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# Engineering Notes

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## Optimizing Trajectories for Suborbital Human Spaceflight

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### Introduction

THE goals of this Note are to show how trajectories for commercial suborbital human spaceflight can be customized to meet the demands of the paying passenger by the manipulation of vehicle performance variables, and to develop a "menu" of possible flight options based on user-defined interests [1]. To accurately analyze the possible suborbital trajectories, EasyPOST, the graphical user interface to POST3D, was used because it allows users to easily generate multiple cases of their vehicle and flight plans. This software is a powerful tool that provides a large range of potential output variables and allows simple to complex trajectory modeling with built-in atmospheric models and higher-order gravitational parameters where applicable.

An example vehicle, the Canadian da Vinci Project's Wild Fire Mk 6 is modeled in EasyPOST and optimal flight profiles of trajectories for suborbital human spaceflight are generated. These trajectories were analyzed and weighted against each other to create a flight menu with different options available for a paying customer who wished to fly on a suborbital flight. This vehicle is carried by a balloon to 21,336 m and the vehicle's nose is elevated 75 deg above the horizontal. The vehicle is then released and a hybrid engine fires for approximately 80 s carrying the vehicle on a suborbital trajectory to the edge of space, defined in this Note as 100 km (in actual operations, dispersions should be taken into consideration and an altitude margin included). An important design factor is that the vehicle remains elevated at 75 deg for 8 s after the initial engine firing to avoid the released helium balloon and then begins to pitch to 90 deg.

Key output variables were identified to be weighted in a parametric tradeoff study to find the best flight for a given set of criteria. These different criteria led the development of a flight menu with six different choices. This method of generating a menu, and the results obtained, show that a parametric study can acquire a collection of optimized trajectories for a variety of paying passengers for suborbital human spaceflight.

### EasyPOST Software

In the 1970s, NASA developed the Program to Optimize Simulated Trajectories (POST) as a space shuttle trajectory simulation program. Written and operated in FORTRAN, POST is a generalized point-mass, discrete-parameter targeting and optimization program that includes equality and inequality constraints, and provides the capability to target and optimize point-mass trajectories for a powered or unpowered vehicle near an arbitrary rotating, oblate planet [2]. POST continued to evolve and eventually became its current 3-DOF version called POST3D. POST3D is an extremely powerful code with the capabilities of vehicle modeling, trajectory simulation, and targeting and optimization [2]. A windows-based graphical user interface known as EasyPOST for POST3D [3] was used in this study.

### The Comfort Zone

The key to selling a suborbital flight is ensuring that the paying passenger can withstand the strenuous gravity loading that is sensed or $g$ load. The $g$-loading force is felt during two specific events in a suborbital trajectory: during the rocket-powered ascent due to the thrust from the engine, and during reentry due to the forces of drag against the vehicle. This Note looks specifically at the launch $g$ load because the "sensed" value lasts for a longer period of time and is fairly constant, whereas the reentry value has a sharp peak but generally a shorter overall impulse.

Several studies have been conducted on the maximum amount of $g$ loading an average human can withstand both for a short duration of less than 0.5 s (such as an impact or crash), and for a long duration of greater than 2 s (for fighter pilots in turns and astronauts on launch). The long-duration accelerations have consistently shown that a human can readily tolerate and function well for 60 min at 3 $g$ [4]. For a shorter duration, such as the time experienced on a suborbital launch, a NASA study showed an average performance plateau of between 10 s and 2 min at 6 $g$ [5]. For two points of reference, NASA's space shuttle experiences a maximum of 3 $g$ on takeoff, and the limit of sustained human tolerance averaged from past testing is about 8 $g$ [6].

For the modeled launch profile used in this study, the duration during the thrusting period is approximately 80 s for the higher $g$ loads and approximately 4 $g$. Those values would be close to the limits of an untrained passenger, which might not be desirable to meet the spectrum of the potential suborbital paying passengers. Alternatively this could add an opportunity for a paying client to undergo a spaceflight training program to prepare for a higher $g$-valued flight.

### Flight Trajectory Case Generation Strategy

EasyPOST has the unique ability to analyze case study after case study with low computation time, allowing for a copious amount of trajectories to be simulated. A menu of suborbital spaceflights can be weighted to determine the best possible flight for a set of predetermined passenger types. A schematic overview of the method is seen in Fig. 1.

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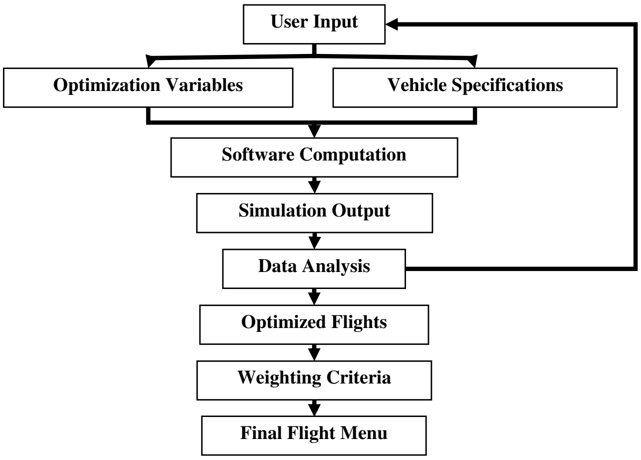


**Fig. 1 Schematic overview of method.**

Six case studies are examined in this Note: 1) Case A: highest possible altitudes with the design specifications for Wild Fire Mk 4, 2) Case B: maximizing payload, 3) Case C: if the reaction control system failed and the vehicle did not pitch up to vertical, 4) Case D: increased engine specific impulse (different engine), 5) Case E: optimizing the onboard fuel, and 6) Case F: minimizing the $g$ load with the two different specific impulse engines.

The 12 variables being used for a suborbital parametric tradeoff study include maximum altitude, time in space (above 100 km), flight time (defined as the time from balloon drop until landing), time with less than 0.01 $g$, time with less than 0.05 $g$, time with less than 0.1 $g$, maximum $g$ load, downrange distance, cross-range distance, takeoff mass addition (for the cases with additional mass), fuel reduction (for the cases with less fuel), and financial multiplier (to account for factors such as described for the cases with a higher $I_{SP}$). Each different type of flight profile designed for a flight menu will have different weighting of these factors to customize a menu of choices.

To determine the near-zero gravity conditions that the passengers would experience, the velocity time step with respect to time was calculated to get the acceleration. Equation (1) shows that the simplified mathematics used to calculate the $g$ value are

$$a = (\Delta V/\Delta t)/g + 1 \tag{1}$$

where $a$ is the acceleration in $m/s^2$, $\Delta V$ is the change in velocity in m/s, $\Delta t$ is the change in time in s, and $g$ is the acceleration at sea-level due to gravity (9.81 $m/s^2$).

Calculated downrange and cross-range distances were achieved by using the longitude and latitude differences between the start of flight and end-of-flight. The only variable added that was not a traditional output variable or quantitative variable was the financial multiplier. This was added to account for factors such as that a higher $I_{SP}$ engine will cost more to develop and operate, that a heavier vehicle will cost more for a passenger because of the extra payload mass that is being brought, and that saving fuel would reduce the price of a ticket. Even if the mass added is for safety reasons, like thermal protection, it will cost more to develop those systems. Values assigned in the trajectories were multipliers such that a value of 2 would double the price of the ticket and a value of 5 would multiply the price by 5.

Each menu item scenario focuses its scaling or weighting on one particular variable. The importance values range from −1.0, which induces a penalty on the performance, to 1.0, which is the highest value and signifies that the variable is very important. This weighting is incorporated into the cost function as

$$\text{Cost} = \sum_{i=1}^{12} \text{weight}_i \times \text{parameter} \tag{2}$$

## Flight Menu

Like any good tourism company, the available choices should meet the demands of the customers. In this study those choices to be made are the type of trajectory. There is no one single trajectory that meets the general market, so a flight menu will be important for a space tourism agency. Six menu items are unique scenarios in which the flights have been weighted to find the best trajectory for that specific need. Overall flight times and times at various $g$ loadings are shown in Table 1. In Table 2, the bold values in the case study rows indicate the focus in each of the case studies.

In each of these cases, both enforced $g$ limits (3-$g$ limit, 2-$g$ limit) and no $g$ limits were examined. For example, in menu item 1, the flight trajectories were being optimized for altitude, whereas menu item 2 examined trajectories in which the payload mass could be increased.

**Table 1 Flight times and time in various levels of weightlessness**

| Tradeoff parameters, units | Time in space, s | Flight time, s | Time <0.01 $g$, s | Time <0.05 $g$, s | Time <0.1 $g$, s |
|---|---|---|---|---|---|
| *Menu item 1: base case maximizing altitude* | | | | | |
| No $g$ limit | 179.5 | 375 | 0 | 79 | 109 |
| 3-$g$ limit | 179 | 375 | 0 | 78 | 108.5 |
| 2-$g$ limit | 133 | 363 | 0 | 31 | 66 |
| *Menu item 2: maximizing payload* | | | | | |
| No $g$ limit | 1.5 | 320 | 0 | 71 | 86 |
| 3-$g$ limit | 1.5 | 320 | 0 | 71 | 86 |
| 2-$g$ limit | 1.5 | 327 | 0 | 62.5 | 77.5 |
| *Menu item 3: no pitching, maximizing downrange distance* | | | | | |
| No $g$ limit | 155 | 362 | 0 | 0 | 0 |
| 3-$g$ limit | 154 | 362 | 0 | 0 | 0 |
| 2-$g$ limit | 100.5 | 350 | 0 | 0 | 0 |
| *Menu item 4: increasing $I_{SP}$ and maximizing altitude* | | | | | |
| No $g$ limit | 232.0 | 413 | 0 | 62.5 | 111.5 |
| 3-$g$ limit | 232.0 | 413 | 0 | 62.5 | 111.5 |
| 2-$g$ limit | 143.5 | 367 | 0 | 69 | 78.5 |
| *Menu item 5: optimizing fuel* | | | | | |
| No $g$ limit | 3 | 314 | 0 | 70.5 | 87 |
| 3-$g$ limit | 3.5 | 314 | 0 | 78.5 | 91 |
| 2-$g$ limit | 3.5 | 325 | 0 | 61 | 76.5 |
| *Menu item 6: special cases* | | | | | |
| Min $g$ | 1 | 348 | 0 | 56 | 69 |
| Min $g$, $I_{SP} = 260$ s | 1 | 348 | 16.5 | 17.5 | 18.5 |
| **WORST** | **1** | **314** | **0** | **0** | **0** |
| **BEST** | **232.0** | **413** | **16.5** | **79.0** | **111.5** |

Table 2 Trajectory and flight performance results

| Tradeoff parameters, units | Maximum altitude, km | Maximum $g$ load, $g$ | Downrange distance, km | Cross-range distance, km | Takeoff mass addition, kg | Fuel reduction, lb | Financial multiplier |
|---|---|---|---|---|---|---|---|
| *Menu item 1: base case maximizing altitude* | | | | | | | |
| No $g$ limit | **137.65** | 3.14 | 20.85 | 0.76 | 0 | 0 | 0 |
| 3-$g$ limit | **137.55** | 3 | 21.26 | 0.76 | 0 | 0 | 0 |
| 2-$g$ limit | **120.7** | 2 | 41.04 | 0.41 | 0 | 0 | 0 |
| *Menu item 2: maximizing payload* | | | | | | | |
| No $g$ limit | 100 | 2.86 | 15.98 | 0.57 | **381** | 0 | 5 |
| 3-$g$ limit | 100 | 2.86 | 15.98 | 0.57 | **381** | 0 | 5 |
| 2-$g$ limit | 100 | 2 | 16.24 | 0.61 | **268** | 0 | 5 |
| *Menu item 3: no pitching, maximizing downrange distance* | | | | | | | |
| No $g$ limit | 128 | 3.21 | **161.53** | 0.31 | 0 | 0 | 0 |
| 3-$g$ limit | 127.86 | 3 | **161.44** | 0.31 | 0 | 0 | 0 |
| 2-$g$ limit | 111.85 | 2 | **151.44** | 0.24 | 0 | 0 | 0 |
| *Menu item 4: increasing $I_{SP}$ and maximizing altitude* | | | | | | | |
| No $g$ limit | **162.62** | 2.86 | 24.24 | 0.89 | 0 | 0 | 2 |
| 3-$g$ limit | **162.62** | 2.86 | 24.24 | 0.89 | 0 | 0 | 2 |
| 2-$g$ limit | **124** | 2 | 8.24 | 0.94 | 0 | 0 | 2 |
| *Menu item 5: optimizing fuel* | | | | | | | |
| No $g$ limit | 100 | 3.08 | 24.24 | 0.54 | 0 | **274.2** | −1 |
| 3-$g$ limit | 100 | 3 | 24.24 | 0.59 | 0 | **274.2** | −1 |
| 2-$g$ limit | 100 | 2 | 8.24 | 0.57 | 0 | **176.4** | −1 |
| *Menu item 6: special cases* | | | | | | | |
| Min $g$ | 100 | **1.84** | 14.24 | 0.74 | 0 | 0 | 0 |
| Min $g$, $I_{SP} = 260$ s | 100 | **1.73** | 14.19 | 0.74 | 0 | 0 | 0 |
| WORST | 100 | 3.21 | 161.53 | 0.94 | 0 | 0 | 5 |
| BEST | 162.62 | 1.73 | 8.24 | 0.13 | 381 | 274.2 | −1 |

For all cases, the spaceship capsule is not landing relatively far away from its initial launch point. The pilot could be adjusting for prevailing winds; the landing could be at the spaceport. The distances reached by menu item 3 are not the maximum possible distance that the vehicle can achieve downrange but are the furthest possible if the spaceship is launched at a 75 deg angle above the horizon. The optimal trajectory angle for downrange distance would be closer to 45 deg depending on wind conditions and vehicle mass distribution. For menu item 1 with a 2-$g$ limit the flight trajectory went further than others downrange but did not achieve a high altitude.

### Menu Item 1

Menu item 1 is designed to maximize altitude and view time as the ultimate important parameters. The time spent within low $g$ accelerations, which is often referred to as weightlessness, is rated as fairly important with the lower $g$ values being worth more to the paying customer. The takeoff mass addition and fuel reduction values are ranked higher, because if these factors can be contributed to a flight it will reduce the cost of the flight. Flight time is relatively neutral because it does not take into account the parachute phases of the decent. Maximum $g$ load is the largest penalty because ideally reducing this value will appear for a broader spectrum of passenger's comfort level and health status. The financial multiplier is fairly large, as this flight needs to be the basic and most popular choice for customers. Downrange has a penalty to account for the fact that most customers will want a controlled flight returning to the launching spaceport. The cross-range is a smaller penalty simply because the distance traversed is very small.

### Menu Item 2

Menu item 2 changes most of the importance weighting factors from the menu item 1 flight to place emphasis on the additional mass added to the spaceship. This added mass could be structural or additional payload. The goal of this flight is to just make it to space with the most mass possible. The importance of altitude, the amount of time in space, and the weightlessness factors are not important for this particular paying passenger. The $g$ load and landing location are also not a large penalty and the cost for this flight is expected to be higher to accommodate for the large payload, and thus the financial multiplier is increased. This menu item would also be ideal for the most passengers into space on one flight.

### Menu Item 3

Menu item 3 reduces the penalty of a higher $g$ load and gives a positive impact for the downrange distance. The importance weighting is centered on the altitude achieved. This flight would be for a passenger who wants to cover the most ground distance at the

Table 3 The final menu

| Performance parameter | Menu item number | | | | | |
|---|---|---|---|---|---|---|
| | 1 | 2 | 3 | 4 | 5 | 6 |
| Maximum altitude, km | 137.55 | 100 | 127.86 | 162.62 | 100 | 100 |
| Time in space, s | 179 | 1.5 | 154 | 232 | 3.0 | 1 |
| Flight time, s | 375 | 320 | 362 | 413 | 314 | 348 |
| Time < 0.1 $g$, s | 0 | 0 | 0 | 0 | 0 | 16.5 |
| Time < 0.05 $g$, s | 78 | 71 | 0 | 62.5 | 70.5 | 17.5 |
| Time < 0.1 $g$, s | 108.5 | 86 | 0 | 111.5 | 87 | 18.5 |
| Maximum $g$ load, $g$ | 3 | 2.86 | 3 | 2.86 | 3.08 | 1.73 |
| Downrange distance, km | 21.26 | 15.98 | 161.44 | 124.24 | 24.24 | 14.19 |
| Cross-range distance, km | 0.76 | 0.57 | 0.31 | 0.89 | 0.54 | 0.74 |
| Takeoff mass addition, kg | 0 | 381 | 0 | 0 | 0 | 0 |
| Fuel reduction, kg | 0 | 0 | 0 | 0 | 274.2 | 0 |
| Financial multiplier | 0 | 5 | 0 | 2 | −1 | 0 |

cost of a higher $g$ load. This menu item is also preferable to the pilot as they can use the ascent drift distance as a targeting parameter to fly back to the spaceport.

#### Menu Item 4

Menu item 4 is a flight that would cost a little more money but would offer the highest possible altitude and time in space. This is achieved in these case studies by an increase in the engine's $I_{SP}$. The financial multiplier is increased for these flights because the passenger would be willing to pay more. This flight would be ideal attaining the highest altitude.

#### Menu Item 5

Menu item 5 is particularly focused on reducing the price of the ticket by reducing the amount of fuel consumed. Thus, the importance weighting is focused on how much fuel is saved and how cheap the flight will be. The financial multiplier is at a minimum to ensure that cost is the driving factor for this flight. Altitude and time in space are important, but the weightlessness factors are not as important. This flight looks at the minimum amount of consumables to fly the spaceship.

#### Menu Item 6

Menu item 6 is a special menu item designed for those passengers who might not be in the best health conditions. Most passengers in the early years of space tourism will be older, wealthier people [7], and to be safe, the amount of $g$ loading will have to be minimal and is therefore the focus of the importance weighting. The altitude and time in space will not be as important for these customers as long as they have the opportunity to safely reach space.

#### The Final Menu

Table 3 is the final menu of suborbital trajectories that could be available for a paying passenger. The six choices represent the majority of different possible civil uses with this specific vehicle design. These flights are the best selected from each weighted menu item table and most have alternative backup flights that ranked close behind. The results in Table 3 reiterate how the design of importance will dictate the final output of flights or the trajectories available for a customer. If a customer wants to go for a roller coaster experience, they might opt for a higher $g$-force flight.

## Conclusions

Optimizing trajectories for suborbital human spaceflight can be achieved using software such as EasyPOST and a parametric tradeoff study, as long as the end customer is kept in mind as the requirements driver. To develop a proper flight menu, knowledge of both the market and the chosen optimization software is essential for developing requirements and deciding which variables should be analyzed and compared against each other.

With the variety of flights generated using EasyPOST for this work, it was shown that the diversity in customer preferences can be met with a systems engineering approach, specifically when working with the engine thrust and $I_{SP}$ values. The performance of the engine is the most critical piece of flight hardware for the ascent. The longer the initial thrust lasts, the more likely that the $g$ loads will build up to a higher value. The higher the engine specific impulse, the more efficient the propellant flow rate and the lower the $g$ load.

The reentry and decent is a completely different problem, which was not addressed here but could be modeled in EasyPOST. During this phase, there are high $g$ loads but they are short duration. The thermal temperatures can rise quite high depending on the reentry mode and directly correlate to the materials used for the vehicle. This subject would be an excellent area to be studied using EasyPOST and various techniques such as bank angles and parachute configuration and deployment timing.

This Note shows representative range of trajectories for suborbital human spaceflight. A variety of different profiles can be generated, weighted differently, and selected as best, but ideally it would be better to model many different vehicle profiles to determine what is technologically feasible and which flight profile gives the best ride to a paying customer. Additional flight profiles could include air launches like that of White Knight and SpaceShipOne, ground launches, and ocean launches (underwater and platform launches).

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