RASCAL: DARPA'S SOLUTION TO RESPONSIVE, AFFORDABLE, MICRO-SATELLITE SPACE ACCESS

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Abstract: RASCAL is a revolutionary space access program initiated by the Defense Advanced Research Projects Agency (DARPA). RASCAL will demonstrate the capability to launch microsatellites into low earth orbit routinely and on short notice using an air-launch system architecture. A propulsion enhancement – Mass Injection Pre-Compressor Cooling (MIPCC) - allows the air vehicle to obtain high-energy flight conditions and provides the capability for exo-atmospheric staging of an expendable rocket with satellite payload attached. This architecture effectively reduces recurring launch costs, which are targeted to be $750,000 per launch.

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Introduction

In March 2002, the Defense Advance Research Projects Agency (DARPA) – the Department of Defense (DOD) agency charged with providing radical innovation for national security – began the Responsive Access Small Cargo Affordable Launch (RASCAL) program. DARPA established a goal of creating a launch system capable of responsively and routinely placing payloads into orbit at reduced cost. Specifically, RASCAL will be capable of placing a 75 kg payload into low earth orbit at a recurring cost below $750,000 per launch. The RASCAL system consists of a highly reusable air-breathing first stage aircraft capable of exo-atmospheric flight. The aircraft utilizes heritage turbojet propulsion with a 'bolt-on' propulsion modification known as Mass Injection Pre-Compressor Cooling, or MIPCC; this enhancement allows engine operation at increased Mach number and altitude with increased thrust. Because MIPCC provides a very significant performance advantage, the RASCAL aircraft is referred to as the MIPCC Powered Vehicle, or MPV. The MPV internally carries a two-stage

Expendable Rocket Vehicle, or ERV, which is released at approximately 200,000 ft and operated at a dynamic pressure of less than 1 psf. Such exo-atmospheric operation and other design features allow the ERV to be produced at low costs.

Since RASCAL provides the potential for significant applications in both commercial and military sectors, DARPA is using a non-standard (but DOD approved) contracting instrument, 'Others Transaction Agreement' with its industry partners. The RASCAL program is being executed in three phases: a system study phase, a design phase, and the final build and flight test phase. In March 2002, DARPA selected six performers to conduct Phase I system studies. This phase was nine months long and ended with the selection of Space Launch Corporation (SLC) of Irvine, Ca. to continue into Phase II. This phase, which began in April 2003 and will last 18 months, will include risk reduction testing efforts and result in detailed system and sub-system level designs. Phase III will serve as the construction, test and demonstration period for the RASCAL system. Flight tests will begin in Fiscal Year '05, with final system demonstrations – including delivery of at least two orbital payloads - in Fiscal Year '06.

RASCAL Figures of Merit

In order to establish clear and tangible objectives for RASCAL, Figures of Merit (FOMs) were established. The FOMs provide absolute rules to be met by the RASCAL system contractor; however, they are not "requirements" in the traditional sense, as no official DOD doctrine established a need for them. The FOMs were created in order to provide a path leading to revolutionary improvements in the nation's space-lift and space force projection capabilities. The FOMs for the RASCAL system are as follows:

• Payload performance: Must have a minimum payload lift of 75kg to a 500 km altitude sun-synchronous orbit. Also, must have a minimum payload lift of 50 kg to any low Earth orbit (LEO). The most demanding LEO mission is defined as a 1250 km altitude sun-synchronous orbit.

• Exo-Atmospheric staging using MIPCC: The maximum dynamic pressure exerted upon the ERV and payload during the entire flight trajectory must be 1 psf or less. Use of the MIPCC propulsion enhancement is required.

• Contractor life cycle cost: Recurring cost of $750,000 or less per mission (amortized MPV non-recurring costs are not included in the recurring cost calculation).

• Loiter, mission flexibility and range to launch point: 1/2 hour on station, 250 nm mission radius, in flight mission planning capability.

• Turn-around time between missions: Turn-around between missions must be less than 24 hours. This time assumes that no payload-to-ERV integration testing and verification is required or, alternatively, it has already been performed.

• Mission scramble capability: Must be able to scramble a mission in less then an hour. This capability assumes the ERV and payload have been integrated into the MPV and the system is maintained in a fueled and ready-to-fly state near the runway. Scramble time is measured from the moment the mission command is given to MPV wheels off the ground.

•Payload vibration/load isolation: Designed to be simple for payload developer (interface, integration, verification, and environments). Frequencies must be limited to 50 Hz or above for axial and torsional modes and 40 Hz or above for lateral modes. Loads must be limited to 5 g axial and 4 g lateral.

• Peculiar support equipment: Minimum amount of special handling equipment when operating from a typical military air base.

• Flight infrastructure: Less than a 2500 Meter runway length, minimum test range requirements (such as telemetry and tracking functions) to help meet the recurring mission cost.

• Reliability and Prognostic Based Monitoring (PHM): Reliability comparable to current tactical fighters and design hooks for PHM on at least the propulsion system.

The Benefits of Air Launch

The concept of utilizing air-launch for space-lift is not new. The U.S. Navy developed the NOTSNIK air-launch system utilizing an F-4D in 1958.[1] The aircraft accelerated to Mach 0.9 and released a three stage spin-stabilized rocket with payload attached at approximately 41,000 ft. The system suffered five failed attempts, but did succeed in lifting a short-lived 1.0 kg transmitting payload to space. The most well-known air-launch system is the Pegasus air-dropped launch system, which in fact was created in a DARPA program in the late 1980's. With an approximate orbital lift capability of 500 kg, the expendable Pegasus vehicle is carried by an L-1011 aircraft to release conditions of about Mach 0.8 and 38,000 ft.

The main benefits attributed to air-launch systems are their responsiveness and flexibility, enabled by the fact that they operate more like aircraft and are free to move to a range of choice, thus providing operational flexibility as well as access to all orbital inclinations for the satellite payloads. Launch costs for both existing and proposed air-launch systems have shown no clear advantage over traditional vertically launched systems with comparable performance. A more detailed analysis though finds that air-launch can theoretically provide cost reductions, with certain constraints. Utilizing the TRANSCOST parametric costing tool, an air-launch system costing model was developed: the results are shown in Figure 1.[2]

The figure shows total system and element launch costs as a function of the Mach number at rocket stage release (assumed to occur endo-atmospherically). The launch costs are normalized to the costs of a traditional 3 stage vertically launched Expendable Launch Vehicle (ELV) capable of the same payload performance
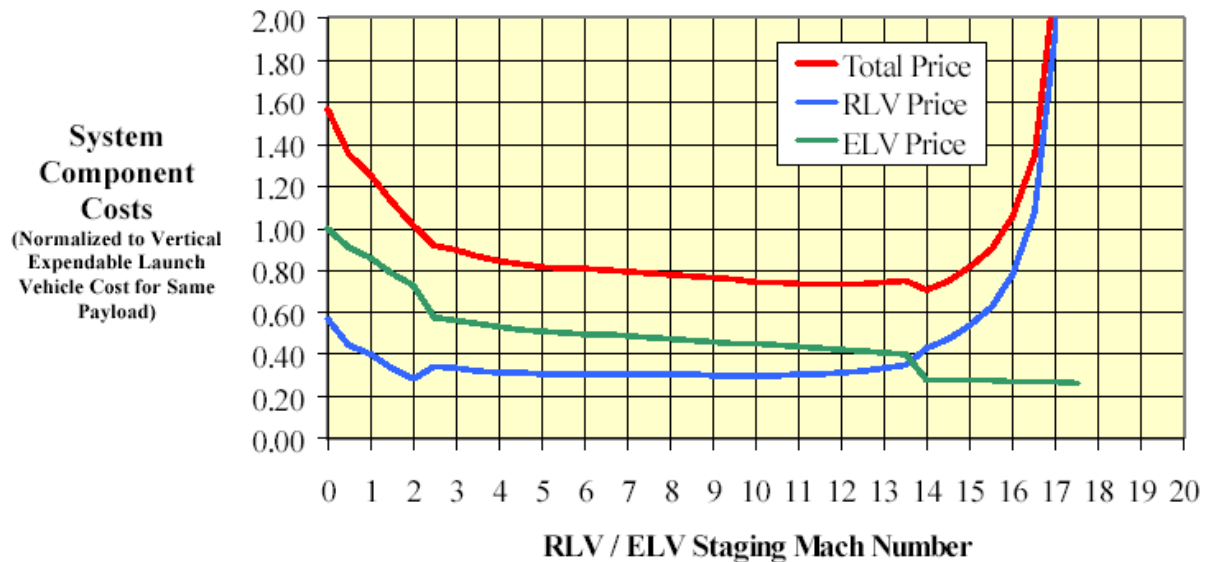
Figure 1. Relative Launch Costs of Air-Launched Components Normalized to Equivalent Costs of Fully Expendable System

(in this case, 50 kg to LEO). Shown are the contributions to the total system costs, namely the Reusuable Launch Vehicle (RLV) and ELV portions of the system. The overarching concept here is that as the RLV-ELV staging Mach number increases (or more specifically, the staging energy condition increases), ELV size will decrease, and so will its cost. Likewise, as ELV size is decreased and Mach number is increased, RLV size- and cost- trends toward a minimum. There are two noticeable drops in the ELV price at Mach 2 and Mach 14: at these points the ELV design changes to a (3-stage to) 2-stage system and then to a (2-stage to) 1-stage system, respectively. It was assumed in this analysis that RLV price is amortized over 100 total launches, with a small percentage of its price contributing to recurring launch costs (for purposes of operations and maintenance). This analysis finds that above a staging condition of about Mach 2.0, air launch systems costs are hypothetically less than traditional vertical launch expendable systems. As

Mach number increases into the hypersonic regime, so little historical air vehicle data is available that in this region RLV costs become more and more uncertain and difficult to model: Thermal Protection System (TPS) and advanced propulsion requirements will have an impact on RLV price. In the very high speed regime (Mach >15), the system architecture resembles a single stage to orbit reusable launch vehicle, and the costs rise exponentially (based on Space Shuttle and X-33 data).

This analysis provides the reasoning that air-launch systems can indeed be more cost-effective than their vertical launch counterparts. The ability to release at high energy conditions is challenging, requiring some advancement in air-breathing propulsion, as well as meeting the need to release a store at very high speed conditions. RASCAL addresses these challenges by symbiotically utilizing the MIPCC propulsion enhancement and exo-atmospheric launch.

MIPCC: RASCAL's Enabling Technology

MIPCC allows a typical turbojet or turbofan engine to operate at both higher Mach numbers and altitudes, while also allowing the engine to produce thrust in excess of designed maximums. MIPCC is a compelling technology not only because it boosts performance, but also because of its simplicity: installation of MIPCC does not require any modifications to be made to the engine rotating machinery; rather, an injection system nominally is 'bolted on' to a section of the engine inlet. Tankage for MIPCC injectants, plumbing, and injection pumps make up the remainder of a MIPCC system.

In a MIPCC system, a fluid (nominally water) is mixed with the incoming engine air stream to decrease the total temperature of the flow. For a given mass flow (corrected to sea-level static conditions), decreasing the inlet temperature allows the engine to intake more air. Since thrust production is in direct proportion to engine mass flow, an increase in actual airflow results in an increase in actual engine thrust. Also, in a typical 'dry-engine' (non-MIPCC), material temperature limits in the compressor and just forward of the combustor prevent the engine from operating above Mach 2 for extended periods of time. By cooling the flow with MIPCC, engine operation at higher Mach numbers is possible before engine temperature limits are reached. It should be noted that other engine design constraints do limit engine operation at higher Mach numbers, but a complete discussion of these effects is not within the scope of this paper.

In addition to injection of a cooling fluid, an oxidizing fluid (e.g. Liquid Oxygen, Liquid Air) can also be injected into the air stream. This will theoretically allow the engine to be operated at higher altitudes where the rarefied air would not be able to sustain a minimal level of net vehicle thrust.

MIPCC research has taken place sporadically in the U.S. for the last 50 years. The first analytical work was performed at the then NACA Lewis Flight Propulsion Laboratory in 1950 – 1954.[3,4] The first experimental work was reported by Sohn in 1956, where both analytical and experimental efforts were conducted. The analytical work showed that at Mach 3.0, thrust could theoretically be increased by 185% over a comparable dry engine. The experimental work focused on evaporation of water in a heated air stream (Mach 2 – 3) using venturi and pintle nozzles.

In the proceeding years, several other research efforts were undertaken, including:

•In 1958, tests of a J57-P-11 engine with MIPCC (then referred to as 'Pre-Compressor Cooling', or PCC) up to Mach 2.5 and 80kft were conducted at the Air Force's Arnold Engineering Development Center (AEDC)[6].

•In 1958, a successful flight test of a PCC system installed in a F8U-3 (J75 engine) was conducted up to Mach 1.9 by Vought. Dash time from Mach 1.3 to Mach 1.7 was cut in half, and rate of climb at Mach 1.7 was doubled. Analytical thrust boost was 7% at Mach 1.3 and 44% at Mach 2.0[7].

•In 1975, the Peace Jack program conducted ground tests of

candidate PCC systems for the RF-4X aircraft (J-79 engine), These tests were conducted up to Mach 2.3 and 75kft.[8]

Little work was done after the Peace Jack program until 1993, when NASA GRC studied MIPCC effects on J-85 engine performance using the NAVY/NASA Engine Program (NNEP) cycle code.[9] Efforts stopped until 2001, when DARPA issued six Phase I Small Business Innovative Research (SBIR) awards to study and test MIPCC effects on turbojet and turbofan engines for space access applications up to Mach 5. This work, as well as the work performed by the RASCAL Phase I contractors, culminated in an improved understanding of the MIPCC engine cycle and evaporative cooling phenomena as well as experimental ground testing of a MIPCC injection system.

The RASCAL Phase II and MIPCC SBIR Phase II programs plan to provide an even better understanding of MIPCC through continued analytical studies of engine cycle and evaporative cooling models. Ultimately ground testing of an F100-class engine at simulated Mach numbers up to 3.5 and altitudes up to 100,000 ft will be conducted at a test facility currently under design and construction.

Exo-Atmospheric Launch

A significant FOM for the RASCAL system is that the satellite payload and ERV, once released from the MPV, are not allowed to experience a dynamic pressure (q) of greater than 1 psf. Figure 2 illustrates the limiting conditions of Mach number and altitude where this 'exo-atmospheric' condition is present.

There are numerous advantages to exo-atmospheric release and subsequent operation of the ERV and payload. To begin with, stability and controls issues make supersonic atmospheric release of stores a very difficult problem: sufficient distance must be maintained between the aircraft and the expendable during the release due to safety considerations. By releasing the ERV in a regime where aerodynamic forces (and therefore, controls issues) are negligible, the RASCAL system is simplified. Other benefits of exo-atmospheric launch are:

• ERV mass is reduced since no fairing or aerodynamic surfaces are required.

• ERV costs – both non-recurring and recurring - associated with fairings and aerodynamic surfaces are eliminated.

•Mission success risks associated with failure of fairings and aerodynamic surfaces are eliminated. For example, one Pegasus failure – the maiden Pegasus XL flight in 1994 – was attributed to aerodynamic modeling and controls issues, while a Lockheed Martin Athena II failure in 1999 was attributed to a problem in the fairing separation system.[10,11]

The exo-atmospheric launch FOM and the recurring cost FOM work together to establish an 'energy space' required for release of the ERV payload. Through detailed analysis, it has been found that release below energy conditions of about 180,000 ft and Mach 1.5 at 1 psf requires at least a 3 stage ERV: recurring costs of ERV's of this size exceed the $750,000
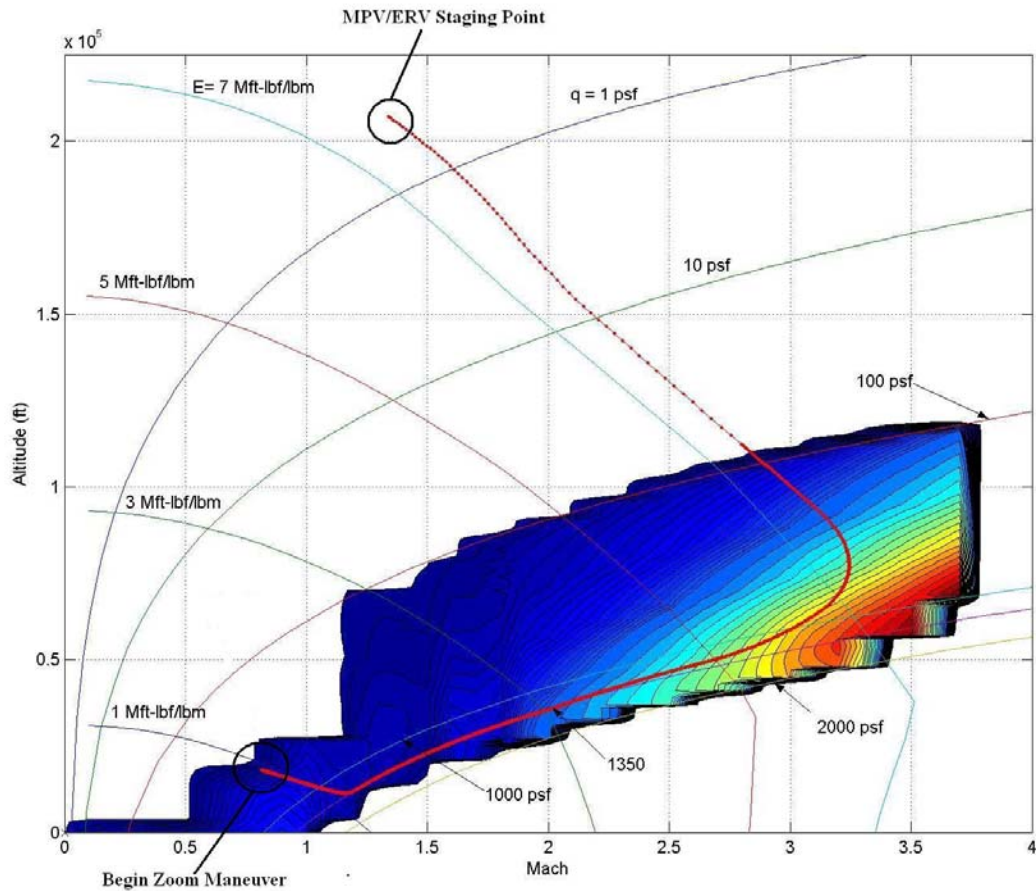
Figure 2. Representative MPV Trajectory and Excess Power Map

total system recurring cost FOM[*]. Likewise, release above energy conditions of about 250,000 ft and Mach 6 at 1 psf requires only a single stage ERV – an attractive solution since the recurring ERV costs will be substantially reduced (note that these results provide further substantiation and refinement of those results originally shown and discussed in Figure 1). A single-stage ERV may in fact represent the 'holy grail' solution.

RASCAL can be evolved to this capability with a turbojet modified for high pressure and high blade speed operations, enhanced TPS, and potentially a rocket system to assist in turning the MPV during the zoom, as well as in providing sufficient excess power to obtain the altitude required. Such modifications, though, were estimated to drive up the MPV non-recurring and recurring cost above that which was acceptable to DARPA for the RASCAL demonstration program.

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[*] It is noteworthy that RASCAL Phase I contractors found that ERV recurring costs are most sensitive to the number of stages (i.e, more stages = higher costs), while at the same time, costs are only a weak function of individual stage mass.

The Zoom Maneuver

In order to execute an exo-atmospheric release of the ERV, the RASCAL MPV

must perform a 'zoom maneuver'. In this maneuver, sufficient total energy (mostly in the form of kinetic energy provided by velocity) is developed at an appropriate endo-atmospheric altitude (less than 75,000 ft) that allows a large amount of thrust to be generated with acceptable drag (i.e. large net positive thrust).

With sufficient energy developed, the MPV can then trade kinetic energy for potential energy to obtain exo-atmospheric conditions: this is the purpose of the zoom. In the zoom, the MPV turns upward at a high rate; as noted in the description of the FOMs, a 4 g total lateral acceleration limit is imposed during this turn. With MIPCC, the turbojet can continue to operate to an approximate altitude of 100,000 ft. At this point, the engines on the MPV are throttled down, and the vehicle enters a ballistic coast period. The MPV will essentially 'ride' a line of constant specific energy at this point, as shown in Figure 2. Once clear of the 1 psf limit, the ERV is released. After sufficient separation distance is achieved to satisfy safety requirements, the ERV then ignites and carries the payload to orbit.

Trajectory Design Considerations

When designing the RASCAL trajectory, the designer is confronted with the competing interests of minimizing recurring cost and maximizing payload delivery capability. However, as previously noted, ERV cost (which is the primary contributor to the $750,000 recurring cost limit) is only weakly correlated to stage mass. As a result, once the number of stages is established, reducing the ERV gross-lift-off-weight (GLOW) yields a diminishing cost savings return. Consequently, a strategic decision was made to maximize the payload capability rather than minimize the size of the ERV, provided that the recurring cost FOM is met. This decision resulted in a fairly large (~15000 lbm.) ERV baseline with considerable excess payload potential. Assuming the ERV trajectory is properly optimized, the result is a payload delivery capability which is almost exclusively dependent upon MPV/ERV staging conditions.

The design of the MPV trajectory is a complicated and highly non-linear optimization problem made more difficult by the fact that no boundary conditions are specified. The objective is to achieve those staging conditions which will result in the maximum payload insertion weight, while simultaneously satisfying the following constraints:

(1) Staging must occur at a dynamic pressure less than or equal to 1 psf

(2) The payload must not experience loads greater than those specified in the FOMs

(3) The maximum dynamic pressure must not exceed the structural limits of the MPV

(4) The vehicle must operate in a flight envelope conducive to engine combustion stability and engine limits

(5) The vehicle must operate below a Mach number dictated by thermal considerations

(6) The angle-of-attack must remain within a reasonably linear range

(7) Fuel loading must not exceed the gross-take-off-weight (GTOW) or storage limitations of the aircraft.

MPV trajectory optimization efforts are ongoing; however several general conclusions have been drawn so far.

The most important consideration in the design of both the MPV trajectory and the aircraft itself is the necessity of sufficient excess power (P_e). Since much of the zoom maneuver consists of an unpowered coast, it is essential that a "critical-mass" of momentum be accumulated during the zoom maneuver. Figure 2 shows a representative P_e map along with a sample trajectory.

Two corollaries to the excess power requirement exist as an outgrowth of the nature of MIPCC. The first is that the magnitude of the net propulsive thrust is invariably more important than its efficiency (i.e. specific impulse). Figures 3 and 4 show representative thrust and I_{sp} contour maps. The second conclusion is that the staging conditions are largely insensitive to GTOW, which suggests that the driving constraints are dynamic in nature.
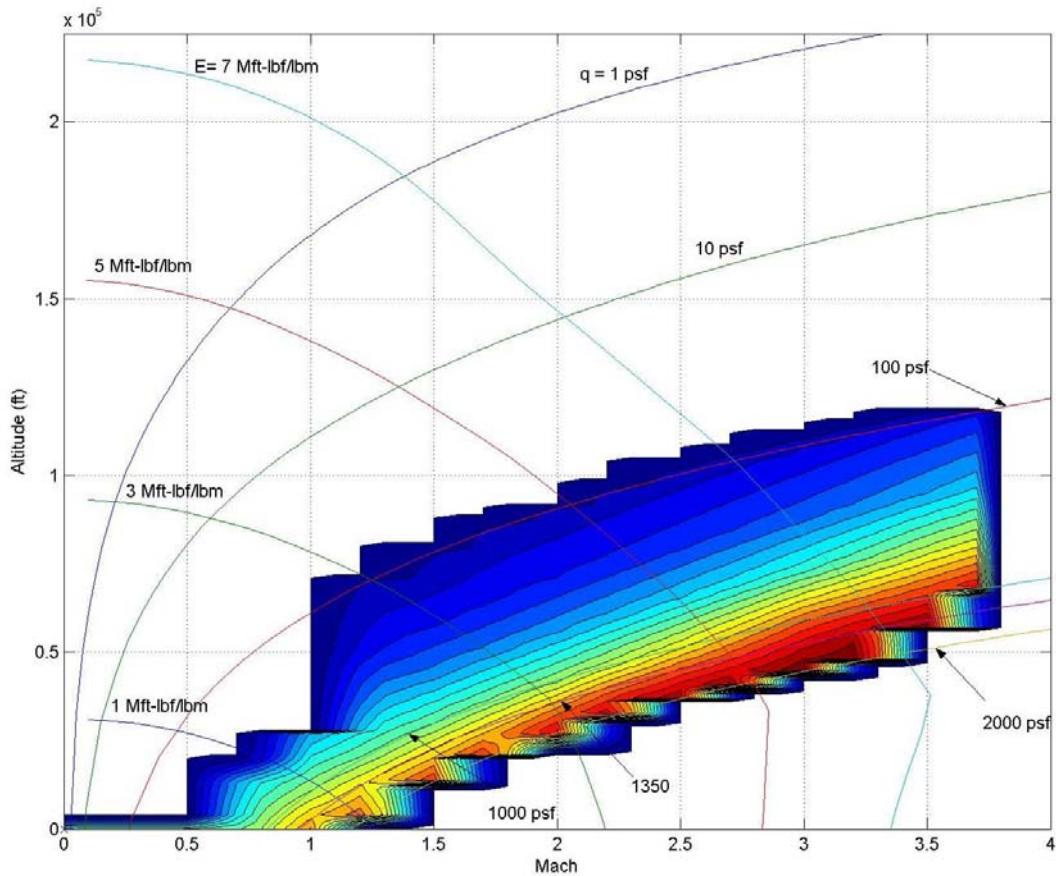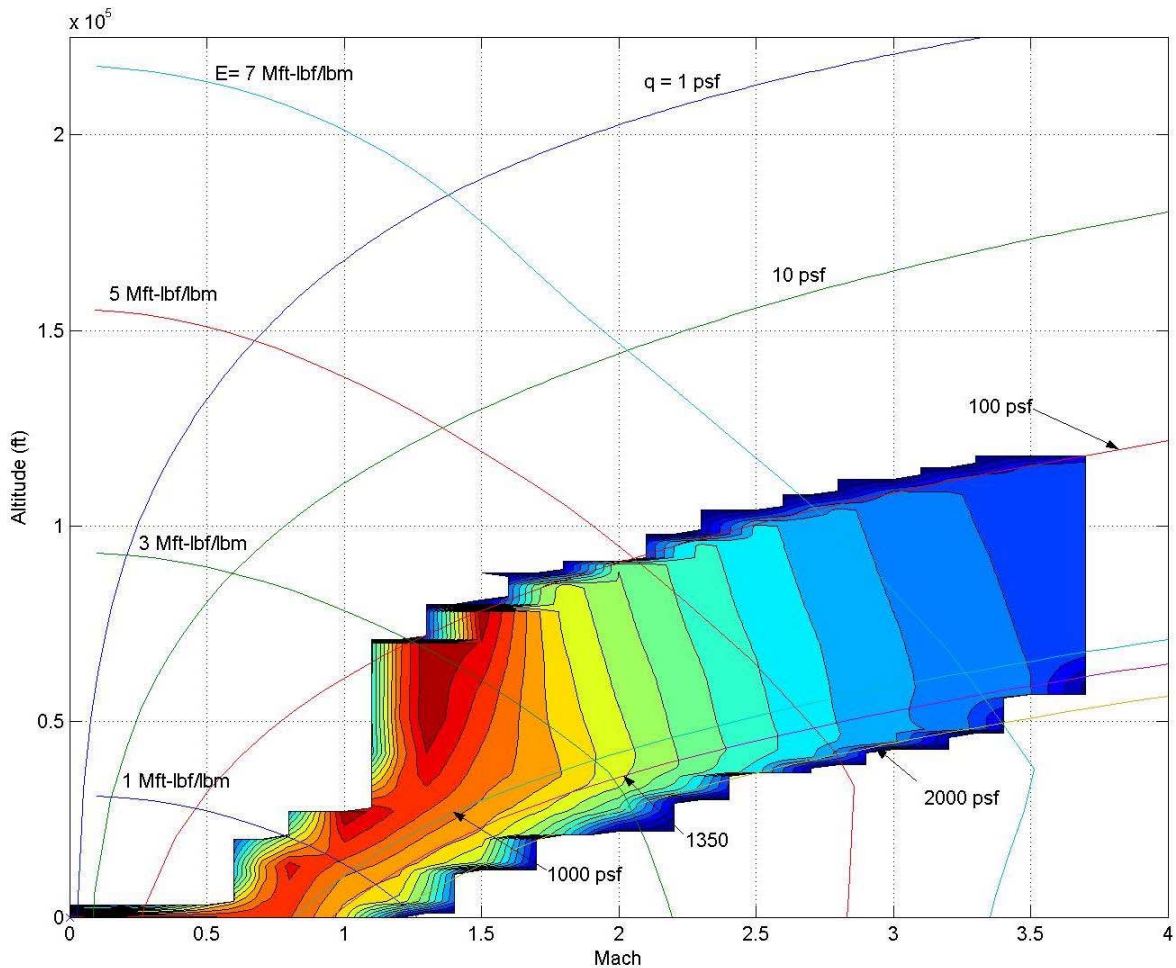

Figure 3. Representative MIPCC Thrust Map

Figure 4. Representative MIPCC I_{sp} Map

This is, in fact, precisely the case. The most restrictive elements of the design are the maximum dynamic pressure, q_{max}, and the maximum normal acceleration. The former dictates the lower bounds of the operating envelope (and thus P_e), while the latter restricts the ability of the MPV to efficiently convert kinetic energy into potential energy. It is interesting to note that at present, q_{max} is determined primarily by engine operability considerations rather than airframe structural limits.

Finally, several sensitivity studies have concluded that of the three staging conditions, payload insertion weight is most heavily dependent upon flight path angle, followed by relative velocity and altitude. Thus, as a general rule, staging energy should be sacrificed to flight path angle (the two are inversely related), and altitude should be sacrificed to velocity, (for a given specific energy).

Trajectory Design Implementation Issues

Two practical trajectory design issues merit discussion. The first is the non-linearity MIPCC adds to the problem (compared with conventional rocket or air-breathing propulsion). The reason for this can be termed the MIPCC-coupling effect. Figure 5 gives a graphical illustration of this effect.

Leaving aside the question of throttleability, the thrust and I_{sp} provided by MIPCC are a function of altitude and Mach number. However, since altitude and Mach number are a function of (among other things) the power plant, there is a feedback loop in the plant dynamics which is much stronger (by comparison) than in problems involving conventional propulsion. This results in a problem that is highly non-linear and has proved challenging to solve, at least from the perspective of a global optimum. Current efforts to identify the optimal flight path involve both numerical and analytical approaches.
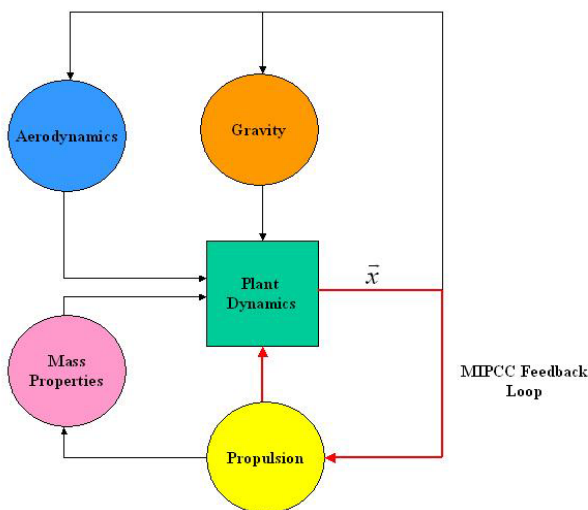

Figure 5. MIPCC Coupling Effect

The second issue is an available simplification of the optimization process, resulting from the relative insensitivity of the MPV/ERV staging conditions to MPV GTOW and the relative masses of the system components. Assuming the weight of the ERV is specified, the effects of changes in payload weight on the MPV trajectory can be reasonably ignored. This simplifying assumption allows the MPV and ERV trajectories to be decoupled. Thus the MPV trajectory can be computed without pre-knowledge of the payload weight. Likewise, the ERV trajectory can be computed based solely on the staging conditions and without regard to the endo-atmospheric path required to achieve them.

One advantage to this assumption is shown in Figure 6. This figure shows representative contours of delivered payload weight as a function of staging Mach number and flight path angle. From the above discussion, we note that these contours are independent of the MPV. The solid constraint line represents the design-specific staging limitation of the MPV. Changes to the MPV or MPV trajectory design require only an adjustment to this constraint line and do not affect the ERV-specific contours. Once the contours and staging constraint line have been determined, the optimal staging condition can be readily discerned from the plot[*].

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[*] In reality, there is a third axis to this plot: altitude. However, since payload insertion weight is more sensitive to staging velocity than altitude, for a given specific energy, the optimal staging condition will, in general, be that point which maximizes velocity. Since this point always occurs at q = 1 psf, the altitude at staging can be computed for any given velocity.
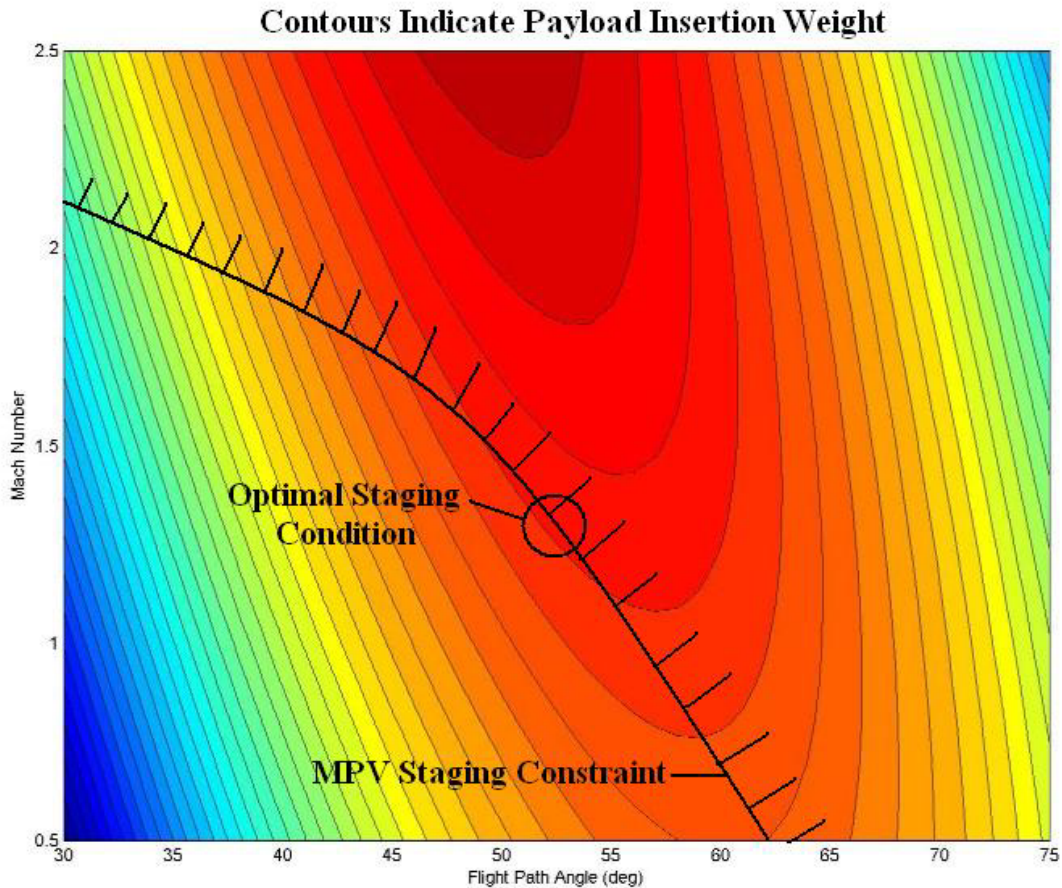
Figure 6. Representative Orbital Payload Performance as a Function of MPV/ERV Staging Conditions

RASCAL Payload Performance Capability

The baseline orbital payload performance capability of RASCAL established in the FOMs is 75 kg to a 500 km altitude sun synchronous orbit. The overall payload performance is of course altitude and inclination dependent: Figure 7 demonstrates the projected payload performance capability of the RASCAL system for a variety of launch conditions and target inclinations.

RASCAL also can deliver ballistic payloads: Figure 8 demonstrates the system's ballistic delivery capability using only the first stage of the RASCAL ERV. The RASCAL system may ultimately exceed these performance trends. A large payload volume capability – 1 m in diameter and 3 m in length – ensures that RASCAL payloads will not be volume limited. It is noteworthy that analysis suggests that a hypothetical RASCAL system is scalable to much larger payload capabilities, while maintaining its reduced cost advantage.

Figure 7. Representative RASCAL Orbital Payload Performance
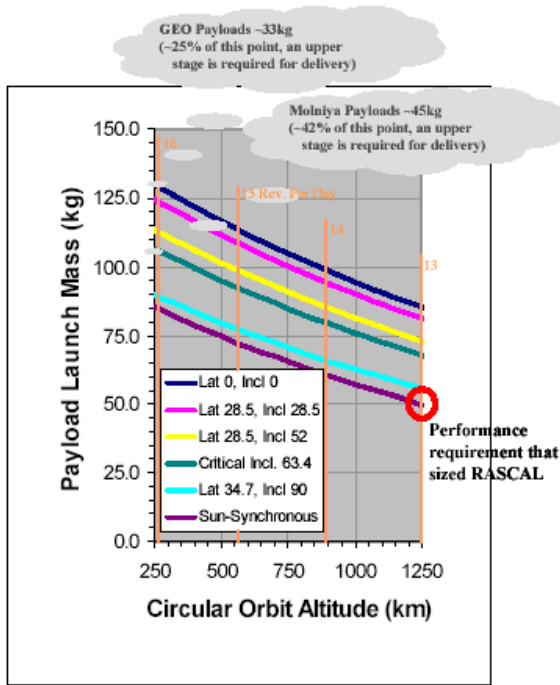

Figure 8. Representative RASCAL Ballistic Payload Performance

RASCAL Design Elements and Architecture

After detailed system trade studies, SLC determined that a "clean-sheet" approach was required for design of the MPV. This MPV will utilize off-the-shelf turbojet engines with the MIPCC enhancement; the vehicle will be designed and manufactured by Scaled Composites of Mojave, CA. With a maximum speed of about Mach 3, a modest TPS system will be required. The MPV will internally carry a two-stage ERV which will utilize mixed propulsion elements for purposes of robustness, performance, and most importantly, reduced recurring costs. Non-traditional approaches to range and flight safety systems will also serve to minimize launch costs.

Summary

DARPA's RASCAL demonstration program will provide the potential for a revolution in rapid and economical access to space. With significant reusability and rocket systems designed for low cost and high flight rates, and by establishing a requirement for exo-atmospheric staging, evolution of the RASCAL system to higher performance capabilities is possible.

Author Biographies

Preston Carter is on assignment, from Lawrence Livermore National Laboratory, to the Defense Advanced Research Projects Agency (DARPA) as a program manager within the Tactical Technology Office. He is currently the program manager for three major programs: The RASCAL program, the HyFly program,
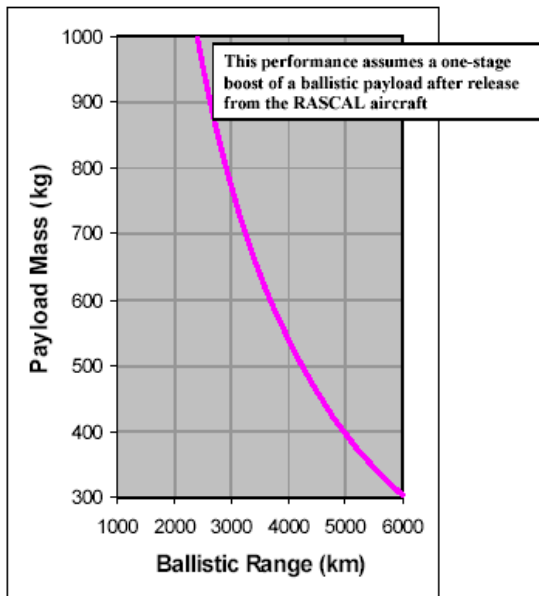
and the Miniature Air Launched Interceptor (MALI) program. Preston was a co-founder of the NASA Lunar Prospector mission and was one of the principal engineers for the DoD / NASA Clementine lunar mission. He is the inventor of the HyperSoar concept, a hypersonic flight and space access platform. Preston holds B.S. and M.S. degrees in Aerospace Engineering.

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Jason's research interests lie in the fields of astrodynamics, optimization and control theory. He is responsible for overseeing multiple DARPA programs and initiatives in the areas of trajectory design and flight controls.

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