

SENSITIVITY OF THE ASTEROID REDIRECT ROBOTIC MISSION (ARRM) TO LAUNCH DATE AND ASTEROID STAY TIME

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National Aeronautics and Space Administration's (NASA's) proposed Asteroid Redirect Mission (ARM) is being designed to robotically capture and then redirect an asteroidal boulder into a stable orbit in the vicinity of the moon, where astronauts would be able to visit and study it.¹ The current reference trajectory for the robotic portion, ARRM, assumes a launch on a Delta IV H in the end of the calendar year 2021, with a return for astronaut operations in cislunar space in 2026. The current baseline design allocates 245 days of stay time at the asteroid for operations and boulder collection. This paper outlines analysis completed by the ARRM mission design team to understand the sensitivity of the reference trajectory to launch date and asteroid stay time.

INTRODUCTION

National Aeronautics and Space Administration's (NASA's) proposed Asteroid Redirect Robotic Mission (ARRM) will robotically capture and then redirect an asteroidal boulder mass from the current reference target, 2008 EV₅, into a Near Rectilinear Halo Orbit (NRHO) near the moon, where astronauts would visit and study it.² After the initial crew visit, this asteroidal mass would be moved into a long-term stable orbit about both the Earth and the Moon, referred to as a Distant Retrograde Orbit (DRO), where it would remain in place for over 100 years enabling potential follow-up visits. ARM will demonstrate high power Solar Electric Propulsion (SEP), on the order of 40 kW to the Electric Propulsion (EP) system, currently being developed for future robotic and human missions to Mars and beyond. In order to understand the sensitivity of the ARRM reference trajectory to asteroid stay time and Earth launch date, a series of analyses have

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been performed to assess the impact that variations in 2008 EV₅ stay time have on the returned boulder mass and allowable spacecraft dry mass. The ARRM spacecraft in this study was assumed to carry a maximum of 5.3 mt of total Xenon propellant for the mission (5 mt usable + 6% margin). This reference mission currently assumed a launch in December 2021 on either a Delta IV Heavy or a Falcon Heavy to a trajectory targeting a series of Lunar Gravity Assist (LGA) maneuvers to reach Earth escape. The reference trajectory is optimized to provide 215 days for operations at the target asteroid, 2008 EV₅, and to support a crewed rendezvous mission in 2026. The results of these analyses, as well as the ground rules and assumptions of the current ARRM reference trajectory, are documented in this paper.

THE CURRENT ARRM REFERENCE TRAJECTORY

The current ARRM reference trajectory assumes that the Asteroid Redirect Vehicle (ARV) would launch at the end of the calendar year 2021 on either a Delta IV Heavy or Falcon Heavy launch vehicle to a trajectory targeting an LGA. In order to provide a > 20-day launch period, the ARV would launch into a set of elliptical phasing orbits to target an LGA in Feb. 2022. This first lunar flyby, LGA1, sends the ARV onto a large elliptical Earth orbit where Solar perturbations increase the ARV energy before a second lunar flyby, LGA2, in June 2022 that would send the ARV onto an Earth escape trajectory. During this 6-month Earth departure process, the ARV will conduct non-critical deployments and checkouts where the SEP system will be calibrated and prepared for interplanetary thrust. The outbound cruise then takes the ARV to the asteroid.

There are currently 215 days allocated for asteroid operations in the reference trajectory. In order to allow for time to make up for missed thrust on the outbound leg of the trajectory, 30 days of coast is inserted into the trajectory as additional stay time at the asteroid. When this resulting 215-day asteroid operations time is added to the 30 day forced coast for missed thrust in the outbound cruise, this leads to a 245-day stay time for trajectory modeling. Additionally, 15 days is reserved on the asteroid approach for observation while not under SEP thrust and is allocated as part of the interplanetary trajectory on the leg to the asteroid for the purposes of trajectory modeling.

The inbound cruise phase of the trajectory maneuvers the combined ARV and boulder back towards Earth. There is an Earth Gravity Assist (EGA) to provide additional plane change to the interplanetary trajectory a year before an LGA that captures the ARV-boulder combination into the Earth-Moon system. After capture, Solar and Lunar perturbations are used to transfer the entire stack to a crew-accessible orbit. In this example trajectory, the ARV would target a crew-accessible, Lunar Near-Rectilinear Halo Orbit (NRHO) for the Asteroid Redirect Crew Mission (ARCM). During ARCM, astronauts are sent in an Orion spacecraft to rendezvous and dock with the ARV. After ARCM, the ARV will transfer to a Lunar DRO with an orbit lifetime in excess of 100 years for storage of the returned boulder.

Spacecraft Technology Assumptions

The ARV is designed to be a technology demonstration mission of a 40 kW class Solar Electric Propulsion (SEP) spacecraft.

The nominal thruster configuration of the ARV for the reference trajectory assumed three active and 1 spare PPU/thruster string (3+1). A duty cycle of 90% is assumed on the trajectory modeling to allow for missed thrust and other non-thrusting operations. The duty cycle is reduced to 70% on the last 15 days prior to asteroid arrival to allow for observation and characterization of the asteroid on approach. A Xe margin of 6% of the useable Xe is carried as an addi-

tional inert mass in the trajectory modeling to account for mission Delta-V (ΔV) margin and trapped residuals.

A total End of Life (EOL) power to the Power Processing Units (PPUs) of 42 kW is required to power 3+1 configuration of 13.95 kW thruster strings.

Reference Trajectory

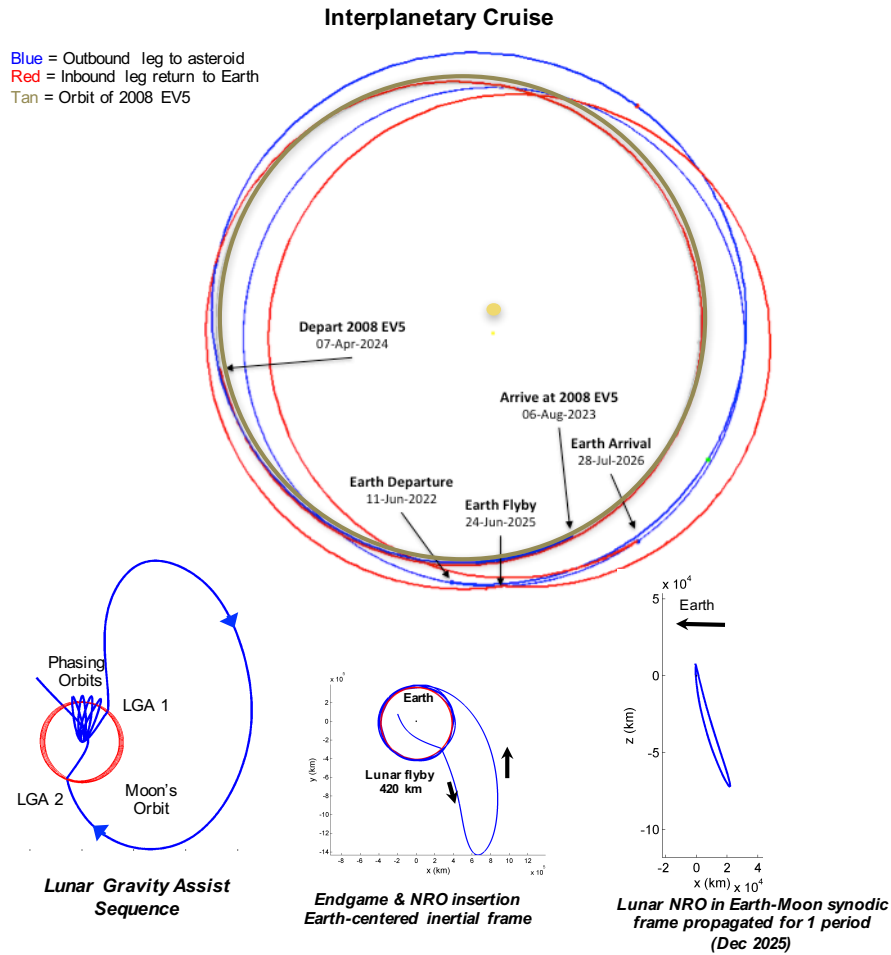
In the current reference trajectory modeling, the dry mass of the ARV is adjusted in order to return approximately 20 t of asteroid mass from the reference target asteroid, 2008 EV₅, given the assumptions documented in the previous sections. Reduction in that dry mass of the ARV would result in an increase of returned asteroid mass for the same set of assumptions.

The heliocentric trajectory starts at Earth departure, after the approximately 6 month LGA has boosted the outgoing velocity to a C3 of 2 km²/s². Table 1 below captures the dates of the heliocentric trajectory of the ARRM. In the reference trajectory, Earth departure starts on June 11, 2022. After completing a thrust-coast-thrust-coast-thrust structured outbound cruise, the ARV arrives at the asteroid on August 6, 2023. After spending 245 days at the asteroid (30 days of missed thrust coasting, 215 days of operations), the ARV departs for Earth on April 7, 2024. In order to change the heliocentric inclination of the incoming trajectory to match that of Earth, an EGA is targeted on June 24, 2025. The heliocentric trajectory ends upon Earth arrival on July 28, 2026. After several months of EP thrusting in cislunar space, the ARV arrives in its final NRHO orbit for the human operations.

Table 1. ARRM Reference Trajectory Dates.

Event	Date
Launch	December 20, 2020
Earth Departure	June 11, 2022
Asteroid Arrival	August 6, 2023
Asteroid Departure	April 7, 2024
Earth Flyby	June 24, 2025
Earth Arrival	June 28, 2026

Below the heliocentric trajectory in Figure 1 are representations of the three near Earth portions of the ARRM complete end-to-end trajectory. On the left side is a depiction of the two lunar flybys of the LGA on Earth escape. The ARV is launched to a C3 less than that of escape, in order to target the moon for a series of flybys. It is after the energy increase to escape from these flybys that the spacecraft starts the interplanetary low thrust trajectory. The center bottom graphic depicts the lunar flyby on Earth return that captures the ARV into cislunar space and sets up the final trajectory to the NRHO. The last image on the bottom right is an example of an NRHO orbit that may be the final orbit of the ARRM vehicle for the potential human mission.



SYNODIC PERIOD OF EARTH AND 2008 EV₅

From the JPL Small Body Database browser³, Table 2 below shows the dates and distances of the close approach points of Earth and 2008 EV₅ around the current proposed ARRM timeline. As can be seen from the table, the closest approach, in December of 2023, is the closest that 2008 EV₅ and the Earth will be in the near term. In order to make observations from Earth of the asteroid operations possible, the current proposed ARRM reference mission is targeting operations at the asteroid during this closest approach to Earth. The current proposed reference mission arrives at the asteroid in August of 2023, ahead of the closest approach of December 20 of that year (highlighted in blue in Table 2), so that operations at the asteroid will be taking place around this time.

Table 2. 2008 EV₅ Close Approach Data.

Date	Minimum Distance (AU)	V-relative (km/s)
2010-Apr-18	0.2397	9.460
2022-Dec-27	0.4236	16.055
2023-Dec-20	0.0422	5.345
2024-Jul-20	0.1410	4.9456
2025-Apr-27	0.1746	7.4511
2038-Dec-23	0.3198	12.922

Figure 2 displays the distance between the Earth and 2008 EV₅ during the 20-year span from 2020 to 2040. As can be seen from the data, the synodic period of the Earth and 2008 EV₅ is approximately 15.7 years. The closest approach being considered for the current ARRM reference trajectory will not repeat again until 2040.

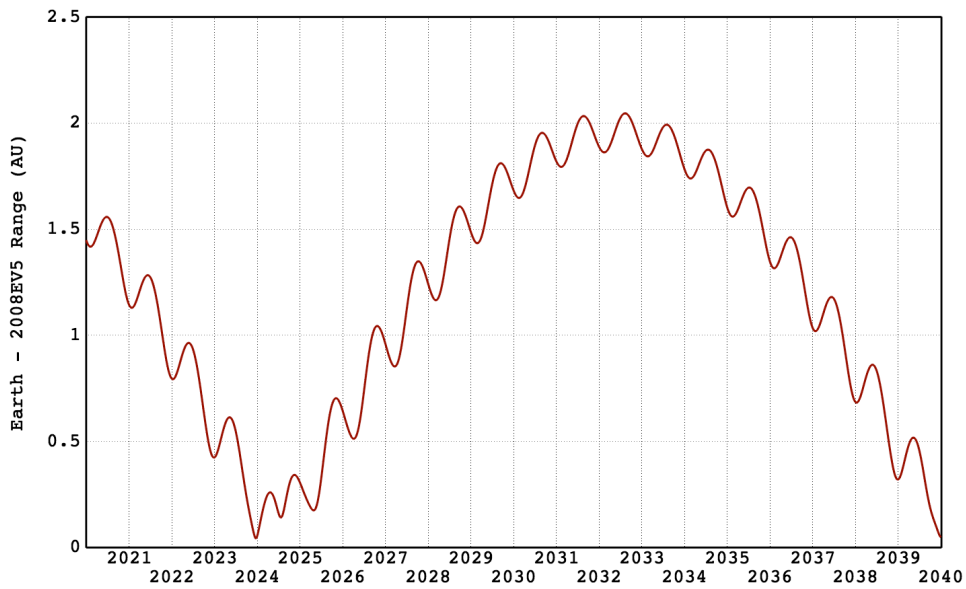


Figure 2. Earth - 2008 EV₅ Range from 2020 – 2040

REFERENCE TRAJECTORY LAUNCH DATE SENSITIVITY

The first time-dependent analysis examined the effect of change in launch date on the reference trajectory. Any change in launch date will impact either the allowable spacecraft dry mass or the returned boulder mass capability or both. Additionally, since this launch is targeting a series of lunar flybys to provide a gravity assist on the outgoing trajectory leg, launch date slips will require coordination with the availability of the Moon. To assess the launch date slips, intervals of 28 days were examined in order to line up with the period of the moon's orbit. This corre-

sponded to Earth arrival date slips of 28 days accordingly with Earth departure dates adjusted to align the outgoing velocity vector with the Moon's velocity direction. Launch slips throughout the reference launch year 2021/2022 and into the following year 2022/2023 were examined. Based on fact that the synodic period between Earth and 2008 EV₅ is 15.7 years and the closest approach between the Earth and 2008 EV₅ occurs in December 2023, as ARRM slips launch dates (and subsequently Earth departure dates) further out from the current reference date, the orbital alignment between Earth and 2008 EV₅ becomes less optimal, driving the trajectory Delta-V (ΔV) requirements and decreasing the asteroidal boulder mass return capability.

Analysis Assumptions

The analysis for this trade study was performed in MALTO (The Mission Analysis Low-Thrust Optimization)⁴, a medium fidelity tool ideally suited for running trade studies about the reference trajectory. The spacecraft is assumed to have the same fixed dry mass of 5014 kg as the reference case and the returnable asteroid boulder mass is maximized for each launch date. For each launch date slip, the Earth return date is allowed to slip accordingly such that the total mission duration is kept the same or less than that of the reference trajectory. Asteroid stay time is assumed to be 245 days. Earth departure is assumed to have an escape characteristic energy (C3) of 1.75 km²/s² and declination of up to 60 degrees relative to the Ecliptic plane, achievable via a pair of LGAs. The higher declination is beneficial for certain launch dates due to the relatively high inclination of 2008 EV₅'s orbit. The Earth return C3 is assumed to be 2 km²/s² and declination up to 30 degrees.

Families of Trajectories

During the trade runs in which the launch date is changed in 28-day intervals, the solution of the previous trajectory is used as initial guess for the next case. The initial guesses may work for a few data points but typically require fresh restarts afterwards due to the drastic change to the orbit phasing between Earth and the asteroid. To overcome this, four families of trajectories are created independently in launch years between 2021 and 2024. Figure 3 shows the maximal boulder mass and corresponding launch dates for each of the four families. To bring back over 20 tons of asteroid boulder mass, seven monthly launch opportunities exist after the reference launch date of December 2021. Three additional launch opportunities exist in late 2022 but none after that since the asteroid is slowing moving away from Earth and the next close approach of the asteroid only arises in 2038.

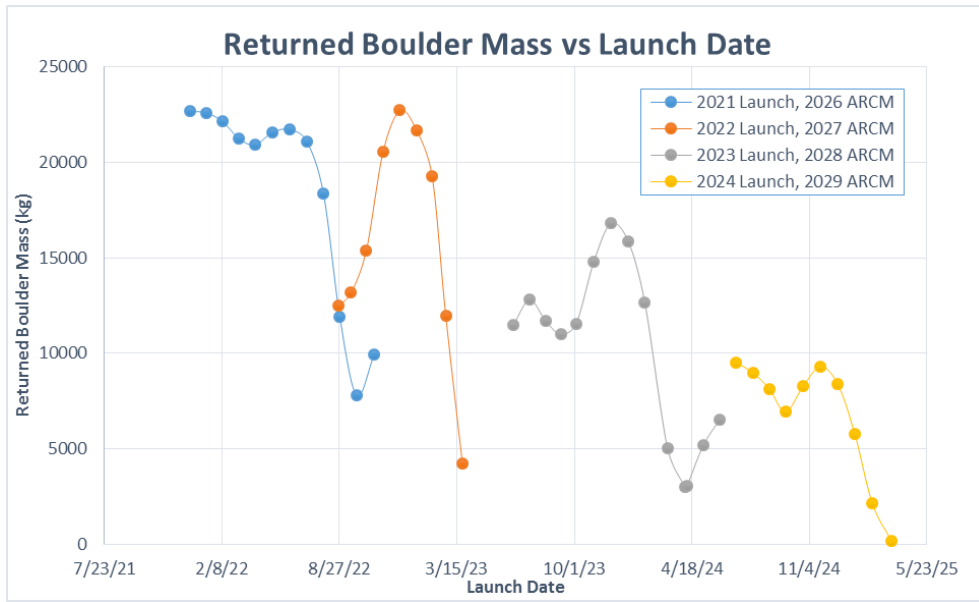


Figure 3. ARRM Returned Boulder Mass vs Launch Date.

REFERENCE TRAJECTORY STAY TIME SENSITIVITY

In addition to the impact of launch date, increasing the stay time at the asteroid will also impact either the allowable spacecraft dry mass or the returned boulder mass capability or both. The reference trajectory is built around a 245 total stay time at the asteroid (215 days of operation and 30 days of margin) to allow for asteroid observation, boulder identification, boulder capture, and a planetary defense demonstration. As analysis is ongoing into the time required for each of these operations, investigation into the impact of extending the stay at the asteroid has been performed. Unlike the launch date slips, the analysis of the impact of asteroid stay time to the reference trajectory assumed a return to Earth of the same date as the reference trajectory. This means there was no one-to-one return date slip for asteroid stay extension examined. Because the reference trajectory was optimized to return 20t of asteroid mass with the assumption that the stay time was 245 days, increasing the stay time above 245 days further constrains the problem and results in decreased returned asteroid mass for a fixed ARV dry mass, or reduced ARV dry mass for fixed asteroid returned mass.

Stay Time Analysis Assumptions

The reference trajectory baseline used for this trade study was modeled in the trajectory tool, Copernicus⁵. Copernicus development started at the University of Texas at Austin and currently continues at Johnson Space Center (JSC).⁶ Copernicus is a generalized spacecraft trajectory design and optimization tool, capable of designing low thrust and impulsive trajectory problems.

Copernicus is currently the baselined tool for performing all higher fidelity ARRM trajectory analysis. The ARRM spacecraft in this study was assumed to carry a maximum of 5.3 t of total Xe for the mission (5t usable + 6% margin) with an additional 360 kg of hydrazine carried for use at the asteroid. The launch mass was constrained to not exceed the Delta IV-H performance to the C3 required for the LGA (-1.5 km²/s²), minus a launch adapter mass of 900 kg.

The results presented were generated by first by fixing the spacecraft dry mass and maximizing returned boulder mass, and then by fixing the returned boulder mass and maximizing the spacecraft dry mass, all while varying the asteroid stay time. In order to return the 20t boulder mass in the reference trajectory, the maximum possible ARV dry mass for a 245-day stay time was 5014 kg. To assess the sensitivity of the reference trajectory, stay time, boulder mass and spacecraft dry mass were varied near these reference values.

Stay Time Analysis Results

Initial analysis of the sensitivity of asteroid stay time varied the stay durations from 10 weeks shorter to 35 weeks longer than the reference of 245 days in 1-week steps. ARV dry mass was held constant at 4800, 5000 and 5200 kg with maximum returned asteroid mass as the objective function. Next, returned boulder mass was held constant at 19t and 20t with maximum ARV dry mass as the objective function. The arrival and departure dates were optimized in this scenario in order to represent a mission that has a planned stay time of the specified duration rather than a mission that required a modified stay time after asteroid arrival.

Figure 4 shows the results of maximizing returned asteroid mass for a range of ARV dry masses and stay times. Each ARV dry mass curve demonstrates similar characteristics for the returned asteroid mass sensitivity. From -10 weeks to +15 weeks relative to the reference stay time, the slope is nearly linear at approximately -0.06 tons/week. That is, an additional week of stay time in this region reduces the maximum return mass by 0.06t (60 kg). From +15 weeks to +25 weeks, a flat region exists where the returned asteroid mass is nearly constant. As the stay time increases beyond +25 weeks, an exponential decline in maximum returned mass is observed, with a peak slope of approximately -0.9 tons/week.

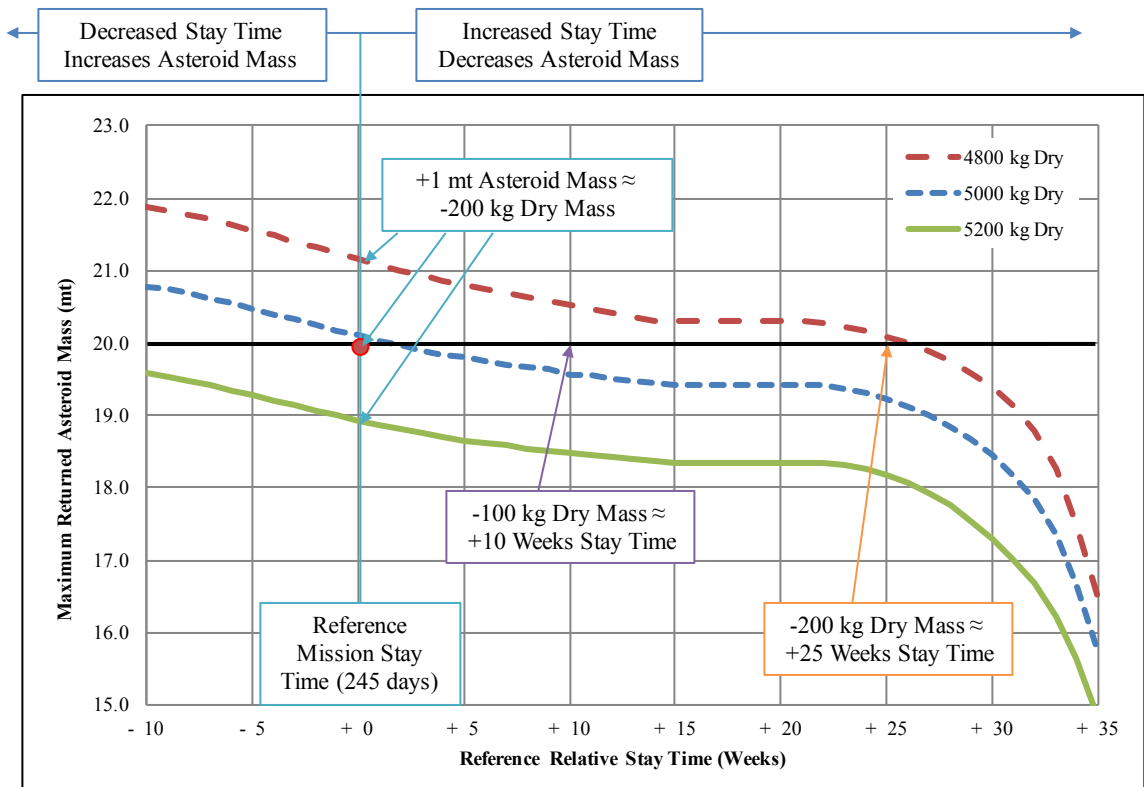


Figure 4. Maximum Returned Asteroid Mass vs. Asteroid Stay Time

Figure 5 shows the results of maximizing ARV dry mass for a range of returned boulder masses and stay times. Each returned asteroid mass curve demonstrates similar characteristics for the ARV dry mass sensitivity. From -10 weeks to +15 weeks relative to the reference stay time, the slope is nearly linear at approximately -10 kg/week. That is, an additional week of stay time in this region reduces the maximum ARV dry mass by 10 kg. From +15 weeks to +25 weeks, a flat region exists where the ARV dry mass is nearly constant. As the stay time increases beyond +25 weeks, an exponential decline in maximum ARV dry mass is observed, with a peak slope of approximately -300 kg/week.

Furthermore, before the region of exponential decline in both ARV dry mass and returned asteroid mass, 1t of asteroid mass is equivalent to approximately 200 kg of ARV dry mass. For example, at the reference stay time, to increase the ARV dry mass from 5000 kg to 5200 kg, returned asteroid mass would have to decrease by approximately 1t. In addition, to add 10 weeks to the stay time and retain a 20t returned asteroid mass, the ARV dry mass must not exceed ~4900 kg. Similarly, if it is desired to stay an additional 25 weeks at the asteroid, but still return a 20t boulder, the ARV dry mass must not exceed ~4800 kg.

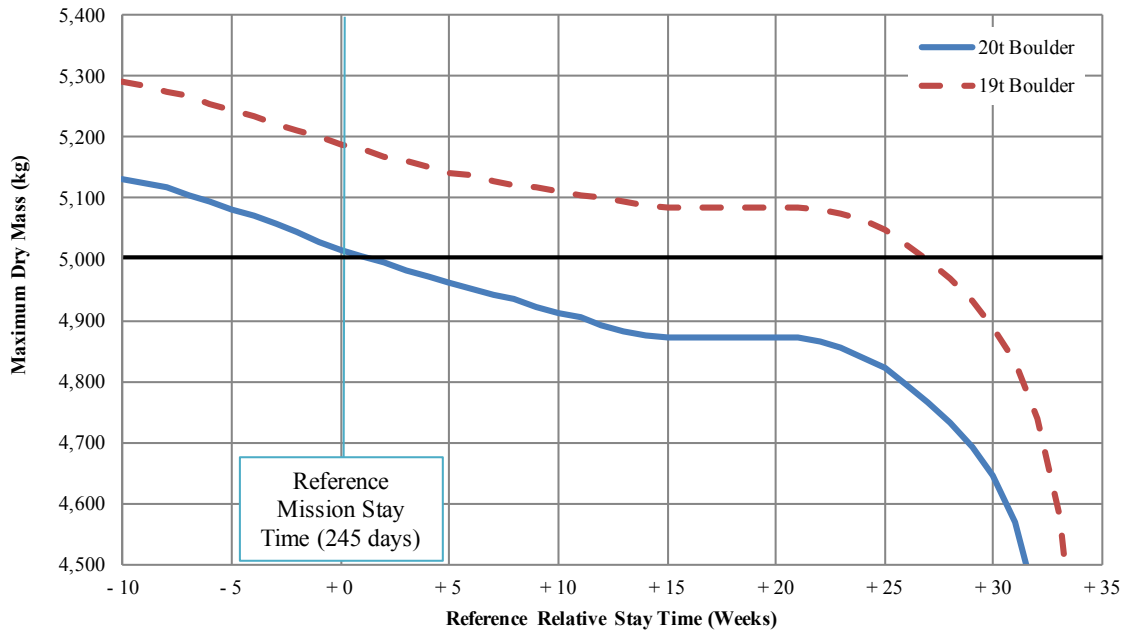


Figure 5. Maximum Spacecraft Dry Mass vs. Asteroid Stay Time.

2008 EV₅ Contour plot of Asteroid Mass and ARV dry mass for asteroid stay times

Additional analysis was completed on the reference trajectory to examine the sensitivity of the round trip trajectory to stay time at the asteroid. Setting the spacecraft mass constant across the analyses, the trajectory optimization maximized the return mass from the asteroid. Figure 6 shows a close up view of the variation of boulder mass with asteroid stay time. The reference trajectory is indicated as “0” days on the x-axis. Stay times of less than the current reference stay at the as-

teroid are to the left, represented by negative stay times, and stay times of more than the reference trajectory assumed stay time are to the right as positive or longer stay times. For the range of ± 17 weeks (~ 120 days) the asteroid return mass varied from 20.1t to 20.85t. Less stay time returns more asteroid mass and more stay time returns less asteroid mass than the reference trajectory for the same Earth departure and Earth return conditions. The 120-day range from the current reference was intended to capture the change to boulder mass due to a potential earlier departure date if the boulder was successfully captured early in the operations phase.

For all of these trajectories, the arrival at the asteroid date was the same, but the departure date varied. All of these cases returned to the same Cartesian state at the start of the Earth-gravity assist preceding the endgame capture phase for a 2026 ARCM.

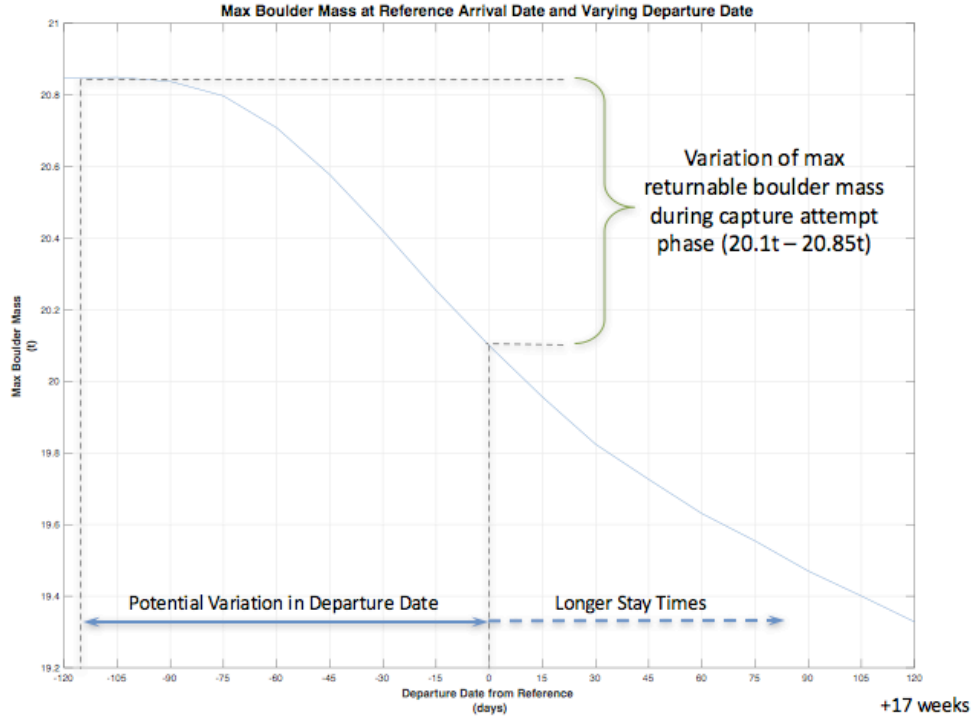


Figure 6. Maximum Asteroid Boulder Returned Mass vs. Asteroid Stay Time.

A contour plot of asteroid boulder returned mass for asteroid arrival and departure date combinations is shown in Figure 7 below. For all of these day combinations, the Earth departure and Earth arrival times remain in 2022 and 2026 respectively and the optimal spacecraft dry mass is assumed to be the reference trajectory derived mass of 5014 kg. The days along the x-axis are expressed in days from the current reference arrival date, with positive days indicating an arrival later than the current reference and negative days indicating an arrival earlier than the current reference. Similarly, the days along the y-axis are expressed in days from the current reference departure date with positive days indicating a departure later than the current reference, negative days indicating a departure earlier than the current reference. The (0,0) point represents the current reference assumption of arrival and departure dates. The difference between the two is the 245 days modeled in the trajectory as days at the asteroid. The diagonal line represents combinations of arrival and departure dates of the trajectory that are also 245 days apart indicating a constant 245-day stay time line for 2008 EV₅. Date combinations above the 245-day constant stay time

line represent stay times > 245 days and date combinations below the 245-day constant stay time represent stay times < 245 days.

Contours of asteroid returned mass were determined for each of these combinations of asteroid arrival and departure dates. As can be seen, the contour of 20t returned mass is possible for arrival departure dates that result in stay times less than or equal to 245 days. If after additional analysis, the reference trajectory requires more than 245 days stay time for operations at the asteroid, the returned asteroid boulder mass will be reduced for the current Earth departure and Earth arrival dates. Contours in red are around 20t, and contour line colors change to orange, yellow, etc. represent lines of less than 20t returned asteroid mass.

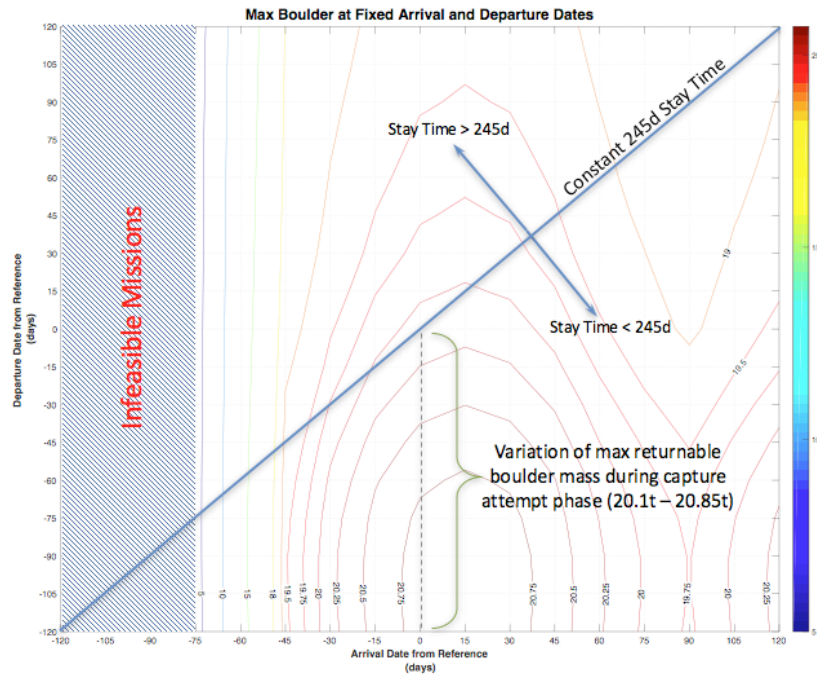


Figure 7. Maximum Asteroid boulder returned Mass vs. Asteroid Stay Time.

Another contour plot of maximum spacecraft dry mass for asteroid arrival and departure date combinations is shown in Figure 8 below. For all of these day combinations, the Earth departure and Earth arrival times remain in 2020 and 2026 respectively and the asteroid returned mass was assumed to be the reference trajectory returned mass assumption of 20t. As with the contours above, the diagonal line represents combinations of arrival and departure dates of the trajectory that are also 245 days apart indicating a constant 245-day stay time line for 2008 EV5. Date combinations above the 245-day constant stay time line represent stay times > 245 days and date combinations below the 245-day constant stay time represent stay times < 245 days.

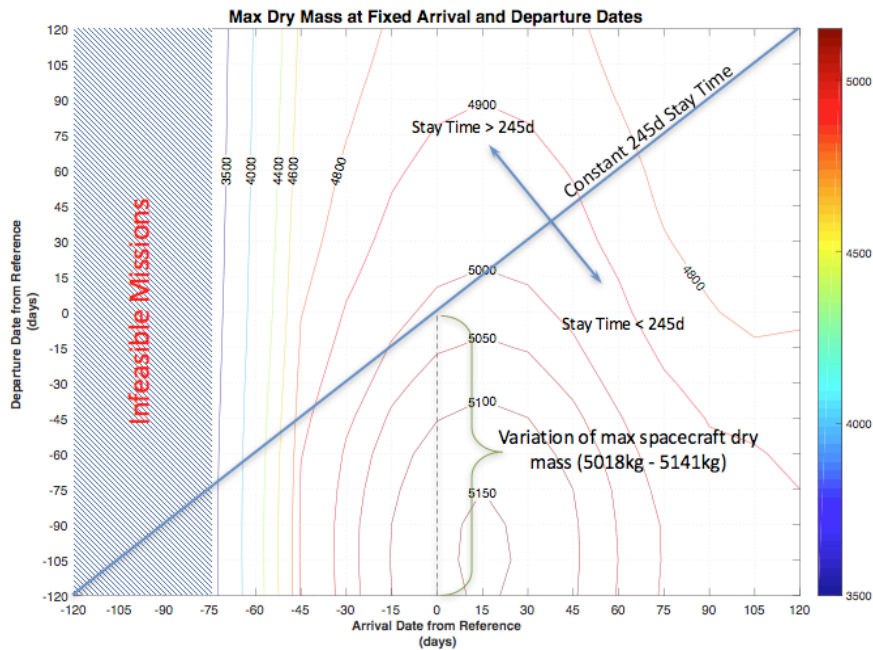


Figure 8. Maximum Asteroid boulder returned Mass vs. Asteroid Stay Time.

CONCLUSION

Because of the alignment of 2008 EV₅ and Earth within their orbits with respect to one another, the current timeline for the proposed Asteroid Redirect Robotic Mission (ARRM) is the optimal time to bring back as much asteroid mass as possible from 2008 EV₅ given the assumed high power SEP in space propulsion system. The synodic period of 2008 EV₅ and the Earth is 15.7 years and the closest approach of December 20, 2023 falls within the currently proposed timeline. Delays in the launch and Earth return dates will result in a capability for less asteroid mass returned. Nevertheless, launch date delays of several years as under study in this analysis, resulting in a one for one Earth return delay are still feasible missions. Additionally, the asteroid stay time can be increased from the current reference trajectory assumptions by either reducing the amount of asteroid mass returned, the dry mass of the spacecraft or both.

Since it is more difficult to reduce mass of the spacecraft as the design commences, a reduction in the returned mass from the asteroid seems to be the more likely trade for asteroid stay time. All of these trades in dates (launch and asteroid arrival/departure) are directly impact the ability of the optimized trajectory to return mass from the asteroid. Any delays in the launch or arrival dates, at Earth and/or the asteroid, from the current proposed reference trajectory presented in this paper will result in a decrease of asteroid returned mass.

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