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Operability Benefits of Airbreathing Hypersonic Propulsion for Flexible Access to Space

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Hypersonic airbreathing propulsion has been considered as an enhancement for access-to-space systems for decades. However, previous research using metrics such as takeoff gross weight and payload weight fraction has not shown conclusive benefits for airbreathing systems when compared with all-rocket launch vehicles. The U.S. Air Force Research Laboratory has developed new operability-based metrics relevant to U.S. Air Force missions: time to rendezvous with a target spacecraft, number of launch opportunities per day, and launch-window duration. Computation of the new metrics requires launch vehicle ascent trajectory optimization, orbital transfer solutions, and Monte Carlo analysis. Ascent optimization uses propulsion throttling, aerodynamic turning, and pitch control to command downrange and crossrange at the orbital insertion point while using minimum propellant. Then the two-point boundary-value problem is solved to find a minimum-propellant transfer orbit to rendezvous with the target. Monte Carlo analysis assigns the orbital target a random starting position over the Earth and then propagates the orbit until rendezvous is accomplished and the metrics can be computed. The Air Force's Reusable Military Launch System all-rocket launch vehicle RMLS 102 is compared against Alliant Techsystems' rocket-based combined-cycle launch system ATK-RBCC. The results of the Monte Carlo analysis show that ATK-RBCC featuring airbreathing propulsion combined with a high lift-over-drag airframe exhibits significant operability benefits. The developed operability metrics could help to transform access to space by demonstrating clear payoffs from airbreathing propulsion.

Nomenclature

C_D = drag coefficient
C_L = lift coefficient
f_{pay} = payload weight fraction
I_{sp} = specific impulse, s
S_{ref} = aerodynamic reference area, ft^2
Φ = fuel equivalence ratio

I. Introduction

SINCE the 1950s, airbreathing hypersonic propulsion has been considered as a means of enhancing the performance of access-to-space (ATS) systems. Within this half-century of research and development efforts, rocket propulsion has consistently served as the means for propelling payloads from Earth to space. To be sure, there have been a multitude of studies and development efforts aimed at bringing the benefits of airbreathing propulsion to fruition for ATS applications. For one reason or another, the benefits have not been realized. One must pause to consider if the failure to field an airbreathing launch system might not stem, in part, from a lack of focus on the expected benefits.

Throughout the history of hypersonics, it appears that the vast majority of payoff analyses have focused on the subjects of weights and weight fractions: takeoff gross weight (TOGW), operating empty weight, and payload weight fraction f_{pay} [1]. Indeed, many detailed studies have explored this potential in great depth and, although it would seem that a 50% reduction in TOGW would be revolutionary, we must remember that the space launch community is quite accustomed to handling systems that weigh millions of pounds at liftoff [2,3]. Furthermore, propellant is relatively inexpensive when compared with the cost of the airframe and propulsion system, and so it is truly difficult for an airbreathing propulsion system to compete simply in terms of vehicle acquisition cost [2,4].

In recent years, researchers have recognized that airbreathing propulsion offers potential operability improvements, usually described as *aircraftlike operations* [3,5,6]. Some have suggested that horizontal takeoff and jet propulsion will confer aircraftlike safety and reliability [3,7]. They may be correct, but it is also apparent that their conclusions have not been universally accepted [4,8].

In summary, the reasons that airbreathing launch systems have failed to materialize are twofold. First, the performance benefits (e.g. TOGW and f_{pay}) of airbreathing hypersonic propulsion are necessary, but not sufficient, to warrant system-level development [4,9]. Furthermore, the potential operability benefits of airbreathing hypersonic propulsion have not been sufficiently well characterized. The need exists to establish a more compelling rationale to justify the application of airbreathing propulsion to space access and missions of importance to the U.S. Air Force [6,10–13].

Since 2001, several studies have been conducted regarding airbreathing propulsion for ATS, and these efforts have been accomplished at varying levels of fidelity for a variety of customers [14,15].§ Taken as a whole, they provide substantial insight into the "hows and whys" of hypersonic flight for ATS applications, and the conclusion is that previous research has not given sufficient attention to the ascent-phase flexibility offered by hypersonic airbreathing propulsion:

Launch systems that have the ability to cruise at hypersonic speeds can fly for hundreds or thousands of miles before they must commit to an ascent-phase trajectory [16,17].

It is necessary to quantify the mission benefits conferred by the ability to cruise downrange and turn aerodynamically during ascent and compare with a state-of-the-art all-rocket ATS concept. A series of questions must be addressed: How far can a launch system fly from the launch site before ascending to orbit? What is the relationship

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§Private communication with K. M. Andrews and M. J. Collatz, 4 March 2008.

between payload weight and fuel required for such an offset maneuver? What is the net result on the ATS launch window? Can the ability to conduct an offset maneuver result in more frequent launch or rendezvous opportunities, or is the capability of only limited utility?

The summary purpose of this research is to determine if this new capability suite provides a compelling reason to apply airbreathing propulsion to space-access systems. The study team recognizes from the outset that the effort may require the definition of a broader set of metrics for quantifying the system-level payoffs in terms of flexibility and operability.

II. Methodology

Ascent flexibility is investigated by comparison of two reference reusable launch vehicles flying a reference rendezvous mission. The first vehicle is solely rocket-propelled and the second vehicle includes both airbreathing and rocket propulsion. A probabilistic analysis is performed to assess rendezvous opportunities when the orbital target begins in a random position relative to the Earth and the orbit is propagated forward in time. Ascent and orbital transfer simulations are used to calculate a minimum fuel burn trajectory to achieve rendezvous with an orbital target. Flexibility metrics are developed that capture the capability of each launch vehicle to rendezvous with an orbital target.

A. Mission Definition

The reference mission to a low-Earth parking orbit is specified by several initial and final conditions. The launch site is Cape Canaveral (28.5°N, 80.5°W). The destination parking orbit is circular at an altitude of 100 n mile. The final inclination is 51.6° and only ascending node rendezvous is considered, to avoid an unfair disadvantage for less maneuverable systems in the initial analysis. The launch vehicles are sized to deliver 40,000 lbm payloads directly into the target orbit with no orbital plane changes or phasing maneuvers. Overflight of geopolitical boundaries during ascent is prohibited, which is a constraint placed on current launch systems [18]. The reference mission is representative of a generic low-Earth-orbit repeat-coverage orbit designed for tactical surveillance [19].

B. Reference Launch Vehicles

The two vehicles selected for this study were independently developed to fly similar missions. The all-rocket concept was developed by the reusable military launch system (RMLS) team, composed of Air Force, NASA, and industry partners. This concept is known as RMLS 102, and it is a two-stage-to-orbit, vertical-takeoff, horizontal-landing launch vehicle. The first and second stages use liquid-oxygen (LOX)/hydrocarbon rocket propulsion. The booster has return-to-launch-site capability and the system is fully reusable. Gross takeoff weight is 1.36×10^6 lbm, and 40,000 lbm can be delivered to the reference orbit [20,21]. A systems weight breakdown is shown in Table 1, and the mated booster and upper stages are shown in Fig. 1.

Fig. 1 RMLS 102 reusable launch vehicle.

Under the Air Force's Robust Scramjet program, Alliant Techsystems (ATK) designed an airbreathing rocket-based combined-cycle (RBCC) vehicle sized to carry 40,000 lbm to 100 n mile with a gross takeoff weight of 1.41×10^6 lbm. The ATK-RBCC is boosted by LOX/hydrocarbon rocket to Mach 4, where staging occurs. The all-rocket first stage then returns to the launch site. The second stage uses liquid-hydrogen scramjet propulsion up to Mach 10, at which point LOX/LH_2 rockets are used to ascend to orbit. A systems weight breakdown is shown in Table 2, and the upper stage is shown in Fig. 2.

The two launch vehicles present a consistent baseline for assessing the differences between all-rocket and airbreathing ascent methods. Each launch vehicle is sized for 40,000 lbm for a minimum-propellant ascent. Any deviation from the optimal ascent, via endo-atmospheric or orbital maneuvering, requires additional propellant. The ascent flexibility analysis assumes that payload weight can be directly traded for propellant weight to gain downrange or maneuvering capability required for rendezvous, resulting in operational payloads of less than 40,000 lbm. Aerodynamic properties are shown in Table 3. Airbreathing propulsion properties are shown for the ATK-RBCC in Table 4, and rocket propulsion properties are shown for both vehicles in Table 5.

For fair comparison, it is assumed that RMLS 102 has the same specific impulse as ATK-RBCC for orbital maneuvering.

Trajectory profiles in Fig. 3 show that the ATK-RBCC has a much shallower flight path than the RMLS 102 so that it retains sufficient dynamic pressure for operation of the airbreathing engines. For offnominal missions requiring additional downrange, an increase in heat load occurs that was not explicitly accounted in the vehicle design. However, the heat load increase is less than 20% above nominal, and the heating occurs mostly below the ATK-RBCC's thermal-balance Mach number. Consequently, it is assumed that the active thermal control system has sufficient excess capacity to accommodate the increase without redesign of the vehicle.

C. Probabilistic Analysis

Because flexibility has been defined as the launch vehicle's ability to rendezvous with a target at any given time, probabilistic analysis is

Table 1 RMLS 102 weight summary (in pounds mass)

	Booster	Orbiter
TPS	6,831	7,447
Structure	55,068	24,887
Propulsion	25,524	6,462
Landing-system	4,110	2,826
Avionics/power	6,792	6,991
Trapped fluids	4,274	2,034
Empty weight	102,599	50,647
Payload	396,871	40,000
Propellant	855,816	306,224
Stage gross weight	958,415	396,871
Total gross weight	1,355,286	396,871

Table 2 ATK-RBCC upper-stage weight summary

Body structure with TPS	77,562
Wing/tail structure with TPS	13,939
Scramjet	45,188
Rocket propulsion	20,287
Subsystems	7,382
Landing gear	6,776
Empty weight	171,134
Payload	40,000
Upper-stage LOX	504,964
Upper-stage LH2	214,805
Stage gross weight	930,903
Booster weight	478,097
Total gross weight	1,409,000

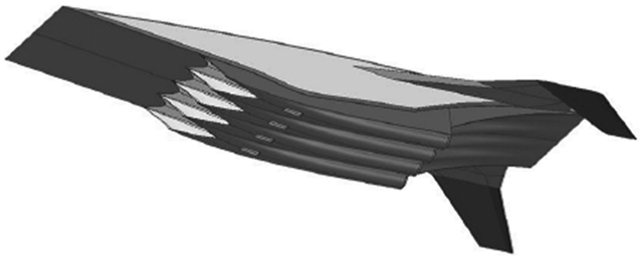

Fig. 2 ATK-RBCC airbreathing upper stage.

used to assess simulated ground-to-rendezvous trajectories with uncertainty in the target's initial orbital conditions. To fully capture the random nature of the target's starting position and the angular position of the Earth relative to the orbital plane, the ground-to-rendezvous trajectory must be simulated many times as a target orbit is propagated. The resulting collection of ascent trajectories gives information relevant to flexibility, such as flight timeline and propellant consumption. Because the rendezvous trajectory must be calculated numerous times, it is necessary to perform this calculation rapidly to save computational resources.

For each rendezvous case, the target is given a random initial true anomaly (angular position of the target within its given orbit) and right ascension of ascending node (RAAN) (angle between the ascending node and Earth's prime meridian) [22]. With the remaining four orbital elements (semimajor axis, eccentricity, inclination, and argument of periapsis) constant for all rendezvous cases, the orbit is propagated forward in time with discrete time steps of 1 min or less. At each time step, the target's latitude/longitude position is calculated, and the propellant-optimal rendezvous trajectory is calculated based on pregenerated databases for each launch vehicle. Although generating the databases depends on computationally intensive trajectory optimizers, once created, they can be accessed in less than a second. Consequently, each orbital propagation time step has an associated propellant weight to achieve rendezvous. If the propellant weight does not exceed the vehicle's maximum propellant load (some or all of the 40,000 lbm payload can be traded for propellant), the rendezvous is considered feasible. Generally, the target will be located at an offnominal location for the launch vehicle, so propellant weight always must be less than 40,000 lbm. For the probabilistic analysis, four payload classes are considered: 30,000, 20,000, and 10,000 lbm and empty (for retrieval missions).

Table 3 Aerodynamic properties for ATK-RBCC and RMLS 102

		ATK-RBCC, $S_{\text{ref}} = 9194$ ft^2		RMLS 102, $S_{\text{ref}} = 955$ ft^2	
Mach	Alpha	C_D	C_L	C_D	C_L
4	0	0.009	0.014	0.108	0.000
4	4	0.017	0.093	0.115	0.087
10	0	0.010	−0.001	0.087	0.000
10	4	0.014	0.044	0.091	0.050

Table 4 Airbreathing propulsion properties for ATK-RBCC

		ATK-RBCC Airbreathing, $\varphi = 1.0$		
Mach	Alpha	Axial force, lbf	Normal force, lbf	I_{sp}, s
4	0	258,467	69,137	2,967.1
4	4	230,914	85,366	2,578.4
10	0	126,735	162,550	1,607.7
10	4	195,144	246,885	1,801.8

Table 5 Rocket propulsion properties for ATK-RBCC and RMLS 102

	Vacuum thrust, lbf	Specific impulse, s
ATK-RBCC upper stage	1,400,000	402.2
RMLS 102 booster	2,212,415	340.3
RMLS 102 upper stage	439,817	350.9

D. Ascent Simulation

The launch vehicle ascent trajectory is simulated and optimized using Optimal Trajectories by Implicit Simulation (OTIS), an industry-standard code developed by NASA John H. Glenn Research Center at Lewis Field [23]. OTIS manipulates the initial launch azimuth, pitch control, bank control, and rocket and airbreathing engine throttle to achieve a minimum-propellant insertion into a 50 n mile circular parking orbit at an inclination of 51.6°. Overflight of land is prohibited during this phase. Both launch vehicles are iteratively scaled so that the minimum-propellant ascent combined with a minimum-propellant orbital transfer yields a payload weight of exactly 40,000 lbm.

Once the minimum-propellant, or nominal, ascent is determined, additional latitude and longitude constraints are placed on the final conditions at parking-orbit insertion. OTIS attempts to reconverge on a minimum-propellant flight path by manipulating pitch, bank, and throttling to achieve the desired location at orbit insertion. When latitude and longitude are commanded to any position other than the nominal ending location, additional steering and throttling losses are incurred to achieve offnominal values for downrange and crossrange. As a result, payload weight is always less than or equal to 40,000 lbm. The sampling of pregenerated ascent trajectories shown in Fig. 4 demonstrate the drastically different flight paths flown by all-rocket and airbreathing launch vehicles.

E. Orbit Simulation

Transfer from the 50 n mile parking orbit to the 100 n mile target orbit is calculated by solving Lambert's two-point boundary-value problem [22]. The initial position is the launch vehicle's commanded location and the final position is on the target's orbital path as a function of time of flight (TOF). With TOF constrained to a maximum of one-half orbit, a minimum-propellant transfer orbit is calculated. The TOF constraint yields large delta-V maneuvers, yet it is necessary to ensure that the orbital transfer phase does not unfairly dominate the time to rendezvous flexibility metric. The resulting trajectories better characterize the flexibility offered by a launch system. However, parameters such as launch window are too constrained to be comparable with current launch systems, which generally execute longer and more complicated rendezvous transfers.

A database of orbital transfers is pregenerated so that an orbital trajectory may be rapidly spliced with an ascent trajectory to complete the ground-to-rendezvous simulation. Although the ascent database is Earth-centric, showing the launch vehicle's reach relative to Cape Canaveral, the orbital transfer database is target-centric, meaning that the orbital transfer database includes a wide swath of orbital transfers from the parking orbit to rendezvous with the target. Figure 5 demonstrates three possible rendezvous trajectories to a single target orbit as interpolated from the orbit transfer database.

F. Computation of Flexibility Metrics

For a single case, the target starts with a uniformly randomized true anomaly, and RAAN and is propagated around the Earth in discrete time steps. At each time step, the Earth-centric ascent database representing the launch vehicle's reach is evaluated along with the target-centric orbital transfer database, showing feasible transfer trajectories to achieve rendezvous. Any geographic area in which the two databases overlap contains a set of feasible ground-to-rendezvous flight paths, and each discrete trajectory has an associated payload weight (after trading for propellant) that is propellant-optimal for that particular geographic location. Of the feasible set, the maximum payload flight path is selected and saved as the optimal rendezvous for that time step in the target's orbit. If no feasible rendezvous trajectories exist, which is the case when the

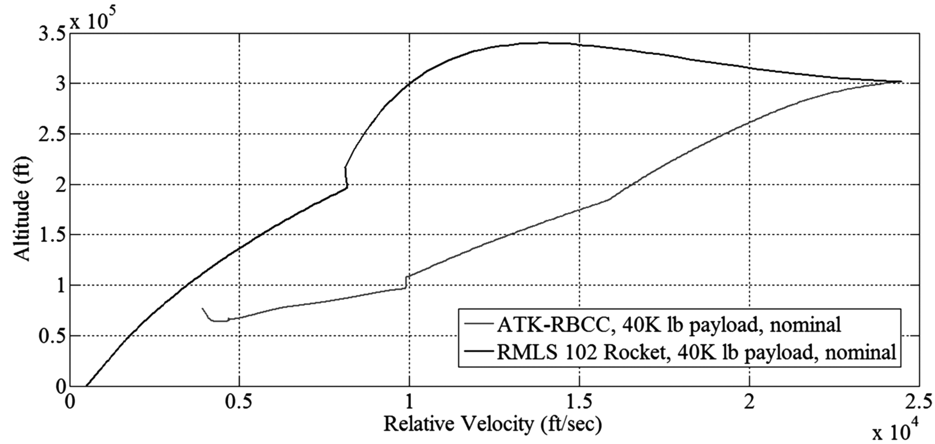

Fig. 3 Comparison of all-rocket and airbreathing ascent trajectories to a 50 n mile parking orbit, excluding the ATK-RBCC boost phase.

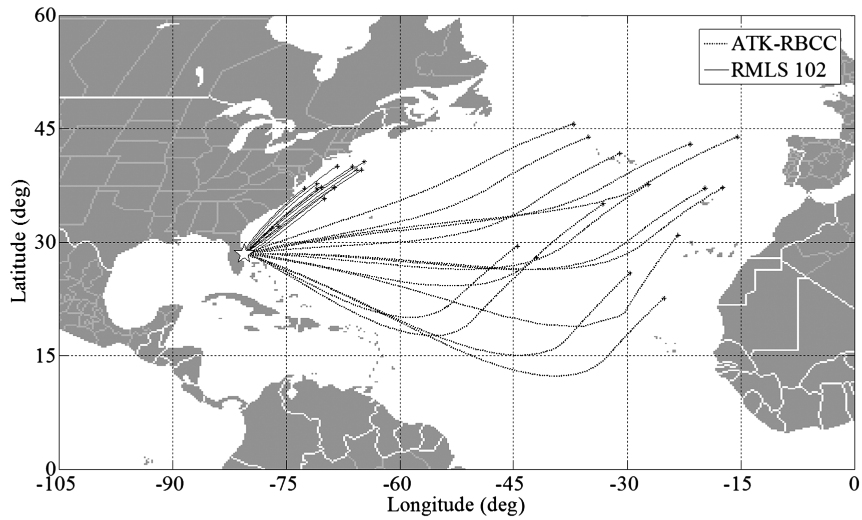

Fig. 4 Sampling of ascent flight paths saved in the ascent database.

target is not near the Atlantic Ocean, no payload weight is recorded and the simulation propagates the target to the next time step. A process flowchart is shown in Fig. 6.

A notional map of the launch vehicle's reach is shown in Fig. 7. The orbital passes that place the target within the launch vehicle's reach are highlighted to represent feasible passes. The longitudinal width of the launch vehicle's reach permits rendezvous on successive orbital passes. Figure 8 displays the overlap of the ascent and orbital databases at a single time step for a given target position, along with the calculation of delta-V and available payload weight.

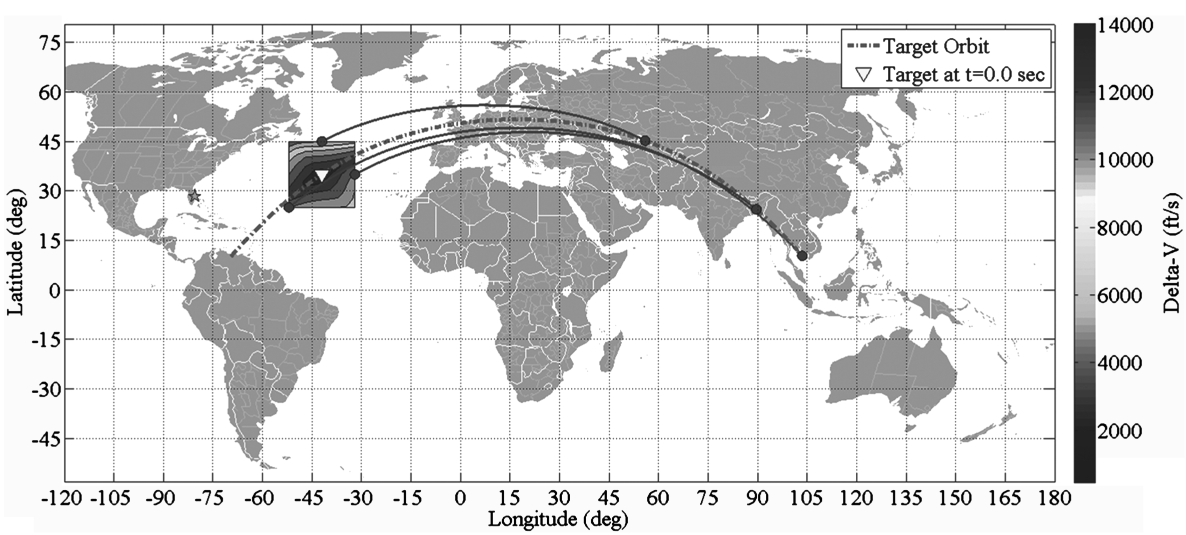

Fig. 5 Delta-V contours are shown for a target over the Atlantic Ocean. The three example orbital transfers begin at parking-orbit altitude and rendezvous with the given target orbit.

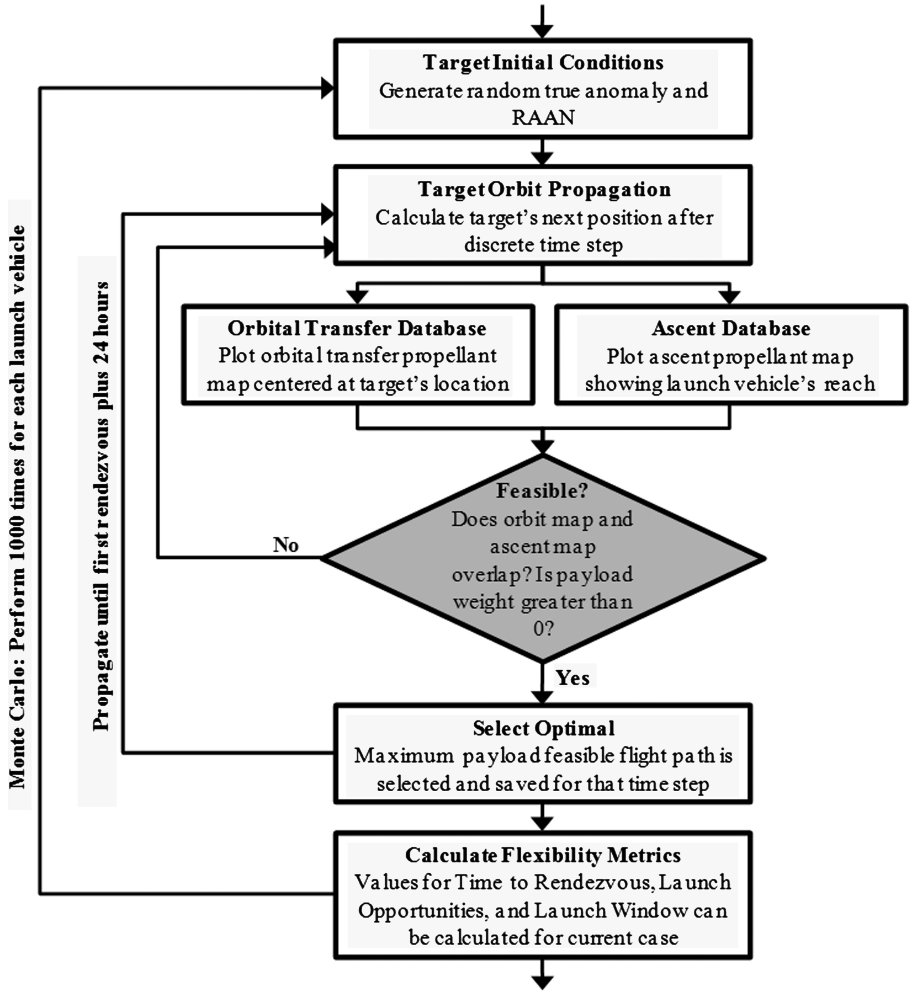

Fig. 6 Process flowchart for calculation of flexibility metrics.

The three flexibility metrics chosen for the analysis are derived from previous research and qualitatively touted benefits of airbreathing launch vehicles: time to first rendezvous, launch-opportunity frequency, and launch-window duration [7,24]. The flexibility metrics are computed for each Monte Carlo case in all four payload classes from 0–30,000 lbm. The time from the start of the simulation to the first feasible rendezvous, including orbit propagation time and launch vehicle time of flight, represents the time to rendezvous. Time to rendezvous is an important parameter for time-critical missions, such as emergency retrieval or rapid satellite deployment [24]. Launch opportunities is computed as the number of feasible target orbit passes, with each pass defined as consecutive feasible points. The frequency of launch opportunities is a measure of robustness against weather and maintenance delays. Launch window

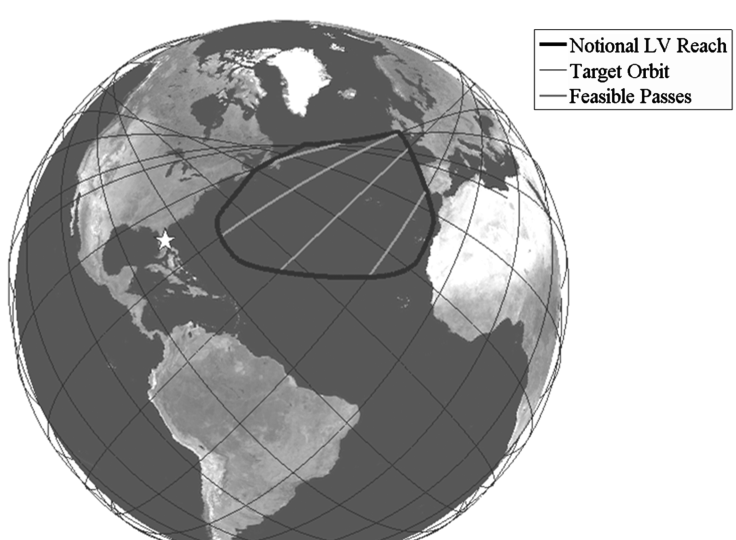

Fig. 7 Feasible passes are highlighted to show when the target passes within the launch vehicle's reach.

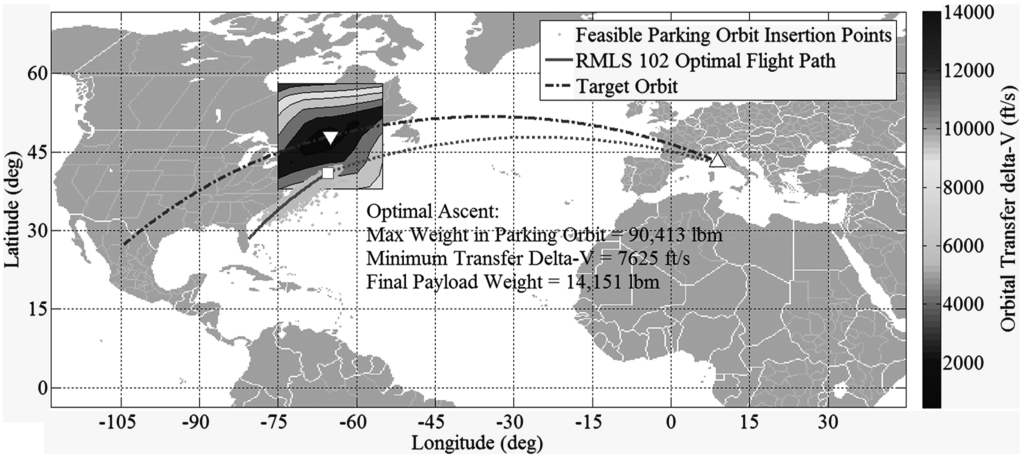

Fig. 8 Ground-to-rendezvous simulation is shown with the cloud of feasible ascents overlapped with the orbit map.

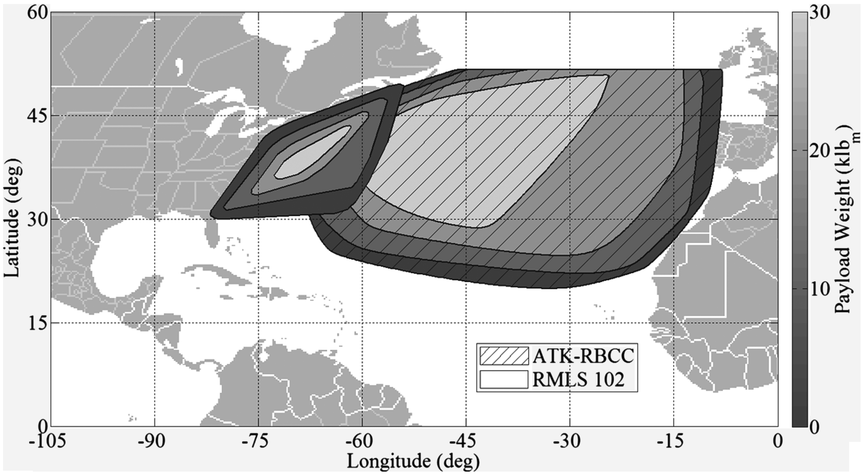

Fig. 9 Cumulative Monte Carlo results show payload weight as a function of target position for both launch vehicles.

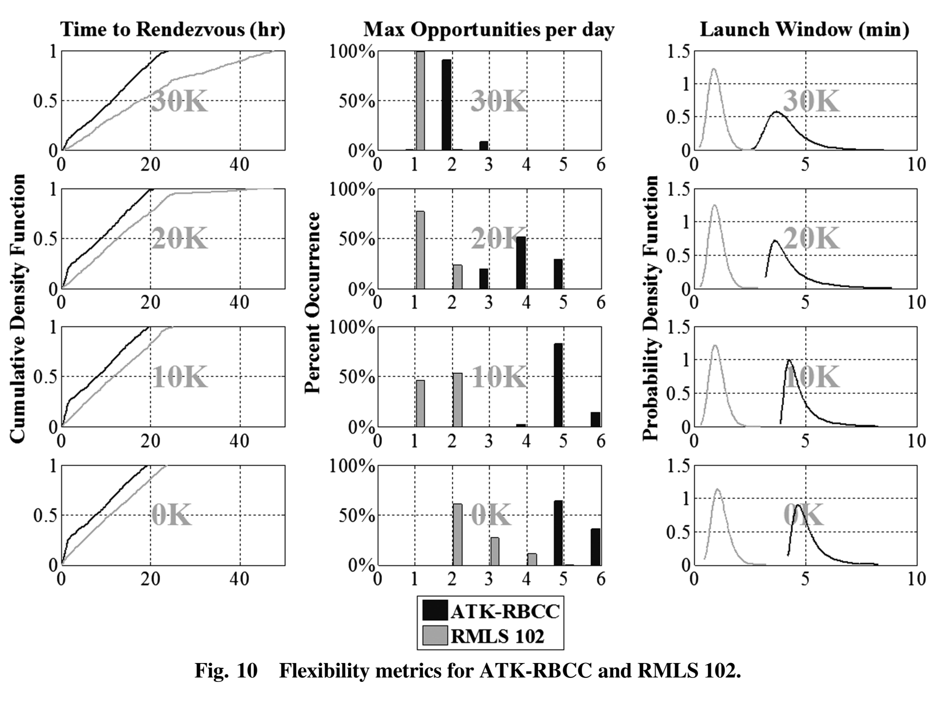

Fig. 10 Flexibility metrics for ATK-RBCC and RMLS 102.

Table 6 Flexibility metrics for ATK-RBCC and RMLS 102

		Time to first rendezvous, h				Mean launch window, min		
Vehicle	Payload, lb	Mean	Min	Max	Opps/day	Mean	Min	Max
ATK-RBCC	30,000	11.2	0.5	23.9	2.2	4.1	2.4	8.5
RMLS 102	30,000	19.8	0.8	47.5	1.1	0.9	0.1	2.0
ATK-RBCC	20,000	9.0	0.4	21.0	4.1	4.4	3.2	8.9
RMLS 102	20,000	13.6	0.4	47.5	1.4	0.9	0.2	2.2
ATK-RBCC	10,000	8.3	0.4	19.7	5.1	4.8	3.9	8.9
RMLS 102	10,000	11.9	0.4	25.2	1.6	0.9	0.2	2.2
ATK-RBCC	0	8.0	0.4	19.5	5.4	5.1	4.2	8.9
RMLS 102	0	11.3	0.4	23.7	2.6	1.1	0.4	2.3

is calculated by subtracting the launch time to rendezvous at the end of a pass from the launch time to meet the beginning of the pass. Window is also a measure of robustness to weather delays. Because the launch vehicle flies downrange at suborbital speeds, window time is shorter than the duration required for the target to traverse a feasible segment. For each Monte Carlo case, the launch-window times for each pass are averaged and then reported. Metrics are compiled for 1000 cases, which is graphically confirmed to present a global distribution of target initial positions. Statistical comparison of launch systems is enabled using probability density functions and cumulative density functions of generalized extreme value distributions fitted to histograms of the flexibility metrics [25].

III. Results

Once 1000 Monte Carlo cases are performed for each launch vehicle, each launch vehicle's payload capability is graphically assessed and the three flexibility metrics are statistically analyzed. The cumulative results of each launch vehicle's payload capacity as a function of target position are shown in Fig. 9. The contours are inferred from more than a million discrete points generated during the 1000 Monte Carlo cases, with each case consisting of thousands of time steps, each resembling the example in Fig. 8.

The three flexibility metrics are positively correlated to the size of the coverage area, and the worst-case 30,000 payload ATK-RBCC possesses at least 1.7 times the coverage area as the most-capable empty RMLS 102. Time to rendezvous and number of launch opportunities are positively correlated to the longitudinal width of the coverage area due to ground track shift for successive target orbits. Launch window is positively correlated to latitudinal height of the coverage area because a target orbit moving mostly from south to north remains within the coverage area for a longer duration.

The flexibility metrics for the Monte Carlo cases are presented in Fig. 10 and Table 6. Time to rendezvous is represented as a cumulative distribution function showing the percentage of cases that achieve rendezvous by a certain time for each payload class. With a maximum 30,000 payload, the ATK-RBCC can always achieve rendezvous within one day, whereas the RMLS 102 can achieve rendezvous in that time for only 70% of target starting positions.

The launch-opportunity plots in Fig. 10 show a 100% increase for ATK-RBCC, improving chances of successful launches despite weather or minor maintenance delays. ATK-RBCC's ability to cruise downrange with high fuel efficiency increases the frequency of launch opportunities by 150% as payload is traded for additional propellant.

The launch-window plots show a probability density function created by fitting a generalized extreme value distribution to the Monte Carlo data [25]. ATK-RBCC shows a 300% increase for all payload cases, and sacrificing payload yields additional launch-window benefits solely for the airbreathing launch vehicle.

IV. Conclusions

Flexibility is an important launch vehicle characteristic for accomplishing responsive space missions. Launch vehicle architecture options exist that can greatly improve mission flexibility, but significant investment is required to mature the enabling technologies. Whereas flexibility is generally touted qualitatively for conceptual launch vehicle designs, rigorous quantifications have been lacking. The developed method computes time to rendezvous, launch-opportunity frequency, and launch window using physics-based trajectory optimization and probabilistic analysis. The computed metrics relate directly to Air Force missions that demand rapid orbital insertion and retrieval, and they provide an indirect indication of operational costs and supportability. Computation of flexibility provides the basis for analytically justifying investment in flexibility-enhancing technology.

Although the flexibility computation can be applied to any launch vehicle architecture, the comparison of similarly sized all-rocket and airbreathing launch vehicles show that an airbreathing upper stage with a high lift-to-drag airframe and efficient airbreathing engines provides substantial mission benefit. When compared with the all-rocket system, the airbreathing launch vehicle showed potential to rendezvous one full day earlier, with twice the frequency of launch opportunities and four-times-greater launch window. Comparison was performed for rendezvous with a relatively benign target orbit that was representative of a current rendezvous mission from Cape Canaveral. Examination of rendezvous flexibility in different orbits will use additional unique capabilities offered by launch vehicles with airbreathing propulsion and further demonstrate the potential for mission flexibility.

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