Design and Analysis of a Lunar Mission Launched From a High Altitude Balloon

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This paper describes the design and analysis of a lunar orbit insertion mission launched on December 3rd, 2013 from Cape Sable Island, Nova Scotia, Canada. With the hopes of developing a low cost method to access space, the author investigated the benefits of launching from 100,000 feet altitude achievable by amateur space enthusiasts for a few hundred dollars. A commercial software package for space mission design, STK Astrogator, was utilized for modelling and simulation. After simulating a traditional ground launched lunar mission, the launch conditions were changed to reflect a high altitude balloon launch, and compared to the previos results.

Contents

I. Introduction

With the advancements in space flight in the 1960's, human civilization began its journey into the final frontier. By achieving Earth orbit, sending probes into deep space, and even landing a man on the moon, the future looked very promising for a space farring civilization. However, as government funding began to fade after the turn of the decade, so did the ambitious human spaceflight projects. As a result, it has been over 40 years since a human has landed on another planet or moon.

Fortunately, in the past decade, companies such as SpaceX, Scaled Composites, Orbital Sciences, etc. have ushered in a new era of space exploration. Building on the successes of what was exclusively preserved to wealthy governments (The United States, Russia, and China), these privatized companies are all aiming to reduce the costs of accessing space. With advancements and reduced price of technology many have successfully achieved Earth orbit, and some have even docked with the ISS for a much lower cost than similar scale NASA missions.

This paper will investigate a proposal for a low cost space launch platform aimed to reduce the cost of accessing space. Section I will provide a background of similar launch systems and a review of available low cost propulsion systems which will be used in Section II, which describes the modelling and simulation tools which will be used for analysis purposes. Section III will provide a step-by-step design of a lunar orbit insertion mission using STK Astrogator. Next, the results will be presented in Section IV and comparisons between traditional and the proposed system will be looked at. Finally a summary and conclusion will be provided in Section V.

A. Proposed Mission

The proposed mission is to launch a rocket from a high altitude balloon platform to take advantage of the reduced atmospheric drag at approximately 100,000 feet altitude. This high altitude balloon/rocket launch configuration is also referred to as a *rockoon.* By avoiding the high atmospheric drag experienced by rockets traveling through low altitudes, reduced amounts of fuel are needed for the same performance, which also reduces costs. Additionally, the low cost and ease of creating a high altitude balloon platform to reach the target altitude of 100,000 feet makes this an attractive option for low cost access to space. Although

Table 1. Known rockoon launch attempts

Date	Name	Launch (ft)	Result	Comments
1957	Far Side I-IV (USAF)	100,000	Unsuccessful	Ignition failure
1957	Far Side V-VII (USAF)	100,000	Unsuccessful	Telemetry failure
1957	Project Sigma (Japan)	90-100,000ft	Unsuccessful	Never accomplished
1957	Project Sigma (Japan)	90-100,000ft	Unsuccessful	Never accomplished
1970	HARP (Austrailia)	100,000	Unsuccessful	Never accomplished
1997	Project HALO (US, HAL5)	100,000	Unsuccessful	Telemetry/balloon failure
1999	CATS Prize (JP Aerospace)	72,00	Unsuccessful	Loss of telemetry
2008	X-Prize Test 1-2 (Team ARCA)	45,000 ft	Unsuccessfull	Loss of balloon/rocket
2010	Iowa State Rockoon Project	100,000 ft	Unsuccessful	Never accomplished
2010	X-Prize Test 3 (Team ARCA)	45,000 ft	Successfull	But rocket lost at sea
2013	Project Atlas (Amentum Aerospace)	70,000 ft	Unsuccessful	Ignition failure

this concept has been proposed in the past, very few attempts have been successful. Figure 1 shows the first rockoon attempt by the United States Air Force in 1957 conceptualized by Paul Van Allen, shortly after the launch of the first soviet satellite (*Sputnik 1*). Named, Project Far Side, the goal was to launch a series of low-cost, solid-fuel, four-stage rockets from balloons at 100,000 feet, ultimately to reach the moon. The first four launch attemps were unsuccessful due to ignition failures (a similar problem experienced by the author). The next two launches, had experienced transmitter failures and therefore no exact data on the peak altitude is available. Japan quickly followed in Van Allen's steps, but the project never got off the ground [1]. Similiarily, Austrialian and Iowa State University rockoon research groups were both formed which never reached past the testing phases [1,2]. Project HALO was a program developed by the Huntsville, Alabama, L5 Society (HAL5), a chapter of the National Space Society. Their goal was to develop cheap access to space for students, researchers, and small clubs. A small rip in the balloon resulted in helium being slowly vented out, and a remote firing of the rocket at 60,000 feet. Due to a loss of telemetry, the apogee was not detected [3]. The Cheap Access To Space (CATS) prize was a $250,000 prize to the first amatuer team to place a 2kg payload to 200km or greater. Many teams had planned rockoon missions, however, JP Aerospace was the only one to make a real attempt. Similar to HAL5, a balloon issue (heavy winds) pushed the launch platform beyond the operations range. The rocket was remotely fired at 26,000 feet and the highest altitude reported was 72,233 ft and climbing at 800 ft/s when telemetry was lost [4]. The only fully successful rockoon mission which achieved all set objectives was completed by a Romanian Google Lunar X-Prize team (ARCA). In October, 2010, ARCA successfully triggered the launch of a hybrid rocket from a balloon at an altitude of 45,000 ft and reached an altitude of 131,000ft, however the rocket was lost at sea [5]. Finally, the first attempt made by the author to launch a rockoon occured August 30th, 2013 in Arnprior, Ontario, and was unsuccessful due to ignition failure [6].

Many rockoon missions were developed with the ultimate goal of reaching the moon for a low cost, others for promises of low cost suborbital research capabilities. However the one thing they all have in common is that they were all incompleted projects. This is most likely a result of the difficulty involved with producing a reliable rockoon launch platform, and an underestimation of the design requirements, time and budget. With rockoon technology still undeveloped, some questions still remain regarding the concept including what are some benefits it may have opposed to ground launch, and if it is possible to use off-the-shelf commercial solid rocket motors to achieve lunar orbit. These questions will be investigated in what follows.

Figure 1. U.S. Air Force "Project Far Side" rocket launching through its balloon.

B. Balloon Platform

In recent years, the price of GPS technology and other electronics have decreased significantly. This has allowed space enthusiasts to reliably launch and recover weather balloons equipped with cameras, tracking device, and a small payload (under 10kg), to altitudes in excess of 100,000 feet. Table 2 overviews the cost of the components used on the Atlas II project rockoon launch platform [6]. With the low cost on the order of a few hundred dollars, this platform is ideal for allowing students and researchers access to space.

Table 2. Component price per launch of a rockoon launch platform.

Item	Manufacturer	Cost
GPS w/ membership	SPOT Messenger	$200
Ignition circuit w/ uBlox MAX-6	Electronics store	$132
600g Weather balloon	Kaymont Balloons	$50
99.9% Purity helium	Praxair	$43
Lifting line and gondola materials	Hardware store	$20

The major downside to this platform is the severely limited lifting capacity. In order to reach a reasonable velocity to achieve lunar orbit insertion, a significant amoung of fuel would need to be used, easily putting the weight above the lifting capacity. Fortunately, a large scale balloon launch facility created by the Canadian Space Agency was opened September, 2013, in Timmins, Ontario. The same basic gondola could be used on these balloons, which offer a lifting capacity of up to 1.75 tons to a maximum altitude of 42 km (137,795 ft) [7]. This should allow for much more feasible size rocket motor to be used on the rockoon.

C. Rocket Size

To keep the entire platform low cost and easy for students and researchers to construct, the required total impulse should be kept within model rocket classifications, if possible. This would allow the user to purchase the parts with no additional licences or fees, and simply focus on their research. Table 3 overviews the different classifications of model rocket motors, from E to O class (after which is not considered amatuer rocketry and requires special permits to purchase and launch). It should be noted that the H-O size motors require high power rocket certifications which involve basic demonstration flights to prove competency in safe rocket design and operations.

Table 3. Model rocket motor classifications.

Class	Total Impulse (Ns)	Cost	Licence Required
G	80-160	$30	None
H	160-320	$35	Level 1 Certification
I	320-640	$60	Level 2 Certification
J	640-1280	$120	Level 3 Certification
K	1280-2560	$160	Level 3 Certification
L	2560-5120	$200	Level 3 Certification
M	5120-10240	$350	Level 4 Certification
N	10240-20480	$800	Level 4 Certification
O	20480-40960	$1000	Level 4 Certification

II. Modelling and Simulation Tools

In order to determine the feasibility of achieving the desired mission task with a given launch condition and total impulse (or deltaV), a valid simulation model is needed. This section will overview the capabilities of the various software packages used for the design and analysis of the space mission described in later sections

A. STK Astrogator

The Satellite Tool Kit (STK) Astrogator package was developed by NASA Goddard Space Flight Center (GSFC) in 1989 [8]. It was originally used for the design and operation of the ISEE-3/ICE mission (first spacecraft to be stationed in the Sun-Earth L1 liberation point. This software was further improved in the 90s by incorporating graphics as a visual aid to the mission designer. It can be thought of as a visual programming language, where the user can add "targets", similar to a while loop, "constraints", similar to if statements, and other programming features similar to for loops, stopping conditions, etc. The software was purchased by Analytical Graphics Inc. and added into their commercial software, STK.

There are many options for the user to specify in regards to the level of accuracy desired in the simulationl. The force models can include multiple gravitational bodies, atmospheric drag, solar radiation pressure, non-spherical bodies (i.e. J2 or J4). All of which can be selected and swapped out for different portions of the mission depending on which one is the most accurate. The numerical integration using Cowell's formulation is employed in the analysis, and many search and optimization algorithms (differential correction, homotopy continuation, and bounded search algorithms) can be used in the design. Another feature is the ability to load motor thrust characteristics, as well as current or historical planetary & satellite ephemerides directly from an actively updated database or historical archive, depending on the nature of the simulation. A summary of space missions that have been designed and supported by STK Astrogator up to 2003 are presented in Table 4.

Table 4. Model rocket motor classifications.

Mission Name	Launch	Mission Type
Clementine	25 January 1994	Lunar Orbit/Asteroid
Wind	1 November 1994	DLS
SOHO	2 December 1995	Sun-Earth L1
ACE	25 August 1997	Sun-Earth L1
AsiaSat 3 Rescue	25 December 1997	Lunar gravity assist
Lunar Prospector	7 January 1998	Lunar orbit
MAP	30 June 2001	Sun-Earth L2
CONTOUR	3 July 2002	Cislunar phasing loop/comet tour

B. Balloon Trajectory Prediction

Additionally, the trajectory of the balloon can be predicted using free online trajectory predictors [9,10] developed by the high altitude ballooning (HAB) community. They are generally used on amateur HAB flights and have been able to reliably predict the landing site on a number of occasions, including some of the authors own HAB flights.

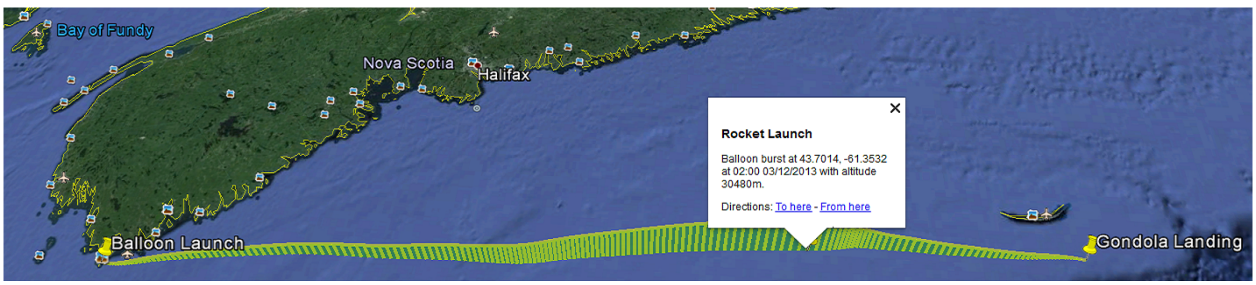

Figure 2. Prediction of the balloon trajectory, rocket launch location, and gondola landing site.

These programs utilized weather data extrated from the Global Forecast System, updated several times a day, and from the authors experience, are reasonably accurate when a suitable burst altitude can be determined. The trajectory prediction can be useful in determine the actual time of flight from ground to launch altitude, and ensure that it remains within the launch window. The drift distances are usually negligible for orbit determination because the distances are quite small relative to the size of the Earth. In addition, a reasonable estimate for the gondola splashdown location can aid in a safe and quick recovery of the rockoon launch platform.

C. Rocket performance prediction

The design of a rocket is a complicated task requiring a great deal of precision. The two main parameters which determine the performance (i.e. altitude, velocity, acceleration) that a given rocket will achieve, are its stability and thrust.

Stability characteristics of a rocket are found by determining the center of pressure of the rocket and calculating the center of gravity. The center of gravity is simply a function of the geometry and can be easily determined, however the center of pressure is a little more difficult. In order to avoid having to conduct wind tunnel testing or CFD in the early stages of design, a rockets center of pressure can be determined using the Barrowman equations or Rogers modified Barrowman equations. Fortunately, these equations have been packaged into a software named RASAero (available for free online [11]), and have been validated against wind tunnel data and rocket flight data up to Mach 25. Ideally, one would wish to link the results from the RASAero simulation directly into the STK simulation. Although for the purposes of this report, this step was left out.

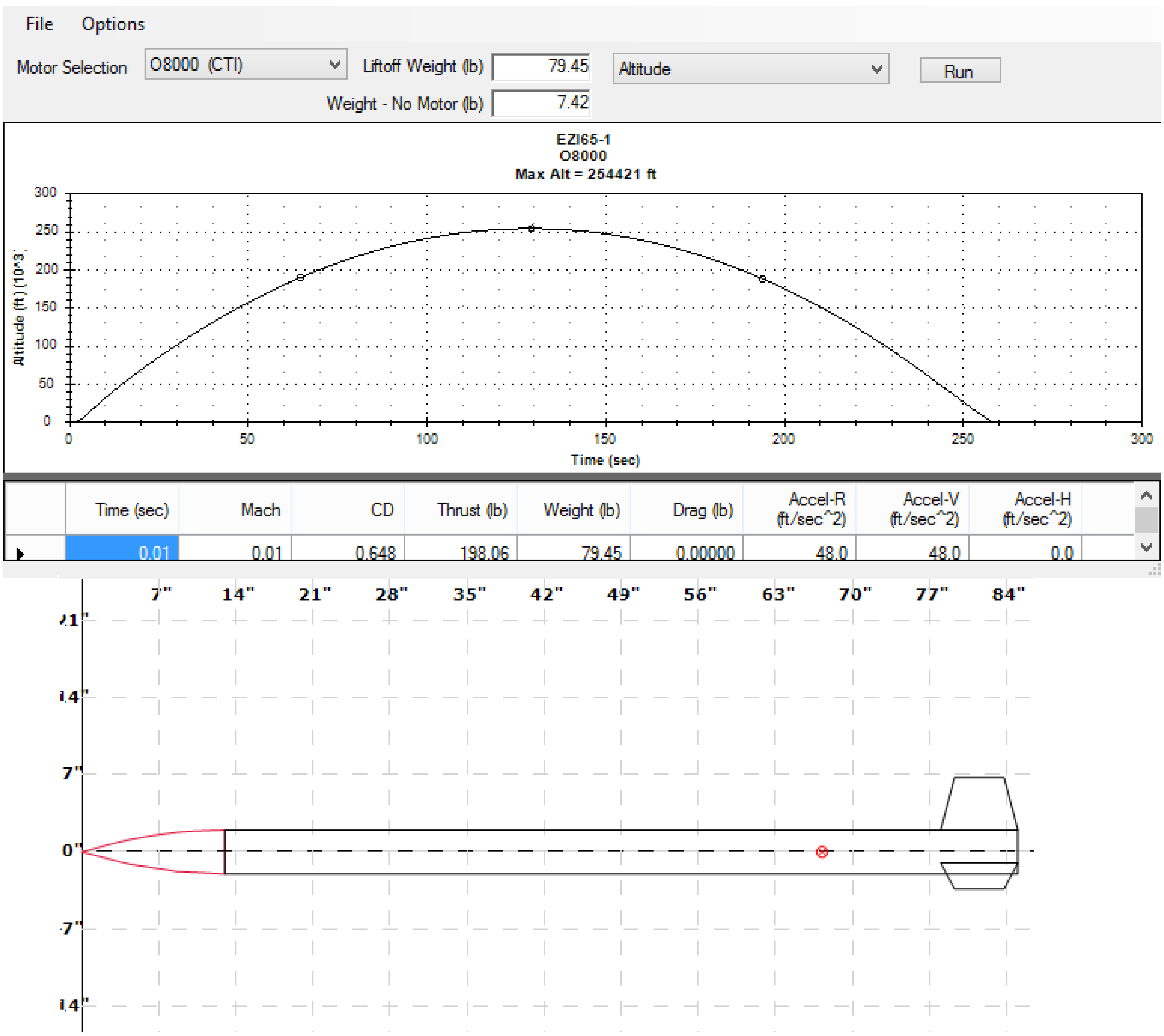

Figure 3. RASAero simulation of a single stage (O-Class) rocket launched from 100,000ft.

The motor thrust characteristics can be taken directly from the published manufacturers thrust curves. A collection of thrust curves are available from ref [12]. Most simulation software (including RASAero) include a list of commercial motors and their thrust curves pre-loaded into their software.

III. Space Mission Design

The first simulation that was investigated in STK was a simple model rocket launch. The launches of A,B,C, and all the way up to O-class motors were simulated from 100,000 feet launch altitude to get an idea of how close they were to obtaining orbit. The burnout velocities were obtained from running an RASAero simulation of the highest total impulse commercial motors of each class.

Figure 4. STK simulation of a single stage (O-Class) rocket launched from 100,000ft.

It is clear that a single stage O-class motor will not be able to achieve orbital speeds (Figure 4), and definitely not reach anywhere close to the moon (Figure 5). For this reason, the design of a lunar mission using amatuer rocket motors was abandoned. It is simply not feasible to reach lunar orbit with the use of commercial, unregulated rocket motors.

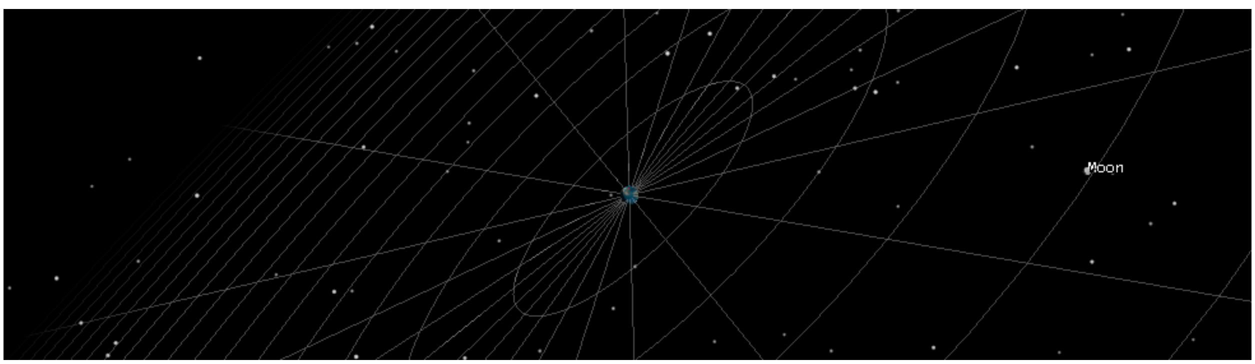

Figure 5. O Class rocket launched from 100,000 ft from the moons perspective (hint: red dot).

With this constrait removed, a lunar orbit insertion mission was designed and the benefits of launching from a high altitude were investigated.

A. Lunar Mission Design - Step 1 - Determining a Launch Location

When designing a space mission, a good place to start is the launch location. There are many suitable locations to launch a rockoon mission, and determining which one depends on a number of factors. These factors are summarized in Table 5.

Table 5. Rockoon launch site determining factors.

Factor Description	Reasoning
Close to equator	Maximum deltaV boost from Earth's rotation
Avoid populated areas	Less risk in case of failure
Easy access to launch site	Reduced transportation to and from the site
Avoid crossing national borders	May cause legal issues
Within Canada	Canada should have its own space program

After considering these factors, the proposed launch site for this mission is Cape Sable Island, Nova Scotia, Canada (Figure 6). The benefits of launching from this location include: the ability to launch over the Atlantic Ocean, avoiding populated areas, one of the closest Canadian locations to the equator, easily accessible, and it provides Canada with its own "Cape"!

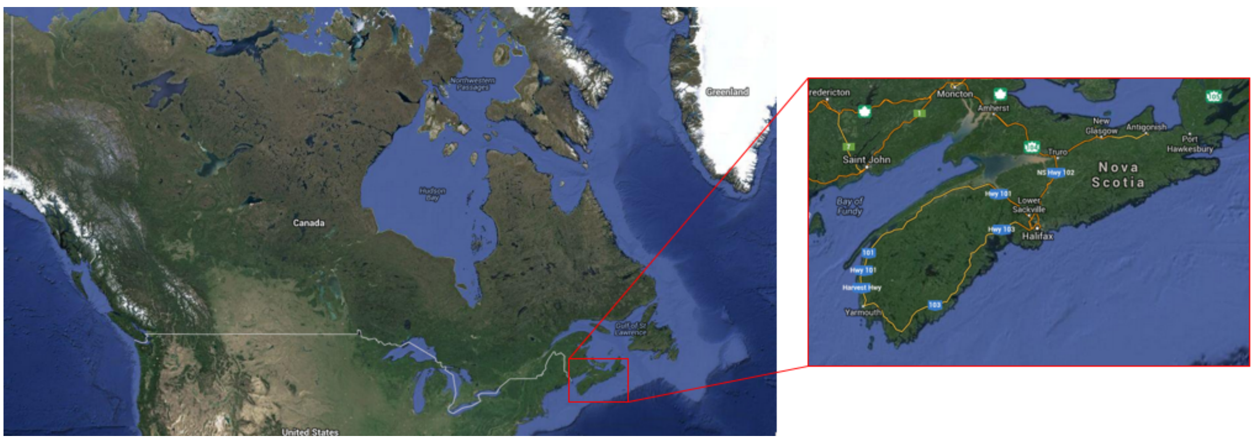

Figure 6. Proposed launch site for the Lunar Orbit Insertion Mission.

B. Lunar Mission Design - Step 2 - Getting Close to the Moon

The next step involves using the differential corrector algorithm in STK Astrogator to find a valid trajectory that will bring us close to the moon. In order to use this feature, two types of parameters are needed: *constraints*, and *control parameters* (Figure 7).

1. Constraints

By setting the declination and right ascention of the spacecraft equal to the declination and right ascention of the moon, a trajectory which is on the moon's plane can be achieved. This is done in STK Astrogator by setting the constraints: Delta_Declination, and Delta_Right_Asc, both equal to zero.

2. Control Parameters

Now we must figure out how to achieve our constraint. This is done by varying the control parameters, in this case, the launch epoch, and the coast duration (after launch burnout). Figure 8 demonstrates the variation of the launch epoch in STK (moving along the earths axis of rotation). The convergence can also be visualized by noticing the gap between the red lines (coast) getting smaller as it moves up.

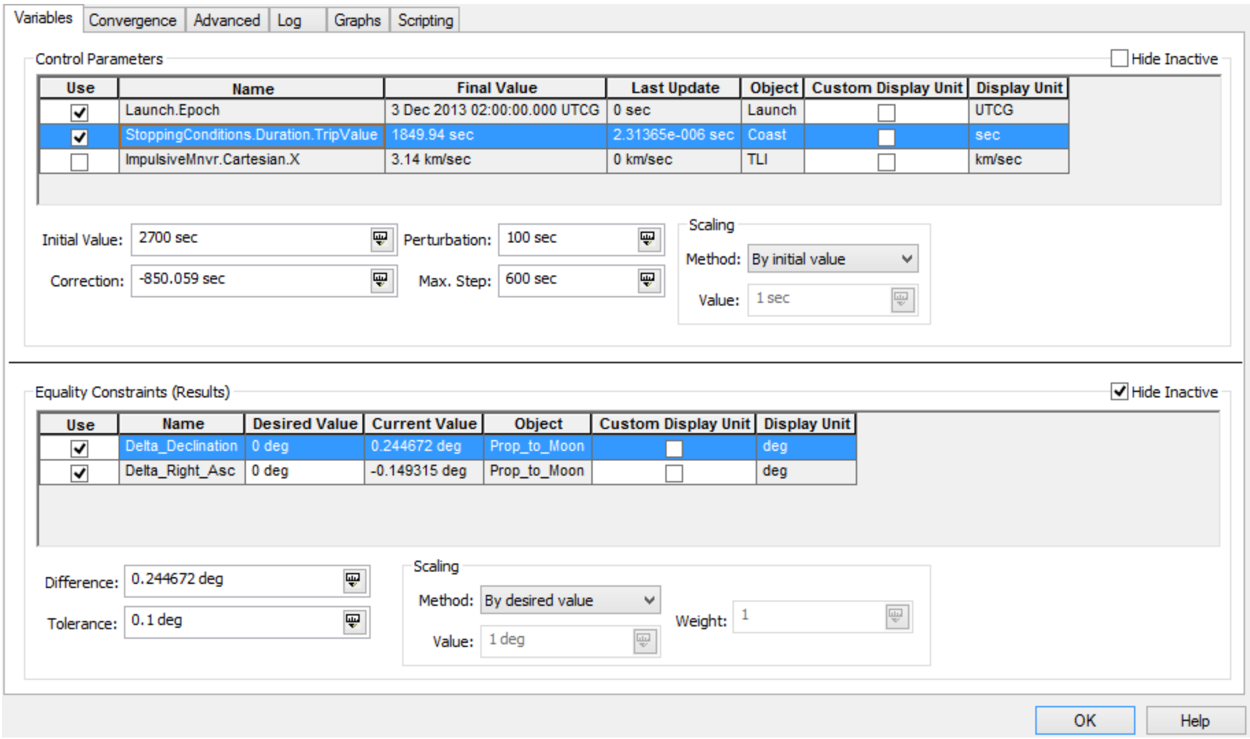

Figure 7. Control parameters and constraints used to reach close to the moon.

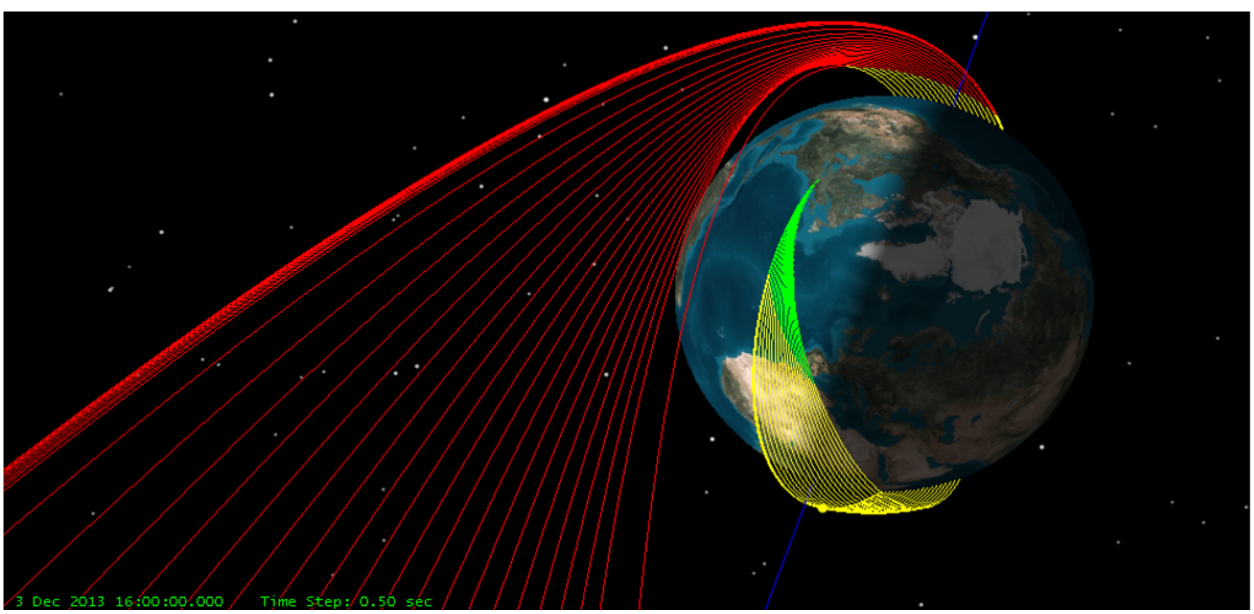

Figure 8. Variation of the launch epoch and coast duration to achieve a trajectory close to the moon.

C. Lunar Mission Design - Step 3 - Targeting the B-Plane

With a reasonable first guess at a suitable launch epoch and coast duration, the moon can now be targeted with some confidence that the iterations will converge. This is done by targeting the B-Plane. STK defines this approach as "attaching a target" to the moon. A derivation is also provided in the STK 10.0.02 web help [13]. Additionally, the orbit propagator was changed from Earth HPOP to CisLunar when the spacecraft reached 70% of the distance to the moon. This was done to increase the accuracy of the simulation by using the correct models.

1. Constraints

The goal of targeting the B-Plane is to achieve a hyperbolic orbit around the moon. Once the spacecraft reaches the vicinity of the moon, a final burn can be used to change the orbit into a lunar parking orbit (next step). To do this, the constraints are set to achieve a BdotT of 0km, and a BdotR of 6000km (Figure 9).

2. Control Parameters

The control parameters used for this step are the trans-lunar-insertion burnout velocity, and coast duration after burnout. Convergence was achieved and the results are shown in Figure 10.

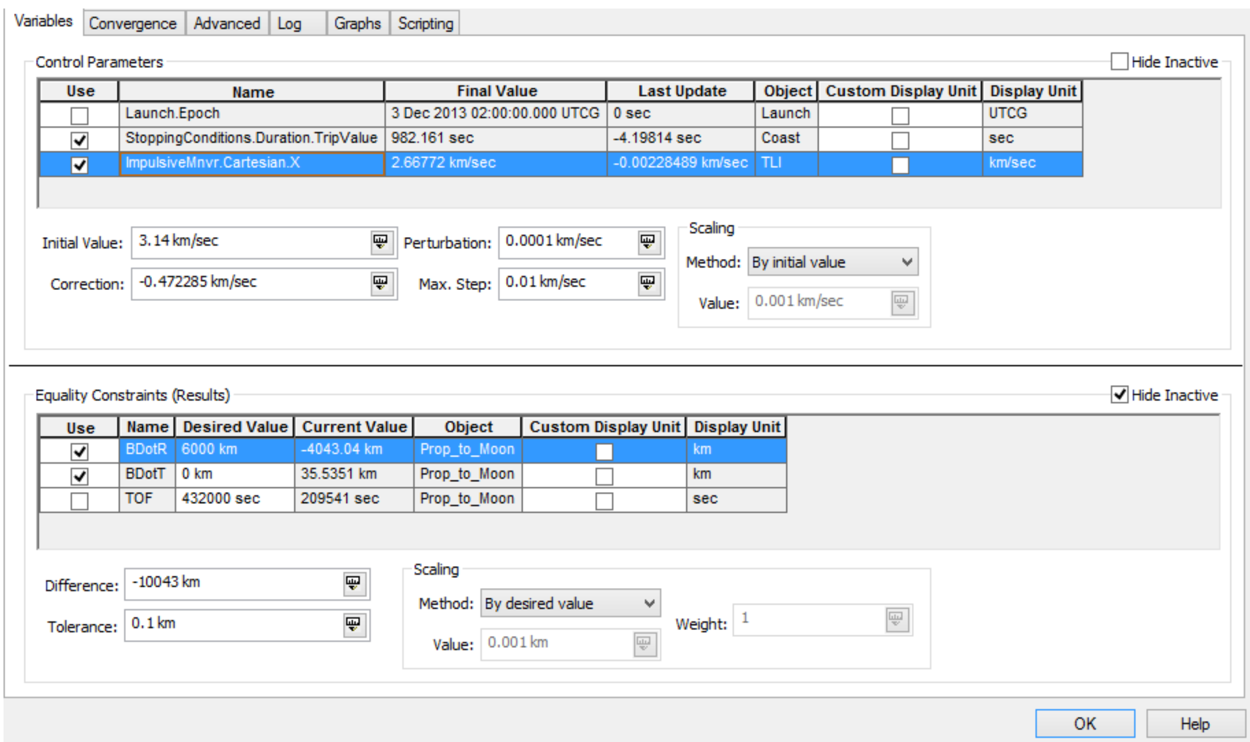

Figure 9. Control parameters and constraints used to target the B-Plane.

After convergence, the spacecraft trajectory was updated and viewed in STK Astrogator. The results showed that the spacecraft was on a very hyperbolic trajectory. Because the spacecraft does not go into an orbit around the moon, another step is needed.

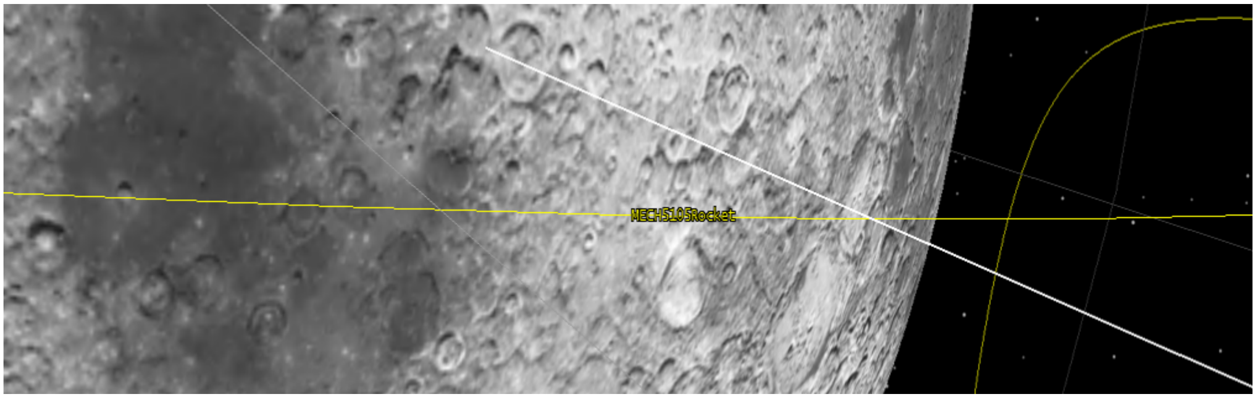

Figure 10. Close approach fly-by of the moon achieved with B-Plane targeting.

D. Lunar Mission Design - Step 4 - Lunar Orbit Insertion

The final step needed to insert the spacecraft into a lunar parking orbit is very similar to the previous two. However, this time the goal is LOI, which will be achieved by setting up final targeting sequence.

1. Constraints

In this case, the goal is to achieve a lunar parking orbit, or in orbital mechanics terms, an orbit around the moon with an eccentricity of 0.

2. Control Parameters

A final impulsive maneuver is added to this section and the thrust magnitude is set as the control parameter. Convergence is quickly achieved, successfully placing the spacecraft into lunar orbit. A picture of the full mission trajectory is available in Appendix A.

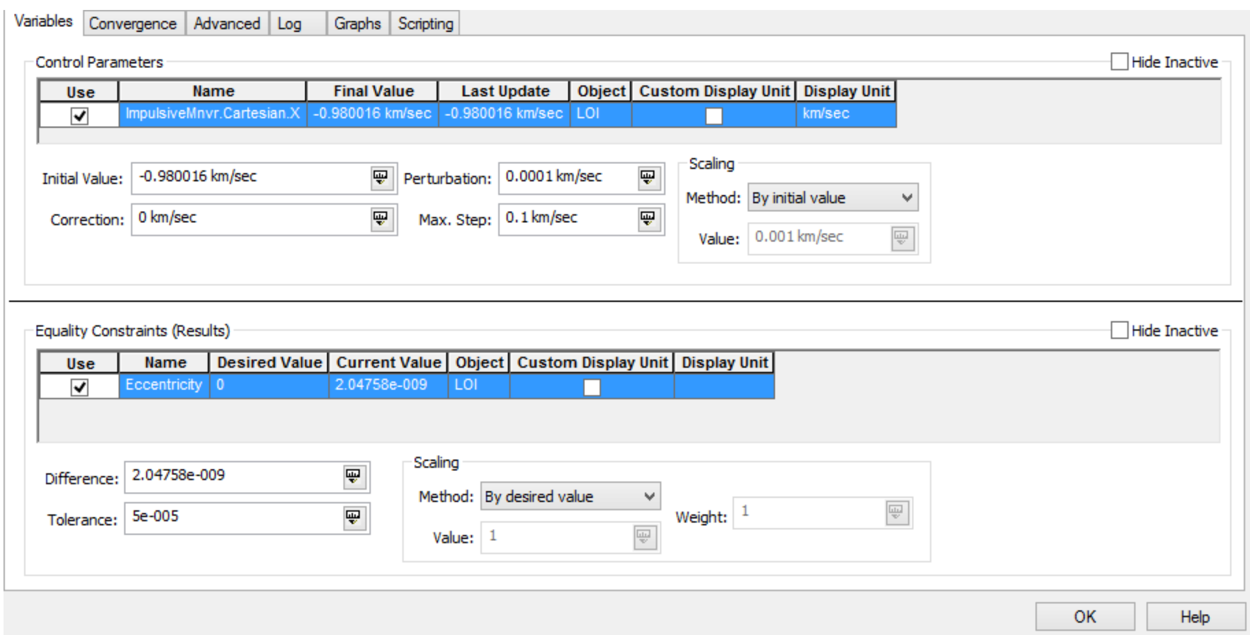

Figure 11. Control parameters and constraints used for lunar orbit insertion.

E. High Altitude Launched Lunar Mission

With a lunar space mission now designed, the launch conditions are revisted and changed to reflect those experienced by rockoon launches. In particular, the launch altitude was changed from 0 feet AGL to 100,000 feet AGL. A similar mission design procedure was followed to that just outlined.

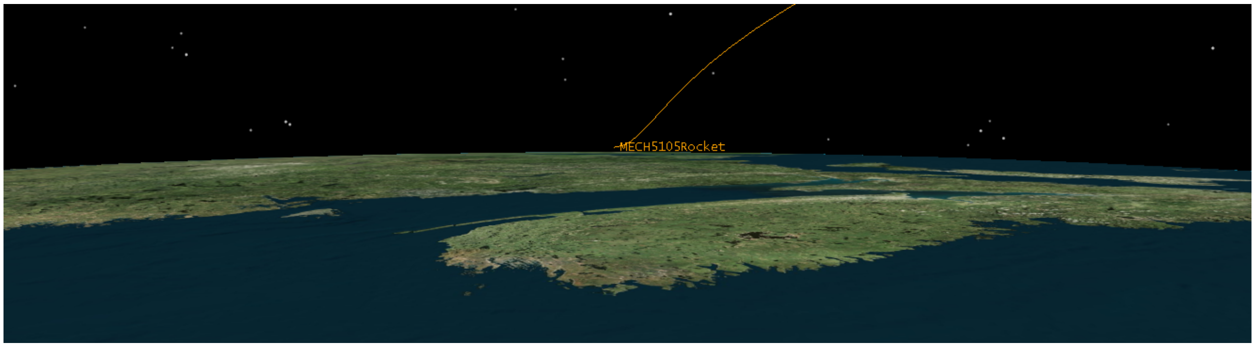

Figure 12. High altitude balloon launch simulation.

F. Risk and Safety Analysis

In addition to analyzing the effects of launching from a high altitude balloon, the opportunity to explore risk and safety analysis techniques in STK were also looked at. One major concern when launching rockets into space is the avoidance of collisions with other spacecraft in orbit. Due to the high speeds of objects in orbit, any small collision would be catastrophic for both parties. The resulting debris would also be of concern to all current and future space travelers, and likely to cause a snowball effect, resulting in even more collisions and debris as time goes on.

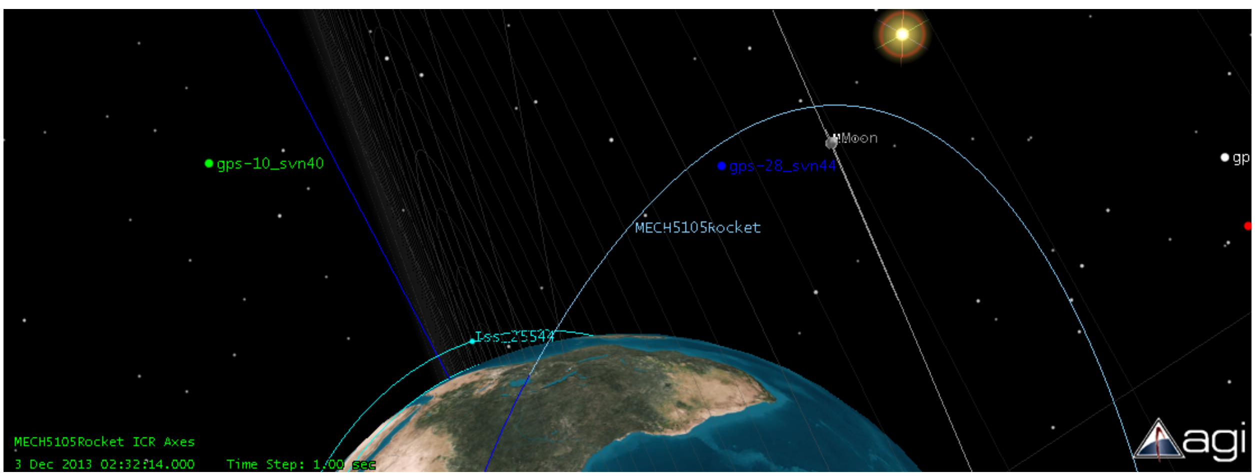

Figure 13. Risk mititgation analysis using STK.

The primary safety concern is to avoid collision with the ISS at all costs, as well as any satellites in service. For these reasons, the most recent ISS ephemeris, and GPS constellation data was obtained from JPL and loaded into STK. An access was then created between the spacecraft, the ISS, and other satelllites, with a range constraint of less than 10km. This will alert the mission designer when the spacecraft reaches within the constraint and displaying a yellow access line connecting the two objects in the 3D window. Additionally, this access could be incorporated into the Astrogator constraints when designing the space mission to avoid missions which risk collision.

IV. Results

It was found early on that commercial solid motors would simply not provide enough thrust enough to reach the moon, and possibly not even to orbit. This means, at the very least, that high power rocketry licences are a *must* in order to attempt to reach space. With the limit of high power rocketry that is available to amatuers capping at O-class motors, a clustered or multi-stage rocket would be needed.

The design of two custom lunar orbit insertion mission launched from Cape Sable Island, Nova Scotia, Canada, were successfully designed and simulated using STK Astrogator, see Appendix A for details. The difference between the two simulations are presented below in Table 6, and compares the high altitude balloon launched simulation to the ground launched simulation.

Table 6. Comparison of ground launched and high altitude launched (100,000ft) lunar orbit insertion missions.

	Ground Launch	High Altitude Balloon Launch
Sequence start	3 Dec 2013 - 2:00:00 UTC	3 Dec 2013 - 2:00:00 UTC
Sequency stop	6 Dec 2013 - 9:33:14 UTC	6 Dec 2013 - 9:20:36 UTC
DeltaV (TLI)	2.6676 km/sec	2.6676 km/sec
DeltaV (LOI)	0.98 km/sec	0.98 km/sec

Table 6 summarizes the findings of this report. Essentially no difference in the required fuel to complete the mission was found. The differences were so small that they were dropped off with rounding. Another important result is the deltaV's for TLI and LOI which agrees reasonably well with similar lunar missions in literature [13, 14].

Finally, the collision risk mitigation of a rocket launched through the orbital traffic was investigated and the ISS or any satellite in the GPS constellation came within 10km of the spacecraft. Although, the ISS did appear to be a within range near the launch condition, and may have led to a possible re-design of the mission in case of a system failure during launch.

V. Conclusion

Some of the capabilities of rockoons were investigated in this paper. It was found that the thrust capabilities of amateur rocket motors do not meet the requirements to reach outer space, and therefore, high power rocket licences are required in order to reach Earth orbit and beyond.

STK Astrogator was found to be a valuable tool for space mission design and risk mitigation, allowing users to design complex space missions with relative ease. Although the simulations proved that rockoon technology will require high power rocketry licences, and even larger motors to reach the moon. There is still some potential for rockoons to become an alternative to reach sub-orbital altitudes and possibly even orbit.

Appendix

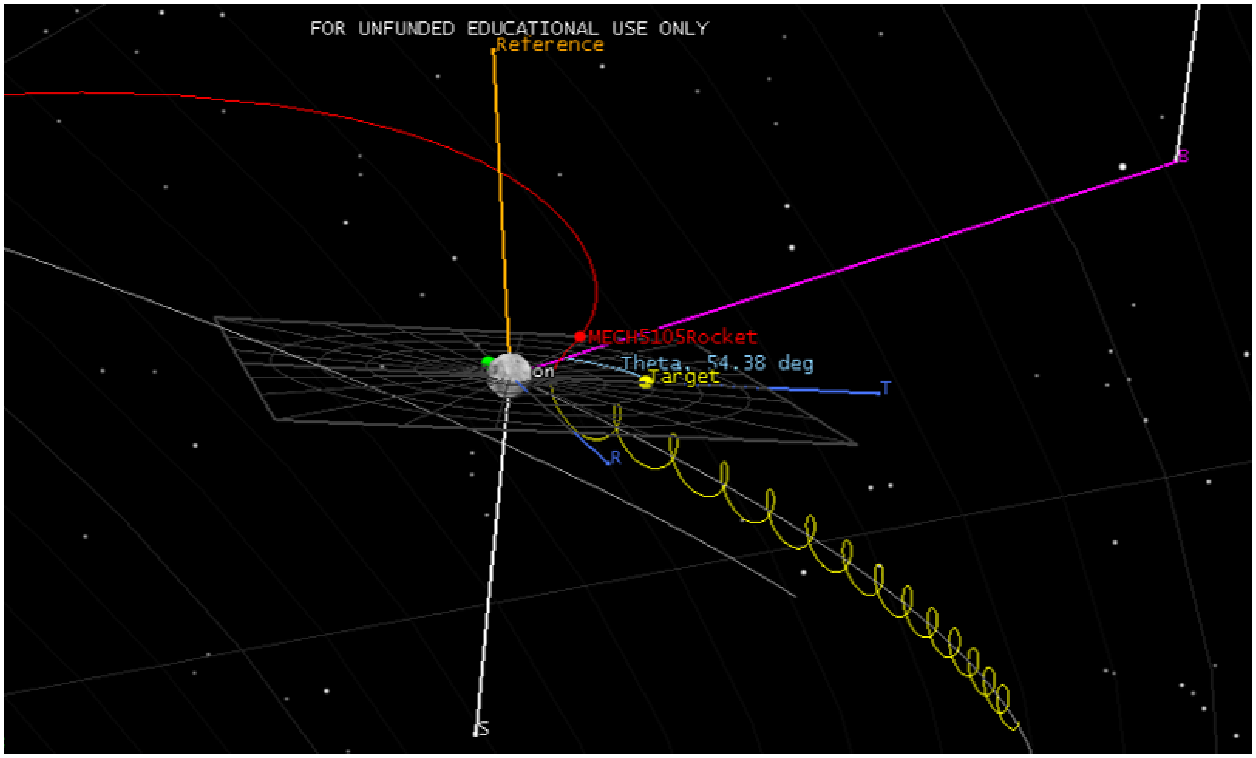

Figure 14. Lunar Orbit Insertion Trajectory With B-Plane.

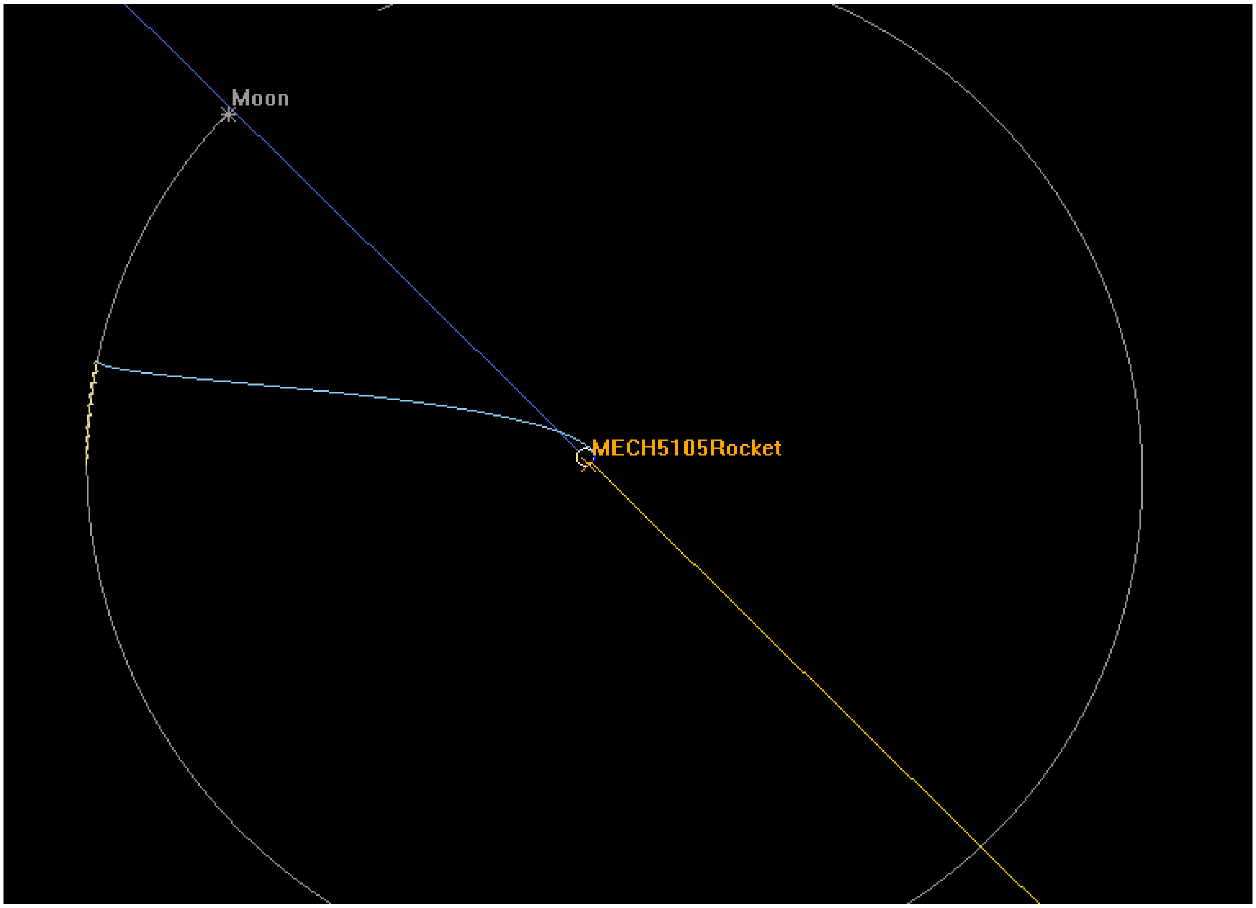

Figure 15. Lunar Orbit Insertion Trajectory in 2D.

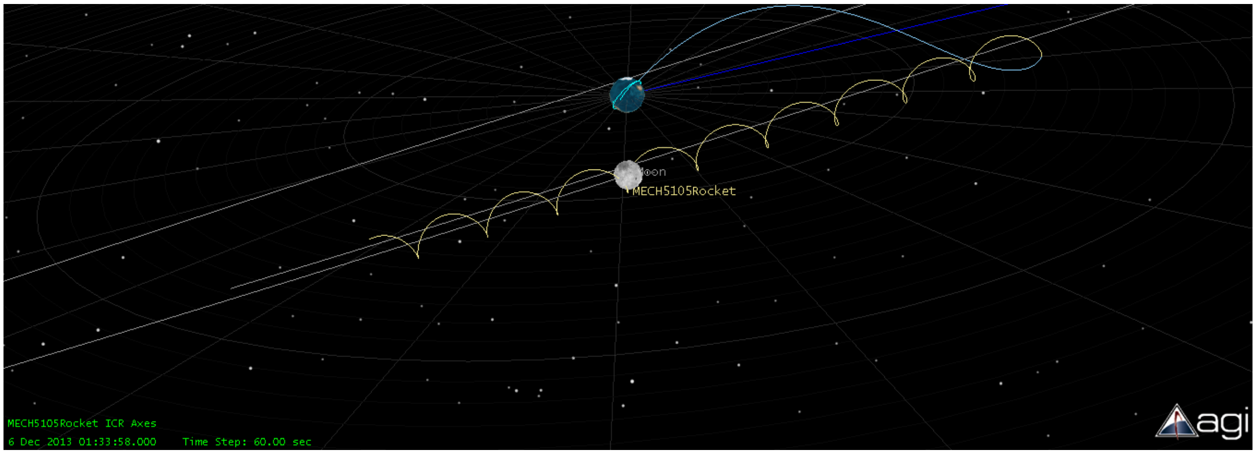

Figure 16. Lunar Orbit Insertion Trajectory.

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