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LOW-THRUST TRAJECTORY MAPS (BACON PLOTS) TO SUPPORT A HUMAN MARS SURFACE EXPEDITION

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Planning the logistics of multiple launches to support a Mars surface expedition requires good trajectory design tools. Traditional ballistic transfers are well characterized by performance maps known as porkchop plots. However, the transportation of cargo can benefit from the use of low-thrust solar electric propulsion, both in terms of mass delivered and the flexibility of flight durations and dates. This paper describes the design and use of bacon plots (the low-thrust analog to porkchop plots) and their application to the architectural design of a human Mars surface expedition.

INTRODUCTION

Transportation logistics always start with good maps and planning tools. This is especially true of an expedition to send humans to the surface of Mars. Most mission architectures, such as the one presented in reference [1], would require multiple launches to pre-position elements and supplies in advance of the crew. Solar electric propulsion (SEP) is an efficient way to send cargo to Mars, but it also adds a complicating factor in that trajectories must be optimized along with their corresponding flight systems, thruster characteristics, power levels, and acceptable flight times.

For ballistic trajectories to Mars, mission designers have long turned to maps of available transfers known as porkchop plots. These contour plots show trajectory details for transfers of given launch and arrival dates. They can be independent of launch vehicles and flight system characteristics when contours of velocities and angles are shown. They highlight the synodic nature of Earth-Mars trajectories (every ~26 months) and the relatively short periods (weeks) of optimal transfers. Launches outside of these narrow windows are prohibitively costly. When multiple launches of heavy-lift launch vehicles are required for the pre-positioning of mission elements, launch frequency quickly becomes an issue as many launches vie for optimal launch periods.

Low-thrust trajectories open up the option space for transportation logistics in many dimensions. SEP is highly flexible in that many mission parameters are directly correlated and tradeable. These include mass, power, time-of-flight, launch and arrival dates, etc. Allowing for longer flight times requires less propellant and leads to more delivered mass, or more power leads to higher thrust and

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the possibility of shorter flight times. The explicit interrelations between mission design and flight system parameters mean that early mission- and architectural-level design changes often require a completely new trajectory and flight system optimization. In this paper we will discuss the creation of low-thrust porkchop plot analogs, or bacon plots[2], and their use as a logistics planning tool in the creation of human Mars exploration architecture.

In response to NASA's desire to have an Evolvable Mars Campaign[3,4], many researchers have proposed the use of hybrid architectures[5,6] that take advantage of the strengths of both chemical and electric propulsion systems[7]. This can be in the form of either separate vehicles, with SEP used for cargo[8] and chemical used for crew[9,10], or truly hybrid vehicles that use SEP in deep space and high-thrust chemical engines in critical regions where they may take advantage of the Oberth effect and greatly reduce trip times[11]. Another common desire of the Evolvable Mars Campaign is to make use of a lunar gateway[12,13] as a staging point for missions beyond Earth. Common mission elements like propulsion, propellant, cargo, and habitats can be aggregated in stable cislunar orbits where they can then depart for various destinations by taking advantage of low-energy transfer techniques.[14] Along with the use of the lunar gateway, it can be beneficial to make use of reusable elements such as propulsion modules that return to the gateway to be refueled after delivering cargo to Mars. In this paper, we explore the use of a reusable SEP tugs and their benefits in launch sequencing for a human Mars expedition.

STUDY ASSUMPTIONS

One of the main objectives of this paper is to show how the use of mission design tools, in the form of trajectory maps, can aid in the logistics and design of human Mars architectures. In order to do so, we introduce some broad assumptions on mission elements used. The primary element studied is a large, solar-powered, reusable SEP propulsion module – or SEP tug. Our notional SEP tug uses 10 HERMeS Hall-effect thrusters[15] and has refillable xenon propellant tanks. These engines are a high-heritage follow-on to the recently cancelled Asteroid Robotic Redirect Mission (ARRM) which was planning to use a 50 kW SEP spacecraft propelled by 4 HERMeS engines. Our SEP tug would be powered by 150 kW (@ 1 AU) arrays and is roughly three times the size of the ARRM spacecraft, making use of many similar components. It is capable of docking/undocking to support multiple round-trips to Mars. The dry mass of the SEP tug is approximately 8 metric tons (mt). A constant 10 kW is diverted for spacecraft systems and margin, leaving 140 kW for the propulsion system. Each HERMeS engine provides 585 mN of thrust and 2660 seconds of Isp when receiving its maximum power of 14 kW. At Earth there is enough power to run all 10 engines, diminishing to 3-4 engines at Mars as available solar power is reduced. Figure 1 shows the key parameters of the tug. A detailed mechanical design of the tug was not carried out, but the mass is consistent with tugs with similar power and capabilities.

One or more of these tugs would be delivered to the cislunar staging point to be mated with cargo modules bound for Mars. While there are many options for staging orbits (see [13]), we chose to use a lunar Near Rectilinear Orbit (NRO). The basic properties of the NRO are a low perilune near one of the poles (90° inclination), high apolune, a period of around 9 days, and an orbital plane facing Earth. This type of orbit balances the competing needs of a staging orbit, providing easier access to the lunar surface than a Distant Retrograde Orbit, and easier access to deep space than a Low-Lunar Orbit[16]. Because the orbits are unstable[*], the tug departs the NRO and vicinity of the Moon with minimal ΔV. A combination of solar perturbations and SEP thrusting increases the energy with respect to the Moon, so that a lunar gravity assist can cause the tug to escape Earth with a C3 of around 2 km^2/s^2. This energy raising process takes approximately 4

[*] NRO orbits require ~10 m/s per year for station keeping

months and 100 m/s of ΔV. At the end of the resupply mission this process is reversed to capture back into the NRO. One important aspect of placing the SEP tug in cislunar orbit is that it is not necessary to use SEP to climb out of the Earth's gravity well, which requires months of spiraling.

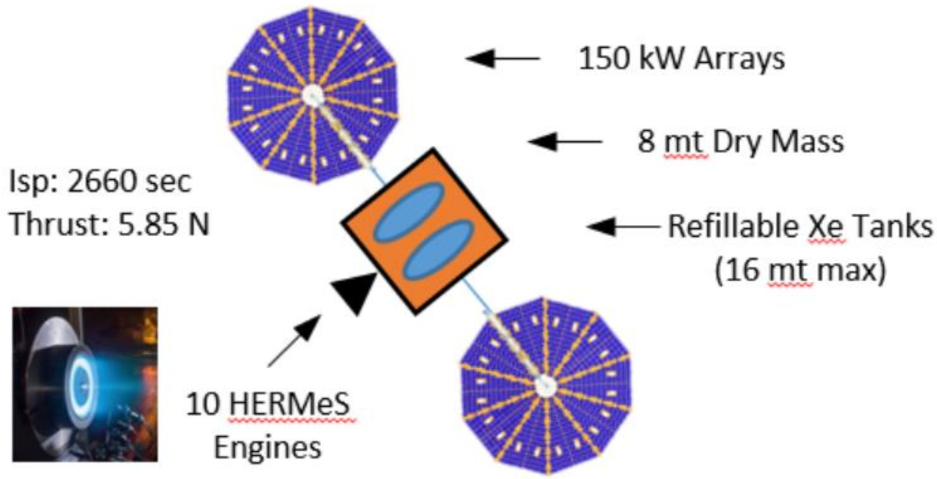

Figure 1 - Our notional SEP tug would weight 8 mt (dry) and use up to 10 HERMeS (inset) engines with 150 kW of power. The Xenon tanks would be refillable through the docking adapter with up to 16 mt of propellant.

For a launch vehicle we make use of the proposed Block 1b variant of the NASA Space Launch System (SLS). SLS is the agency's selected launch vehicle for exploration class crewed missions as well as potential deep space science missions. In its initial configuration, the SLS would use a core stage with four RS-25 main engines, 2 five-segment solid rocket boosters, and second stage called the interim cryogenic propulsion stage (iCPS), which is derived from the Delta IV Heavy launch vehicle. The initial configuration, known as Block 1, is capable of sending approximately 25 mt to trans-lunar injection (TLI). After its maiden voyage, it is anticipated that it will quickly evolve to a Block 1b configuration that would use a larger upper stage known as the Exploration Upper Stage (EUS). The Block 1b configuration is expected to deliver 40 mt to TLI and up to 30 mt to trans-Mars injection (TMI).

Human Mars expeditions require multiple elements to transport and sustain the crew. These elements include habitats, propulsion modules, landers, ascent vehicles, etc. In some architectures, everything is taken at the same time in one massive flotilla. Most architectures, however, propose many launches to send the infrastructure needed to assist the crew throughout their journey. There are virtually an unlimited number of ways to orchestrate the mission architecture in terms of types of mission elements, staging locations, and mission sequences. For the purposes of this study we use the following element masses[17,18,19]:

- Orion (Command + Service, includes propellant) - 20 mt
- Deep-Space Habitat (DSH) - 30 mt
- Surface Habitat (HAB) - 35 mt
- TEI Stage (includes propellant) - 26 mt
- MOI Stage (includes propellant) - 28 mt
- LMO-to-HMO Booster Stage (includes propellant) - 18 mt
- Crew Lander/MAV (includes propellant) - 50 mt
- Exploration Upper Stage (EUS) - 14 mt
- Orbital Resupply Module - 15-30 mt

- Surface Resupply Module - 20-30 mt

BALLISTIC TRANSFERS

The most straightforward way to get to Mars is via direct launch from Earth. One large (TMI) burn is applied by the launch vehicle upper stage to achieve the heliocentric orbit necessary to reach Mars with the desired conditions. Only small course correction maneuvers are applied during an otherwise quiescent cruise. Upon arrival, either a large insertion maneuver (MOI) is used to achieve orbit or the spacecraft enters the atmosphere directly and uses heatshields, parachutes, and thrusters to come to rest on the surface. Lambert's equations dictate that the dates of Earth departure and Mars arrival fully specify the energy and geometric conditions necessary to make the transfer.

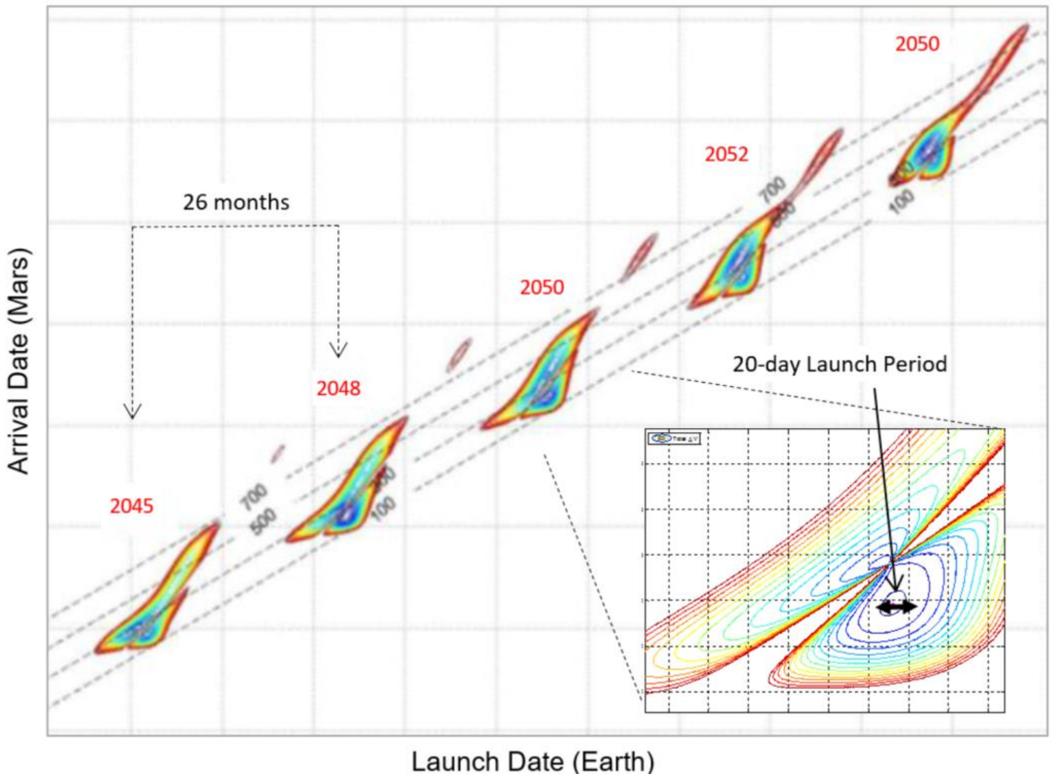

Figure 2 - Porkchop plots for 5 opportunities. The contours lines are representative of deliverable mass to Mars, with blue being the highest and red the lowest. The dashed lines are transfer times in days.

Figure 2 shows the "islands" of Earth-Mars transfers available ballistically, occurring every 26 months with the synodic period. Realistically, transfers that take full advantage of a launch vehicle's lift capability occur near the center (blue contours). Launch periods typically span 20 days and occupy a large portion of most efficient departure dates. If two or more launches are required during the same opportunity compromises must be made. Additional launch periods must be pushed to areas of the porkchop plots with higher launch C3's and/or arrival V-infinity. Also, for an added degree of difficulty, there may be additional time required between launches of a large vehicle such as the SLS for pad refurbishments, launch vehicle production, and other considerations. This could cause launches to be separated by a minimum of a month or more. Table 1 shows the C3 penalties for 2 launches in the same opportunity for various launch separations. For separations of a few months the launch vehicle's capacity may be reduced by half, and for 6 months it may not even be feasible.

Table 1 – Minimum C3 energy (km^2/s^2) required for TMI for multiple launches per opportunity. The first column is for a single launch in the best 20-day launch period. For 2 launches, the launch periods are separated by 0, 2, 3, or 6 months, and the minimum C3 for either period is given. The higher C3's required by large separations can result in 30-70% reductions in SLS launch capacity.

	1 Launch	2 Launches per Opportunity			
Year	(20-day)	Adjacent	2 Months	3 Months	6 Months
2039	12.7	13.8	29.0	42.2	82.1
2041	10.5	11.7	33.3	43.1	83.9
2043	9.2	9.9	29.0	36.8	73.1
2046	8.7	9.3	22.4	27.8	54.4
2048	8.6	9.8	16.7	17.9	35.4

One way around the restrictions of the ballistic porkchop plots is to launch early and loiter in Earth or lunar orbit. For example, it is possible to launch to a multi-day, highly-elliptical orbit and wait for a number of months for a favorable alignment for Earth departure that may even take advantage of a lunar gravitational assist. Another possibility would be to wait at the lunar gateway staging point until the proper time to leave efficiently. However, these options add a number of complications including propellant storage in space, additional operations and critical events, engine restarts, etc.

Some mission elements of a human expedition require the relatively quick transfer times of direct trajectories. While this is especially true for the crew themselves, it may also be necessary for the timely delivery of prepositioned elements, depending on the sequence of a particular architecture. On the other hand, some elements may have very little impetus for a fast transfer and would rather benefit from a more efficient route. This is where the benefits of SEP come in to play. As was previously mentioned, many researchers have proposed hybrid mission architectures where some elements are sent earlier on low-thrust trajectories, thereby saving fuel and delivering more useful mass with the same launch vehicle. Low-thrust trajectories are not as simple as their ballistic counterparts, but they can be extremely flexible, depending on the performance of the vehicle itself. Every trajectory must be optimized for the given performance and constraints of the mission. In the next section we discuss the use of low-thrust trajectories in multi-element architectures by using trajectory maps analogous to the porkchop plot.

CREATING BACON PLOTS

When constructing a multiple-launch human expedition architecture, it is necessary to keep track of the various requirements and constraints of each individual mission. For example, it may be necessary to send a hab to the surface, a descent/ascent module to low Mars orbit, and a TEI stage to high-Mars orbit, all before the crew arrives on a direct trajectory. Each module has a required mass, which sometimes is greater than the capability of the direct throw capability of the launch vehicle. That would mean multiple launches or the use of a more efficient SEP tug. The SEP tug has the added benefit of very flexible departure and arrival dates, albeit trip times can be much longer for large masses. Given the fact that dates, times, locations, and masses are so complicated and interrelated, it is crucial that we have a map of all of the possible low-thrust trajectories that we may consider to use alongside the porkchop plots. For this reason we create the SEP analog, known as a bacon plot.[2]

The solutions to date-constrained transfers using low-thrust are not unique as they are with ballistic transfers. Each trajectory must be optimized using a set of mission unique parameters – such as thruster performance (Isp, thrust, efficiency), power level, and mass – as well as an optimization method to select a thrusting scheme that maximizes a figure of merit, such as delivered mass. In order to characterize mission design parameters (dates, masses, and durations) for cargo missions, thousands of optimized trajectories were generated. By exploring a wide range of parametric combinations, we are able to create a better map of the trade space we seek to explore. This allows us to evaluate where desired missions are feasible, and to know whether any problematic regions that may be nearby. Figure 3 shows a typical bacon plot with an equivalent porkchop plot superimposed. In this case the colored contours show the maximum mass delivered to low-Mars orbit starting from a given launch vehicle. The width of this plot is 26 months and illustrates the fact that SEP: 1) can deliver much more mass, 2) typically takes much longer to deliver that mass, and 3) can launch at virtually any time if arrival date is not constrained.

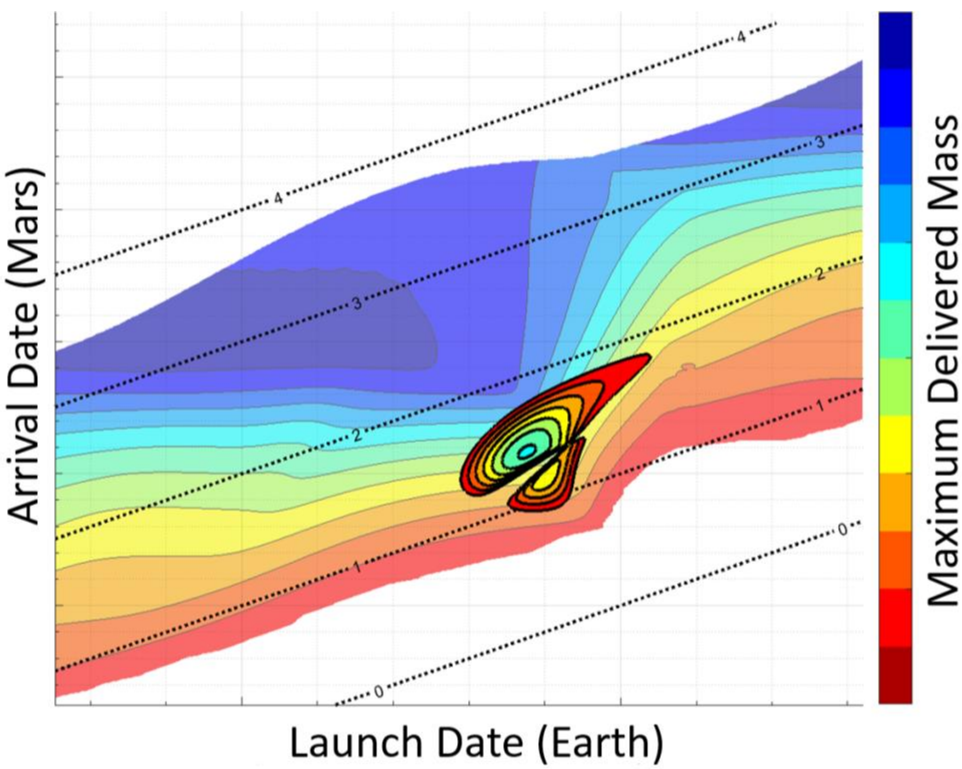

Figure 3. Ballistic porkchop plot superimposed on a low thrust bacon plot. The launch date at Earth spans one synodic period (780 days). Diagonal lines show transfer times in years. Contour lines show the total delivered mass to Mars for a given launch vehicle – with blue being the highest. SEP allows for nearly continuous launch periods and increased delivery mass for longer flight times.

In order to create bacon plots for our application of delivering cargo to Mars using a SEP tug, we must first start with the parameters laid out in the assumptions section. A large, 150-kW reusable SEP tug, weighing 8 mt dry, would be used to ferry cargo from a stable NRO lunar orbit to Mars orbit, and then return to be refilled and used again. The SLS 1b launch vehicle can deliver 40 mt to NRO, which is mated with the tug. Xenon required for the round trip is then transferred to the tug. The maximum initial mass is thus 48 mt. Each mission begins with the aforementioned lunar/solar boost that takes ~4 months and departs with a C3 of 2 km^2/s^2. Low-thrust mission design analysis from this point is carried out using MALTO*, a fast, medium-fidelity low-thrust optimizer developed at JPL.[20] Upon arriving at Mars, the tug begins a short spiral down to a 5-sol elliptical staging orbit (HMO). The spiral would roughly require 750 m/s and 90 days. But with some assistance from the ACS thrusters this can be reduced to 250 m/s and 30 days.

Bacon plots are made by running MALTO in parametric mode, varying launch date and arrival date at 10 day increments. The maximum delivered mass is calculated by subtracting the xenon mass needed for departure from NRO and spiral to HMO, as well as the dry mass of the tug itself along with the xenon it needs to return to NRO. We also allocate mass for 6% propellant margin on all xenon. Plotting the contour lines of the net deliverable mass creates a plot such as the one shown in Figure 4, which is the Earth-Mars plot for three synodic periods from 2040-2046. A complete set of bacon plots was generated for the years 2038-2054 (see Appendix). This covers a complete set of the 15-year (7 opportunity) Earth-Mars cycle. For dates outside this range the results can just be "shifted" from the representative results 15 years away. However, it was found that low-thrust trajectories do not vary as significantly from opportunity to opportunity as do ballistic transfers.

* MALTO stands for Mission Analysis Low Thrust Optimizer. This tool generally exhibits robust convergence and can be run in parametric mode with fast, accurate results. Individual trajectories typically converge in 1-3 seconds. A complete 1 synodic cycle bacon plot will complete in a few hours, but many points will need further refinement to find the true optimum and keep the contours smooth. Interpolation between grid points yields very accurate results.

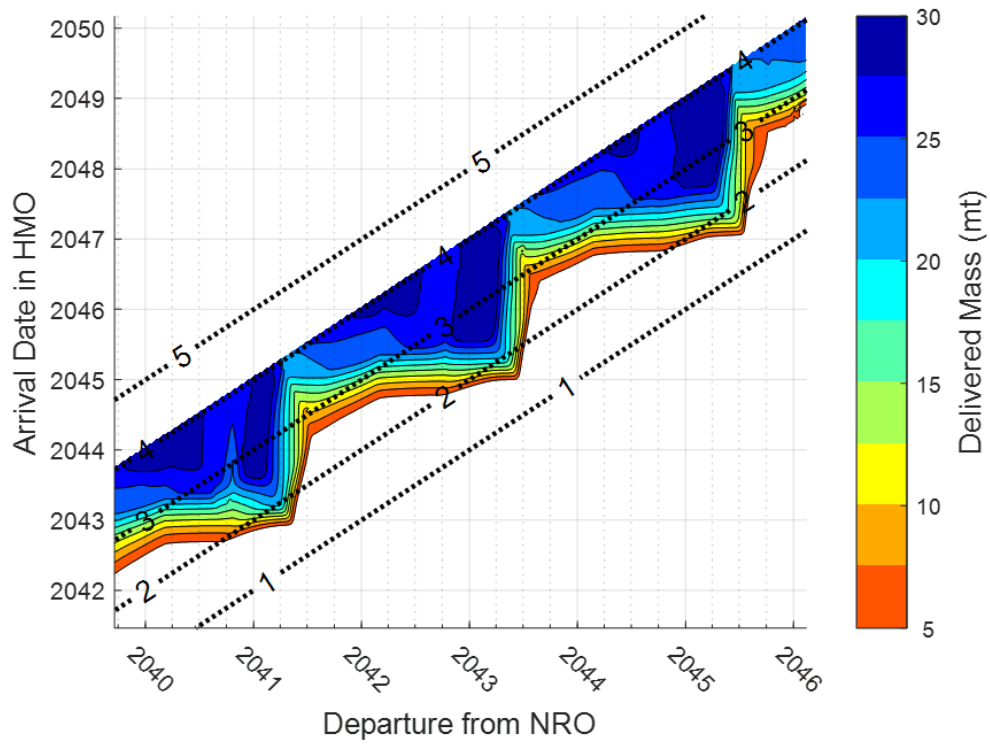

Figure 4 - Bacon Plot for Earth-to-Mars transfers for 2040-2046. Colored contours show the maxi-mum delivered cargo mass to HMO for any date pair over 3 synodic periods. The diagonal dashed lines show constant transfers times in years. This includes 3 months to leave NRO and 1 month to spiral down to HMO.

One of the key features of the SEP bacon plot is that a feasible trajectory exists for any launch date. However, the effects of the planetary synodic period are still present. There are only certain times where fast transfers (~2 years) are possible. These dates roughly correlate with the natural ballistic opportunities. The other feature to note is the nearly constant arrival date for a given mass over a very long span of launch dates. If you follow the light blue contour (20 mt) in **Error! Reference source not found.Error! Reference source not found.** you will notice that the arrival date at Mars is around February of 2043 for launches from late 2039 until April of 2041. At that point the Mars arrival date jumps to mid-2045 and the pattern repeats. Also note that the cutoff of data longer than 4 years of transfer time is simply due to the limits of the parameters explored. Feasible trajectories exist for all durations longer than this, presumably with delivered masses in the "deep blue" range of near 30 mt as SEP transfers tend to get more efficient as time-of-flight increases. There is a natural asymptote as the transfer ΔV approaches that of a Hohmann transfer (which in this cases is very close to 30 mt).

Bacon plots were also created for all Mars-Earth trajectories for the SEP tug to return. In this case the mass delivered to NRO is fixed at the dry mass of the SEP tug – 8 mt. MALTO then seeks to find the minimum propellant mass for the return trip. The large solar arrays and powerful engines lead to faster natural trip times for the lighter vehicle. The Mars-to-Earth Bacon plot in Figure 5 shows contours of required propellant mass instead of maximum delivered mass. We can see the similar pattern of a near constant arrival date for a given mass over a long period, followed by an abrupt jump to an arrival 26 months later. For transfers that begin before July of 2043 the tug will arrive around October of 2044. After that date the arrival date at NRO jumps to late 2046. There is a period of about 9 months out of every 26 where a return transfer of less than 2 years is possible.

Note that most return transfers can be covered by 2000 kg of xenon (light blue and darker). A full allocation of 2000 kg for the return leg was used in Earth-Mars maximum delivered mass calculations rather than optimizing the exact return xenon needed for every date combination. Mars-Earth bacon plots were primarily used just to find return dates and durations.

Using a SEP tug to deliver a surface payload does not require that the tug stop in Mars orbit. It is only necessary to approach on a hyperbolic trajectory and drop off the entry vehicle with suitable entry conditions (< 6.5 km/s was assumed here). In this way, the SEP tug flies an Earth-Mars-Earth trajectory and returns to NRO. No detailed simulations or designs of the entry vehicle were performed, but rather a rule-of-thumb was used that roughly 1/3 of the entry mass was usable cargo on the surface. When optimized, this results in a significant (> 35 mt) delivery mass to entry. These missions require 30-40% less xenon than orbital missions due to the fact that they do not need to descend and ascend from the Mars gravity well. Surface cargo drop-off missions typically take 3 to 3.5 years to complete the round trip, with roughly 2/3 of that being the outbound leg. Maximum drop off mass is only achieved near the optimal alignment dates each opportunity. This does not cause problems with launch frequency, however, since they can loiter in NRO post-launch for an indefinite amount of time awaiting a favorable alignment.

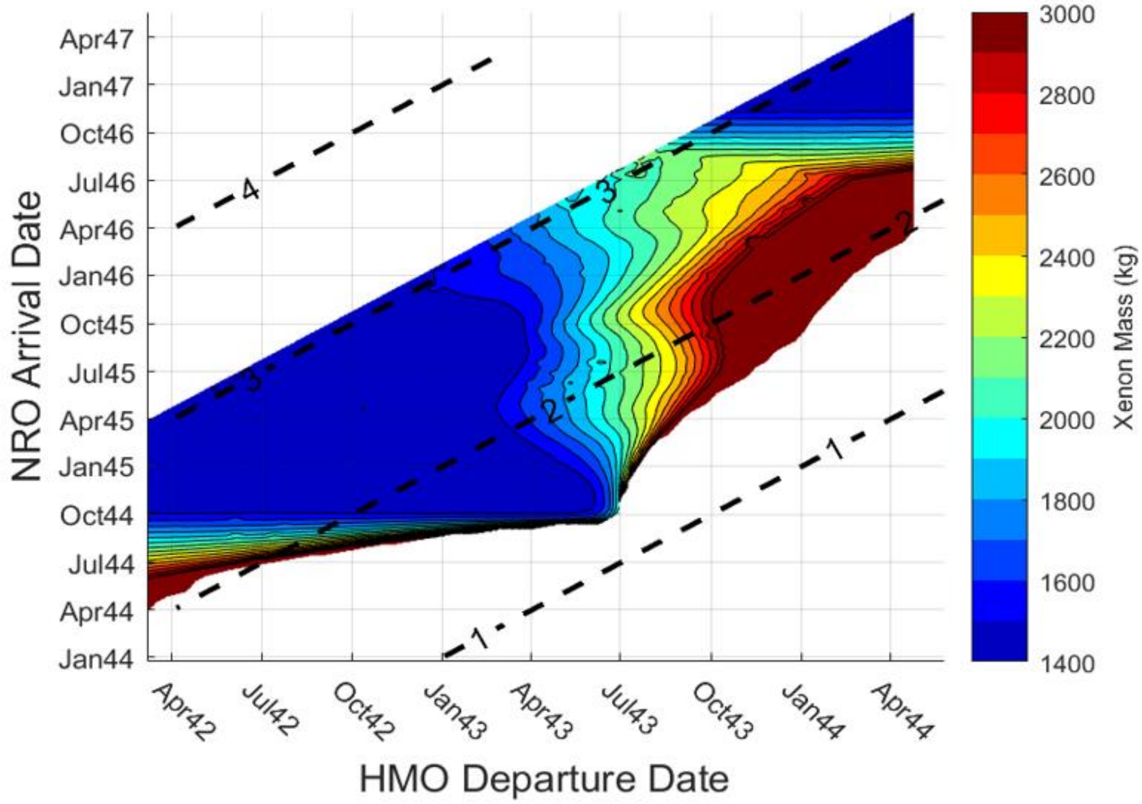

Figure 5 - Mars-to-Earth Bacon Plot for 2043. Colored contours show the xenon mass required to deliver the 8 mt SEP tug from HMO to NRO. The diagonal dashed lines show constant transfers times in years. This includes 1 month to spiral up from HMO and 4 months to achieve NRO.

USING BACON PLOTS

In order to construct a plan required for a human Mars expedition, it is necessary to first lay out the individual missions and determine what needs to be where and when. Next, we look at what mode of transfer would be best for each element (i.e. SEP vs. ballistic, fast vs. slow). Lastly, we must make sure that the launch sequence and element availability are feasible and do not violate any imposed constraints.

For elements going to HMO, the SEP tug can deliver up to 30 mt in as little as 2.5 years. For longer transfer times the launch period can be extended for many months. Of course, cargo missions can be launched directly to Mars without the use of a SEP tug. The SLS 1b, after all, is capable of throwing ~30 mt to a C3 of 10 km^2/s^2. For orbital missions, a chemical MOI of roughly 800 m/s would be needed, which reduces the delivered mass to < 22 mt. Since most elements going to HMO are larger than this, in addition to launch frequency issues around ballistic minima, it was decided that a SEP tug was enabling.

For elements going to the surface, the SEP tug can only deliver ~10% more mass to entry than a direct launch. A direct SLS launch and entry was found to deliver sufficient mass in most scenarios and eliminates the complexity of the SEP tug architecture for surface resupply. Other elements, such as the surface habitat, are more massive than either methods' capability and therefore requires two launches. For this reason we do not use SEP for landed elements in the architecture considered.

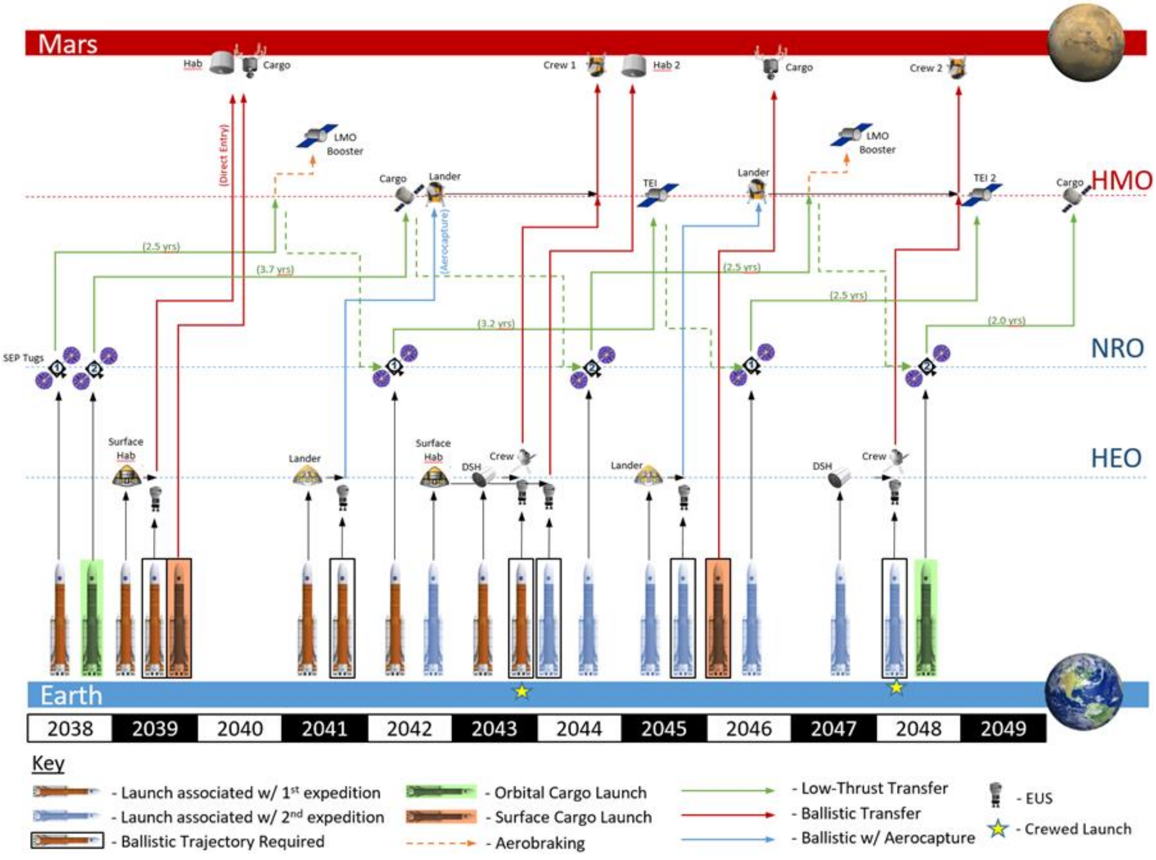

Figure 6 - Representative architecture sequence for the first 2 crewed expeditions to Mars. SEP tugs are used to deliver elements and logistics to high Mars orbit (HMO) and cycle back to a Near-rectilinear orbit (NRO) at the Moon. Surface cargo is delivered via ballistic

trajectory and direct entry. Launches are separated by at least 3 months, which is facilitated by the flexible nature of SEP trajectories.

In our example architecture[1] in Figure 6, we require that a surface habitat, descent and ascent vehicles, and all required provisions be in place before the first crew launch. We use NRO and a 5-sol HMO as potential staging points. The first element to launch is the propulsion stage to boost the crew from low-Mars orbit (LMO) up to the DSH and TEI stage waiting in HMO. The SEP tug delivers the stage to HMO first, then the stage uses aerobraking to get to LMO. This stage weighs 18 mt and departs in May of 2038, taking 2.5 years to get to Mars. The empty SEP tug must turn back immediately to be able to make it back in time to rendezvous with the next element, the TEI stage, in 2042. This round trip of ~4 years is about as fast as the SEP tug can be. Typical round trips take closer to 6 years if the optimal portions of the bacon plots cannot be used. This is the case with the second SEP tug, which departs 4 months after the first, in September of 2038, taking the cargo/provisions for the return trip to HMO. This transfer takes 3.7 years and tug 2 does not return until 2044.

While the SEP tugs are delivering elements to HMO, direct ballistic launches occur in 2039 and 2041. The surface hab requires 2 launches which are mated in high Earth orbit (HEO), before departing for Mars in 2039. In the next opportunity the Lander/MAV module is sent directly to Mars (again, using 2 launches mated in HEO) where it uses its heatshield to aerocapture to HMO and await the crew. In this manner, launches are choreographed so as to maintain a separation of at least 3 months, get all of the elements where they need to be, and coordinate the use of 2 cycling SEP tugs. It requires 10 total launches for the first crewed expedition, with the 10th launch being the crew themselves. If we wish to continue this cadence for a new crew 4 years later, the set of 10 launches must be repeated, with some of the first launches of the second expedition taking place before the first crew even launches. It is this level of complexity that obviates the need to have very flexible trajectory maps in order to meet the various requirements and construct a feasible architecture.

CONCLUSIONS

The paper discusses the details and assumptions that went into creating the required bacon plots, along with their features and morphology. We then describe our methods to use these “maps” effectively to create human Mars architectures. Bacon plots can be used alongside more traditional porkchop plots as visual design tools in orchestrating the multiple launches that will be necessary.

ACKNOWLEDGMENTS

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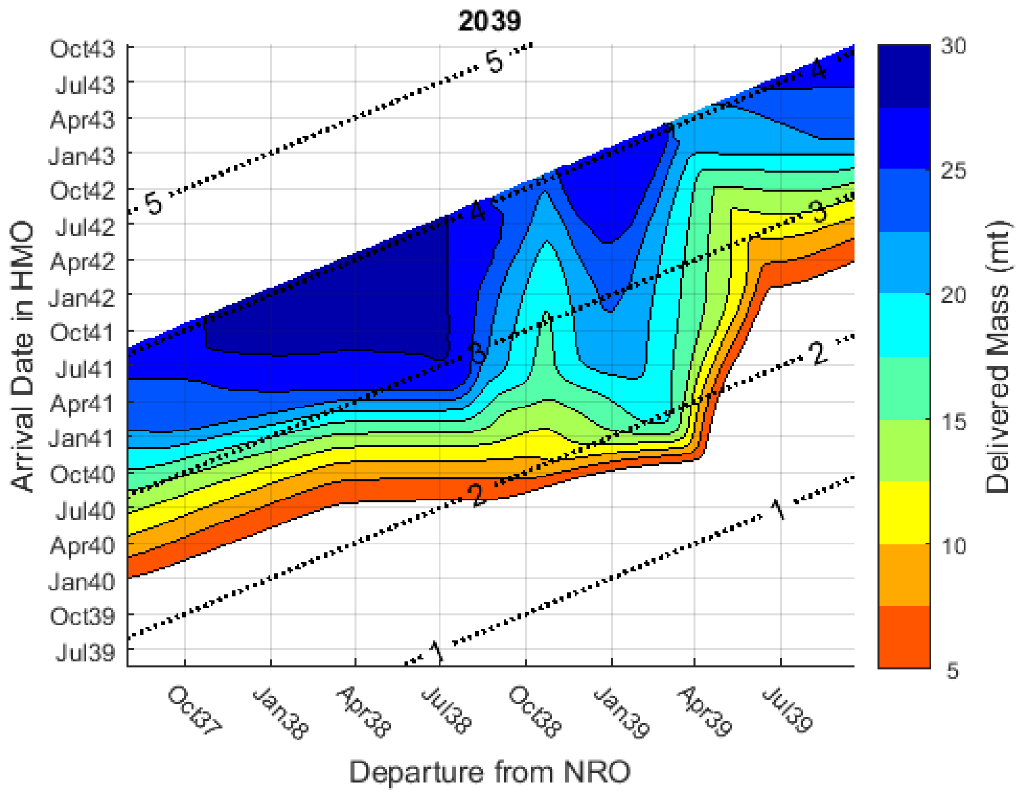
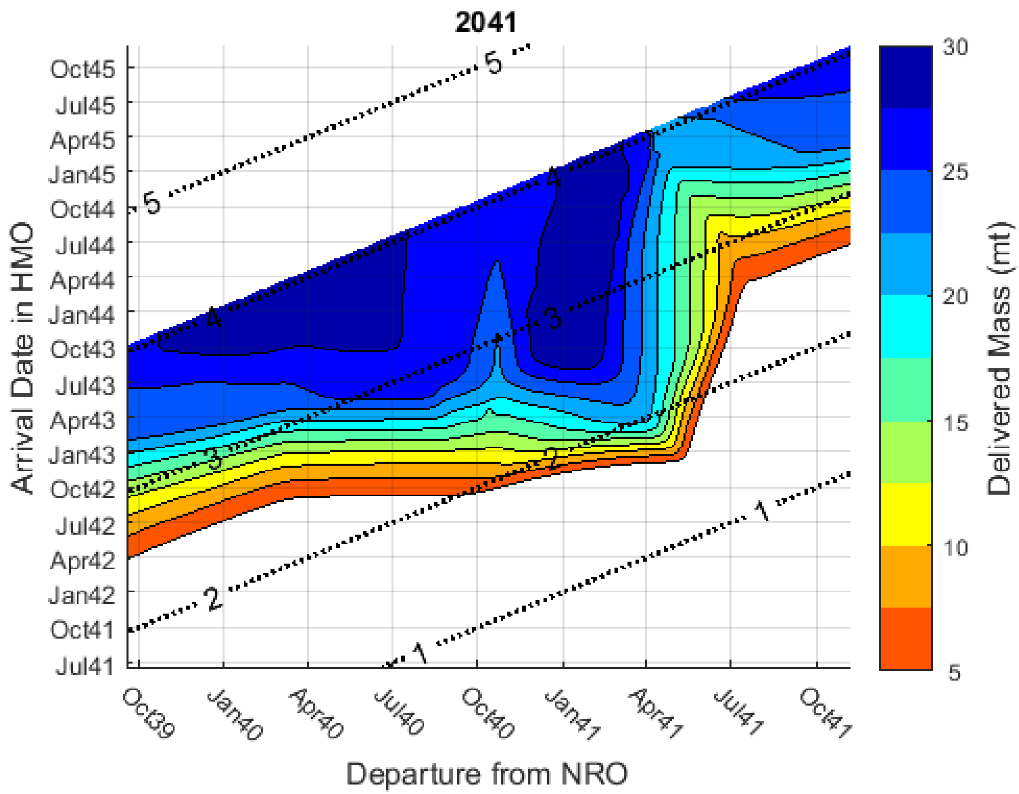
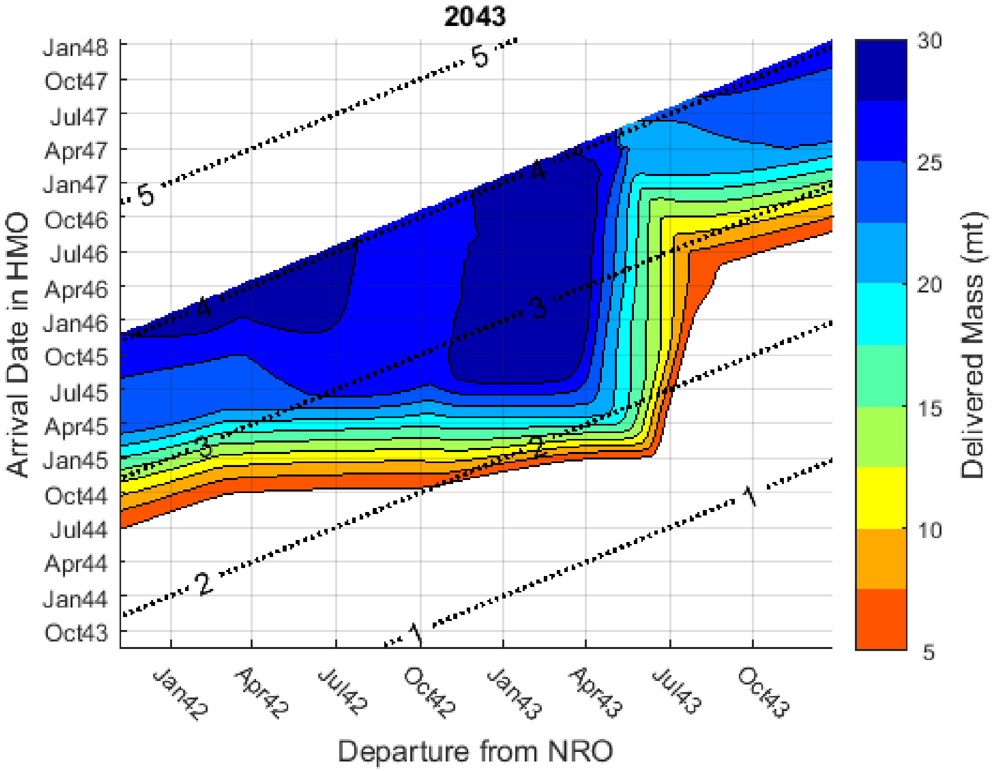
APPENDIX: BACON PLOTS FOR 2039-2052






2043
Arrival Date in HMO
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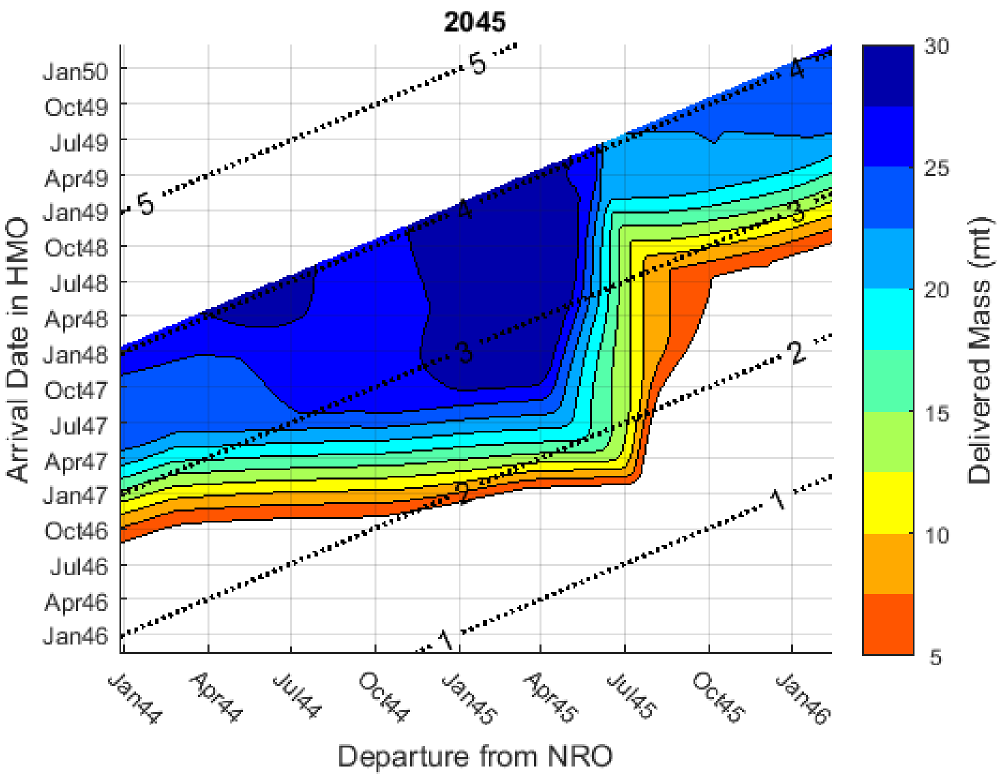
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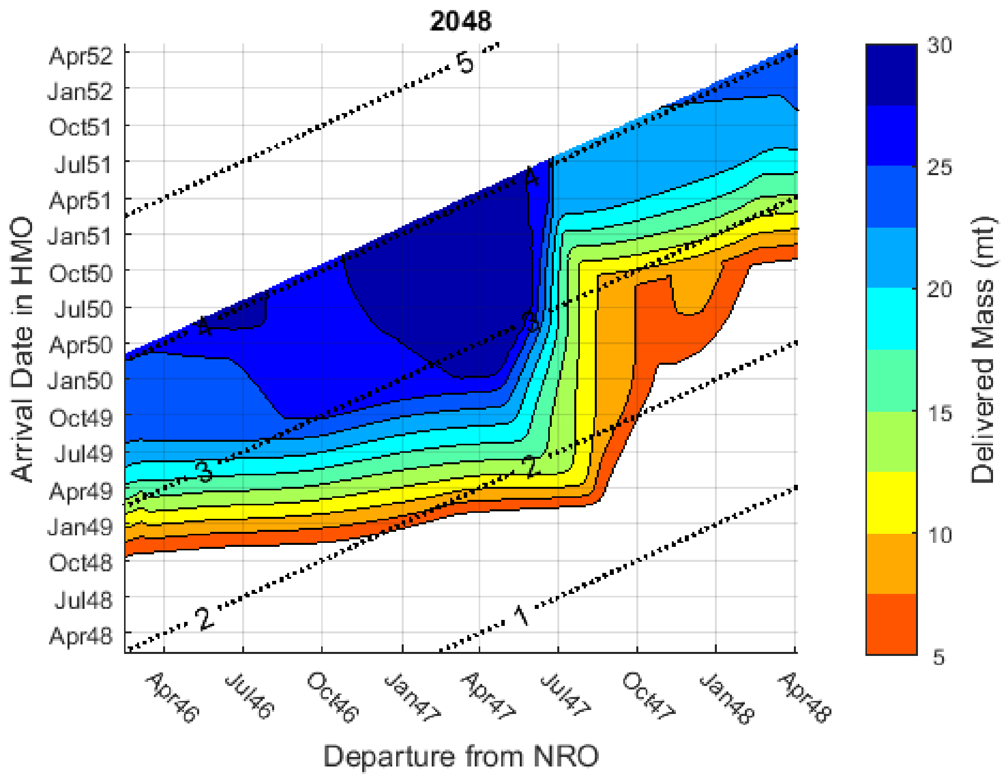
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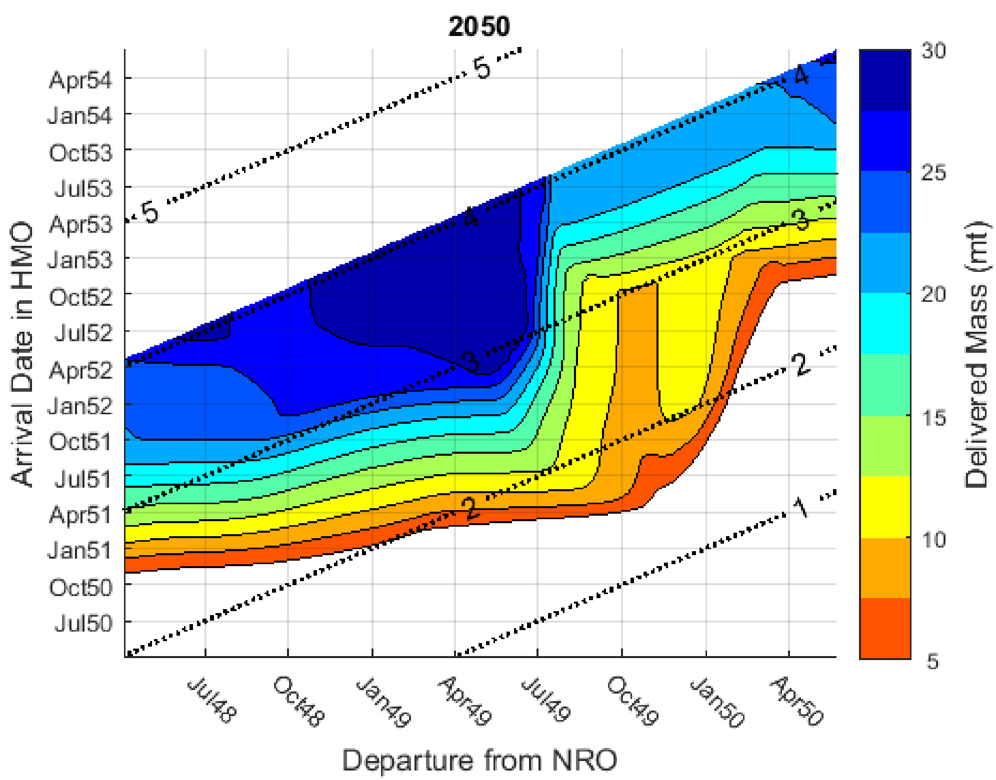
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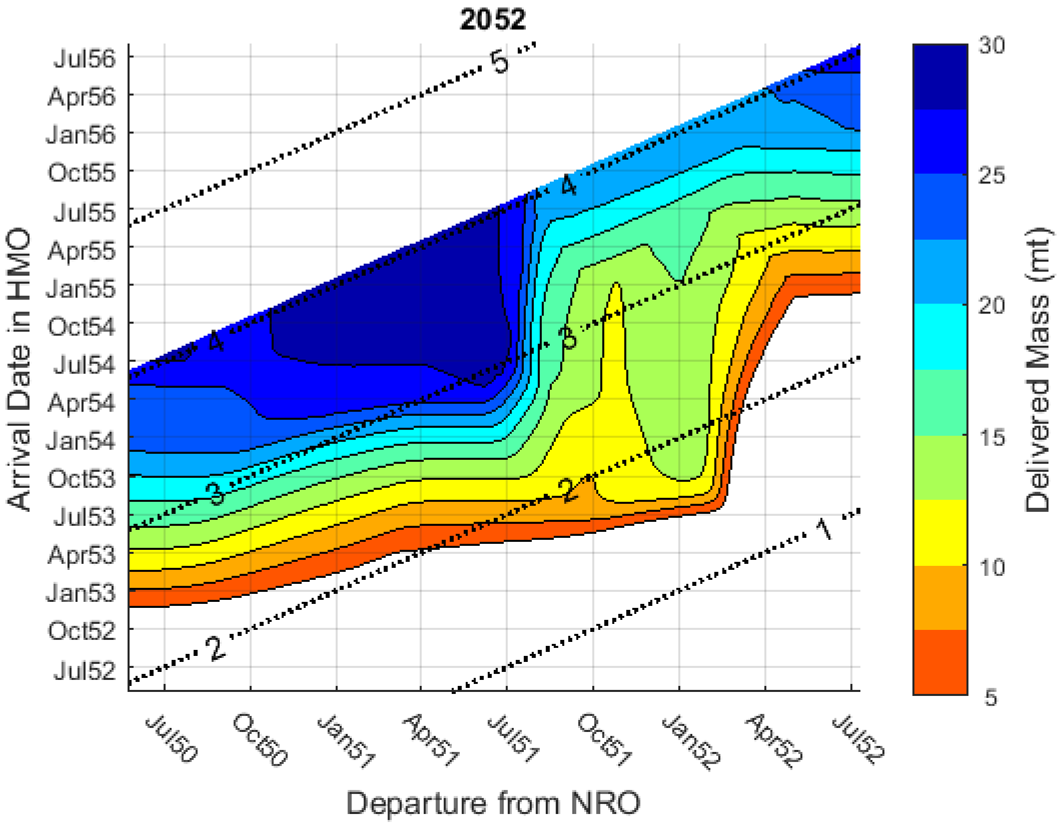

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