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USING THE PARAMAT SYSTEM IN MISSION ANALYSIS AND DESIGN

Darrel J. Conway*, and Darren D. Garber†

Thinking Systems is building a general purpose parallel processing mission analysis tool, Paramat, for large scale analysis problems and for a new class of dynamic mission analysis problems. The new analysis features stem from the introduction of small launch vehicles, and from improved electric propulsion systems and rideshare opportunities. Paramat, an extension of GMAT, runs GMAT's core numerical engine into a parallel processing environment. Paramat has been used previously for Monte-Carlo analysis studies. Recent additions to the tool enable launch window analysis and parametric scans to seek and find useful trajectories. Current development tasks include enhancements to facilitate trajectory optimization.

In this paper, the combination of Paramat and GMAT is used to demonstrate three new trajectory design tasks. Each of these missions is currently under consideration and tasked to NXTRAC and Thinking Systems to assess the feasibility and utility of each proposed trajectory. The first is a transfer from low Earth orbit to the Moon; the second, a deep space trajectory from a asteroid-bound rideshare to an orbital capture at Venus. The final example is the design of a rideshare and ensuing Earth flyby trajectory that raises the spacecraft out of the ecliptic plane. The work flow used for these mission designs is described for each example, starting from initial concept, through early examination of the problem, and into exploration of design options.

The lunar transfer problem examines the feasibility of designing the trajectory of a low mass spacecraft launched from a commercially available small launch vehicle and thruster. The spacecraft performs a flyby of the Moon with the purpose of imaging the far side and returning the images to Earth. The transfer is modeled starting from a parking orbit achievable using a small launch vehicle. The payload is a small spacecraft that uses a solid upper stage for the transfer orbit insertion. Paramat is used to scan through potential transfer insertions from the initial orbit, searching for a suitable transfer to generate the desired lunar flyby trajectory.

The Venus transfer starts from a piggyback ride on the launch vehicle for the Lucy mission. The insertion state obtained from this ride is used to seed the Venus transfer trajectory. Paramat is used to scan through options for a small correction maneuver that tunes an Earth flyby, locating a close approach to Venus on a subsequent orbit. Once the close approach has been found, an insertion maneuver is performed to place the spacecraft into orbit.

The final example uses the same Lucy piggyback state, followed by a tuning maneuver, to perform an Earth flyby that raises a spacecraft's trajectory out of the ecliptic plane. The goal of the mission is to reach a height of fifty million kilometers above the ecliptic in order to study the density and distribution of interplanetary dust responsible for the zodiacal light.

The combination of GMAT and Paramat results in a set of tools that enable mission planning like the cases presented here. Lessons learned from these design exercises are used to update Paramat as it nears public availability.

*Senior Scientist and CEO, Thinking Systems, Inc., 437 W Thurber Rd, Suite 6, Tucson, AZ 85718.

†President, NXTRAC, 800 S PCH Suite 8-247, Redondo Beach CA 90277.

INTRODUCTION

NASA's General Mission Analysis Tool, GMAT,[1] is an open source flight dynamics tool used for mission analysis, maneuver planning, trajectory optimization, and navigation. GMAT is in operational use in the Flight Dynamics Facility at Goddard Space Flight Center. Thinking Systems' Paramat uses the GMAT numerical engine to perform large scale analysis on high performance computer workstations. Paramat has been demonstrated for large scale Monte Carlo analysis problems consisting of hundreds[2,3] to hundreds of thousands of runs.[4]

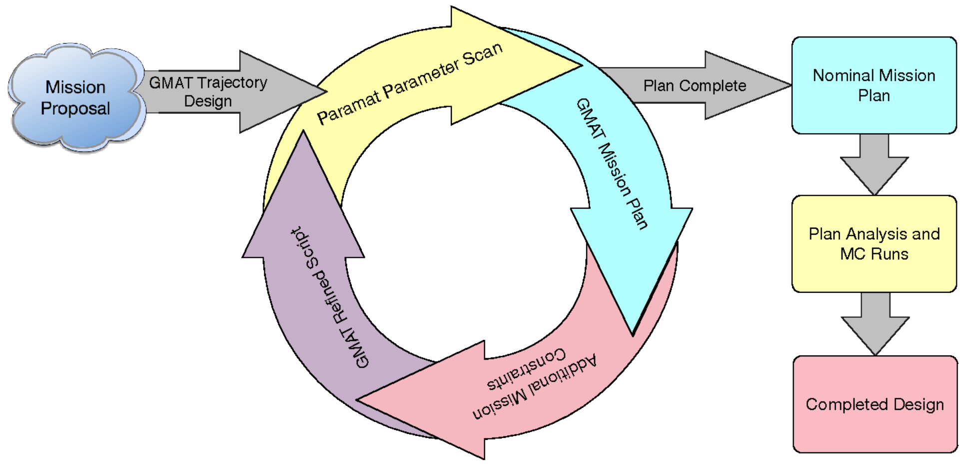

Figure 1. The GMAT/Paramat Mission Design Workflow

The combination of GMAT and Paramat enables mission design for a variety of mission analyses. Figure 1 illustrates the typical mission design approach described in this paper for these tools. The procedure is this:

1. The idea for a spacecraft mission is proposed.
2. Working from the proposed mission concept, an analyst uses GMAT to sketch out the mission in broad strokes, producing a GMAT script that is ready for refinement. This script need not fully satisfy mission needs, but should be sufficient to initiate a parametric scan for a set of mission parameters that do meet mission needs.
3. Adjustable mission parameters are identified and added to the GMAT script, along with measurements that can be used to evaluate how well a given set of parameters meet the mission goals.
4. The parameterized script is run in Paramat to determine a nominal configuration for the mission.
5. The resulting mission is fed back into GMAT, allowing for further analysis and mission tuning.
6. As more analysis needs are identified for the mission, the analyst adds these criteria to the script. The iteration procedure then repeats from step 3.

7. The analyst iterates between GMAT and Paramat until the desired fidelity is obtained in a nominal mission plan, consisting of a GMAT script and associated planning data.
8. The nominal mission plan is then used for further analysis, possibly including Monte-Carlo runs in Paramat to evaluate design margins and navigation requirements, completing the design process.

Three examples of this iterative design procedure are presented in the following sections.

A LUNAR FLYBY

In November 2017, Thinking Systems evaluated use of the Vector-R launch system[5] as a platform to place a small spacecraft into low Earth orbit that would then transfer from the Earth to the Moon, reproducing the Russian Luna-3 and NASA Pioneer 4 missions that returned the first images of the far side of the Moon. The lessons learned from that use case provide the first example presented here.

Spacecraft and Launch Vehicle Characteristics

Vector Launch, Inc. is developing a family of launch vehicles designed to place small spacecraft onto Earth orbit. The Vector-R vehicle can place a small payload – up to 60 kg – into low Earth orbit for less than $2M. For the purposes of this study, we planned the trajectory design around a 21 kg payload placed into a 300 km circular orbit.

The 21 kg payload consists of an instrument cluster attached to a Star 9 rocket motor.[6] The Star 9 has a total mass of 18.6 kg, 14.4 of which is fuel. The 21 kg payload leaves 2.4 kg for the instrumentation package, communications, flight processor, and attitude control. Using the published Star 9 performance data, a basic rocket equation calculation yields a maximum delta-V of about 3.29 km/s for the lunar orbit transfer maneuver. These parameters defined the starting point for the mission design.

The initial study for the lunar transfer trajectory was performed entirely in GMAT. Trajectory scans varied the time to coast in the initial orbit, the total thrust from the Star 9, and the right ascension of the ascending node of the initial orbit, searching for a lunar encounter on September 2, 2018. Using by-hand iteration through orbital parameters, several potential lunar flyby trajectories were found that allowed the spacecraft to fly past the far side of the Moon for the purpose of imaging the lunar surface while it was illuminated by the Sun. That initial study suffered from one critical defect: the parking orbit used had an inclination of 13.5 degrees, too low for the characteristics of a vehicle launching from Florida. However, this initial look at the trajectory provided insight into the components that would enable parallel processing analysis for the transfer using Paramat. Paramat was updated with these components in the spring of 2018, enabling the analysis presented here.

A new analysis of the lunar flyby trajectory has now been made, using a 300 km circular orbit with a 50 degree inclination as the Vector-R injection state. Using this orbit, Paramat was set to iterate over start epoch and maneuver magnitude, searching for a suitable flyby trajectory, as described below.

Preliminary Mission Design

The Vector-R launch vehicle is scheduled to be operational during the first half of 2019. Accordingly, the lunar flyby mission design was updated using Paramat for a launch in October 2019. The far side of the Moon is fully illuminated when the near side is fully dark. In other words, the far side is fully illuminated at the new Moon. The new Moon in October 2019 occurs on October 27, so the target flyby of the lunar orbit was set to occur near this date. Table 1 contains the initial Earth-Centered Earth-Fixed state used to represent the low Earth orbit obtained from the Vector-R.

Table 1. The Vector-R Earth-Fixed Orbit Insertion State

Component	Position	Velocity
X	-1126.659 km	-4.411468 km/s
Y	6574.156 km	-0.753472 km/s
Z	2.827 km	-5.934051 km/s

In order to search for the trajectory desired to image the far side of the Moon, GMAT was configured to use this initial state with a October 27, 2019 22:00:00 starting epoch. The state was propagated to the intersection of the spacecraft's orbital plane with the Moon's orbital plane, at which point a 3.0 km/s maneuver was performed to transfer from low Earth orbit to a trajectory heading towards the Moon. That trajectory was propagated to lunar periapsis, evaluated by the dot product of the Moon-centered position and velocity vectors, and then for an additional day. The resulting mission, run in GMAT, produces the trajectory shown in Figure 2. In the figure, the trajectory color changes from red to yellow when the lunar periapsis is crossed. As can be seen in the figure, the transfer orbit does not reach lunar orbit.

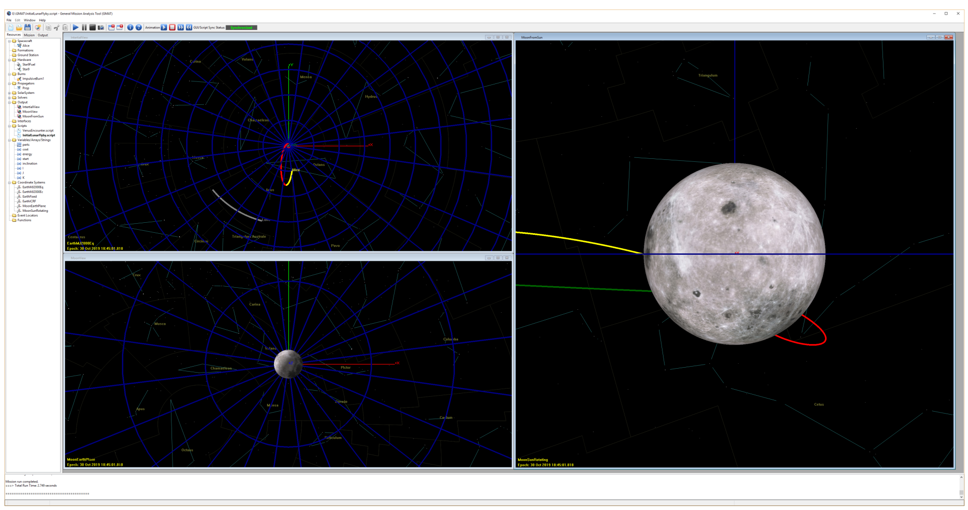

Figure 2. Starting Conditions for the Flyby Search. The upper left view shows the inertial trajectory as seen from above the Earth. The lower left view shows the Moon from above. The right view looks at the trajectory along the Sun-to-Moon vector.

Figure 2 shows the trajectory used to seed a scan of settings in Paramat. The goal of this scan is to find a set of conditions that place the spacecraft near the Moon when the far side of the Moon is nearly fully illuminated. The Paramat script takes the GMAT script used to produce Figure 2, and varies the epoch of the initial state and the magnitude of the manever. Paramat changed the epoch in one minute steps over a 3 hour interval, and the velocity component of the maneuver in 5 m/s increments from 3.0 km/s to 3.2 km/s. The flyby conditions were evaluated by computing the Moon-centered solar Beta-angle at Lunar periapsis. Figure 3 shows a plot of Beta-angle versus lunar periapsis distance for the Paramat scan, as generated in Paramat.

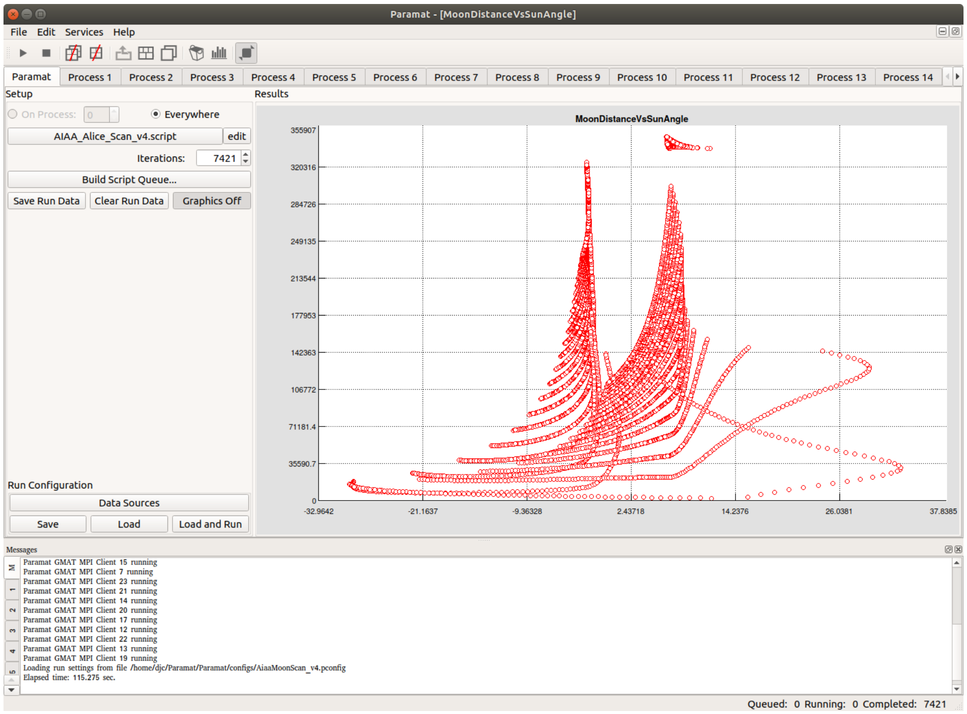

Figure 3. Lunar Periapsis Distance vs Solar Beta Angle for 7421 trajectories

Using the Paramat scan, the conditions for select Lunar beta-angle and approach distances can be selected. The analyst set Paramat to tabulate the values of the scanned parameters along with the beta angle and the lunar approach distance. From this scan, we find that when the epoch of the insertion state (Table 1) is set to October 27, 2019 23:13:00.000, with an insertion maneuver of 3.110 km/s at the Lunar orbit plane crossing, the spacecraft will pass 3,082.6 km from the Moon (altitude 1344.4 km) with a Lunar beta angle of 0.23 degrees. The resulting trajectory, meeting the mission goals, is shown in Figure 4.

A RIDE TO VENUS

Small spacecraft designed for deep space data collection may be carried on the launch vehicle for larger missions. This rideshare sets the orbital parameters for the small vehicle, trading ideal orbit selection for the cost of the launch. With the advent of the SLS and Space X Falcon Heavy/Starliner, rideshare opportunities will continue to increase requiring analysts to assess new mission possibilities. The upcoming launch of the Lucy mission provides one such ride along opportunity that Xplore Inc has requested NXTRAC and Thinking Systems to investigate. Lucy launches in October, 2021 and performs a pair of Earth flybys used to transfer to a trajectory to the L4 Jovian asteroid cluster. By releasing shortly after leaving the vicinity of Earth, a small spacecraft can use the mass margin of the Lucy launch vehicle to be placed on a deep space trajectory without the expense of the launch. Figure 5 shows the trajectory a spacecraft would take when released from Lucy without any maneuvering, propagated for 603 days from release. A spacecraft flying this trajectory will encounter the Earth-Moon system about one year after separation, receive a small gravitational perturbation, and continue to a point that is in the same angular region as Venus when viewed from the Sun.

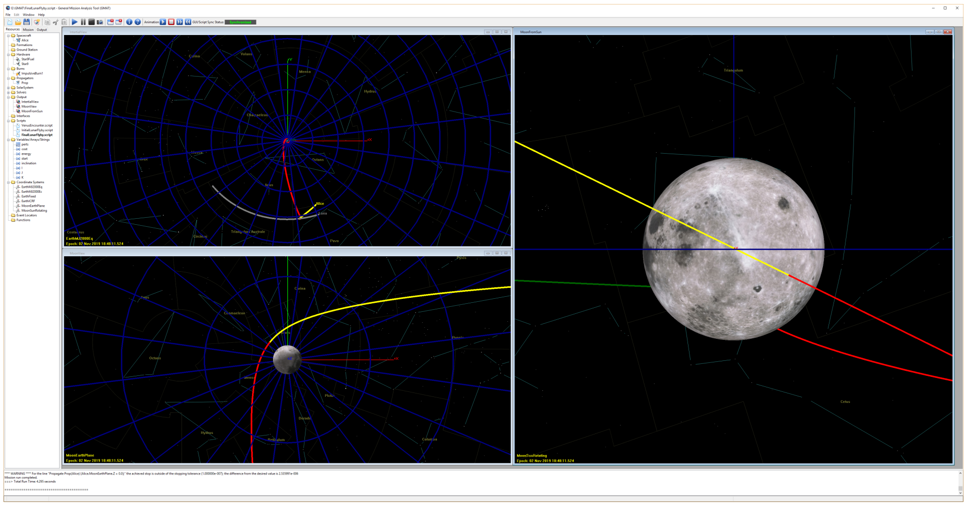

Figure 4. The Selected Lunar Encounter

Parametric Scan for Venus Arrival

Given the somewhat favorable geometry of the release trajectory alignment with Venus, a small maneuver between the Lucy separation and the Earth flyby provides the opportunity for the piggy-backed spacecraft to arrive at Venus after the flyby. In order to explore this possibility, the GMAT script used to model the trajectory shown in Figure 5 was updated with a maneuver 50 days after the separation epoch for the spacecraft state. The post separation maneuver was used to tune the Earth flyby such that the resulting Earth gravity assist targets arrival in the neighborhood of Venus.

The trajectory shown in Figure 5 models a path that is always outside of the orbit of Venus. When the targeting maneuver is performed, the trajectory of the spacecraft will have a smaller semimajor axis than shown in the Figure, resulting in a faster trip to the Venus orbital distance. The spacecraft arrives at the Venus orbit well in advance of the planet. However, when the spacecraft is propagated further, we find that there is a good opportunity for arrival at Venus one orbit later. The script used to model this mission tunes the trajectory for that Venus encounter.

The Paramat script modeling the release from the Lucy launch vehicle varies maneuver parameters for the burn 50 days after release, targeting B-plane parameters at the Earth flyby and continuing on to the closest approach to Venus as determined by local Venus periapsis. Figure 6 shows the result of scanning through 2,121 targeting runs of B-plane settings using Paramat, searching for a close approach suitable for entering Venus orbit. The points lowest on the plot represent the closest approaches to the planet. The minimal located value, placing the spacecraft 2,450,000 km from Venus at closest approach, is reached with a delta-V cost of 8.885 m/s.

Finer examination of the B-plane targeting variables shows that this set of target values is essentially as close as can be achieved with the current targeting for the Earth flyby maneuver. The closest approach maneuver settings can be read from a table of values generated during the Paramat run. Those values give the 8.885 m/s maneuver at 50 days referenced above. The remaining separation at this point in the mission design comes from the inclination of Venus' orbit with respect to the ecliptic plane. Venus' orbit has a 3.4° inclination to the ecliptic. A plane change for the spacecraft's trajectory is needed in order to come closer to Venus than the 2.4 million kilometer approach

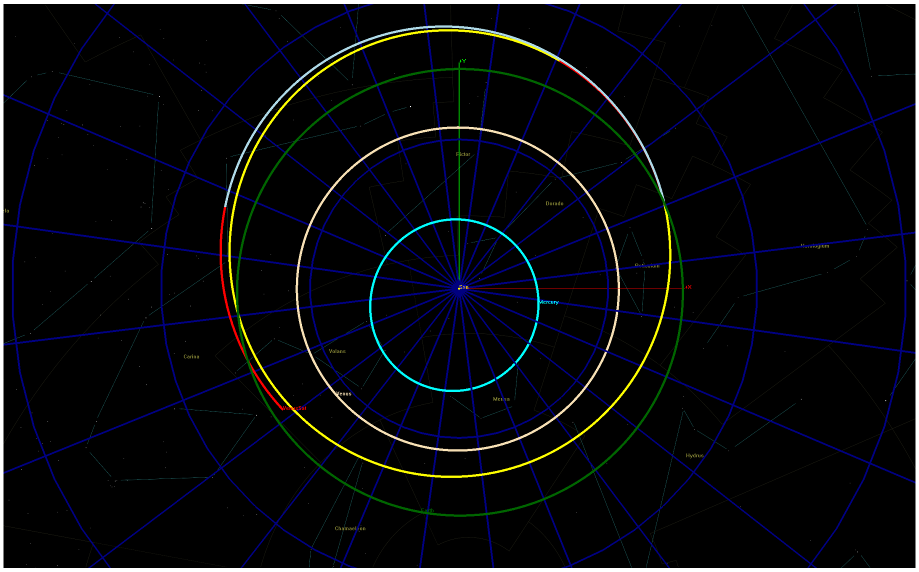

Figure 5. The Trajectory of a Maneuver Free Release from Lucy. Note Locations of the Spacecraft (Red) and Venus (White) at the end of propagation.

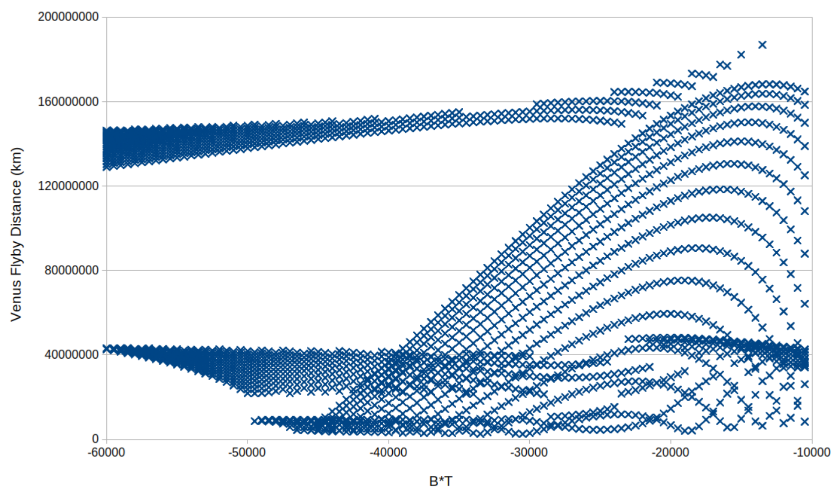

Figure 6. Scan of Transfers from Release to Venus

distance achieved with the Earth B-plane targeting maneuver. The plane change is accomplished using a second maneuver inserted into the trajectory design following the Earth flyby, achieving the desired close approach to Venus.

Final Venus Arrival Targeting

Paramat was used to find the B-plane parameters for the Earth flyby that brings the spacecraft from near Venus in angular separation to a point that, when projected into the Venus orbital plane, aligns with Venus. The remaining orbit tuning is generated using GMAT. The maneuver that aligns the spacecraft's orbit for a Venus close approach is targeted in GMAT using the built-in differential corrector and a custom object referenced coordinate system. Using these settings, GMAT is configured to target Venus with B-plane settings placing the spacecraft ahead of the planet, so that Venus' gravity slows the spacecraft as it approaches and performs an orbit insertion maneuver. The plane alignment maneuver for the Venus B-plane targeting occurs 674 days after separation from the launch vehicle, and has a magnitude of 752 m/s. This maneuver places the spacecraft on a trajectory that encounters Venus at an altitude of 1467 km (7519 km from the planet's center) 798 days after separation, at which point an orbit insertion maneuver is performed to place the spacecraft into orbit around Venus.

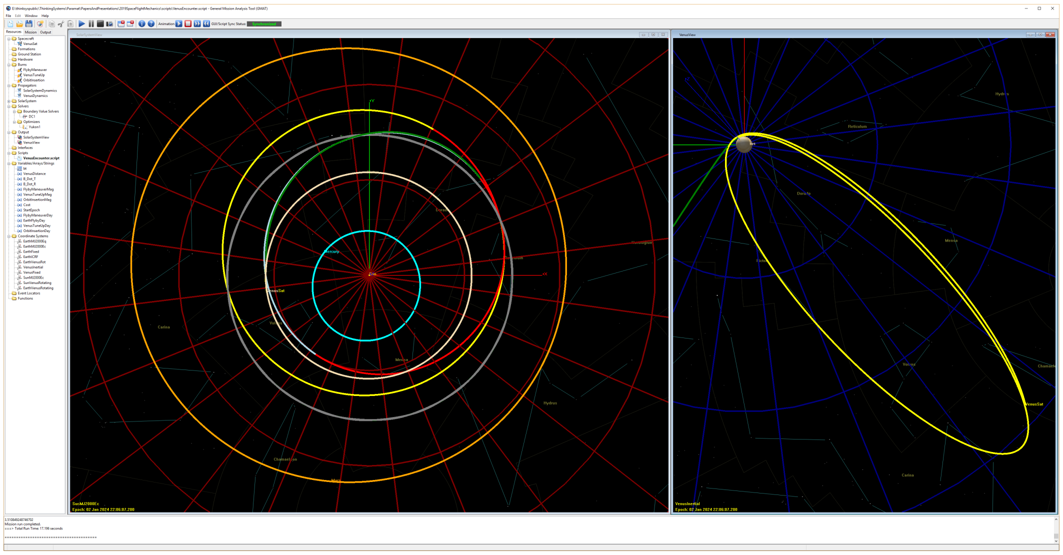

Figure 7. The Full (Preliminary) Transfer to Venus

Table 2 captures the key events on this preliminary mission plan. Figure 7 shows the full trajectory (on the left) and the capture at Venus (on the right). The mission design is treated as preliminary at this point for two reasons. The 752 m/s plane change maneuver tabulated here remains expensive. Further analysis is needed to determine if this maneuver can be reduced or eliminated by opening up the B-plane angle at the Earth flyby. This analysis is a candidate for a second Paramat configuration, restricting the B-plane settings to near-Venus flybys while scanning through the B-vector angle to reduce the out of plane separation at the Venus close approach. Second, the current capture at Venus is more eccentric than desired. The current burn value of 2.75 km/s is a first guess at the maneuver, and needs refinement as the mission plan evolves. Finally, once a full mission plan is in place, a further run in the GMAT optimization subsystem may further reduce the fuel costs for the mission.

Table 2. Maneuvers and Events for the Transfer to Venus

Maneuver/Event	Time to Maneuver (Days)	Delta-V (m/s)
Earth Flyby Maneuver	50.0	8.885
Earth Flyby	364.9	
Venus Periapsis Targeting Maneuver	674.1	751.964
Venus Orbit Insertion Maneuver	798.5	2750.000
Total		3510.849

OBSERVING THE ZODIACAL LIGHT SOURCE

On a dark night with a clear horizon, shortly after sunset or before sunrise, observers can see a faint, diffuse, roughly triangular glow in the direction of the Sun, oriented around the ecliptic. This glow is the zodiacal light. It is attributed to sunlight scattered by interplanetary dust in the plane of the ecliptic. The third mission presented here places a spacecraft above the Ecliptic plane so that it can measure the characteristics and distribution of this dust. Northrop Grumman Aerospace Systems with their teammates at IPAC/Caltech requested NXTRAC and Thinking Systems to assess the feasibility of placing a small spacecraft at least fifty million kilometers above the Ecliptic plane so that the instruments onboard can observe the interplanetary dust from within and above.

The Venus transfer problem described in the preceding section targeted arrival at a specific location: a trajectory placing a spacecraft close enough to Venus to enter orbit. The zodiacal light observer has a much simpler goal of computing the maneuvers needed to place a spacecraft well above the ecliptic plane. Working from the same script defining the trajectory shown in Figure 5, we can define a new set of B-plane targeting goals for the spacecraft so that it passes below the south ecliptic pole of the Earth in order to raise the spacecraft's trajectory out of the ecliptic plane. Maneuvering during the flyby raises the trajectory further from the ecliptic plane. Paramat was configured to use this strategy to vary the magnitude of the B-vector and maneuver delta-V while targeting south pole B-plane goals, and to propagate to the peak of the resulting ecliptic trajectory, measuring the height above the ecliptic at that point as a function of B-vector magnitude and delta-V.

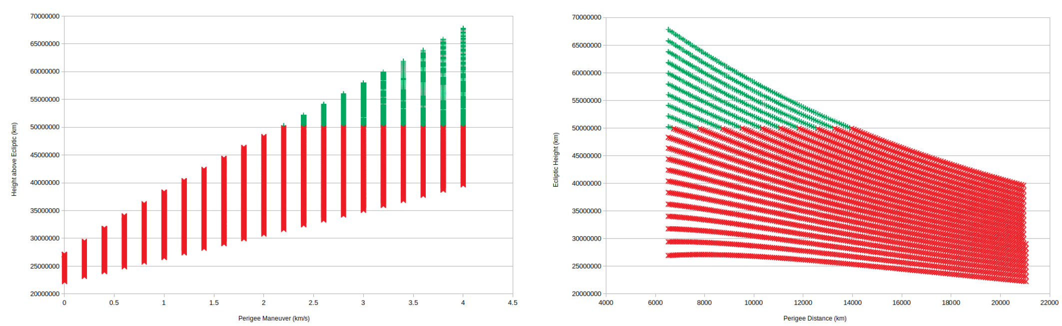

Figure 8. The Trade-off Between Earth Flyby Distance and Maneuver Delta-V. The points in green achieve the mission goal of a minimum 50,000,000 km above the ecliptic.

The results of that scan, shown in Figure 8, identify the minimum flyby burn magnitude for a variety of flyby distances. The graph on the left in the figure shows the ecliptic height as a function of burn magnitude, ranging from a burn free flyby to a 4 km/s burn at perigee. Each point on the vertical lines corresponds to a different flyby distance. The graph on the right shows the ecliptic height as a function of flyby distance. Each curve represents a different delta-V magnitude. As can be seen on these plots, the 50 million kilometer ecliptic height requires a burn of at least 2.2 km/s. That minimum required burn requires a very low Earth flyby (6526.5 km, or roughly 150 km altitude). As the delta-V magnitude increases, so does the minimum flyby distance required to reach the target altitude.

For the purposes of this study, the Lucy piggyback spacecraft has a total mass of 180 kg, with a 10 kg instrument package and a booster consuming the remaining mass. If the mass fraction for the system is similar to the 0.78 mass fraction for the Star 9, we have 140.4 kg of fuel, a 29.6 kg dry thruster, and a 10 kg instrument package, yielding a bit over 4.45 km/s of delta V available for flyby targeting and periapsis maneuvers. Table 3 shows the maneuver magnitudes, perigee altitude, and ecliptic height attainable with this configuration for several different flyby distances using a 4.4 km/s perigee burn, showing that the target 50 million kilometer ecliptic altitude is well within the capabilities of the vehicle.

Table 3. Tradeoffs between Earth Periapsis and Ecliptic Heights

Targeting Burn (m/s)	Periapsis Burn (km/s)	Geocentric Altitude (km)	Ecliptic Height (km)
20.40	4.4	740.74	69,961,138
20.43	4.4	1042.00	68,999,480
20.47	4.4	1499.84	67,574,878
20.53	4.4	2042.46	65,944,303
20.64	4.4	3072.36	63,019,713
20.74	4.4	4045.93	60,451,822
20.85	4.4	5038.89	58,016,908

CONCLUSION

The combination of GMAT and Paramat provides a useful tool chain for mission design. Starting from a mission concept, this paper has shown several use cases for the concept analysis and preliminary mission design for small spacecraft system, either from launch or from a piggyback ride to a deep space trajectory. While the piggyback ride shown here uses a ride on the Lucy spacecraft, preliminary investigation shows that similar results could have been obtained for the zodiacal light observer using a release state from the OSIRIS-REx vehicle. The planetary alignment for the Venus transfer, had it been attempted from OSIRIS-REx, would have required a different transfer strategy to reach correct the timing for the Venus arrival.

Setup for any of these studies is straightforward: Begin with a GMAT script that approximates the mission, identify the parameters that can be adjusted to tune the mission, and scan through these parameters using Paramat. The Paramat run time is fast: Table 4 shows the run time needed for each of the parameter scans shown in this paper using Paramat, running on a 12-core engineering workstation. From the resulting data generated, select a set of parameters that best meet the goals of the mission. As the mission needs evolve, repeat the process until a mission plan is in place.

Table 4. Run times for the Paramet Scans used in this Paper

Analysis Problem	Trajectories Computed	Run Time (s)
Lunar Flyby	7421	87
Venus Transfer	2121	116
Zodiacal Light Observer	3600	295

The GMAT system is a mature, open source system in active use at NASA and in other facilities. Paramat is a proprietary extension to GMAT that builds on identified needs from GMAT mission analysis to implement large scale computations with the proven GMAT engine. As new mission problems are encountered that benefit from parallel processing implementations, Thinking Systems adds new features to Paramat to address those needs. The combination of these two tools enables rapid development of plans for spacecraft missions, along with the evaluation of those plans as the mission evolves from concept to flight readiness.

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