FOREWORD

This report was prepared by the Crew Stations Section, Human Engineering Branch, Behavioral Sciences Laboratory, 6570th Aerospace Medical Research Laboratories, under Project No. 7184, "Human Performance in Advanced Systems," Task No. 718405, "Design Criteria for Crew Stations in Advanced Systems," and grew out of research projects conducted aboard a zero-G aircraft.

The authors wish to acknowledge the help of T/Sgt Harold F. Espensen, who conducted the soaring experiments aboard the zero-G airplane, and Edward Perret, formerly of the Aeronautical Research Laboratory, Wright-Patterson Air Force Base, who did the original analytical work on which this report is based.

ABSTRACT

While performing maintenance and assembly tasks outside of space vehicles under weightless conditions, a worker may accidentally propel himself away from his vehicle. To determine the speed of such a single-impulse launch, subjects under weightless conditions in a zero-G KC-135 aircraft propelled themselves away from a surface with their legs. They attained maximum velocities of approximately 10 mph. Using various launch speeds and directions, theoretical trajectories have been projected for both coplanar and noncoplanar launches. These trajectories indicate that any launch having a velocity component parallel to the direction of orbital motion will result in a trajectory such that the worker will never return to his vehicle.

PUBLICATION REVIEW

This technical documentary report has been reviewed and is approved.

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Contrails

WEIGHTLESS MAN: SINGLE-IMPULSE
TRAJECTORIES FOR ORBITAL WORKERS

INTRODUCTION

In future space missions, man must be able to perform maintenance and assembly operations outside of his own vehicle, and there is always the possibility that he may accidentally launch himself from the vehicle. The object of this study was to investigate the trajectories that will result from single-impulse launches of man from an orbiting earth satellite.

After a man launches himself by pushing away from his vehicle with his legs, we have assumed that he is without any further means of self-propulsion. Section I describes an experiment, performed aboard the KC-135 zero-G research aircraft, to determine the maximum launch speeds of which man is capable. The trajectories resulting from various launch speeds and directions are developed and plotted in Section II.

SECTION I

EXPERIMENTAL DETERMINATION OF MAXIMUM LAUNCH SPEED

To get some idea of the maximum speed a man could attain by pushing himself away from a surface, a simple experiment was conducted aboard a zero-G research aircraft. The method of attaining zero-G is described in ref. 1, pp. 9-13. The speeds attained by six subjects as they propelled themselves from the rear bulkhead of a KC-135 aircraft were measured by observers with stop watches.

In the experiment, the subjects crouched against the rear bulkhead, held onto a rope for balance, waited until aircraft oscillations ceased, and then attempted to propel themselves in a path parallel to the floor (see figure 1). Although the subjects moved in a parabolic path relative to the earth, their flight path in relation to the cabin appeared as a nearly straight line. At the forward end of the cabin, the subjects were stopped by a nylon net. Considerable practice was required before subjects could soar the full 30 feet without striking the floor or ceiling or without imparting unwanted rotations to their body during the push-off maneuver. Each subject was allowed to make three successful runs. The maximum speed attained by each subject, measured over a 30-foot soaring distance, is listed in table I.
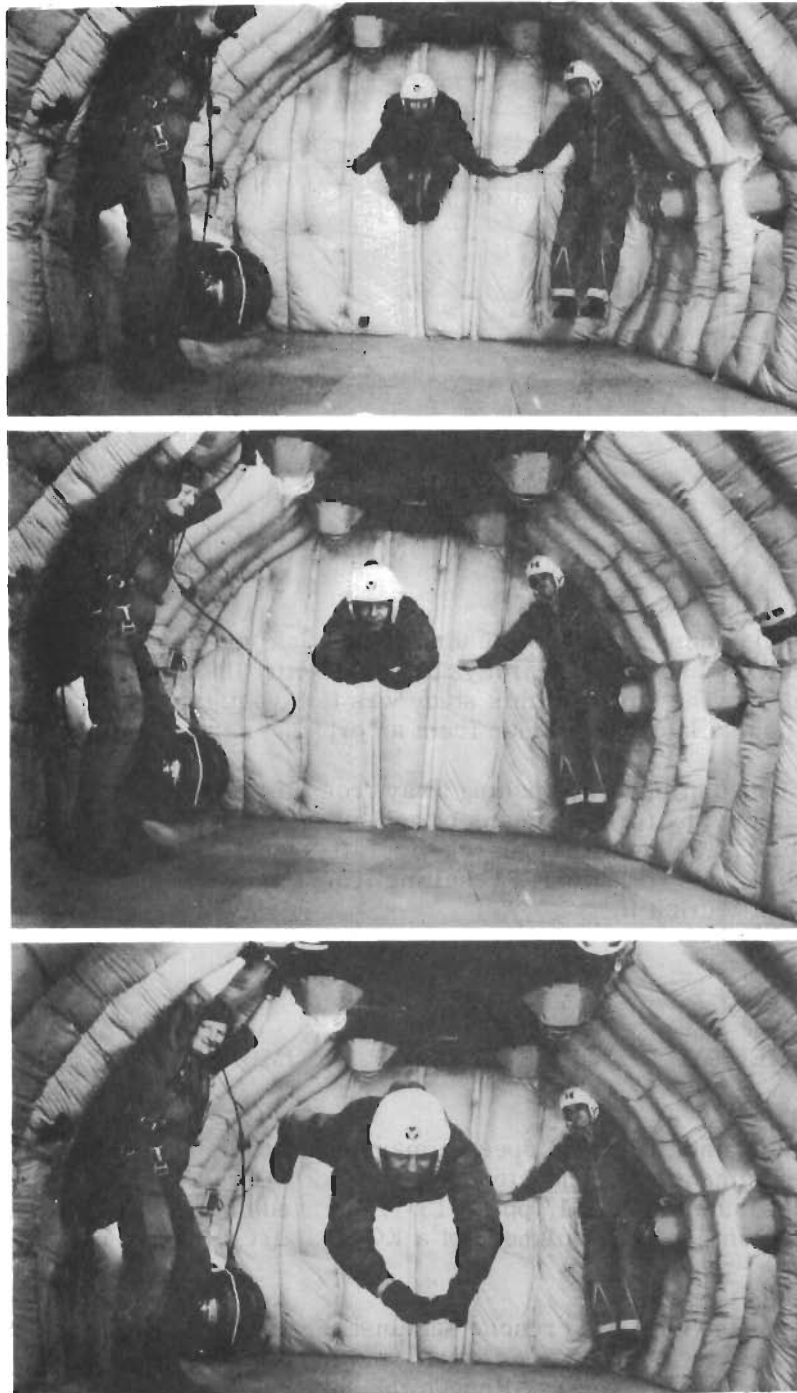
Figure 1.   Soaring Sequence in Zero-G Aircraft

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TABLE I

MAXIMUM SOARING SPEEDS OF SIX SUBJECTS

Subject	Time, Sec	Speed, ft/sec	Speed, mph
A	2.50	12.0	8.2
B	2.25	13.3	9.1
C	2.05	14.6	10.0
D	2.95	10.2	6.9
E	2.60	11.5	7.9
F	2.04	14.7	10.0

From these data, approximately 15 feet per second or 10 miles per hour appears to be the maximum speed at which an orbital worker can deliberately propel himself from his space vehicle.

Since the subjects in this experiment were not wearing pressure suits and thus had complete limb mobility, the maximum speeds they achieved are considerably higher than those a man wearing a pressure suit could be expected to attain.

SECTION II

EQUATIONS OF MOTION AND TRAJECTORIES

Coordinate Frame

Man's motion in space after a self-applied impulse is conveniently described in a rectangular coordinate system fixed to the space vehicle and oriented to the local vertical. Figure 2 shows the origin of the xyz frame to be at the vehicle, with the y axis along the local vertical, the x axis horizontal in the direction of orbital motion, and the z axis perpendicular to the vehicle's orbital plane.
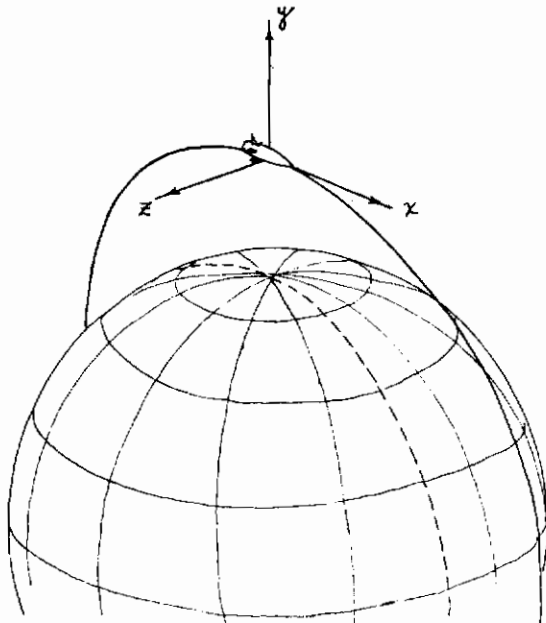

Figure 2. The xyz Coordinate System

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Equation of Motion

If we assume that the earth's gravity is the only force acting on either the vehicle or the man, and that the distance between the man and the vehicle is always small compared to the distance between the vehicle and the center of the earth, then the equations of motion can be accurately approximated by

$$\ddot{x} = -2\omega \dot{y} \tag{1}$$

$$\ddot{y} = 2\omega \dot{x} + 3\omega^2 y \tag{2}$$

$$\ddot{z} = -\omega^2 z \tag{3}$$

where $\ddot{x}, \ddot{y}, \ddot{z}$ = x, y, z accelerations

$\dot{x}, \dot{y}$ = x, y velocities

ω = angular velocity of the coordinate frame, radians/second.

Equations 1, 2, and 3 are derived and discussed in reference 2, p. 155. The solution to these equations is given by:

$$x = \frac{-2\dot{y}_0}{\omega} - 3\dot{x}_0 t + 4\frac{\dot{x}_0}{\omega}\sin \omega t + \frac{2\dot{y}_0}{\omega}\cos \omega t \tag{4}$$

$$y = 2\frac{\dot{x}_0}{\omega} - 2\frac{\dot{x}_0}{\omega}\cos \omega t + \frac{\dot{y}_0}{\omega}\sin \omega t \tag{5}$$

$$z = \frac{\dot{z}_0}{\omega}\sin \omega t \tag{6}$$

where $\dot{x}_0$, $\dot{y}_0$, and $\dot{z}_0$ are the x, y, and z components of launch velocity, and t is time.

Equations 4, 5, and 6 accurately describe the relative motion of the man and the vehicle provided that the vehicle's orbit is nearly circular (less than 100 miles difference between apogee and perigee altitudes).

As the man pushes himself from his vehicle, he will impart a velocity not only to himself, but to his vehicle as well. The share of the total launch velocity which each receives will be inversely proportional to its mass. If the vehicle is initially in a perfectly circular orbit, any small change in its velocity will put it into a slightly elliptical orbit. Fortunately, we can ignore this apparent complication since equations 4, 5, and 6 describe motion relative to the vehicle. In the equations ω must be an average value determined by the expression

$$\omega = \frac{2\pi}{P}$$

where P is the period of the vehicle's orbit.

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Coplanar Trajectories

Equations 4 and 5 describe the path of the man relative to the vehicle in the orbital plane. Regardless of the launch velocity, the resulting trajectory can be described by a point moving on the perimeter of an ellipse whose center is initially at

$$x_c = \frac{-2\dot{y}_0}{\omega} \tag{7}$$

$$y_c = \frac{2\dot{x}_0}{\omega} \tag{8}$$

and is drifting in the x direction with the velocity

$$v_c = -3\dot{x}_0 \tag{9}$$

The drifting ellipse is shown in figure 3 below.
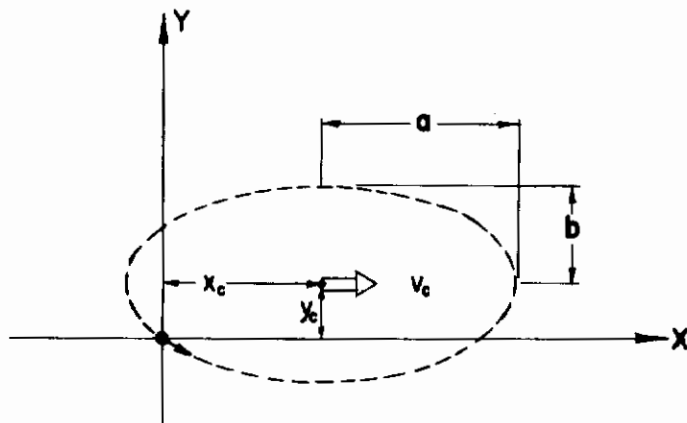
Figure 3.   Geometry of the Drifting Ellipse

The semimajor axis, a, of the ellipse is always twice the semiminor axis, b. The size of the ellipse is given by

$$b = \sqrt{\left(\frac{\dot{y}_0}{\omega}\right)^2 + 4\left(\frac{\dot{x}_0}{\omega}\right)^2} \tag{10}$$

The point that generates the path of the man moves counter-clockwise about the drifting ellipse and its position at any time can be determined graphically by the simple construction shown in figure 4.
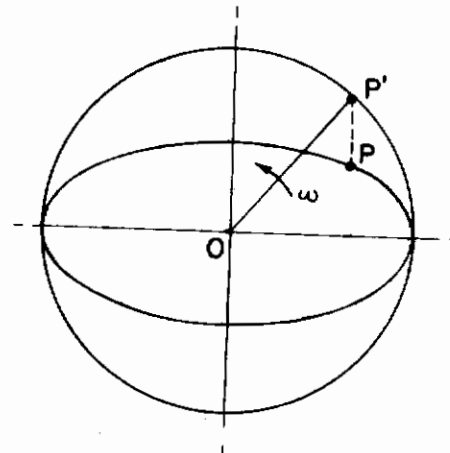
Figure 4.   Movement of Point Along Perimeter of Ellipse

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Imagine a circle of radius, a, circumscribed about the drifting ellipse. If the point, P', moves around the circumference of the circle at a constant rate, ω, the point, P, on the ellipse moves so that it always lies on the vertical projection from P'.

To illustrate the trajectories that will result from single-impulse launches, consider an example in which the vehicle is in a near-circular orbit at 230 statute miles (sm) or 200 nautical miles (nm) altitude. (ω = 0.00114 radians per second). If the man launches himself vertically (skyward), so that $\dot{x}_0$ is zero and $\dot{y}_0$ is positive, we can immediately see from equation 9 that the drift velocity of the ellipse is zero and the man will describe an elliptical path, returning to the vehicle from below after one orbital period (93 minutes).

Figure 5 illustrates the trajectories resulting from vertical launches (both skyward and earthward) at speeds of 2.5, 5, and 10 mph.
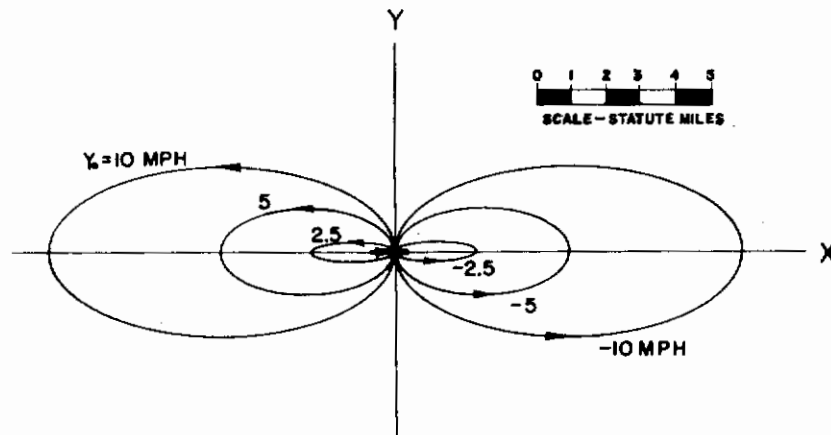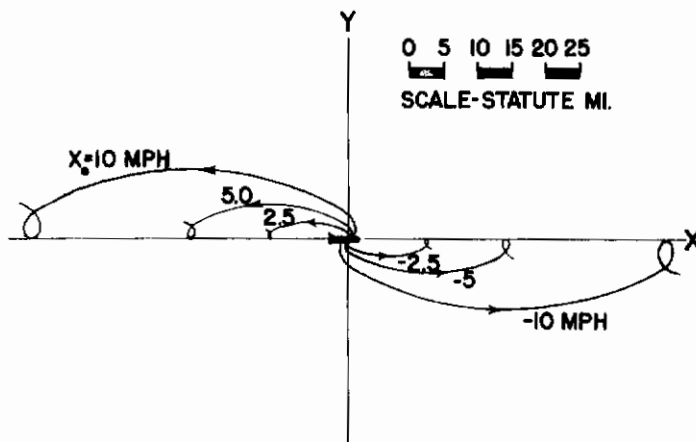

Figure 5. Trajectories Resulting From Vertical Launches
(Vehicle in 230 sm near-circular orbit)

If the man launches himself in any direction other than vertical, his trajectory will not be a closed curve and he will not return to the vehicle after one orbital period. Instead, he will cross the vehicle's orbital path ahead of or behind the vehicle.

Figure 6 shows the trajectories resulting from horizontal launches (both forward and aft) at 2.5, 5, and 10 mph.

6. Trajectories Resulting From Horizontal Launches

(Vehicle in 230 sm near-circular orbit)

Note that a forward launch at 10 mph will put the man 46.5 miles behind his vehicle after one orbital period.

Launches at 45 degrees to the vertical in the forward or aft directions produce paths similar to those in figure 6. In general, we can say that the man's distance ahead of or behind the vehicle after one orbital period depends only on the horizontal component of launch velocity. Figure 7 shows how this distance varies with horizontal launch velocity.
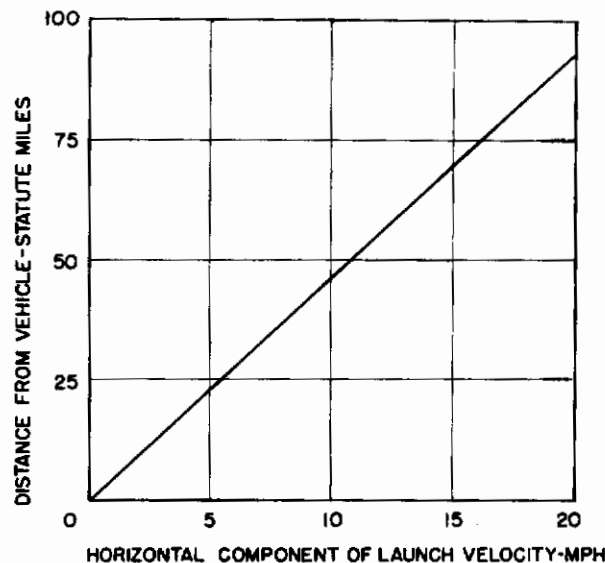

Figure 7.   Distance Ahead of or Behind Vehicle
After One Orbital Period

Coplanar soaring trajectories of short duration are plotted in figure 8. From this chart it is possible to determine the man's position after launching at any velocity. The horizontal and vertical scales give distances in feet as multiples of the launch velocity, Δv, feet per second.
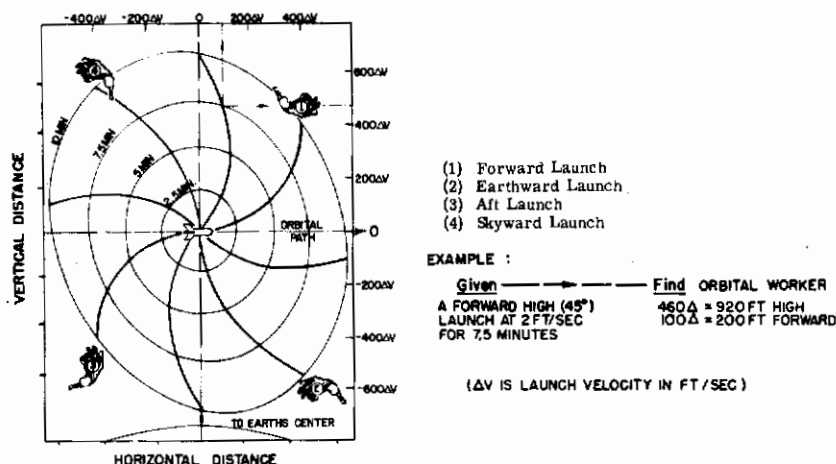

Figure 8.   Short Time Coplanar Trajectories
(Vehicle in 230 sm or 200 nm Near-
Circular Orbit)

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Non-coplanar Trajectories

Equation 6 describes the out-of-plane motion of the man as a function of time. This noncoplanar motion is completely independent of the man's motion in the orbital (x-y) plane (for small excursions in the z direction) and can be superimposed on the coplanar trajectory.

A plot of z versus time for a horizontal launch to the left at 2.5, 5, and 10 mph is shown in figure 9. Note that the man oscillates sinusoidally across the orbital plane, crossing through the plane of the vehicle's orbit twice during each orbital period. Figure 10 depicts the orbital situation. Note that the noncoplanar orbits intersect at two points. For half a period the man will be on one side of the vehicle's orbital plane, and for the other half-period, he will be on the opposite side.
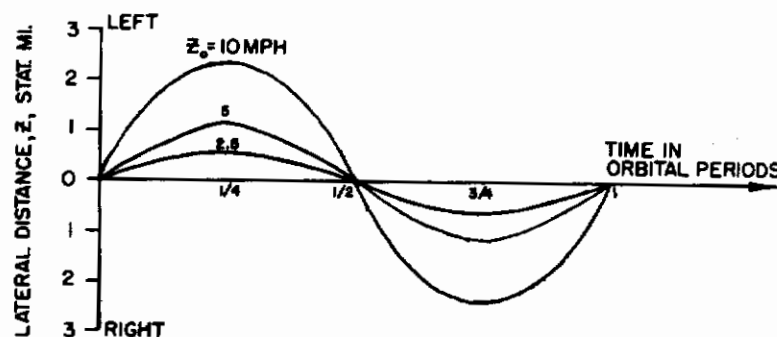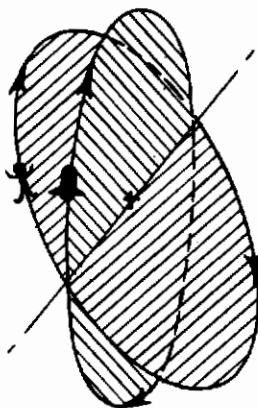

Figure 9.   Z versus Time for a Left, Horizontal Launch

Figure 10.   Noncoplanar Orbits

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SECTION III

CONCLUSIONS

Man is capable of propelling himself from a surface at a maximum speed of 10 mph while weightless.

A simple analysis of the relative motion between the man and his space vehicle shows that the coasting trajectory of the man after a single-impulse launch can carry him to great distances from his point of departure. In some cases he may return to his vehicle after one-half or one full orbital period but in most cases he will never return.

If the man has any component of his launch velocity in the forward (horizontal direction of orbital motion) or aft direction, he will enter a new orbit whose period is different from that of his vehicle and, hence he will never return to the vehicle.

If the vehicle is in a 230 sm (200 nm), near-circular orbit and the man launches himself at 10 mph, after one period:

(a) a skyward launch will return man to his vehicle from below after having described an elliptical path behind the vehicle;

(b) a forward launch will place the man 46.5 miles behind his vehicle after describing a cycloidal path above and behind his ship;

(c) similarly, an aft launch will place the man 46.5 miles ahead of his ship;

(d) a horizontal-left launch will cause the man to approach his vehicle from the right after having made horizontal excursions of 2.5 miles to the left and right of his ship.

The trajectories described above illustrate the results of deliberate or inadvertent launches of men (or equipment) from an orbiting vehicle. They emphasize the importance of securing to the vehicle, not only the orbital worker, but all of his tools and equipment. The trajectories also define to some extent the magnitude of any rescue or retrieval problems that could arise from accidental launchings.

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2. Jensen, J., G.E. Townsend, Jr., J.D. Kraft, and J. Kork, Design Guide to Orbital Flight, p. 155, McGraw-Hill Book Co., Inc., New York, 1962.