

3) Frontend integration

Finally, a document is generated that includes all the input conditions that the user can modify to define both the departure and arrival orbital states as well as the mission date. This document also presents the relevant outputs, which serve as support for the analysis of the resulting mission, offering organized data with their corresponding units, images of the final orbit, and illustrative graphs. For the creation of this document, a comprehensive analysis of the mission is carried out, and the key points that need to be highlighted in the results are identified, thus ensuring a clear and comprehensive presentation of the information in the frontend.

The Software team will be responsible for providing all the necessary visual elements, based on the detailed information presented in this document about the new capability. In this final step, the user inputs are integrated with the ".json" file that initializes the mission and the presentation of outputs through the ".csv" reports obtained in item 2 of this subsection.

V. RESULTS

A. Warning Departure Epoch

One of the capabilities of the CTK platform is to optimize departure dates from parking orbits to the moon. The person in charge of this capability was able to identify situations in which a change of departure epoch was necessary with the intention of improving the total delta V and time of flight These cases typically occur when the arrival inclination angle at the moon is defined by the client between 0 to 10 degrees and/or when the departure inclination angle is < 20 degrees. When taking into account the behavior of this capability on the platform, it was evidenced that after the mission was implemented in these cases the epoch changes are performed correctly, but the client was not specifically notified of this change.

For a better interaction with the client and the platform, it was decided to implement a warning message, where the user who configured the initial parameters is informed that the trajectory has been optimized with the requested characteristics to an epoch close to the departure time entered. Therefore, an analysis of the inputs and outputs of the code done by the previous intern was conducted to determine which epochs needed to be compared and where it was necessary to add this warning, as seen in Fig. 9 , "epoch" is the variable that indicates the output epoch entered by the user and "sc.epoch" is the optimized output epoch or resulting from the mission. These are compared at the end of the mission to know if they are the same or not and thus show the warning message to the customer when they are different.

```
# "epoch" is the departure epoch requested by the user and the "sc.epoch" is the optimized one by the simulation.
#  this is relevant for p2m simulations specifically
warningf = joinpath(genIn.gmatf,"$(genIn.name)$(sc.naifid)_warning.csv")
if epoch != sc.epoch
   warning_message ="The departuve epoch has been optimized to: $(sc.epoch)."
   @warn (warning_message)
   open(warningf, "w") do f
       write(f, warning_message)
   end
end
```

Fig. 9. Epoch comparison for warning.

Initially, this message only appeared alongside the outputs of the backend (Fig. 10). After this initial result, it was tested for correct operation with a variety of backend simulations.

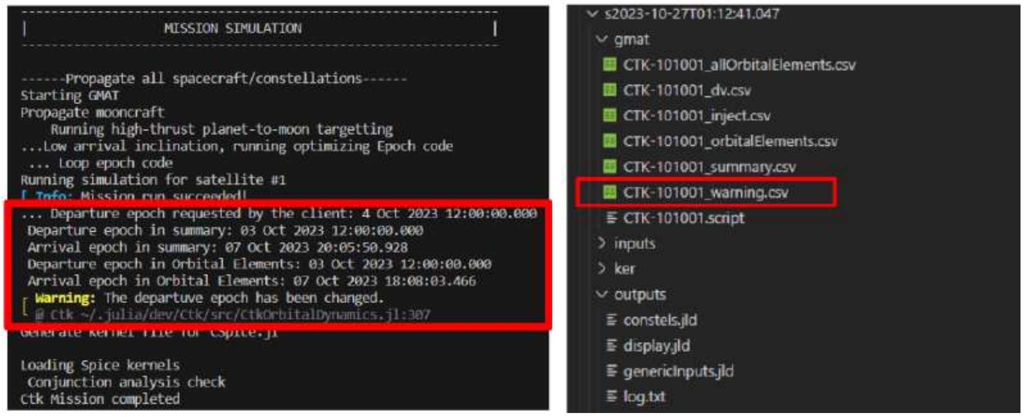

Fig. 10. Backend outputs with warning.

To implement this message in the frontend, a CSV document was added within the "if" statement, as shown in Fig. 9, which is included a report to the missions that use the function makeGMATscriptP2MTransfer_ImpulsiveParkingOrbit_OptEpoch, which are the ones that implement the output epoch optimization, through this file the message display can be delivered to the front-end, which will finally show to the customers this message in the CTK platform interface.

Then, if we start from a mission whose initial characteristics are detailed in TABLE III (arrival inclination = 0), the user will be able to visualize, together with the results of the mission design, a warning message on the platform (Fig. 11). This provides them with the opportunity to consider this optimization as a crucial aspect for the implementation of their final mission.

TABLE III
INPUT FEATURES FOR MISSION SAMPLE

	Departure Date	**2023-10-04 12:00:00**
Inputs Orbit	Departure	Arrival At the Moon
SMA (km)	18000	100
ECC (deg)	0.7	0
INC (deg)	28.5	0
RAAN (deg)	0	0
AOP (deg)	0	0

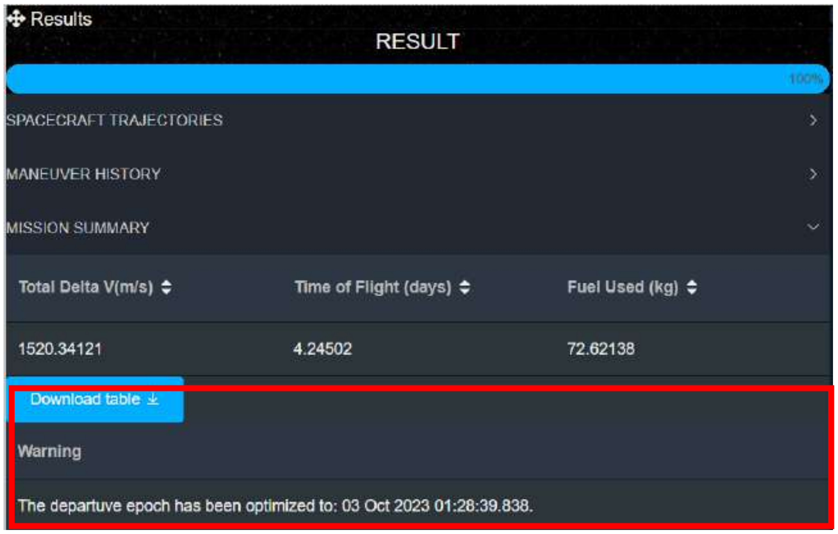

Fig. 11. CTK outputs with warning.

B. Expanded Departure Capabilities

The "To The Moon" module hosted on the CTK platform, described above, has different departure capabilities for lunar missions, among which are departures from Low Earth Orbit (LEO) and Geostationary Transfer Orbit (GTO). With the intention of having more flexibility in the planning and execution of missions implemented by the CTK platform, a new departure capability to the Moon was developed in this internship.

There are two possible methods for leaving the Earth and targeting the vicinity of the Moon. The first is lunar injection from a direct launch, and the second is lunar injection from a parking orbit. Having already covered departures from parking orbits (LEO and GTO), the new departure capability to be developed was lunar arrival from a direct launch, which as seen in Fig. 12. In this method, the rocket not only provides the energy to depart from Earth but also, through an injection maneuver, places the vehicle on a translunar trajectory.

Following the company's methodology for incorporating new capabilities into its platform (Fig. 7 y Fig. 8), it started with the development of a script in the GMAT software. This script, which represents the prototype of the direct transfer mission, was developed during the academic internship and served as the basis for the CTK code in later stages of the process.

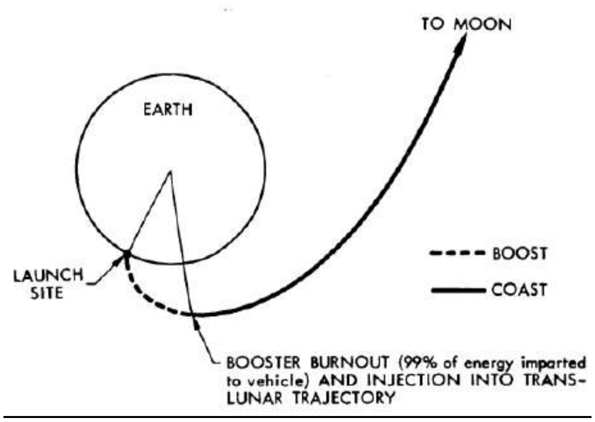

Fig. 12. Lunar injection from a direct launch.

Source: [11].

The design of direct transfer orbits is based on the delta V costs inherent to the vehicle, which begin immediately after entering the lunar trajectory. To obtain the initial state parameters of the satellite, it was decided to use the "CTK-101001_dv" report. This report is generated each time a mission from the "To The Moon" module is executed and contains data corresponding to the simulated satellite just after performing its lunar injection maneuver (TLI burn). In other words, this specific moment of lunar injection is crucial as it represents the necessary initial state for the script of the new capability.

```
Maneuver Name, S/C ID, Phase, Mnvr Duration (s), DV (km/s), Epoch (UTC), X (km), Y (km), Z (km), VX (km/s), VY (km/s), VZ (km/s), DM (kg)
TLI,-101001,0,0,0.7142114261448196,01 Jan 2022 10:31:20.162,-6268.883866602889,3049.460805542058,2210.954036137673,-3.08138070752278,-9.102085639701848,3.817191533249495,0
LOI,-101001,0,0,0.8458819717206987,05 Jan 2022 18:26:33.631,306331.6008972454,-175326.8430888293,-113673.7916920997,-0.02887989795513157,-0.5895038734744463,0.9094609027816951,0
```

Fig. 13. CTK report regarding the maneuvers.

To obtain various of these reports at different epochs, simulations were conducted by changing the date for each mission. These reports were then used as initial states which were subsequently employed to evaluate the new capability at its different stages. The initial state data used from these reports were as follows (Fig. 13):

- Epoch (UTC): Represents the date and time at which the satellite is located after the lunar injection (Initial Epoch).
- The Cartesian element set: contains the position (X, Y, Z) and velocity (VX, VY, VZ) of the spacecraft.

In reference to how the script was started, GMAT has several example missions, including one called "Ex_LunarTransfer.scrip" that implements a transfer orbit to the moon. This script was considered an appropriate starting point, since it served as a basis for knowing the mission sequence used. By implementing a different initial state than the default one in the example, the need to improve the "targets" within the GMAT "mission sequence" to achieve a code capable of converging in various direct lunar transfer missions became evident. This implies a deeper understanding of the mission and its targets. In the specific case of CTK, these are customers seeking to vary different initial parameters and obtain optimized results, especially in terms of total V deltas. All of the above and the results obtained in the example were taken into account to start developing the script that would be the main trunk of this new capability.

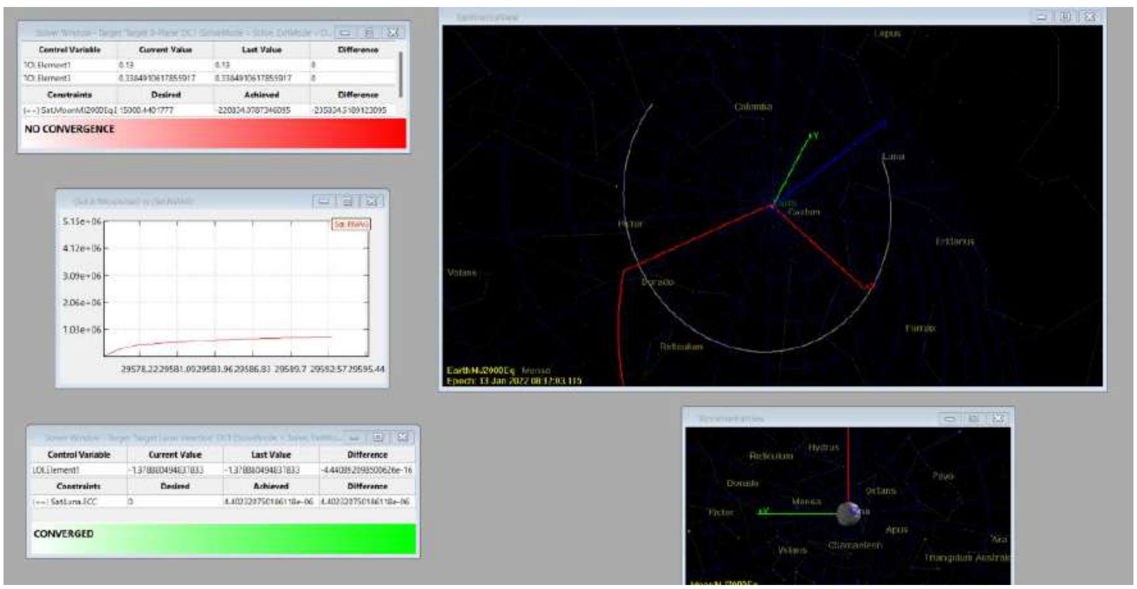

Fig. 14. Example script results.

The preceding Fig. 14 illustrates one of the results derived from the execution of the GMAT example mentioned above. Although different initial states were employed, the results showed similarities, indicating a lack of convergence in the mission. Nevertheless, it was decided to use the structure of the "Mission Sequence" of this example as the basis for the initial tests of the prototype, implementing new "targets" and "achievements" that helped to create a more complex prototype suitable for different times of direct translunar transfer. The results obtained in the process of this task are presented below.

C. TCM Implementation Test

As mentioned previously, the initial state of the spacecraft is established when it is already in a specific position and velocity on its lunar trajectory. This implies that the only planned ignition in the direct orbit design would be for lunar orbit injection (LOI burn), since the initial thrust was already provided by the rocket or booster that performed the Lunar Orbit Insertion (TLI).

A From the baseline example, the use of an additional maneuver to correct or improve the trajectory of this initial state was observed. Therefore, the first consideration was the implementation of a Trajectory Correction Maneuver (TCM burn), i.e., the inclusion of a low energy (small delta-V) maneuver that would redirect the spacecraft to ensure that the GMAT propagator converged correctly to the vicinity of the Moon.

As illustrated in Fig. 15, the initial orbit design involved the use of an optimizer that adjusted the three elements of the TCM and the velocity in the X-axis. Subsequently, the maneuver was applied, propagating the spacecraft to bring it to lunar distance and then to perilune, with a nonlinear constraint to ensure it remained at specific distance and angles. All of this was achieved by optimizing the delta-V used in the TCM maneuver, as it is crucial to keep energy consumption to a minimum.

```
%-------------------------------
%  Optimal Trajectory Correction Maneuver Lunar B-plane
%-------------------------------
Optimize NLPOpt {SolveMode = Solve, ExitMode = DiscardAndContinue, ShowProgressWindow = true};

   Vary NLPOpt(TCM.Element1 = 0.2, {Perturbation = .0000001, MaxStep = .01, AdditiveScaleFactor = 0.0, MultiplicativeScaleFactor = 1.0});
   Vary NLPOpt(TCM.Element2 = 0.1, {Perturbation = .0000001, MaxStep = .01, AdditiveScaleFactor = 0.0, MultiplicativeScaleFactor = 1.0});
   Vary NLPOpt(TCM.Element3 = 0.1, {Perturbation = .0000001, MaxStep = .01, AdditiveScaleFactor = 0.0, MultiplicativeScaleFactor = 1.0});

   Maneuver 'Apply TCM' TCM(Sat);

   Propagate 'Prop to Moon SOI' EarthFull(Sat) {Sat.Earth.RMAG = 325000, StopTolerance = 1e-05};

   Propagate 'Prop to Periselene' MoonFull(Sat) {Sat.Luna.Periapsis, StopTolerance = 1e-05};

   NonlinearConstraint NLPOpt(Sat.Luna.RMAG = 2500); % Periapsis
   NonlinearConstraint NLPOpt(Sat.MoonMJ2000Eq.BVectorAngle = 40); %Arrival angle

   GMAT DV = sqrt(TCM.Element1^2+TCM.Element2^2+TCM.Element3^2);

   Minimize NLPOpt(DV);
EndOptimize;  % For optimizer NLPOpt
```

Fig. 15. TCM maneuver test code.

The plot (Fig. 16) summarizes the TCM Delta-V results from 18 simulations performed on three different days, starting on November 14, 2022, and the following two 5 days and one month apart, respectively. From this plot, a pattern is observed that indicates a slight increase in Delta-V required when a smaller Moon arrival inclination is required, which decreases as a larger arrival inclination is requested. In other words, a smaller correction maneuver may be needed if the inclination of the orbit arriving at the Moon is requested at larger angles.

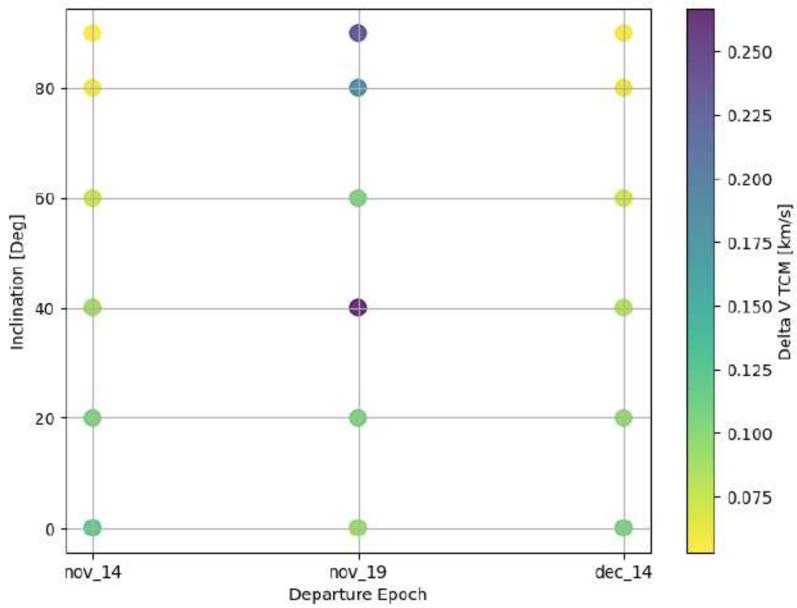

Fig. 16. Results plot of inclination vs. departure epoch using TCM.

During the data collection of delta-V to generate the previous graph, it was observed that although convergence was achieved in many of the initial test states, in some of them, especially when modifying the arrival inclination angles at the Moon, it was necessary to slightly adjust the initial data in terms of decimals of the satellite velocity components. An example of this phenomenon is presented below (Fig. 17). This finding was crucial to understand that, despite having a correction maneuver, the values of the components of such maneuver might not be sufficient to improve convergence in all cases, which implied finding different values for these components in each simulation, posing an additional challenge.

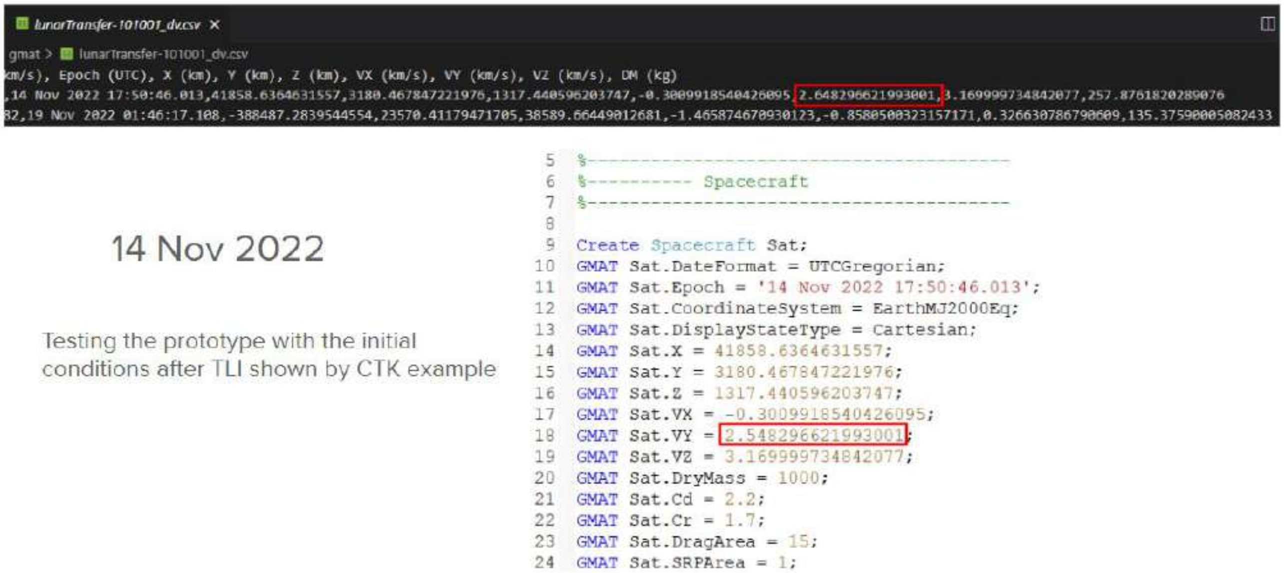

Fig. 17. Initial value setting.

The solution turned out to be simpler than expected. It was proposed to implement a "course target" before the optimizer, which varies the orbital elements RAAN and AOP, along with course refinement by varying the X and Y components of the satellite velocity. This target (Fig. 18), through velocity variations, ensured convergence at all epochs, and it showed improvement in the convergence speed, as the RAAN and AOP data converging in this target are saved to be used in the optimizer as initial data, saving steps for it to resolve. The target ends by defining a pair of "achieves", RA = 0 and DEC = 0, which, when propagating the satellite towards the Moon, ensure that the line of apsides aligns with the Moon.

Fig. 18. Course target test code.

After incorporating the "course target" into the script, it became evident that it had the potential to significantly improve the initial characteristics, to the extent that the TCM maneuver might not be necessary. Multiple tests were conducted to identify the best characteristics that would ensure convergence and minimize the total delta-V. In this regard, a comparison of results was made with TCM and without TCM (TABLE IV), obtaining:

TABLE IV
COMPARISON OF SIMULATIONS WITH TCM AND WITHOUT TCM

	Total Delta V		
Dec 14 – 2022 Arrival INC (deg)	with TCM Vary km/s	without TCM vary km/s	Difference km/s
0	0,69537015	0,69510806	0,00026209
20	1,05810333	0,691958	0,36614533
40	0,68998809	0,689084	0,00090409
60	0,68978648	0,68767	0,00212048
80	0,69049561	0,686529	0,00396661
90	0,68917371	0,685872	0,00330171

As can be seen, the discrepancy between using or not using the TCM is not considerable, but there are circumstances where it can have a significant impact on the total delta-V, as observed in the case of a 20-degree arrival inclination on December 14, 2022. The optimizer created for the lunar B-plane arrival works correctly even without the TCM, and convergence is even faster. By finding greater efficiency and lower delta-V without the TCM, this maneuver became unnecessary, and its use in the final script was discarded.

D. Final Script: Direct Lunar Transfer

After a series of adjustments and improvements in the script with the objective of complying with three fundamental aspects: to ensure convergence in most possible epochs and initial conditions, to minimize the total delta-V and to design the inputs of the mission considering the comfort of the user, the script in GMAT named "FinalPrototype_DirectLunarTransfer.script" was successfully developed. This script allows to carry out departure missions to the Moon both by direct launch and after Translunar Injection (TLI). In addition to satisfying the above criteria, the script has been appropriately simplified and focused on the needs of incorporating a new capability into the "To

The Moon" module. This prototype developed in GMAT [17] served as the basis for the integration of this capability into the CTK platform.

Current input limitations:

- **Departure**: After injection into translunar trajectory
- **Arrival**: [0-10000] km of perilune altitude and eccentricity
- **Dynamical Model**: point mass model for Moon, Earth, and Sun.

In this section, the different parts of the final script and the results obtained in GMAT with it are presented. Before the "Mission sequence," there is the section of general mission configuration, which includes:

1. General spacecraft description, where initial parameters, epoch, and Keplerian element set are entered. The coordinate system for positioning elements, although initially Cartesian, ended up being included as Keplerian for the customer's convenience in the use of the platform.
2. Three force models used: EarthPointMass_ForceModel, AllForces y MoonAllForces.
3. Three propagators: EarthPointMass, EarthFull y MoonFull.
4. One burn, in this case, an impulsive burn created for the LOI maneuver.
5. Three coordinate systems: EarthSunRot, MoonMJ2000Eq y EarthMoonRot.
6. Two Solvers: DifferentialCorrector (DC1) y Yukon (NLPOpt).

In the second important part of this script, there is the GMAT "Mission Sequence" which refers to a sequence of events and commands that are used to model and simulate a specific space mission. This sequence describes the flow of activities that occur during the execution of a mission, including initial configuration, orbital maneuvers, trajectory corrections, engine burns, data collection, and any other relevant event for the mission.

Within this Mission Sequence, a series of steps and actions that are performed during the mission simulation were specified and programmed. These steps include orbit setup, maneuver planning, and report generation. Below are the steps designed in this internship for the direct transfer from Earth to the Moon using an impulsive maneuver:

1) Course Lunar Target

The first step of the mission involves obtaining the first arc of the orbit (Fig. 19) by calculating and adjusting the satellite's heading to ensure an approach to the Moon. This ensures that the initial position and direction of the satellite are correctly oriented towards the Moon. Since the system is dynamic, the mission is propagated to achieve the expected final position. This step was crucial, as highlighted in the "TCM Implementation Test" section, as it adjusts the satellite's velocity components and ensures that the line of apsides aligns with the Moon by achieving a "achieve" of the RA and DEC.

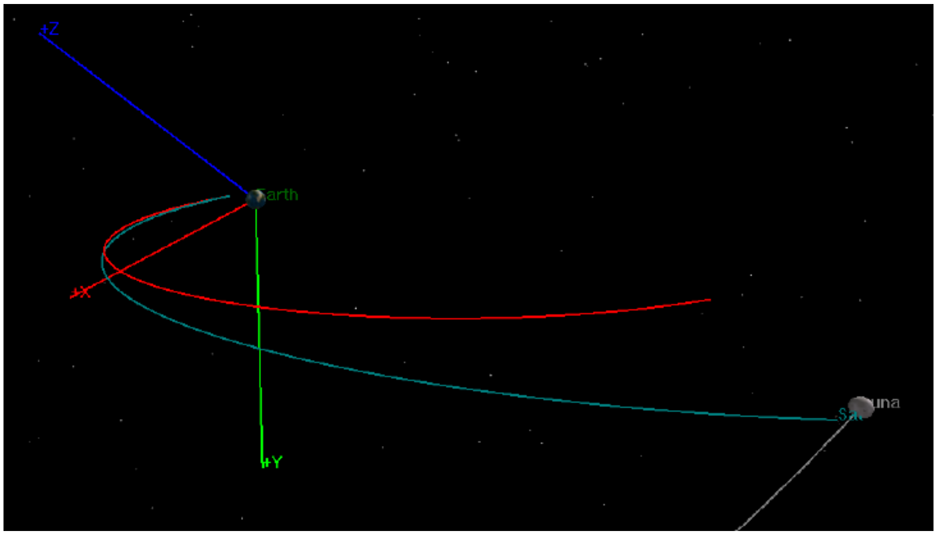

Fig. 19. RA and DEC achieve with course target.

After performing numerous simulations, it was found that for some initial states the "course lunar target" did not converge with the mentioned achieve. As can be seen in the diagram (Fig. 20), this situation implies a decision-making process. To address this situation, it was decided to implement an "alternative course lunar target", which defines as a constraint the RMAG, allowing the satellite to propagate towards the vicinity of the Moon. This "alternative course lunar target" serves as an alternative solution for those cases in which the solver "DC1" fails to converge to the first target and ensures the implementation of a course target for the following steps. Fig. 19 shows a case where this happens, the red line is the first target that did not converge and the blue line is the second alternative target.

Another important consideration in this step is that the values of RAAN and AOP are saved for the next step. These data are crucial for reducing the computational load of the propagators in the next step, as well as to facilitate fast convergence within the step parameters enabled for the solver.

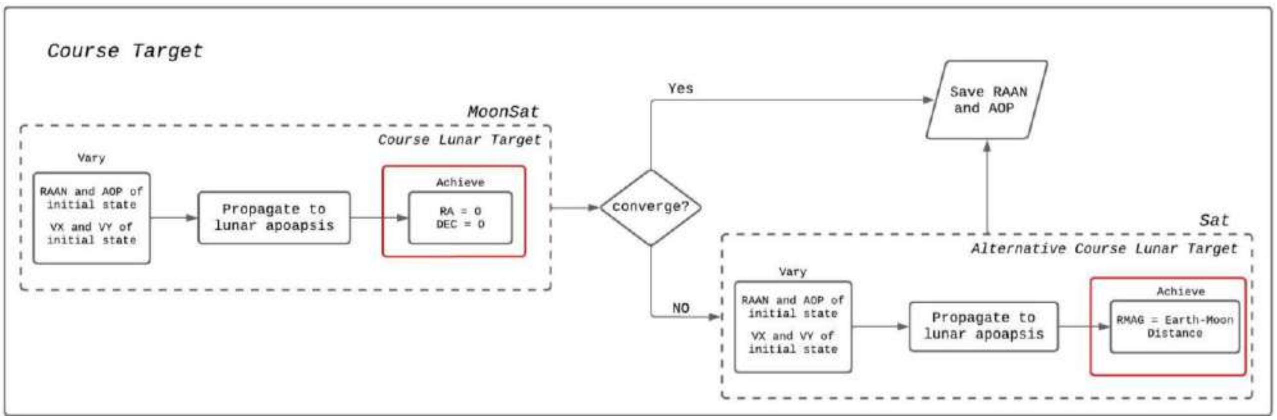

Fig. 20. Block diagram of the code part for course target.

2) B-plane Lunar target

This next step is responsible for positioning the spacecraft directly on the B-plane of the Moon. Building upon the previous step, information is available indicating that the satellite is relatively close to the Moon, along with RAAN and AOP data that serve as a starting point for variation in this target. During the variation of these parameters, the spacecraft propagates towards the Moon's sphere of influence (SOI) and also towards the periselene, which facilitates the identification of the point at which the maneuver will be applied in the next step.

The achieve of this step are directly related to defining the initial parameters of the orbit in which the spacecraft will reside on the Moon, as it involves propagating the spacecraft towards the B-plane of the Moon, also known as the body plane, which happens to be a useful mechanism for targeting a specific hyperbolic pass. In general terms, a spacecraft approaching a target planet will be in a hyperbolic orbit, with its periapsis as the insertion point near the opposite side of the Moon in this case (Fig. 21).

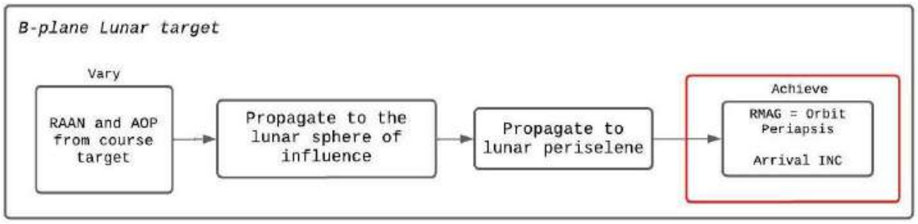

Fig. 21. Block diagram of the code part for B-plane.

The relationship between the target insertion point (periapsis) and the spacecraft velocity is nonlinear. However, the B-plane formulation allows modeling a linear relationship between the B vector of the target and the current velocity vector of the spacecraft, which is fundamental for the design of the LOI maneuver, developed in the next step. In conclusion, in this step, the periapsis of the hyperbolic orbit entering the Moon and the inclination angle with which it will enter are defined (Fig. 22).

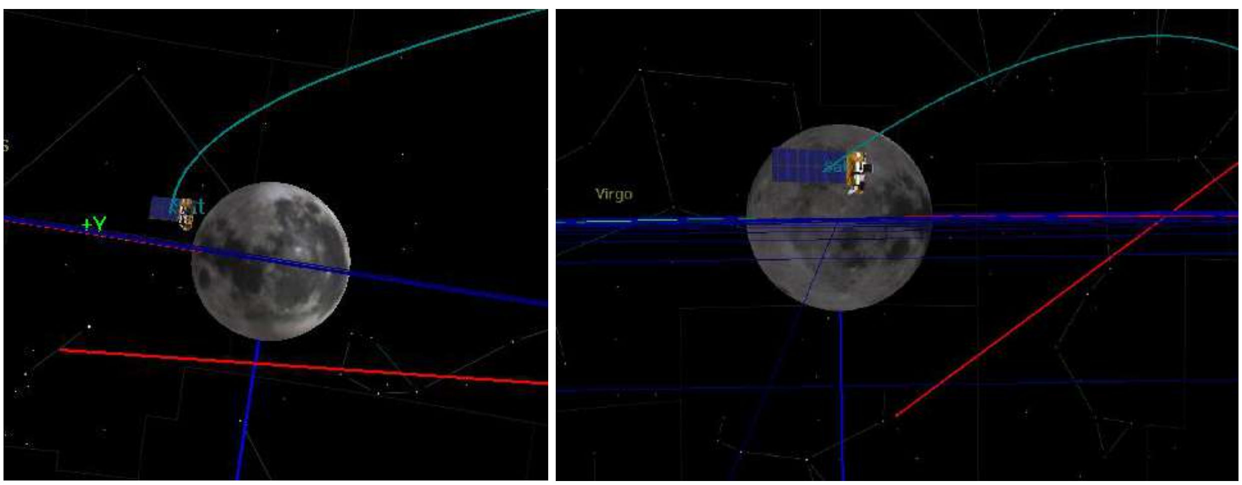

Fig. 22. Arrival course to the Moon using the B-plane, with an angle of inclination of 40 degrees (blue line).

3) Lunar insertion optimizar

This last step involves the use of an optimizer in GMAT. Optimization is a common practice in trajectory scenarios, where one seeks to find an optimal solution by determining the minimums or maximums of a known derived function. The optimal solution can be the absolute minimum or maximum (global optimum), depending on the application.

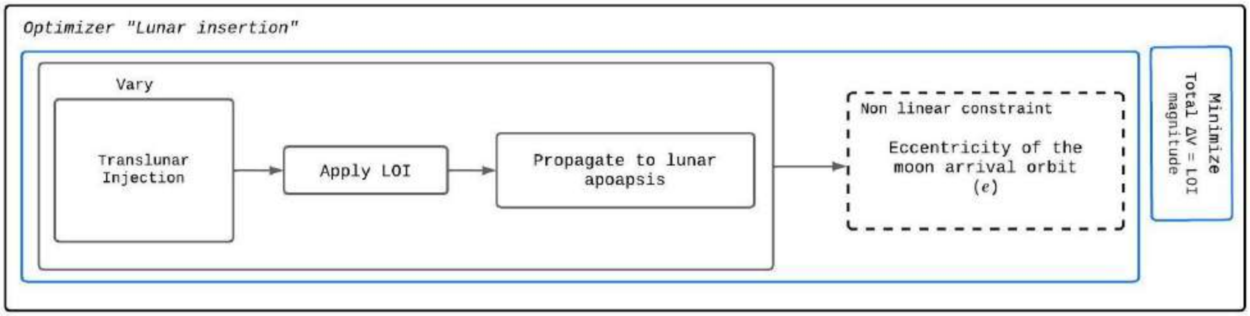

Fig. 23. Block diagram of the code part for optimizer insertion.

In this case, the goal is to optimize the trajectory of a spacecraft for its insertion into a lunar orbit (Fig. 23), satisfying specific initial and final conditions. By varying the initial value (LOI calculated analytically), the orbit propagates to reach its apoapsis, with the eccentricity of the final orbit as a nonlinear constraint (Fig. 24). The optimizer's task is to find the value for a minimized burn-in impulse (LOI), this being the only maneuver in the entire mission and the parameter that customers usually wish to minimize.

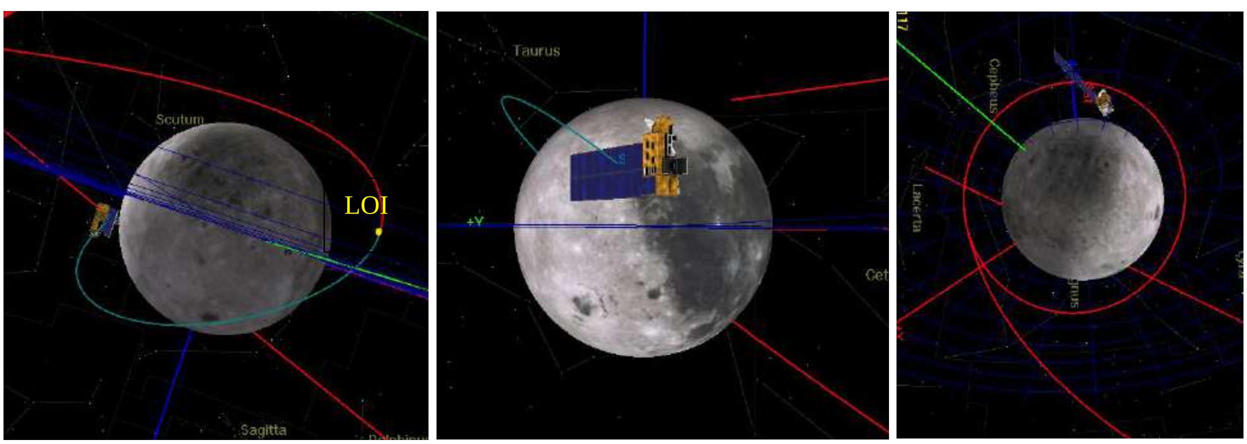

Fig. 24. Lunar insertion maneuver point and final orbit.

In summary, after describing in detail the mission steps in the GMAT script, 36 simulations were performed between November 9 and November 14, 2022, where the arrival inclination was varied to calculate the total delta V values. These results were subsequently plotted in the following graph (Fig. 25).

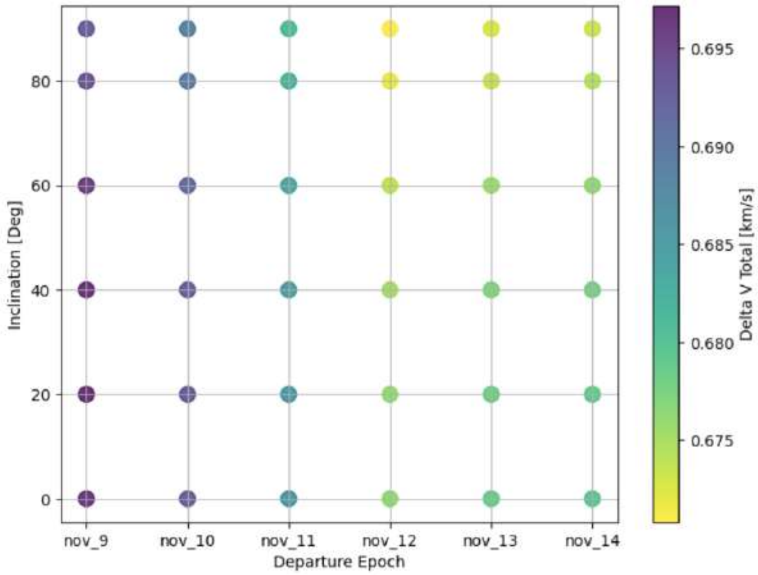

Fig. 25. Plot with results obtained by final script.

From the plot, it can be inferred that due to the precession or changing relative position of the Moon with respect to the Earth in terms of the reference angles, there are days when insertion into the Moon requires a higher energy expenditure for a body to orbit it. Additionally, the Moon arrival inclination is a parameter that can also influence the delta V used for insertion on the same day. In other words, there is a correlation between the departure date and the arrival inclination, where it is observed that the higher the inclination angle, the lower the delta V required, while the lower the angle, the higher the delta V required.

E. Direct Lunar Transfer in CTK

The final integration of the final script into CTK was carried out, following the methodology presented in Chapter IV Section B. In the backend of CTK, there is a DirectLunarTransfer.JSON file containing the mission's input data (Fig. 26). These data are initialized from the code hosted in CtkInitialize.jl, allowing the identification of the mission type and execution of the corresponding function for Direct Lunar Transfer missions, located in the DirectLunarTransfer.jl code file.

```
"id":"mooncraft",
"orbit":{
  "cbs":"MyEarth",
  "constellation":"single_orbit",
  "single_orbit_orbel":[
    // Define departure orbit
    {"aso":216733.0838380638,        //km
     "eso":0.8062134434860992,
     "iso":49.99999999494605,         //deg
     "aopso":22.03841579891865,      //deg
     "RAANso":17.83083410281042,     //deg
     "Mso":359.9999987925818,         //deg
     "launch_date":"15 Jul 2022 00:00:00.000"} //not used
    ]
```

```
  "inputs":[
    {"sc_id":1,"self":true,"transfer_type": "p2m_direct",
     "cb_arr":"Moon",
     "burnType": "impulsive",
     "capture": true,
     "piggy_back": false,
     "dep_coast_revs":0,
     "arr_orbits":[{
     "type": "custom",
     // Define the arrival lunar orbit
     "hpso":100.0,       //km
     "haso":100.0,       //km
     "iso":40.0,         //deg
     "aopso":0,          //deg
     "RAANso":60,        //deg
     "Mso":0,            //deg
     }]}
  ]
},
"missionsettings":{
  "t0":"14 Dec 2022 17:50:46.013",   //UTC, begin epoch
```

Fig. 26. Main inputs of the .JSON file.

The results obtained are presented in the VS code terminal (Fig. 27), the work of this internship reaches this point of application, in which we can see a complete implementation in the backend of CTK, where different missions of this platform are hosted. It is important to point out that the frontend application is managed by another extension of the company, in charge of executing what has already been designed for direct transfer missions to the Moon in the interface.

```
-------------------------------------------------------------
|                     INITIALIZATIONS                       |
-------------------------------------------------------------
Initialize generic inputs
Initialize Ctk infrastructure objects
    Making body MyEarth
    Making body Moon
    Making constellation mooncraft
        Initialize Orbit
        Initialize Spacecraft hardware
        Initialize Mission Settings
            N-BODY PERTURBATIONS is true
        Initialize Analysis specific data structures
            TRANSFER analysis is ON
             tranIn.self = true - nothing further to do
p2m direct
-------------------------------------------------------------
|                   MISSION SIMULATION                      |
-------------------------------------------------------------

------Propagate all spacecraft/constellations------
Starting GMAT
Propagate mooncraft
 ...Running direct lunar transfer targetting
    Input Departure and Arrival Orbital Elements:
2×8 DataFrame
 Row │ Type       SMA_km     ECC       INC_deg  RAAN_deg  AOP_deg  TA_deg       MA_deg
     │ String     Number     Number    Number   Number    Number   Number       Number
─────┼─────────────────────────────────────────────────────────────────────────────────
   1 │ departure  2.16733e5  0.806213     50.0   17.8308  22.0384  -1.9022e-5   360.0
   2 │ arrival       1837.4       0.0     40.0      60.0      0.0         0.0     0.0
Running simulation for satellite #1
[ Info: Mission run succeeded!
Generate kernel file for CSpice.jl
    Optimized Orbital Elements:
4×11 DataFrame
 Row │ sma (km)    ecc          inc (deg)  raan (deg)  aop (deg)  ta (deg)  ma (deg)  depEpoch                  OrbitType  Delta V (m/s)  Delta Mass (kg)
     │ Float64     Float64      Float64    Float64     Float64    Float64   Float64   String                    String     Any            Any
─────┼────────────────────────────────────────────────────────────────────────────────────────────────────────────────────────────────────────────────
   1 │   2.16733e5  0.806213        50.0     17.8308    22.0384     360.0     360.0   14 Dec 2022 17:50:46.013  Initial    -              -
   2 │   2.16733e5  0.806213        50.0     17.8308    22.0384    172.46   139.389   14 Dec 2022 17:50:46.013  Departure  -              -
   3 │ 1837.87      0.000300061     40.0    163.536    313.006      180.0     180.0   18 Dec 2022 19:15:52.998  Arrival    774.412        197.122
   4 │ 1837.87      0.000299891     40.9012 163.534    313.1        179.9     179.9   18 Dec 2022 22:12:17.657  Final      -              -

Loading Spice kernels
 Conjunction analysis check
Ctk Mission completed
-------------------------------------------------------------
```

Fig. 27. CTK backend terminal results for the dec 14, 2022 direct lunar transfer mission.

In addition to the results displayed on the backend terminal, GMAT generates the reports requested in the final script and saves them in the folder designated for the simulation, together with the mission-specific script (Fig. 28). These reports are in CSV format:

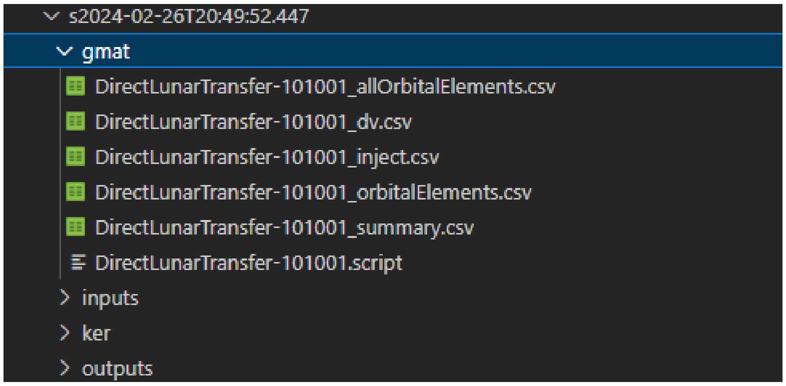

Fig. 28. GMAT report outputs in simulation folder.

- _allOrbitalElements: Shows the Keplerian orbital elements for four moments of the trajectory (Initial, Departure, Arrival, Final).
- _dv: Displays the maneuver performed (LOI), maneuver duration time, delta-v used and Cartesian orbital elements.
- _inject: Shows the Keplerian orbital elements just after the maneuver.
- _orbitalElements: Shows the same as "_allOrbitalElements", but only for two moments (Departure and arrival).
- _summary: Shows the Cartesian orbital elements of the initial and final states of the trajectory.

VI. CONCLUSIONS

The results of this degree work reflect the success achieved in the analysis, improvement and expansion of the "To The Moon" module of the CTK platform, focused on the planning of orbital trajectories to the Moon. The new capability of departure from a translunar injection state was introduced, which significantly expands the options for lunar mission planning, offering greater flexibility to CTK platform users to tailor their missions to their specific needs.

The development process of this new capability, based on creating a prototype in the GMAT software, ensured a smooth transition from the development phase to practical implementation in the CTK backend, guaranteeing consistency and compatibility between all stages of the project. The GMAT prototype allowed the design of a final script, named "FinalPrototype_DirectLunarTransfer.script", facilitating missions departing to the Moon after a Translunar injection (TLI). The inclusion of a "course target" and an "alternative course lunar target" in the script ensures convergence in most possible departure epochs and initial conditions that may occur in this capability. Moreover, the implementation of an optimizer in the final GMAT script for optimized lunar insertion proved effective in minimizing the total delta-V required for the mission.

A correlation was observed between the departure date and the Moon arrival inclination, where the higher the inclination angles, the lower the delta-V required. These results significantly strengthen the "To The Moon" module and contribute to the possibilities of using CTK, being direct lunar transfer a conventional and widely used method to reach the Moon.

Finally, as part of the module enhancements, adjustments were made to the user interface to provide better understanding and analysis of planned trajectories to the Moon, including the implementation of a warning message to inform users of optimized epoch changes.

A. *Recommendations*

Some recommendations for future research or improvements within the CTK platform include:

- Explore methods for inputting initial conditions for the new capability: Given the complexity and inherent dynamism of space and space missions, it would be beneficial to conduct a detailed analysis of specific initial conditions in missions that do not involve a parking orbit transition. For example, exploring the possibility of obtaining these initial data from launcher capabilities or available launch data could be considered. This alternative approach would provide an additional pathway to acquire and refine the initial data necessary for lunar mission planning, thus enriching the versatility and effectiveness of the CTK platform in managing various space operations.

- Perform extensive validation testing: It is essential to conduct comprehensive validation testing to ensure the accuracy and reliability of the improved module. This includes testing under different conditions and scenarios to evaluate its performance in a variety of situations.

- Research could be extended to explore the applicability of maneuvers other than impulsive maneuvers, both for arrival around the Moon and for mission-long variations of the arrival orbit.

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Una Facultad para una sociedad del aprendizaje

Enhancing Lunar Mission Capabilities: CTK

Presentación de semestre de industria

Fernanda Mendoza
Departamento de Ingeniería Mecánica
Ingeniería Aeroespacial
Universidad de Antioquia

24 Abril 2024 - Carmen de Viboral

Continuum Space Systems

Is a Software-as-a-Service for space startup. The service is based, in part, on technologies licensed from California Institute of Technology (Caltech), which is the parent company of the Jet Propulsion Laboratory (JPL).

Mission is to accelerate space exploration for the benefit of humanity. We provide ‘picks & shovels’ to the emerging space entrepreneurs.

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OBJECTIVES

The goal of this internship is to analyze, augment and extend the "To The Moon" module of the CTK platform, aimed at orbital trajectory planning to the Moon. This objective closely aligns with Continuum's current roadmap, driving the development of essential capabilities for lunar and space exploration.

- Validate the current performance of the module, identifying areas for improvement in terms of accuracy and efficiency in the generation of trajectories to the Moon.
- Enhance the functionality of the module by optimizing the code and implementing more efficient algorithms for orbital trajectory design, with the goal of increasing reliability and accuracy in planning missions to the Moon.
- Expand the module's capability to enable departure from a translunar injection state, overcoming the current limitations of departure only from parking orbits, and thus providing greater flexibility in lunar mission planning.
- Develop enhancements for the "To The Moon" module interface to enable users to better understand and analyze planned trajectories to the Moon.

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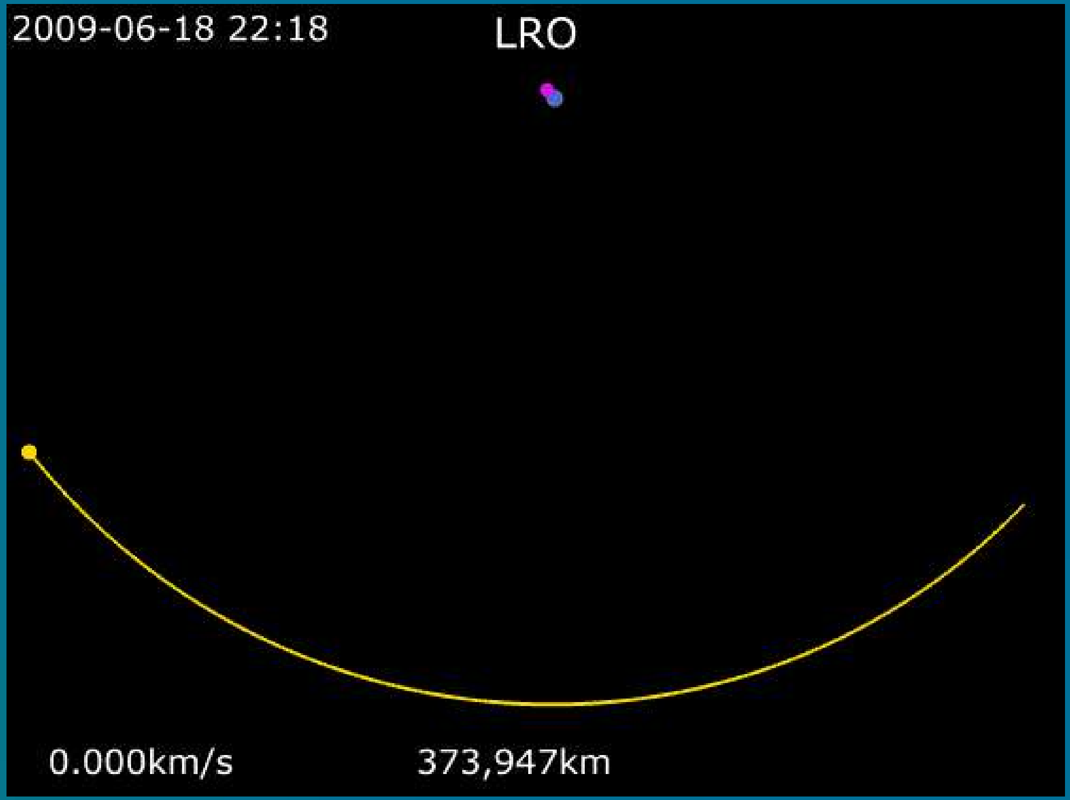

THEORETICAL FRAMEWORK

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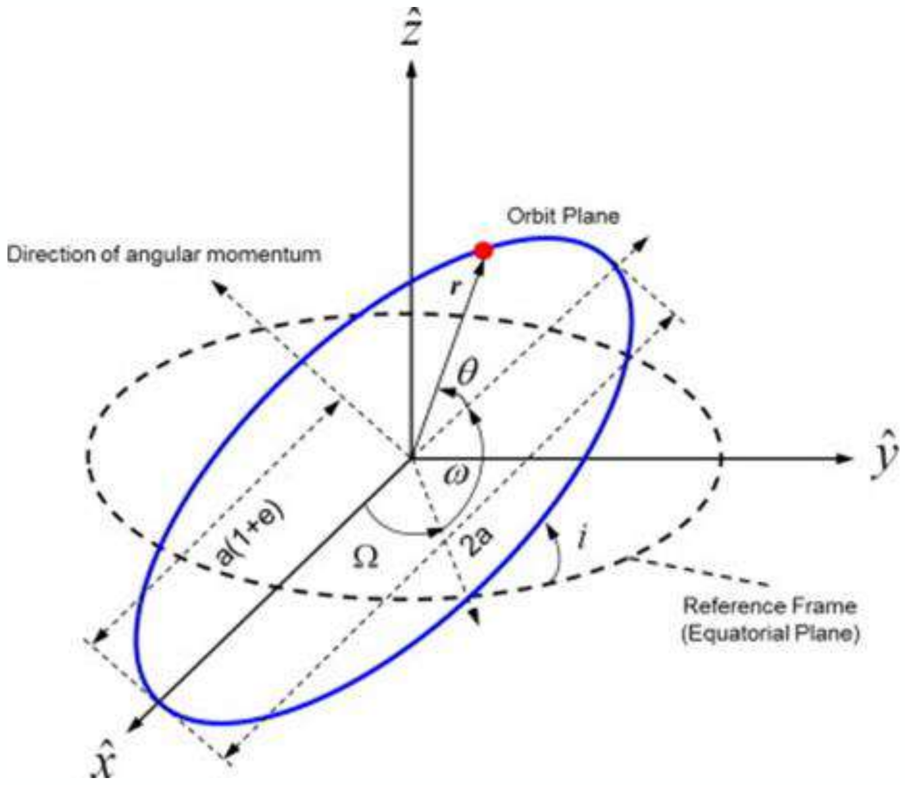
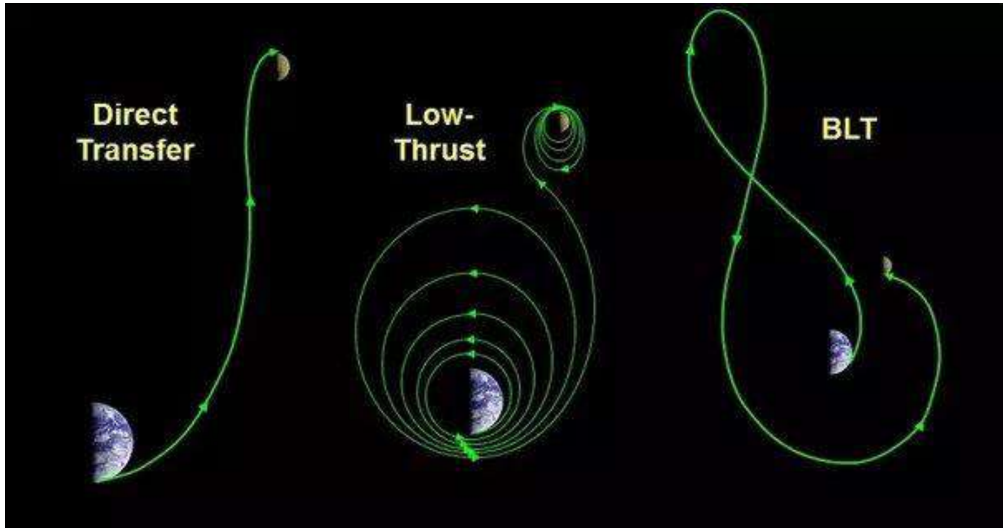
This work is based on the premise that, ideally, there are no perturbing forces affecting the spacecraft and that the orbital motion can be modeled using the two-body equation



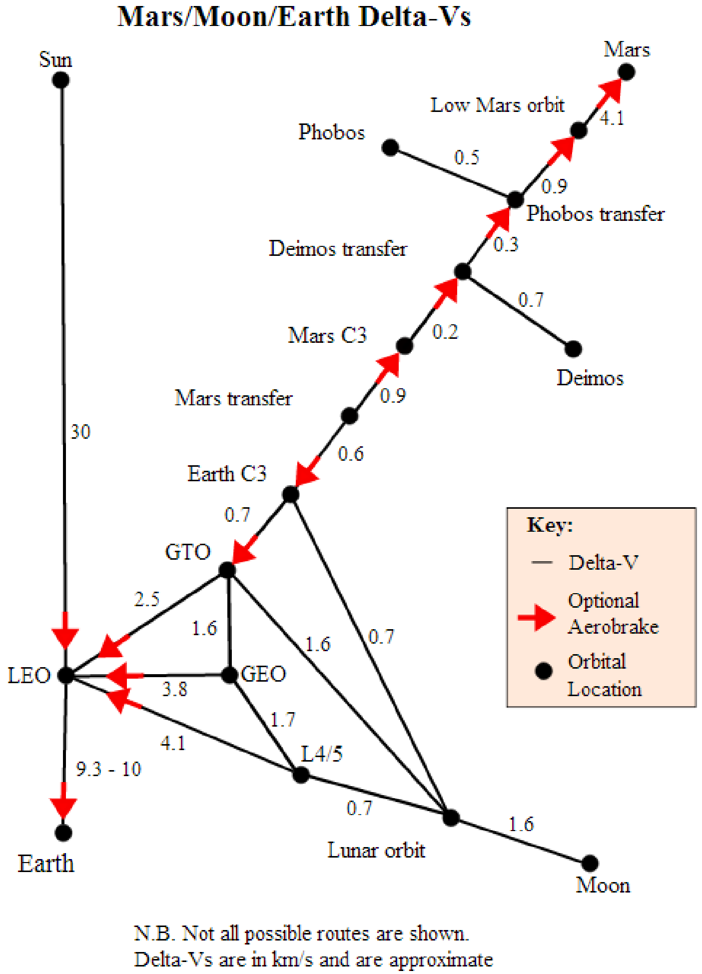
$$\ddot{\mathbf{r}} = -\frac{\mu}{r^3}\mathbf{r}$$

The Lunar Transfer Problem:

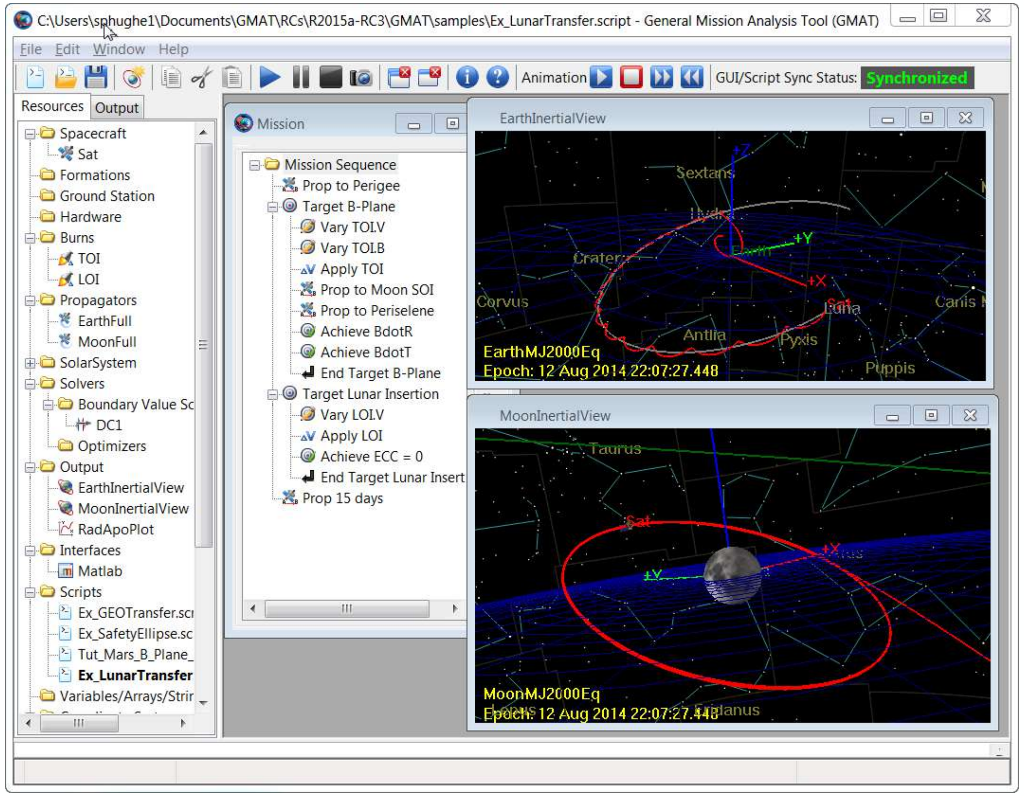
1. Earth parking orbit
2. Transfer Orbit
3. Lunar orbit



	Delta V Maneuver	km/s
TLI		3.2 – 4
LOI		0.6 – 1
TCM		< 0.05



Typically, a mission might require a trajectory that minimizes fuel consumption, power usage, flight time, or improvements in arrival or departure positions. Therefore, it is crucial to understand the objectives of a particular mission to select the optimization variables.



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METHODOLOGY

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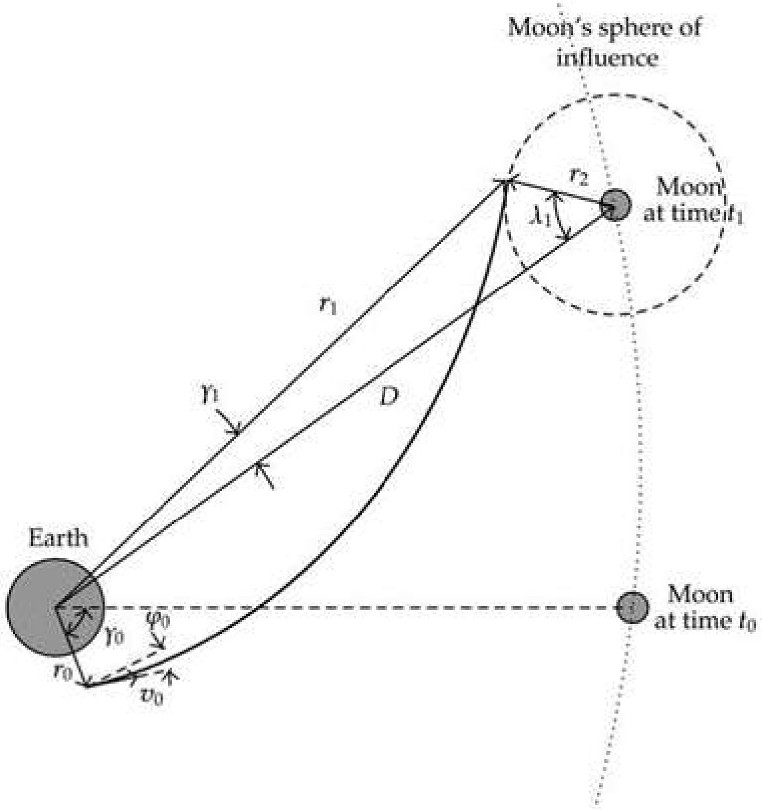
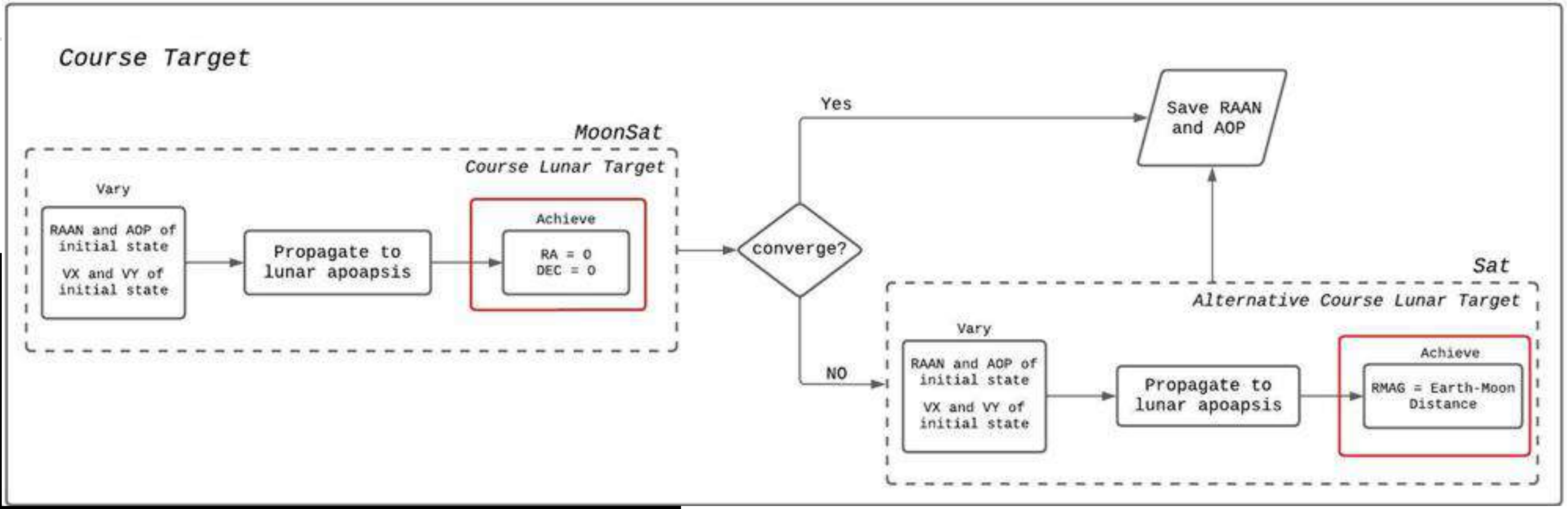
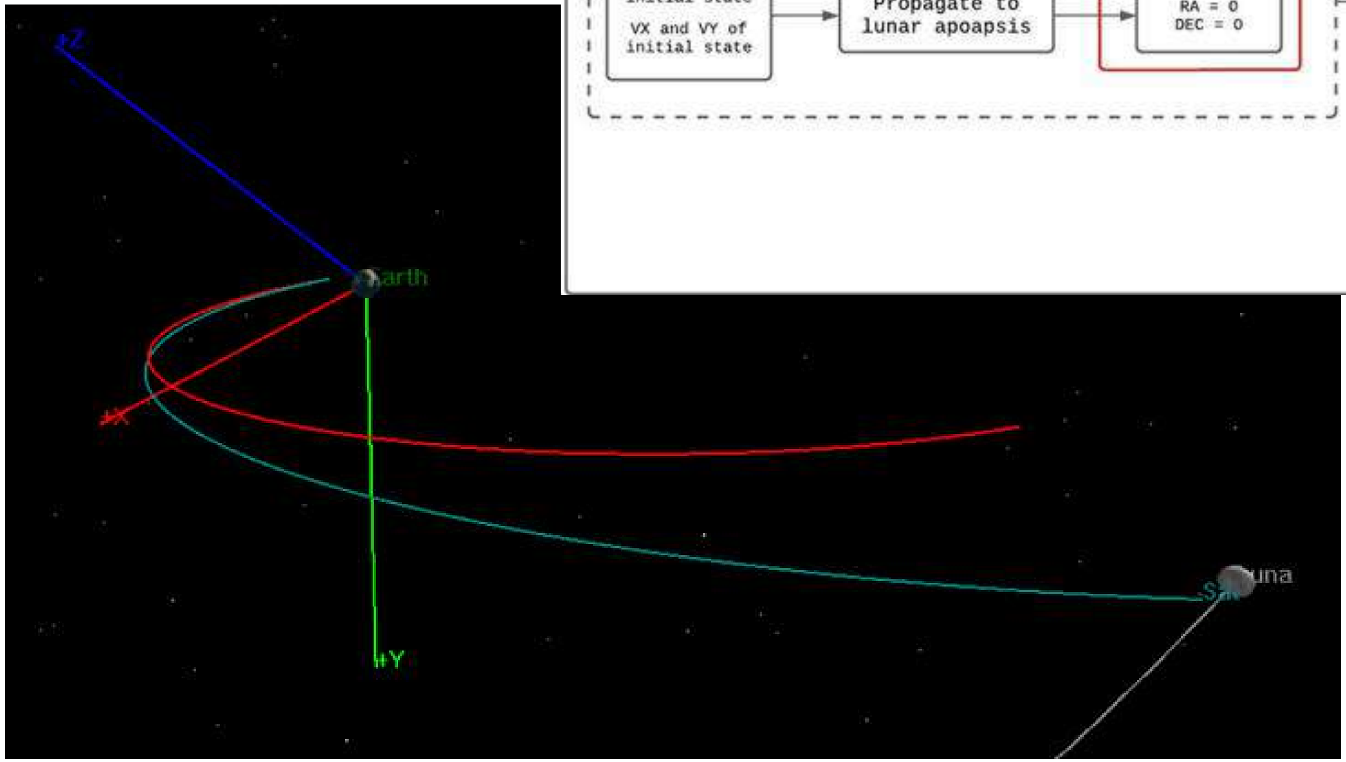
After TLI Inputs

The biggest challenge is to find initial values that simulate this type of mission.

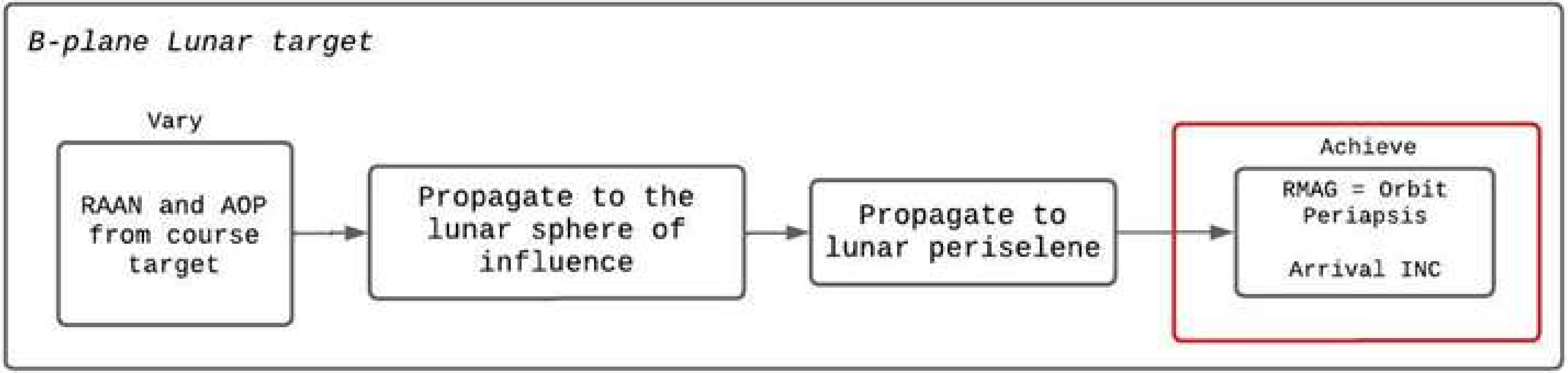
```
"id":"mooncraft",
"orbit":{
  "cbs":"MyEarth",
  "constellation":"single_orbit",
  "single_orbit_orbel":[
    // Define departure orbit
    {"aso":216733.0838380638,       //km
     "eso":0.8062134434860992,
     "iso":49.99999999494605,        //deg
     "aopso":22.03841579891865,     //deg
     "RAANso":17.83083410281042,    //deg
     "Mso":359.9999987925818,        //deg
     "launch_date":"15 Jul 2022 00:00:00.000"} //not used
    ]
```

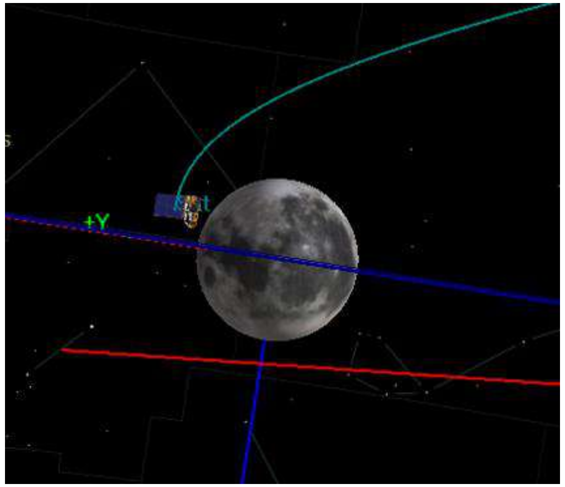


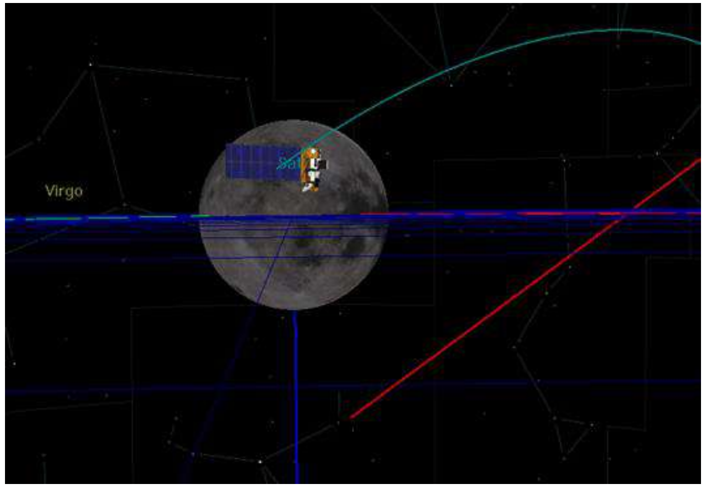

Course Target
MoonSat
Course Lunar Target
Vary
RAAN and AOP of initial state
VX and VY of initial state
Propagate to lunar apoapsis
Achieve
RA = 0
DEC = 0
converge?
Yes
NO
Save RAAN and AOP
Sat
Alternative Course Lunar Target
Vary
RAAN and AOP of initial state
VX and VY of initial state
Propagate to lunar apoapsis
Achieve
RMAG = Earth-Moon Distance


+Z
+X
+Y

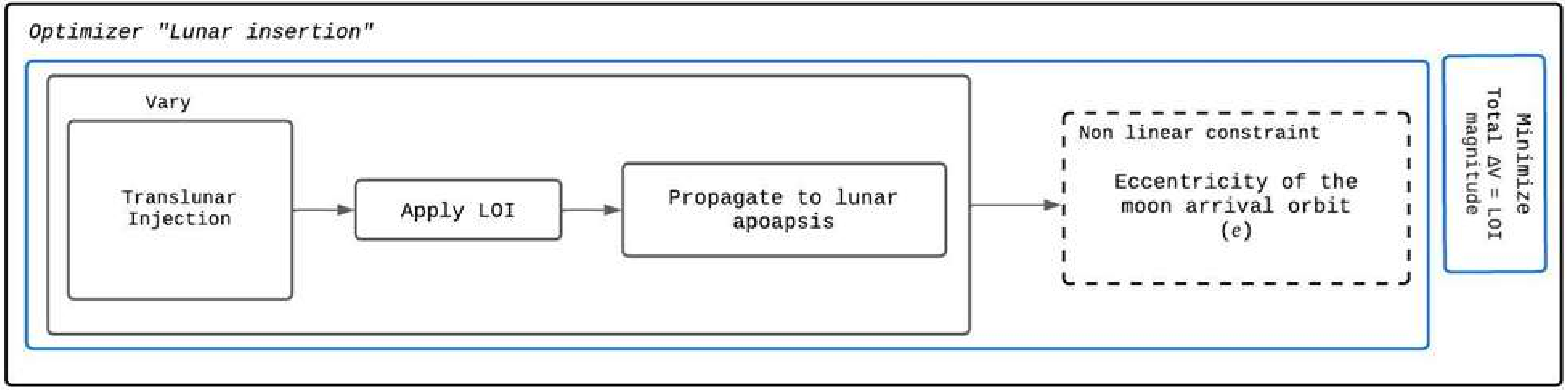
B-plane Lunar target implementation

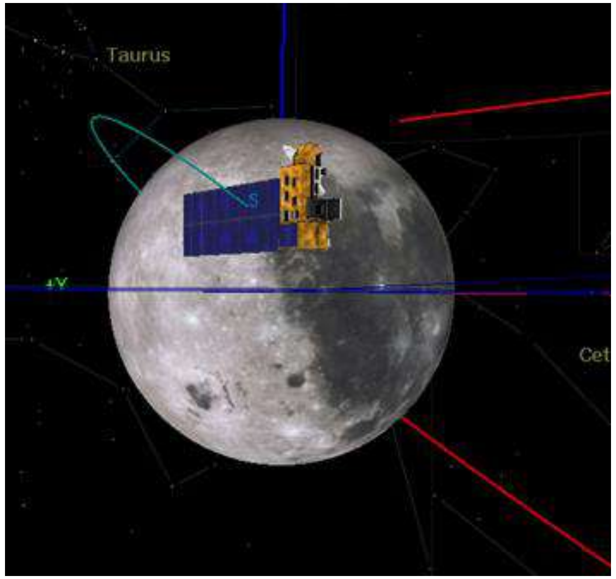


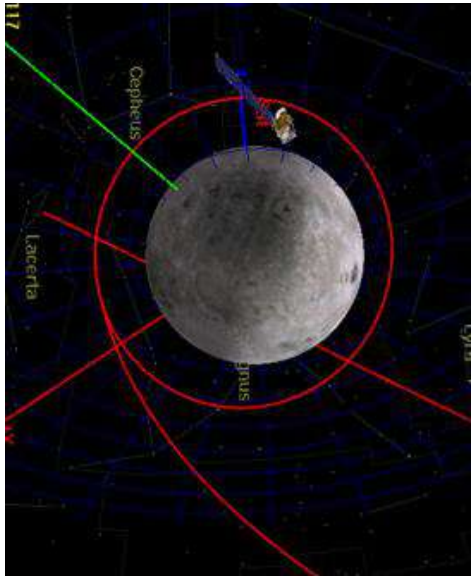




Lunar insertion optimizer implementation

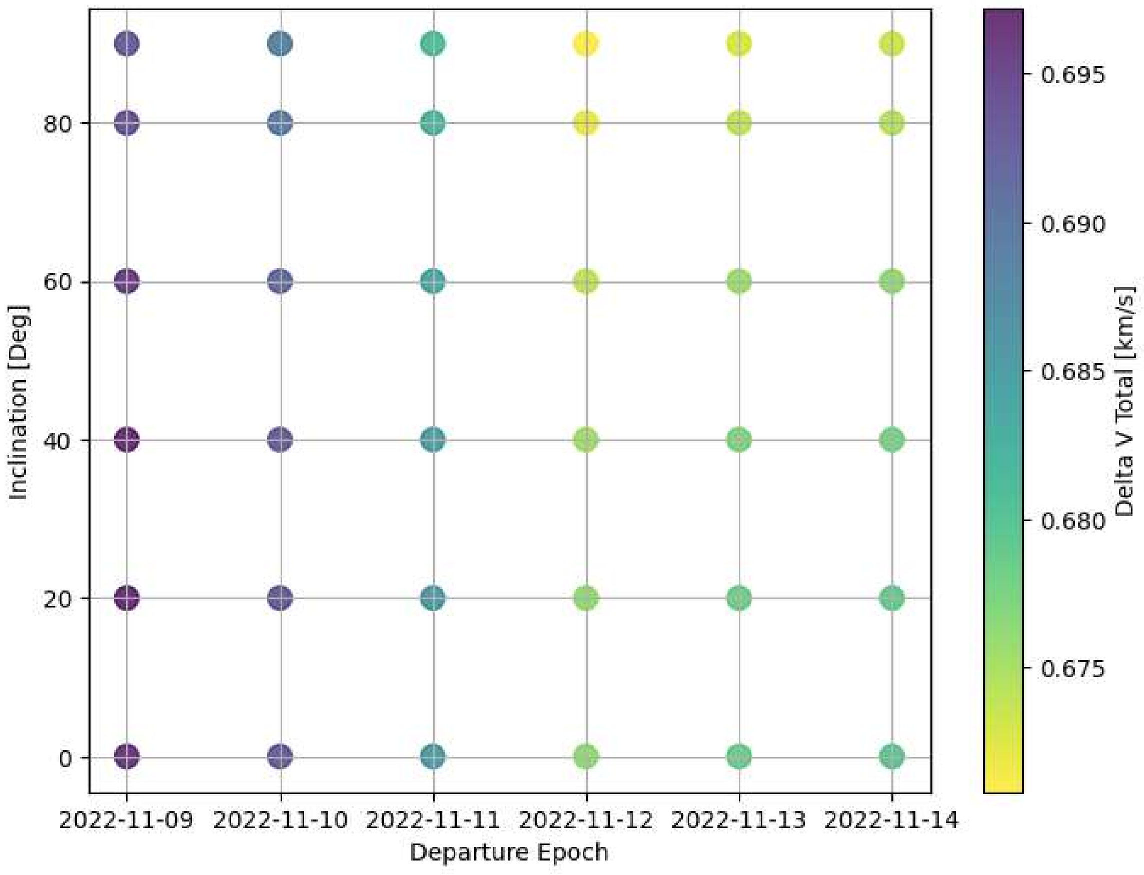






RESULTS AND ANALYSIS

- Moon arrival inclination is a parameter that can also influence the delta V used for insertion on the same day.
- By precession, there are days when insertion into the Moon requires a higher energy. expenditure for a body to orbit it.
- Results for delta v are consistent with other reference LOI maneuvers.



CTK backend terminal results

```
---------------------------------------------------------------
|                      INITIALIZATIONS                        |
---------------------------------------------------------------
Initialize generic inputs
Initialize Ctk infrastructure objects
    Making body MyEarth
    Making body Moon
    Making constellation mooncraft
        Initialize Orbit
        Initialize Spacecraft hardware
        Initialize Mission Settings
            N-BODY PERTURBATIONS is true
        Initialize Analysis specific data structures
            TRANSFER analysis is ON
             tranIn.self = true - nothing further to do
p2m direct
---------------------------------------------------------------
|                    MISSION SIMULATION                       |
---------------------------------------------------------------

------Propagate all spacecraft/constellations------
Starting GMAT
Propagate mooncraft
 ...Running direct lunar transfer targetting
    Input Departure and Arrival Orbital Elements:
2×8 DataFrame
 Row │ Type       SMA_km     ECC       INC_deg  RAAN_deg  AOP_deg  TA_deg     MA_deg
     │ String     Number     Number    Number   Number    Number   Number     Number
─────┼─────────────────────────────────────────────────────────────────────────────────
   1 │ departure  2.16733e5  0.806213     50.0   17.8308  22.0384  -1.9022e-5   360.0
   2 │ arrival       1837.4       0.0     40.0      60.0      0.0        0.0      0.0
Running simulation for satellite #1
[ Info: Mission run succeeded!
Generate kernel file for CSpice.jl
    Optimized Orbital Elements:
4×11 DataFrame
 Row │ sma (km)     ecc          inc (deg)  raan (deg)  aop (deg)  ta (deg)  ma (deg)  depEpoch                  OrbitType  Delta V (m/s)  Delta Mass (kg)
     │ Float64      Float64      Float64    Float64     Float64    Float64   Float64   String                    String     Any            Any
─────┼──────────────────────────────────────────────────────────────────────────────────────────────────────────────────────────────────────────────────
   1 │   2.16733e5  0.806213       50.0       17.8308    22.0384    360.0     360.0    14 Dec 2022 17:50:46.013  Initial    -              -
   2 │   2.16733e5  0.806213       50.0       17.8308    22.0384    172.46    139.389  14 Dec 2022 17:50:46.013  Departure  -              -
   3 │ 1837.87      0.000300061    40.0      163.536    313.006     180.0     180.0    18 Dec 2022 19:15:52.998  Arrival    774.412        197.122
   4 │ 1837.87      0.000299891    40.9012   163.534    313.1       179.9     179.9    18 Dec 2022 22:12:17.657  Final      -              -

Loading Spice kernels
 Conjunction analysis check
Ctk Mission completed
---------------------------------------------------------------
```

```
⌄ s2024-02-26T20:49:52.447
  ⌄ gmat
      DirectLunarTransfer-101001_allOrbitalElements.csv
      DirectLunarTransfer-101001_dv.csv
      DirectLunarTransfer-101001_inject.csv
      DirectLunarTransfer-101001_orbitalElements.csv
      DirectLunarTransfer-101001_summary.csv
      DirectLunarTransfer-101001.script
  › inputs
  › ker
  › outputs
```

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CONCLUSIONS

The results of this degree work reflect the success achieved in the analysis, improvement and expansion of the "To The Moon" module of the CTK platform, focused on the planning of orbital trajectories to the Moon. The new capability of departure from a translunar injection state was introduced, which significantly expands the options for lunar mission planning, offering greater flexibility to CTK platform users to tailor their missions to their specific needs.

Dedication

To women who, through knowledge,
have decided to transform their
environments into more pleasant places to
grow and live.

"Lo que da verdadero sentido al encuentro es la búsqueda y… es preciso andar mucho para alcanzar lo que está cerca."

- José Saramago

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¡THANKS!

Por el compromiso institucional
y por el trabajo en equipo.

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del aprendizaje