AIAA/AAS Astrodynamics Specialist Conference and Exhibit
5-8 August 2002, Monterey, California

AIAA 2002-4421

A LOW-THRUST VERSION OF THE ALDRIN CYCLER

K. Joseph Chen,[*] T. Troy McConaghy,[†] Masataka Okutsu,[‡] and James M. Longuski[§]
School of Aeronautics and Astronautics, Purdue University
West Lafayette, Indiana 47907-1282

In this paper we seek a low-thrust version of a cycler orbit between Earth and Mars known as the Aldrin cycler. The principal goal is to design trajectories that have low flyby V_∞ at both planets while minimizing the total propellant cost. Our research is aided by several powerful software tools, including a recently developed low-thrust optimizer. With these tools, we are able to produce several promising low-thrust versions of Aldrin cyclers. Our analysis shows that such cyclers can significantly reduce the total propellant cost.

Introduction

SEVERAL circulating orbits have been proposed over the years to enable periodic human missions between Earth and Mars.[1-8] These cycler concepts can be traced back as far back as the late 1960s. A particular cycler, called the Aldrin cycler, is the focus of this paper.

In the late 1980s, Aldrin proposed a cyclical trajectory that would make use of the gravity of Earth and Mars to reshape and turn the orbit at each planetary encounter.[4] Deep space maneuvers must be performed at predetermined locations in the trajectory to satisfy altitude constraints. There are two types of Aldrin cyclers: the Outbound cycler, which allows fast trips (under 6 months) from Earth to Mars, and the Inbound cycler, which allows fast return trips from Mars to Earth. Two space stations, one in each cycler, would allow frequent and regular visits to and from each planet. The relatively short transit times also eliminate the need for artificial gravity.[7]

These autonomous, solar-electric-propelled space stations have been dubbed Astronaut Hotels, or Astrotels, by Global Aerospace Corporation. At each planetary encounter, smaller spacecraft called Taxis will rendezvous with the Astrotels and transport astronauts to and from Spaceports located in the vicinity of the planets. These Taxi transits are typically less than 10 days.[7]

[*]Graduate Student
[†]Graduate Student, Student Member AIAA, Member AAS
[‡]Graduate Student, Student Member AIAA, Member AAS
[§]Professor, Associate Fellow AIAA, Member AAS

One of the main disadvantages of the Aldrin cycler is the moderate to high flyby velocities at each planet. This causes concerns especially on the Inbound (Mars to Earth) cycler, where the Taxis from Mars Spaceports must be placed on hyperbolic trajectories to rendezvous with the Astrotels. Due to the high flyby V_∞ (ranging from about 7 km/s to almost 12 km/s) of the Astrotel, the propulsion costs on the Taxis are tremendous. All rendezvous opportunities require the Taxis to be staged to carry augmentation (auxiliary) propellant tanks.[7] Since these Taxis operate on LOX/LH engines, the necessary propellant must be transported from production plants on Earth by cargo vehicles. Due to the significant amount of propellant needed, these transportation trips are very costly.[7]

In this paper, we reduce the total propellant costs of the cyclers in two ways. The first is to maximize the final mass of the Astrotels, or equivalently, to minimize Astrotel propellant consumption. The second part is to reduce the flyby velocities at Mars on the Inbound cycler and therefore reduce the Taxi propellant cost. (In this study, we ignore the problem of reducing Earth flyby velocities, because the impact of reducing Taxi propellant cost at Earth is much less significant than the reduction at Mars). To achieve these goals, we use powerful software tools developed at Purdue University and the Jet Propulsion Laboratory (JPL).

Overview of Research Activities

To obtain a working model of the Aldrin cyclers as a benchmark for optimization, we first use the Satellite Tour Design Program (STOUR),[9] a conic trajectory propagator, to reconstruct the Outbound and Inbound cyclers. STOUR is a software tool that was originally developed by JPL for the Galileo mission tour design. This program was later enhanced and extended at Purdue University. At this stage of our work, we make no attempt to optimize with STOUR, we only require the reconstructed cyclers to be similar to the published results.[4,7]

Once we complete the reconstruction work, we then improve the resulting trajectories with JPL's ballistic optimizer, the Mission Design and Analysis Software (MIDAS).[10] MIDAS is a patched-conic interplanetary trajectory optimization program that minimizes the total ΔV by varying event times (i.e. launch, flyby, and arrival dates). MIDAS is also capable of adding and deleting deep space maneuvers.

The Purdue version of STOUR is also capable of propagating low-thrust trajectories.[11-13] STOUR-LTGA (Low-Thrust Gravity-Assist) has the ability to connect any two specified target bodies using four possible trajectories: 1) pure thrust arc, 2) pure coast arc, 3) coast-thrust arc, and 4) thrust-coast arc. We use STOUR-LTGA to perform automated searches for low-thrust cyclers.

STOUR-LTGA, however, does not provide optimized results, so we use our Gravity-Assist Low-Thrust Local Optimization Program (GALLOP)[15] to maximize the final spacecraft mass. We also use GALLOP to optimize trajectories based on candidate guesses found by other means.

Optimization and Results

The low-thrust optimization of Aldrin cyclers is carried out by using the low-thrust optimizer GALLOP. GALLOP is based on a direct method developed by Sims and Flanagan.[14]

In the Sims and Flanagan trajectory model, the trajectory is divided into legs, which are further subdivided into segments of equal duration. Continuous thrusting is modeled as a series of impulses, each occurring at the midpoint of the segment. The magnitude of the impulse is limited by the amount of ΔV that could be accumulated over the duration of the segment, which is in turn limited by the power available to the low-thrust engines. To ensure proper targeting, so that the spacecraft leaves the initial body and arrives at the target body, the trajectory is propagated backward from the target body and forward from the initial body. These half-legs then must meet at a "matchpoint" located in the middle of the leg (see Fig. 1). If the half-legs don't meet up for some reason, we say there is a "mismatch". One of our optimization constraints is that the position and velocity mismatches must be driven to (nearly) zero. In the numerical results we present in this paper, the mismatches are acceptably small. Gravity assists are modeled as an instantaneous rotation of the V_∞ vector. The flyby altitude and the B-plane angle determine the magnitude and direction of the rotation.

NPOPT, which is a nonlinear programming optimizer available from Stanford Business Software Inc., is used as the optimization engine in GALLOP. NPOPT uses a sequential quadratic programming algorithm to find locally optimal solution that is near the initial guess.[15] The set of variables that we work with are the following:

- Magnitude and direction of the impulsive ΔV on each segment.
- Julian dates at the initial, flyby, and final bodies.
- V_∞ vector at launch.
- Flyby V_∞ vectors with respect to the flyby bodies.
- Astrotel mass at each body.
- Flyby altitude at each gravity-assist body.
- B-plane angle at each gravity-assist flyby.

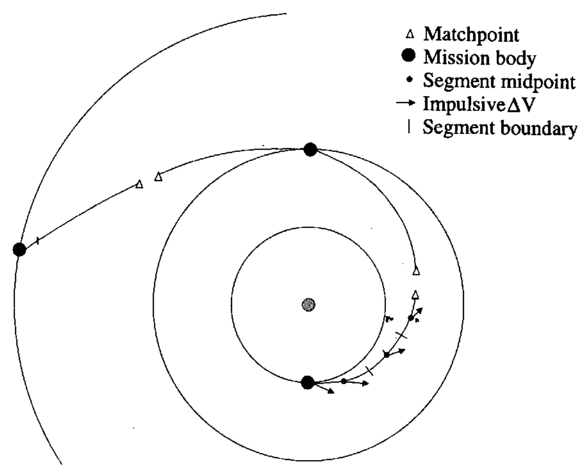

Fig. 1 LTGA trajectory structure.[14, 15]

Our optimization goal is to find a trajectory that gives the largest mass at the final body. We match the spacecraft specifications in GALLOP with the data from the Phase I report. However, since GALLOP presently does not have multi-engine capabilities, we model the eight Astrotel solar electric propulsion (SEP) engines as one large engine in our optimization.

In our study, we extend the Aldrin cycler missions from 15 flybys (15 years) to 17 flybys (17 years). Two additional flybys are added at the end to avoid terminal boundary effects. Our studies conclude that the there is no boundary effect issue at the beginning of the mission.

Our initial approach is to use STOUR-LTGA to find candidate trajectories for optimization. However, we find that STOUR-LTGA tends to significantly change the flyby dates, and usually results in orbits with varying periods. This is undesirable, since we want the cyclers to have transit times similar to the requirements listed in the Phase I report. Our subsequent approach is to import Phase I trajectory results directly into GALLOP as the initial guesses for optimization. We find that this approach yields cyclical trajectories that satisfy the mission requirements.

Our optimization starts with designing a low-thrust cycler similar to the ones designed by Science Applications International Corporation (SAIC) for the Phase I report.[7] In SAIC's low-thrust cycler, the impulsive ΔV of the conic cycler are replaced by continuous low-thrust arcs. The arcs replace the legs with impulses in the conic solution. The resulting cycler consumes about 3 metric tons (mt) of propellant over the 15-year mission. Our goal is to design a cycler that consumes about the same amount of propellant, but we allow continuous thrusting on all legs of the trajectory, instead of just three legs, as SAIC has done.

Inbound Cycler Results

Optimizing the Inbound cycler is our main challenge. This is because in addition to minimizing the Astrotel propellant consumption, we also want to decrease the flyby V_∞ at Mars in order to save Taxi propellant.

We obtain a relationship between Astrotel V_∞ at Mars and Taxi propellant consumption for rendezvous by fitting a curve through the data points from the Phase I report.[7] The data are summarized in Table 1.

Figure 2 shows a curve-fit for these data points. An exponential curve is used to approximate the trend, which is motivated by the rocket equation. The equation of the curve is shown in Fig. 2, which we use to estimate Taxi propellant savings on our cycler results. We now list three candidate Inbound cyclers appropriate for the Astrotel mission.

Inbound Cycler Candidate 1. This cycler candidate is one of our earliest results that conforms to the mission requirements listed in the Phase I report. We design this cycler to be comparable (in terms of Astrotel propellant usage) to the low-thrust analysis performed by SAIC.[7] As previously mentioned, all trajectory legs are allowed to be thrusting legs. The mission begins on May 22, 2010, and ends on April 28, 2025. All the encounter dates are identical to the trajectory results published in the Phase I report. No constraints are placed on the Mars

Table 1: Inbound Taxi propellant[7]

Flyby	Date (mm/dd/yyyy)	Astrotel V∞ (km/s)	Taxi Propellant (mt)
E-1	05/22/2010	5.978	
M-2	01/08/2012	9.102	104.1
E-3	06/25/2012	5.954	
M-4	02/15/2014	7.744	73.1
E-5	08/04/2014	6.102	
M-6	04/19/2016	7.221	67.2
E-7	09/15/2016	6.207	
M-8	07/11/2018	6.826	54.8
E-9	12/08/2018	5.963	
M-10	09/24/2020	9.781	123.8
E-11	02/18/2021	5.750	
M-12	11/09/2022	11.936	237.6
E-13	03/30/2023	6.010	
M-14	12/01/2024	11.114	182.8
E-15	04/28/2025	5.528	

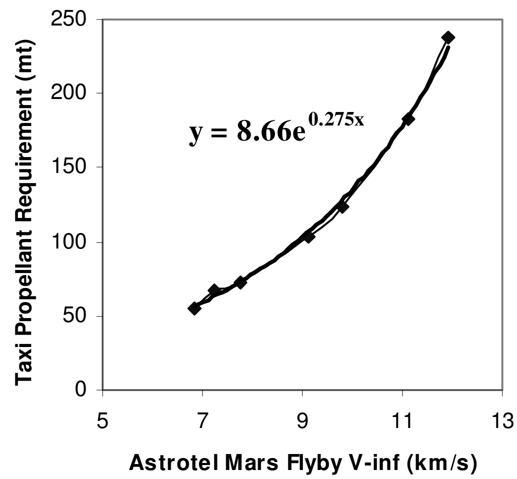

Fig. 2 Taxi propellant curve fit.

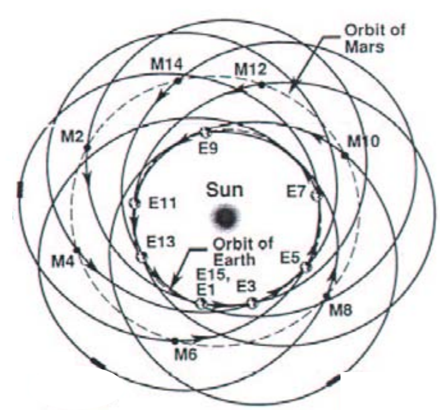

Fig. 3 Trajectory of inbound cycler.[4]

Figure 3 shows the trajectory profile of the Inbound cyclers. The trajectory propagates in the following manner: the Astrotel starts from Earth-1 (E-1), encounters Mars-2 (M-2), goes back to E-3, then to M-4, and so on. The sequence of flybys repeats for the 15-year duration of the mission. Each time the Astrotel encounters the Earth, the inertial position of the Earth is shifted counterclockwise from its previous location. Gravity assist at the Earth then bends the orbit and enables the Astrotel to encounter Mars. The remainder flybys are displayed on Fig. 3.

A summary of the trajectory is listed in Table 2. Inbound cycler candidate 1 compares favorably to the trajectory presented in the Phase I report. (The first three columns of Table 2 pertain to the Phase I trajectory). The low-thrust trajectory in the Phase I report consumed 3.007 mt of Astrotel propellant over the 15-year span, while ours expended only 2.535 mt. Thus we are able to save 0.466 mt (or about 15%) of Astrotel propellant. In addition, we are also able to produce a Taxi propellant savings of about 11.79 mt over the Phase I report.[7] Considering that the total Taxi propellant consumption listed in the report is 843.4 mt, our savings of 11.79 mt represents only a 1.4% savings. We then use this trajectory as an initial guess for subsequent GALLOP iterations to produce the other cycler candidates.

Inbound Cycler Candidate 2. The trajectory summary of cycler candidate 2 is listed in Table 3. In cycler candidate 2, all the flyby dates are totally unconstrained, while the starting and ending (E-1 an dE-15) dates are fixed. Comparing Tables 2 and 3, we see that varying the flyby dates have a clear improvement on the Astrotel propellant usage. We also note that we also achieve a higher Taxi propellant savings than in Table 2. We also see that the even though the flyby dates are unconstrained, they still don't deviate from the Phase I dates by more than seven days. Our next approach is to use velocity constraints to reduce the V_∞ at Mars and concentrate on reducing the Taxi propellant requirement.

Inbound Cycler Candidate 3. Table 4 lists the trajectory summary of candidate 3. Candidate 3, just like candidate 2, has unconstrained flyby dates. Using this trajectory, the Astrotel uses considerably more propellant than that of the Phase I report (about three times as much), but we are able to achieve a very significant savings in terms of Taxi propellant (about 34.13%). The most dramatic reductions in V_∞ (and propellant requirement) come from encounters at M-1, M-10, M-12, and M-14, where the V_∞ used to reach as high as nearly 12 km/s. At this point, we could continue pushing the constraints and obtain even higher savings, but since the Astrotel propellant usage is already close to our (selected) upper limit of 10 mt, we choose to focus our attention on the Outbound cycler for now.

Outbound Cycler Results

We optimize the Outbound cyclers in the same fashion as with the Inbound cyclers. The only major difference is that we do not explicitly try to reduce the flyby V_∞, which is consistent with our assumption that it is much easier to obtain and produce propellant on Earth than on Mars. The emphasis of Outbound cyclers optimization is on reducing the Astrotel propellant consumption while keeping the flyby V_∞ close to the Phase I results. Table 5 (from the Phase I report) shows that the Taxi propellant cost is about 20 mt for each of the Earth flybys. We make no attempt to reduce the Earth flyby V_∞ (The Earth Taxi cost in terms of propellant is small compared to the Mars Taxi, so we choose to ignore the V_∞ at Earth in our optimization analysis.) As a result, we sometimes produce cycler candidates that have negative savings on the Taxi propellant (i.e. worse performance than Phase I). However, the savings we are able to achieve on the Inbound cyclers will offset the negative savings (on the Taxi propellant) on the Outbound cyclers. We now present two Outbound cycler candidates.

Outbound Cycler Candidate 1. Candidate 1 retains all the original Earth and Mars flyby dates as listed in the Phase I report. A summary of the trajectory is listed in Table 6. We note that this Outbound cycler has a net Taxi propellant savings of -1.29 mt compared to Phase I result. This means that candidate 1 has slightly higher Earth V_∞ than those of the Phase I trajectory. The increased Taxi propellant usage of 1.29 mt corresponds to about 1% increase (where total Taxi propellant consumption for the 15-year period is 140.15 mt). On the other hand, we are able to reduce the Astrotel propellant usage from the Phase I cycler's 2.767 mt to 2.590 mt, a saving of 0.177 mt (or about 6.4%). Thus we are able to achieve a small overall savings. We now investigate the effect of varying the Earth encounter dates.

Outbound Cycler Candidate 2. As with the Inbound cycler candidates, we now allow the Earth encounter dates to vary by a maximum of four days. A summary of this trajectory is listed in Table 7. We see that candidate 2 has a more negative Taxi propellant savings than candidate 1, meaning that the Taxi propellant usage again increases. The good news is that we are able to lower the Astrotel propellant consumption to 2.430 mt, a saving of 0.337 mt, or about 12%. (The outbound case is opposite to that of the Inbound candidates, where we

Table 2: Inbound cycler candidate 1 trajectory summary

Phase I			***GALLOP***				
Encounter	**Date (mm/dd/yyyy)**	**V_∞ (km/s)**	**Encounter**	**Date (mm/dd/yyyy)**	**V_∞ (km/s)**	**Astrotel Mass (mt)**	**Taxi Savings (mt)**
E-1	5/22/2010	5.978	E-1	5/22/2010	5.905	75.00	
M-2	**1/8/2012**	**9.102**	M-2	**1/8/2012**	**9.025**	74.95	2.22
E-3	6/25/2012	5.954	E-3	6/25/2012	5.880	74.95	
M-4	**2/15/2014**	**7.744**	M-4	**2/15/2014**	**7.709**	74.86	0.70
E-5	8/4/2014	6.102	E-5	8/4/2014	6.077	74.86	
M-6	**4/19/2016**	**7.221**	M-6	**4/19/2016**	**7.216**	74.77	0.09
E-7	9/15/2016	6.207	E-7	9/15/2016	6.207	74.77	
M-8	**7/11/2018**	**6.826**	M-8	**7/11/2018**	**6.824**	73.79	0.03
E-9	12/8/2018	5.963	E-9	12/8/2018	5.774	73.50	
M-10	**9/24/2020**	**9.781**	M-10	**9/24/2020**	**9.704**	72.58	2.67
E-11	2/18/2021	5.750	E-11	2/18/2021	5.694	72.58	
M-12	**11/9/2022**	**11.936**	M-12	**11/9/2022**	**11.903**	72.53	2.08
E-13	3/30/2023	6.010	E-13	3/30/2023	5.976	72.53	
M-14	**12/1/2014**	**11.114**	M-14	**12/1/2014**	**11.034**	72.47	4.00
E-15	4/28/2025	5.528	E-15	4/28/2025	5.469	72.47	
					Propellant Mass Fraction =	**0.034**	**11.79**
					Propellant Used =	**2.54**	

Table 3. Inbound cycler candidate 2 trajectory summary

Phase I			***GALLOP***				
Encounter	**Date (mm/dd/yyyy)**	**V_∞ (km/s)**	**Encounter**	**Date (mm/dd/yyyy)**	**V_∞ (km/s)**	**Astrotel Mass (mt)**	**Taxi Savings (mt)**
E-1	5/22/2010	5.978	E-1	5/22/2010	5.976	75.00	
M-2	**1/8/2012**	**9.102**	M-2	**1/8/2012**	**9.101**	75.00	0.03
E-3	6/25/2012	5.954	E-3	6/25/2012	5.948	75.00	
M-4	**2/15/2014**	**7.744**	M-4	**2/15/2014**	**7.746**	75.00	-0.04
E-5	8/4/2014	6.102	E-5	8/3/2014	6.077	75.00	
M-6	**4/19/2016**	**7.221**	M-6	**4/18/2016**	**7.118**	75.00	1.76
E-7	9/15/2016	6.207	E-7	9/16/2016	6.201	75.00	
M-8	**7/11/2018**	**6.826**	M-8	**7/10/2018**	**7.036**	74.16	-3.36
E-9	12/8/2018	5.963	E-9	11/30/2018	5.828	74.16	
M-10	**9/24/2020**	**9.781**	M-10	**9/21/2020**	**9.326**	73.06	15.00
E-11	2/18/2021	5.750	E-11	2/20/2021	5.594	73.06	
M-12	**11/9/2022**	**11.936**	M-12	**11/9/2022**	**11.887**	73.06	3.09
E-13	3/30/2023	6.010	E-13	3/30/2023	5.993	73.06	
M-14	**12/1/2014**	**11.114**	M-14	**12/01/2024**	**11.111**	73.06	0.15
E-15	4/28/2025	5.528	E-15	4/28/2025	5.513	73.06	
					Propellant Mass Fraction =	**0.026**	**16.62**
					Propellant Used =	**1.94**	

Table 4. Inbound cycler candidate 3 trajectory summary

Phase I			***GALLOP***				
Encounter	**Date (mm/dd/yyyy)**	**V_∞ (km/s)**	**Encounter**	**Date (mm/dd/yyyy)**	**V_∞ (km/s)**	**Astrotel Mass (mt)**	**Taxi Savings (mt)**
E-1	5/22/2010	5.978	E-1	5/22/2010	5.195	75.00	
M-2	**1/8/2012**	**9.102**	M-2	**12/31/2011**	**8.212**	74.25	22.97
E-3	6/25/2012	5.954	E-3	6/27/2012	5.577	74.25	
M-4	**2/15/2014**	**7.744**	M-4	**2/10/2014**	**7.493**	74.10	4.86
E-5	8/4/2014	6.102	E-5	7/30/2014	5.721	74.10	
M-6	**4/19/2016**	**7.221**	M-6	**4/08/2016**	**6.436**	73.72	12.25
E-7	9/15/2016	6.207	E-7	9/12/2016	5.651	73.72	
M-8	**7/11/2018**	**6.826**	M-8	**6/30/2018**	**6.120**	72.61	9.98
E-9	12/8/2018	5.963	E-9	11/30/2018	5.419	72.61	
M-10	**9/24/2020**	**9.781**	M-10	**9/12/2020**	**9.081**	71.44	22.33
E-11	2/18/2021	5.750	E-11	1/24/2021	4.565	71.44	
M-12	**11/9/2022**	**11.936**	M-12	**10/21/2022**	**8.697**	69.55	136.00
E-13	3/30/2023	6.010	E-13	4/08/2023	5.056	68.71	
M-14	**12/1/2014**	**11.114**	M-14	**11/14/2024**	**9.057**	66.14	79.49
E-15	4/28/2025	5.528	E-15	4/28/2025	4.441	66.14	
					Propellant Mass Fraction =	**0.118**	**287.88**
					Propellant Used =	**8.86**	

Table 5: Outbound Taxi propellant[7]

Flyby	Date (mm/dd/yyyy)	Astrotel V∞ (km/s)	Taxi Propellant (mt)
E-1	5/22/2010	5.808	19.916
M-2	1/8/2012	10.142	
E-3	6/25/2012	5.854	20.62
M-4	2/15/2014	11.449	
E-5	8/4/2014	5.902	20.079
M-6	4/19/2016	11.488	
E-7	9/15/2016	5.791	19.514
M-8	7/11/2018	8.914	
E-9	12/8/2018	5.765	19.45
M-10	9/24/2020	5.682	
E-11	2/18/2021	5.831	20.108
M-12	11/9/2022	7.142	
E-13	3/30/2023	5.961	20.463
M-14	12/1/2014	8.156	
E-15	4/28/2025	5.946	

Table 6. Outbound cycler candidate 1 trajectory summary

Phase I			***GALLOP***				
Encounter	**Date (mm/dd/yyyy)**	**V_∞ (km/s)**	**Encounter**	**Date (mm/dd/yyyy)**	**V_∞ (km/s)**	**Astrotel Mass (mt)**	**Taxi Savings (mt)**
E-1	**11/13/2011**	**5.808**	E-1	**11/13/2011**	**5.860**	75.00	-0.255
M-2	4/24/2012	10.142	M-2	4/24/2012	10.187	75.00	
E-3	**12/18/2013**	**5.854**	E-3	**12/18/2013**	**5.900**	74.96	-0.226
M-4	5/18/2014	11.449	M-4	5/18/2014	11.480	74.96	
E-5	**1/26/2016**	**5.902**	E-5	**1/26/2016**	**6.000**	74.87	-0.481
M-6	6/16/2016	11.488	M-6	6/16/2016	11.603	74.54	
E-7	**3/17/2018**	**5.791**	E-7	**3/17/2018**	**5.754**	74.44	0.181
M-8	8/9/2018	8.914	M-8	8/9/2018	8.977	73.49	
E-9	**6/3/2020**	**5.765**	E-9	**6/3/2020**	**5.809**	73.49	-0.216
M-10	11/10/2020	5.682	M-10	11/10/2020	5.748	72.49	
E-11	**8/22/2022**	**5.831**	E-11	**8/22/2022**	**5.873**	72.49	-0.206
M-12	1/24/2023	7.142	M-12	1/24/2023	7.204	72.44	
E-13	**9/26/2024**	**5.961**	E-13	**9/26/2024**	**5.985**	72.44	-0.118
M-14	3/14/2025	8.156	M-14	3/14/2025	8.186	72.41	
E-15	**11/1/2026**	**5.946**	E-15	**11/1/2026**	**5.939**	72.41	0.034
					Propellant Mass Fraction =	**0.035**	**-1.29**
					Propellant Used =	**2.59**	

Table 7. Outbound cycler candidate 2 trajectory summary

Phase I			***GALLOP***				
Encounter	**Date (mm/dd/yyyy)**	**V_∞ (km/s)**	**Encounter**	**Date (mm/dd/yyyy)**	**V_∞ (km/s)**	**Astrotel Mass (mt)**	**Taxi Savings (mt)**
E-1	**11/13/2011**	**5.808**	E-1	**11/12/2011**	**5.889**	75.00	-0.397
M-2	4/24/2012	10.142	M-2	4/24/2012	10.191	75.00	
E-3	**12/18/2013**	**5.854**	E-3	**12/18/2013**	**5.891**	75.00	-0.181
M-4	5/18/2014	11.449	M-4	5/18/2014	11.480	75.00	
E-5	**1/26/2016**	**5.902**	E-5	**1/26/2016**	**5.985**	74.98	-0.407
M-6	6/16/2016	11.488	M-6	6/16/2016	11.603	74.98	
E-7	**3/17/2018**	**5.791**	E-7	**3/16/2018**	**5.747**	74.70	0.216
M-8	8/9/2018	8.914	M-8	8/9/2018	8.800	74.56	
E-9	**6/3/2020**	**5.765**	E-9	**6/1/2020**	**5.824**	73.64	-0.289
M-10	11/10/2020	5.682	M-10	11/10/2020	5.827	73.64	
E-11	**8/22/2022**	**5.831**	E-11	**8/21/2022**	**5.882**	72.60	-0.250
M-12	1/24/2023	7.142	M-12	1/24/2023	7.204	72.60	
E-13	**9/26/2024**	**5.961**	E-13	**9/25/2024**	**5.988**	72.57	-0.132
M-14	3/14/2025	8.156	M-14	3/14/2025	8.186	72.57	
E-15	**11/1/2026**	**5.946**	E-15	**11/2/2026**	**6.041**	72.57	-0.466
					Propellant Mass Fraction =	**0.032**	**-1.91**
					Propellant Used =	**2.43**	

spend more Astrotel propellant to reduce Taxi propellant consumption.)

Discussion of V_∞ Constraints

The savings of the results presented here can potentially be even higher, especially the Taxi savings. Presently, GALLOP represents the velocity of the Astrotel in heliocentric inertial coordinates, the V_∞ at Mars is found by subtracting the velocity vector of Mars from that of the Astrotel. Thus we cannot directly constrain the magnitudes of the V_∞ vectors. Currently, we implement constraints on the velocity vector of the Astrotel by setting appropriate upper and lower bounds on the inertial x, y, and z velocities at each Mars encounter. We then gradually adjust these bounds to achieve higher Taxi propellant savings. We note, however, that these constraints have a significant impact on the convergence behavior of the solution. It is not uncommon for GALLOP to return nonoptimal or even infeasible results even if the initial guess is a locally optimal solution from a previous run. Thus we frequently have to adjust these constraints by relaxing or tightening the bounds on each of the Mars encounters. We speculate that the process will be much simpler and smoother if we are able to directly work with the magnitudes of the V_∞. In a future work we plan to test the effects of reparameterization of the V_∞ vectors in spherical coordinates.

Conclusion

Using low-thrust propulsion, we achieve moderate to high Taxi propellant savings for the Aldrin cycler. In addition, the Astrotel propellant savings are modest. The long-term savings can be significant, keeping in mind the goal to establish a permanent human presence on Mars.

Acknowledgements

This work has been supported in part by Global Aerospace Corporation under contract number 521 1282-0030 / Proposal #DW41 (K. T. Nock, President, and S. E. Gruber, Business Operations and Contracts Manager). We acknowledge the generous support, enthusiastic collaboration, and expert guidance of Kerry Nock and Paul Penzo.

References

1. Hollister, W. M, "Castles in Space," *Astronautica Acta,* Vol. 14, 1969, pp. 311-316.
2. Rall, C. S. and Hollister, W. M, "Free-Fall Periodic Orbits Connecting Earth and Mars," American Institute of Aeronautics and Astronautics, AIAA Paper No 71-92, AIAA 9th Aerospace Sciences Meeting, New York, NY, Jan. 25-27, 1971.
3. Friedlander, A. L., Niehoff, J. C., Byrnes, D. V., and Longuski, J. M., "Circulating Transportation Orbits Between Earth and Mars," American Institute of Aeronautics and Astronauics, AIAA Paper 86-2009, AIAA/AAS Astrodynamics Conference, Williamsburg, VA, Aug. 18-20, 1986.
4. Byrnes, D. V., Longuski, J. M., and Aldrin, B., "Cycler Orbit Between Earth and Mars," *Journal of Spacecraft and Rockets,* Vol. 30, No. 3, May-June 1993, pp. 334-336.
5. Hoffman, S. J., Friedlander, A. L., and Nock, K. T., "Transportation Node Performance Comparison for a Sustained Manned Mars Base," American Institute of Aeronautics and Astronautics, AIAA Paper 86-2016, AIAA/AAS Astrodynamics Conference, Williamsburg, VA, Aug. 18-20, 1986.
6. Bishop, R. H., Brynes, D. V., Newman, D. J., Carr, C. E., and Aldrin, B, "Earth-Mars Transportation Opportunities: Promising Options for Interplanetary Transportation," American Astronautical Society, AAS Paper 00-255, The Richard H. Battin Astrodynamics Conference, College Station, TX, Mar. 20-21, 2000.
7. Nock, K. T, "Cyclical Visits to Mars via Astronaut Hotels," Phase I Final Report, NASA Institute for Advanced Concepts, Universities Space Research Association Research Grant 07600-049, Nov. 30, 2000.
8. Nock, K. T., and Friedlander, A. L., "Elements of a Mars Transportation System," *Acta Astronautica*, Vol. 15, No. 6/7, pp. 505-522, 1987.
9. Rinderle, E. A., "Galileo User's Guide, Mission Design Systems, Satellite Tour Analysis and Design Subsystem," Jet Propulsion Laboratory, California Institute of Technology, Pasadena, CA, JPL D-263, July 1986.
10. Sauer, Jr., C. G., "MIDAS: Mission Design and Analysis Software for the Optimization of Ballistic Interplanetary Trajectories," *The Journal of the Astronautical Sciences,* Vol. 37, No. 3, July-Sept. 1989, pp. 251-259.
11. Petropoulos, A. E., Longuski, J. M., and Vinh, N. X., "Shape-Based Analytic Representations of Low-Thrust Trajectories for Gravity-Assist Applications," AAS/AIAA Astrodynamics

Specialist Conference, AAS Paper 99-337, Girdwood, AK, Aug. 16-19, 1999.

12. Petropoulos, A. E., and Longuski, J. M., “Automated Design of Low-Thrust Gravity-Assist Trajectories,“ AIAA/AAS Astrodynamics Specialist Conference, AIAA Paper 2000-4033, Denver, CO, Aug. 2000.
13. Petropoulos, A. E., “A Shape-Based Approach to Automated, Low-Thrust, Gravity-Assist Trajectory Design,” Ph.D. Thesis, School of Aeronautics and Astronautics, Purdue University, West Lafayette, May 2001.
14. Sims, J. A. and Flanagan, S. N, “Preliminary Design of Low-Thrust Interplanetary Missions,” American Astronautical Society, AAS Paper 99-338, AAS/AIAA Astrodynamics Specialist Conference, Girdwood, AK, Aug. 16-19, 1999.
15. McConaghy, T. T., Debban, T. J., Petropoulos, A. E., and Longuski, J. M., “An Approach to Design and Optimization of Low-Thrust Trajectories with Gravity Assists,” American Astronautical Society, AAS Paper 01-468, AAS/AIAA Astrodynamics Specialists Conference, Quebec City, QC, Canada, Jul. 30-Aug. 2, 2001.