Table 2 Approximation errors in three-segment approach examples in V-bar and R-bar directions[a]

Segment endpoint	Time error, s	Time error, %	Position error, cm	Position error, %	Velocity error, cm/s	Velocity error, %
V-bar approach						
1	3.0	1.96	6.0	0.30	0.0503	0.378
2	6.0	1.96	12.0	0.30	0.1012	0.758
3	9.0	1.96	18.0	0.30	0.1520	1.141
R-bar approach						
1	6.0	3.85	31.6	1.58	0.612	4.59
2	12.0	3.85	72.8	1.82	0.641	4.81
3	18.0	3.85	153.0	2.55	0.705	5.29

[a]Assumed 10-deg departure angle and 20-m segment length. Reference orbit altitude 300 km.

It is important to recognize that, during the final target approach phase, some small measurement and execution errors are inevitable. These can be of the same order of magnitude as the approximation errors inherent in the proposed simplified algorithm. It is reasonable, therefore, to make use of this algorithm to control or correct the immediate and subsequent trajectory execution steps. Approach safety constraints can, thus, be met instantly by continuous assessment of the effect of a departure from the initially planned final approach conditions.

Conclusions

The simple algorithm presented here offers a major reduction of computational effort associated with determining the characteristics (e.g., the correction maneuvers ΔV_i) of multisegment chaser-to-target approach paths of the type currently postulated in target rendezvous and docking approaches. The approximation also will be useful in comparing approach modes or different specific characteristics in the process of conducting actual rendezvous and docking missions rather than the more precise solution of the C–W equations.[3] Determination of the detailed time history of each approach segment is unnecessary, and the time interval for its completion is explicitly known on the basis of the other transfer arc parameters. The approximation errors are sufficiently small to be of little concern for the short distances and time intervals considered during the final rendezvous and docking approach. In particular, using the C–W equations as an alternative to determine all parameters of interest requires more extensive calculations based on assumed segment lengths and transfer times or the initial velocity components in the x and y directions.

Of particular interest is the quick-look determination of approach path changes and terminal conditions reached resulting from various velocity magnitude and direction changes. Determination of approach path characteristics and effects of any parameter changes can be of major importance, even during the final minutes of an actual rendezvous mission, for example, if unforeseen conditions require a modification of the approach mode. This assessment can be of major concern in meeting overall safety constraints and determining required approach-phase protection procedures. These and other advantages are relevant in justifying the simplified terminal flight-path algorithm described here.

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Low-Cost Small-Satellite Delivery System

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Introduction

DESIGN studies are being funded for a low-cost, small-satellite launcher with the capability of delivering a 110-lb payload to low Earth orbit.[1] Contracts have been awarded to three teams of companies (airframers, engine makers, and rocket builders) participating in the Responsive Access Small Cargo Affordable Launch (RASCAL) project. The concept being pursued is development of a new airbreathing carrier aircraft with a "souped up" turbojet engine (as a reusable first stage) to boost an expendable two-stage rocket to an altitude of about 90,000 ft and a speed of about Mach 4. Then, after coasting to about 130,000 ft, separation of the rocket from the boost vehicle would occur, with the rocket continuing its ascent to orbit and the boost vehicle descending into the lower atmosphere for recovery and reuse. An important factor in any air-launch concept is providing independence from use of a dedicated launch facility with a significant saving in ground support costs. Along with enabling rapid delivery of military satellites to orbit, the goal of the RASCAL project is to have launch on short notice (within 24 h) and at a cost of no more than $22,000 per pound of payload. It is anticipated tht the gross takeoff weight of the boost vehicle would be about 22,000 lb, including 6000 lb for the expendable rocket.

At the present time the Pegasus XL is the only space launch vehicle in the entire U.S. inventory[2] that is air launched. It is a stretched version of the earlier Pegasus vehicle, which was also air launched but had less performance. The Pegasus XL is a three-stage, solid-propellant rocket with a delta wing attached to the first

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stage. It weighs about 51,000 lb with a 977-lb payload for low Earth orbit (LEO) and is air launched from an L-1011 TriStar aircraft. Scaled-down versions of the Pegasus XL may be used to develop preliminary designs of smaller rockets for air launch.[3] The weight and nominal payload capability of a downsized Pegasus XL rocket can be obtained by simply multiplying the weight and payload of the full-size rocket by the scale factor of the smaller rocket cubed. Thus, a half-size Pegasus XL rocket would weigh about 6375 lb and could place only about 122 lb of payload in LEO. It is assumed, of course, that all hardware on the ful-size rocket (and the avionics) can be scaled down the same way.

The purpose of this Note is to propose an alternative low-cost system (to that being studied in the RASCAL project) for air launch of small rockets using existing jet trainers/fighters as relatively inexpensive carrier aircraft. Such aircraft, flying at high subsonic speed above 40,000 ft, could air launch downsized Pegasus rockets carrying small satellites in any direction from horizontal to nearly vertical. Steeper launches (close to vertical) would obviate the need for a wing on the first stage, with a saving in rocket weight and a reduction in drag losses (due to a shortening of the flight path through the lower atmosphere). Because the innovative system proposed would make use of existing carrier aircraft and proven air-launch technology, it would not require the long development time and the kind of funding projected for the RASCAL project. Moreover, system reliability could be even higher with the probability of lower operating costs.

Downsized Pegasus XL Rockets

It is assumed herein that multistage rockets like the Pegasus XL can be scaled down to produce smaller versions capable of attaining orbit with lighter payloads.[3] In this downsizing process, the fraction of mass for each stage to total vehicle mass is maintained, and the mass of each component is determined by using the scale factor and the cubic scaling law. This law infers that (for the same average density) the ratio of scaled-down mass to full-size mass is given by the cube of the scale factor. If the scale factor is one-half, the mass ratio is one-eighth, and a half-size component ideally has only one-eighth the mass of the full-size component. The scaling of solid rocket motors requires special scaling of the nozzle size for each stage so that the burn times and the thrust-to-weight levels are maintained at the proper values. Because it is unlikely that the avionics and the attitude control hardware can be scaled down the same way, there may have to be some adjustment of the downsized payload to compensate. However, in this preliminary analysis of a low-cost air-launch system, the assumption is made, for simplicity, that elimination of the wing in the downsized rocket will be sufficient compensation for the inability to scale down avionics, etc., ideally. In Table 1 nominal size, weight, and payload specifications are listed for the full-size Pegasus XL rocket along with such specifications for three different, scaled-down rockets, which would be suitable for air launch from potential carrier aircraft like those described in the following section.

Potential Carrier Aircraft

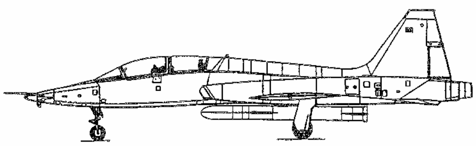
Three potential carrier aircraft for air launch of three downsized Pegasus XL rockets carrying small satellites into LEO are shown to the same scale in Fig. 1. Overall descriptions of these aircraft (and the much-larger carrier aircraft for the full-size Pegasus XL rocket) are given in Table 2. The T-38A Talon[4] can air launch a one-third-size Pegasus XL rocket capable of delivering a 36-lb satellite to LEO. This supersonic, two-place jet trainer was designed for

Table 1 Nominal size, weight, and payload capability of full-size Pegasus XL rocket and of three different scaled-down Pegasus XL rockets

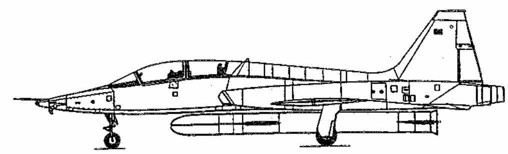
Specification	Pegasus XL rockets: Full Size	$\frac{2}{3}$ Size	$\frac{1}{2}$ Size	$\frac{1}{3}$ Size
Length, ft	55.4	36.9	27.7	18.5
Diameter, ft	4.2	2.8	2.1	1.4
Wingspan, ft	22.0	14.7	11.0	7.3
Weight, lb	51,000	15,111	6,375	1,889
Payload to LEO, lb	977	289	122	36

Table 2 Descriptions of carrier aircraft for full-size Pegasus XL rocket and of potential carrier aircraft for three different scaled-down Pegasus XL rockets

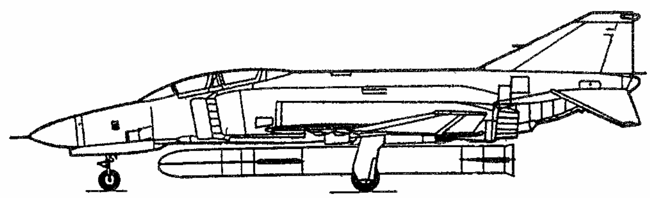
Specification	Carrier aircraft: L-1011 TriStar	F-4E Phanton II	F-5F Tiger II	T-38A Talon
Length, ft	178.66	63.0	48.16	46.33
Wingspan, ft	155.33	38.42	26.66	25.25
Empty weight, lb	234,275	29,535	9,683	8,912
Rocket weight, lb	51,000	15,111	6,375	1,889
Maximum takeoff weight, lb	430,000	61,651	24,680	15,513
Maximum static thrust, lbf	126,000	35,800	10,000	7,700
Maximum Mach number	0.8	2.2	1.63	1.24
Service ceiling, ft	42,000	62,250	51,800	54,000



T-38A Talon with one-third-size Pegasus XL



F-5F Tiger II with one-half-size Pegasus XL



F-4E Phantom II with two-thirds-size Pegasus XL

Fig. 1 Potential carrier aircraft for air launch of downsized Pegasus XL rockets.

low cost and minimum maintenance. The F-5F Tiger II[5] can air launch a one-half-size Pegasus XL rocket capable of delivering a 122-lb satellite to LEO. This high-performance, two-place aircraft was derived from the same basic design used for the T-38A Talon but is slightly larger and heavier with more-powerful turbojet engines. The F-4E Phantom II[5] can air launch a two-thirds-size Pegasus XL rocket capable of delivering a 289-lb satellite to LEO. This high-performance, two-place fighter aircraft has a long history of reliable service but has been phased out of frontline operation. The U.S. Air Force has an Aerospace Maintenance and Regeneration Center at Davis–Monthan Air Force Base in Arizona, where many of these three aircraft are in storage.

The listings in Table 1 indicate that the three downsized rockets have wings, which could or could not be the case, depending on whether they are air launched in a horizontal direction or with the carrier aircraft climbing at a high flight-path angle. The latter option is not available when large carrier aircraft like the L-1011 TriStar are used for air launch. The manner in which the three downsized rockets without wings could be positioned under the fuselages of the three potential carrier aircraft is shown in Fig. 1. Fixed or folding fins could replace the Pegasus XL conventional tail to provide directional stability during flight through the atmosphere. It is important to locate the center of gravity of each rocket close to the aircraft c.g. to minimize the amount of trim control required. With the wings gone from the downsized rockets, air launch would probably have to take place with the carrier aircraft climbing steeply at a flight path angle of 60 deg or higher. Small, movable cruciform fins attached to a control section on the third stage could provide adequate steering capability to bring the flight path close to vertical during ascent through the lower atmosphere.

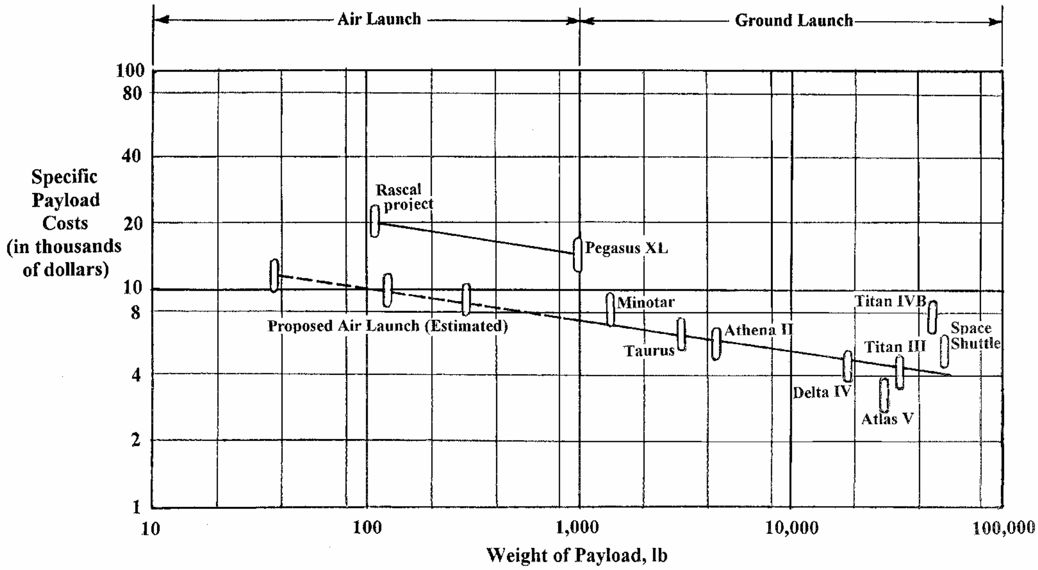


Fig. 2 Variation of specific payload cost with weight of payload on a variety of U.S. launch vehicles.

Estimate of Specific Payload Costs

The total cost of placing a small payload in orbit can be divided into launch vehicle costs and ground support costs. In general, changing from ground launch of a rocket into orbit to air launch increases the former (due to replacing the booster stage of a rocket with a carrier aircraft) but reduces the latter (due to less use of ground facilities and personnel involved in the launch). The net effect on specific payload costs, that is, total launch cost per pound of payload, can be either favorable or not, depending on how much one cost effect outweighs the other. A case in point (with an unfavorable effect) is provided by consideration of specific payload costs for the air-launched Pegasus XL rocket and the ground-launched Taurus rocket. These related rockets are essentially the same except for use of a carrier aircraft or an additional booster stage. As is subsequently shown, specific launch costs are considerably higher for the air-launched rocket, due, in part, to use of a very expensive carrier aircraft. Thus, minimizing operating costs of carrier aircraft can be a significant factor in lowering specific payload costs for air launching payloads of small size. That is the primary basis for the claim that the proposed system of air launch for rockets carrying small satellites into orbit is by any measure a low-cost delivery system.

Further insight into the matter of launch costs is provided by the data for a number of launch vehicles presented in Fig. 2, which shows (on logarithmic scales) the variation of specific payload cost with payload weight. The advantage of this kind of log/log plot is that it tends to eliminate the curvature associated with any consistent trend in the data. That is, if the data are roughly of the form $y = cx^a$, then $\log(y) = \log(c) + a\log(x)$, with a being the slope of the straight line through the data plotted on logarithmic scales. Because the line through the data shown in Fig. 2 has a slope of -0.1445, the nominal variation of specific launch cost with payload weight can be expressed in the form $y_2/y_1 = (x_2/x_1)^{-1/7}$, where x and y represent payload weight and specific launch cost, respectively. When this expression is used, with $x_1 = 100$ lb and $y_1 = \$10{,}000$, it is found that $y_2 = \$5140$, when $x_2 = 10{,}000$ lb, which confirms its accuracy (if not the validity of extrapolation). However, there is good reason to believe that extrapolation of the line to smaller values of payload weight is probably valid.

The trend of specific payload cost increasing with a reduction in payload weight can be explained by the fact that ground support costs are roughly fixed at different levels for all sizes of air-launched rockets and for all sizes of ground-launched rockets. As the size of payload and required rocket get smaller, ground support costs do not diminish at the same rate as rocket cost, and so become more significant. However, there appears to be a discontinuity between the variation shown in Fig. 2 for air launch and that for ground launch (which suggests that the level of specific payload costs for the Pegasus XL rocket and that projected as a goal for the RASCAL vehicle are probably too high). However, as alluded to earlier, such inordinately high costs are most likely a result of using a large and expensive carrier aircraft or, in the case of the RASCAL project, a result of using unproven new technology with high development and operating costs. Finally, estimated values of specific payload costs shown for the proposed system of air launch are simply based on extrapolation of the line through the data obtained for several ground-launched vehicles. It is seen that, for air launch using the three small aircraft described herein, specific payload costs could be about \$10,000 per pound. This is roughly half the goal set for the RASCAL project and, if attainable, would justify characterizing the proposed air-launch system as being low cost in both development and operation.

Conclusions

A low-cost system for air launch of multistage rockets carrying small military and scientific satellites to LEO could be operational in a few years using present technology and a minimum of investment. Development of such a system would only require the acquisition of existing small jet trainer/fighter aircraft (from such aircraft presently in service or out of service and in need of restoration) and the downsizing of a three-stage solid rocket in the U.S. inventory. The potential carrier aircraft are the T-38A Talon, the exported F-5F Tiger II, and the phased-out F-4E Phantom II. All of these aircraft are supersonic with a crew of two and the capability of carrying a small rocket under the fuselage for subsonic air launch above 40,000-ft altitude. A one-third-size Pegasus XL air launched from a T-38A would be able to place about 36 lb in LEO, and a one-half-size Pegasus XL air launched from an F-5F would be able to place about 122 lb in LEO. The higher performance F-4E could air launch a two-thirds-size Pegasus XL carrying about 289 lb into LEO. It is estimated that, in all three cases, specific payload costs for air launch into orbit could be the order of \$10,000 per pound. Thus, there is good reason to seriously consider including such a system in the RASCAL-project competition to design a small-satellite launch system.

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