N89-21740

1988

NASA/ASEE SUMMER FACULTY FELLOWSHIP PROGRAM

MARSHALL SPACE FLIGHT CENTER

THE UNIVERSITY OF ALABAMA

GUIDANCE FOR AN AEROASSISTED ORBITAL TRANSFER VEHICLE

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Date:	August 24, 1988
Contract No:	NGT 01-002-099 The University of Alabama

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ABSTRACT

The use of atmospheric drag for slowing satellites in high energy, high apogee orbits to a lower energy, lower apogee orbit about the earth is investigated. The high energy orbit is assumed to intercept the earth's atmosphere. Guidance for the atmospheric phase of the trajectory may be done using the aerodynamic forces generated by the passage through the atmosphere. This research was concerned with the investigation of several methods of guidance during the atmospheric phase to cause a significant reduction in the final velocity as the vehicle leaves the atmosphere. In addition, the velocity direction was controlled to exit to a desired target orbit. Lastly excess aerodynamic lift was used to effect a plane change between the entry orbit plane and the exit orbit plane to achieve a desired orbit plane.

The guidance methods were applied to a 3 degrees-of-freedom simulation which included an oblate earth gravity model and a rotating atmosphere. Simulation results were compared on the basis of speed of computation of the guidance parameters and amount of added velocity necessary to achieve the desired orbit.

ACKNOWLEDGEMENTS

I am grateful for the opportunity to participate in the Summer Faculty Fellowship Program at Marshall Space Flight Center. I am especially grateful for the support and encouragement of my NASA colleague, Roger Burrows, and the members of his branch who supplied help cheerfully, whenever I asked. I am also deeply indebted to Wayne Deaton, head of the Flight Mechanics Branch, and Wilton Causey, deputy division chief, for their aid. Lastly but not least, Greg Dukeman worked on a similar task and enjoyed some of the same headaches and successes.

I would like to thank Dr. Mike Freeman for his encouragement and guidance throughout the program. The experience at Marshall Space Flight Center was very enjoyable. I am indebted to the National Aeronautics and Space Administration and to the American Society of Engineering Education for providing me with this unique opportunity.

Guidance For An Aeroassisted Orbital Transfer Vehicle

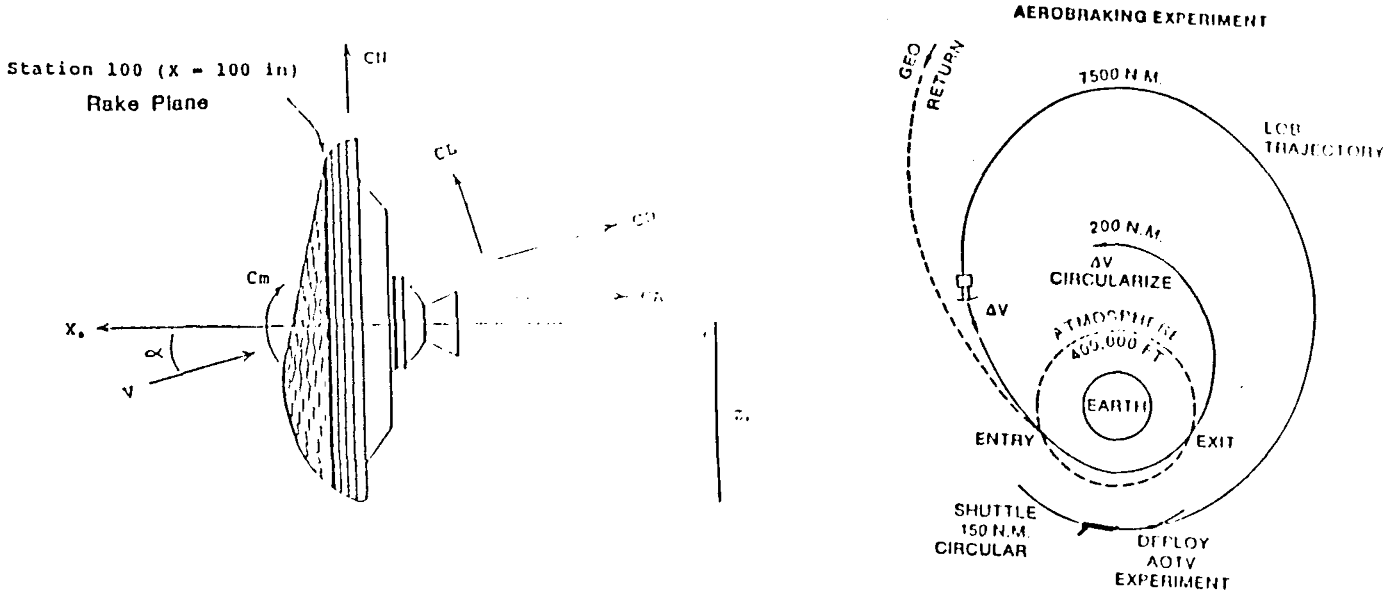
There is currently underway a study concerning the use of atmospheric braking for vehicle transfer from a high energy orbit to a lower energy orbit about the earth. The use of atmospheric drag is seen as an excellent way to decrease the vehicle speed in the high energy orbit to the speed required for the lower energy orbit. In addition to the decrease in the speed of the vehicle, the plane of the new orbit may not coincide with the plane of the original orbit. This study is concerned with the investigation of the guidance requirements for the atmospheric braking portion of the vehicle trajectory with targeting to a final orbit.

Problems of this type are generally analyzed by the iterative methods of perturbation analysis. The trouble with this case is that the time required for the calculation of the solution to the two point boundary value problem arising from the perturbation analysis may be too time-consuming for use in the vehicle guidance system. The atmospheric flight phase of the trajectory is characterized by sensitivity to the time in which maneuvers are accomplished. This sensitivity may even lead to atmospheric capture of the vehicle or to a final orbit which is nowhere near the target orbit. In addition to the time sensitivity, the atmospheric flight is characterized by large changes in atmospheric density and dynamic pressure on the vehicle. Due to the requirement that the guidance system operate the guidance loop rapidly and effectively, a reduced complexity set of differential equations was chosen for the guidance system model and approximate solutions were employed for guidance and targeting. These solutions were applied to a 3 degree of freedom, point mass simulation with full complexity simulation differential equations including an atmospheric model with perturbations which rotates with the earth and an oblate earth model with the J2 harmonic terms included in the gravity model.

The figure below represents a shuttle launched experiment for testing the vehicle and the guidance system. The shuttle launches the vehicle into a a high apogee lob trajectory. Just before returning to the original launch point, the on-board engine increases the speed and changes the velocity direction to simulate a vehicle returning from a geosynchronous orbit. The new orbit intersects the "reasonable" atmosphere of the earth at an altitude of 400000 feet, passes through the atmospheric transfer portion of the trajectory during which atmospheric forces are employed to effect velocity and orbital plane changes to target to the final desired orbit at the exit from the atmosphere. The target orbit is characterized by an apogee altitude of 200 miles and a specific orbital plane inclination. At the apogee of the achieved final orbit, additional changes are made in the orbit to circularize the final orbit and to reach the desired orbital inclination. For this simulation, the specified entry conditions and the desired exit conditions are tabulated below.

ENTRY CONDITIONS	EXIT CONDITIONS
H=400000 FT	H=400000 FT
V=33828 FPS	HP=50. MILES
γ=-4.5 DEG	HA=200. MILES
i=27. DEG	i=28.5 DEG

FIGURE 1. PROBLEM DEFINITION IN GRAPHICAL FORM



During the atmospheric transfer portion of the trajectory, the AOTV is assumed to maintain a constant angle of attack with the resulting constant lift coefficient (C_L) and constant drag coefficient (C_D). Control of the AOTV during this phase of the trajectory is done by rolling the vehicle to orient the lift force to cause in-plane vertical acceleration for altitude control and out-of-plane transverse acceleration for control of the orbital plane inclination. The equations of motion used in the guidance model may be written as follows:

GUIDANCE EQUATIONS OF MOTION

$$\frac{dV}{dt} = -\frac{C_D S}{2M} \rho V_R^2 - \frac{G}{V} \frac{dH}{dt}$$

$$\frac{d^2H}{dt^2} = \frac{V^2}{R} - G + \frac{C_L S}{2M} \rho V_R^2 \cos(\phi)$$

In the equations above, V is the inertial velocity magnitude, V_R is the airspeed or speed relative to the rotating atmosphere, ρ is the density of the atmosphere at altitude H above the surface of the earth, G is the gravitational acceleration at altitude H above the surface, R is the distance from the center of the earth to the AOTV, M is the constant mass of the AOTV, C_L and C_D are the lift and drag coefficients of the AOTV, and ϕ is the roll angle used to control the vehicle. Using the second equation, the guidance equation may be specified as follows:

GUIDANCE ROLL COMMAND EQUATION

$$\cos(\phi)_{COM} = \frac{2M}{C_L S \rho V_R^2} \left[\left(\frac{d^2H}{dT^2} \right)_{COM} + G - \frac{V^2}{R} \right]$$

Two items are apparent from the equation above: (1) The roll angle is specified in cosine form, and (2) The roll angle cosine depends upon the specification of the vertical acceleration. For the first item, use the guidance roll command equation to specify the cosine of the roll angle. Use the direction of the desired plane change maneuver to determine the sign of the sine of the roll angle. The combination of the roll angle sine and cosine will then uniquely determine the roll angle. A characteristic of this method is that the roll angle "ratchets" in that the amount of roll angle for plane control may be too great and the sign of the sine may need to be reversed periodically to stay within an allowable deadband of the desired final inclination angle. Typical trajectories will display four or more sign reversals on the sine term during the atmospheric pass. The second item, the commanded vertical acceleration in H is a different story. This study explored four methods of completing the roll command equation.

METHOD 1. ASSUME A CONSTANT ALTITUDE RATE

For a constant altitude rate, the commanded acceleration is zero which simplifies the guidance equation. For the entry phase, this application is straightforward as the initial conditions to start the "equalibrium glide" are specified. For the exit phase, the initial conditions are not specified and one must use iteration to determine the speed with which to begin the exit phase and the altitude rate command for the exit phase, which in combination yield the desired exit conditions. (See C. Cerimele's paper listed in the references for a detailed explanation of this method.) This method does succeed but relies upon the iteration technique for commands during the exit phase. In actual practice, the commanded roll angle is augmented by commands which will produce desired values of altitude rate and dynamic pressure, as otherwise the command would drive the AOTV down the constant altitude rate path into the lower atmosphere from which it would not be able to initiate an exit phase.

CONSTANT ALTITUDE RATE ROLL COMMAND

$$\cos(\phi)_{COM} = \frac{2\ M}{C_L S\ \rho V_R^2}\ [G - \frac{V^2}{R} - GH\ (\frac{dH}{dt} - \frac{dH}{dt}_{COM}) - GQ\ (QB - QB_{COM})]$$

The GQ and GH terms are dynamic pressure and altitude rate gains used in combination with altitude rate, $\frac{dH}{dt}$, and dynamic pressure ,QB, to produce the desired trajectory upon entry. For the exit trajectory, GQ is zero and the $\frac{dH}{dt}_{COM}$ is determined iteratively.

METHOD 2. ASSUME A CONSTANT ROLL ANGLE COSINE

This is another easily implemented option as the constant roll angle cosine eliminates any control determination for the vertical acceleration. The sign of the roll angle sine is still chosen to produce the desired plane change. The determination of the actual roll angle cosine is done in an iterative manner using a numerical perturbation in the constant roll angle to determine numerical partials of the target conditions with respect to the chosen roll angle cosine. Again, this method will work, but it depends upon solving a two point boundary value problem iteratively, and speed of guidance calculations may be its demise.

CONSTANT ROLL ANGLE COSINE COMMAND

$$\cos(\phi)_{COM} = \text{CONSTANT.}$$

METHOD 3. ASSUME AN ALTITUDE TIME HISTORY

For this method, assume a polynomial in time for the altitude. Include in the polynomial enough coefficients to be determined to allow the method to fit an optimum criteria. For example:

ASSUMED ALTITUDE POLYNOMIAL

1. ASSUME $$H = H_1 + \frac{dH_1}{dt} T + \frac{d^2H_1}{dt^2}\frac{T^2}{2} + \frac{d^3H}{dt^3}\frac{T^3}{6}$$

$$\frac{dH}{dt} = \frac{dH_1}{dt} + \frac{d^2H_1}{dt^2} T + \frac{d^3H}{dt^3}\frac{T^2}{2}$$

$$\frac{d^3H}{dt^3} = \frac{2}{T_2^2}\left[\frac{dH_2}{dt} - \frac{dH_1}{dt} - \frac{d^2H_1}{dt^2} T_2 \right]$$

$$T_2^2 \left[\frac{1}{6}\frac{d^2H_1}{dt^2} \right] + T_2 \left[\frac{2}{3}\frac{dH_1}{dt} + \frac{1}{3}\frac{dH_2}{dt} \right] + \left[H_1 - H_2 \right] = 0$$

$$T_2 = \frac{-B \pm \left[B^2 - 4AC \right]^{1/2}}{2A}$$

GUESS UNKNOWN VALUES AND ITERATE TO A SOLUTION.

$$\frac{d^2 H}{dt^2}_{COMMAND} = \frac{d^2 H_1}{dt^2} + \frac{d^3 H}{dt^3} T$$

$$COS(\phi)_{COMMAND} = \frac{2 M}{C_L S \rho V_R^2} [(\frac{d^2H}{d T^2})_{COMMAND} + G - \frac{V^2}{R}]$$

The method above has merit in that it will allow targeting to a specific altitude with time, altitude rate, and vertical acceleration involved in the iteration. Analytical approximations allow quadrature approximations for integration which allow speed increases in iterative passes. It is still an iterative scheme but is a fast iterative scheme with explicit targeting.

METHOD 4. ASSUME A VERTICAL ACCELERATION FUNCTION

This last method involves assuming that the AOTV will act like a damped harmonic oscillator with specified damping ratio and natural frequency. The vertical acceleration command is then easily determined from the following equation:

ASSUMED OSCILLATOR FORM

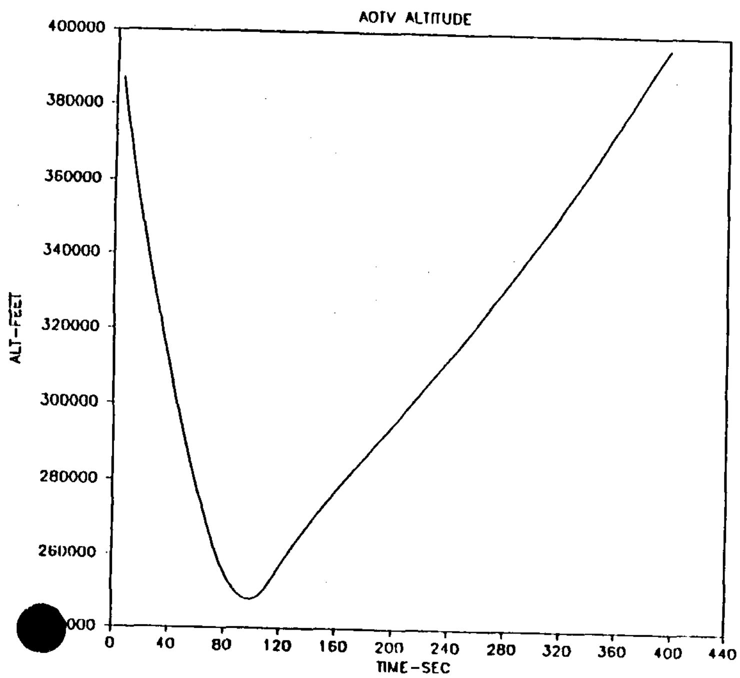
$$\frac{d^2 H}{dt^2}_{COM} = -2 \zeta \omega_N \frac{d H}{dt} - \omega_N^2 (H - H_{COM})$$

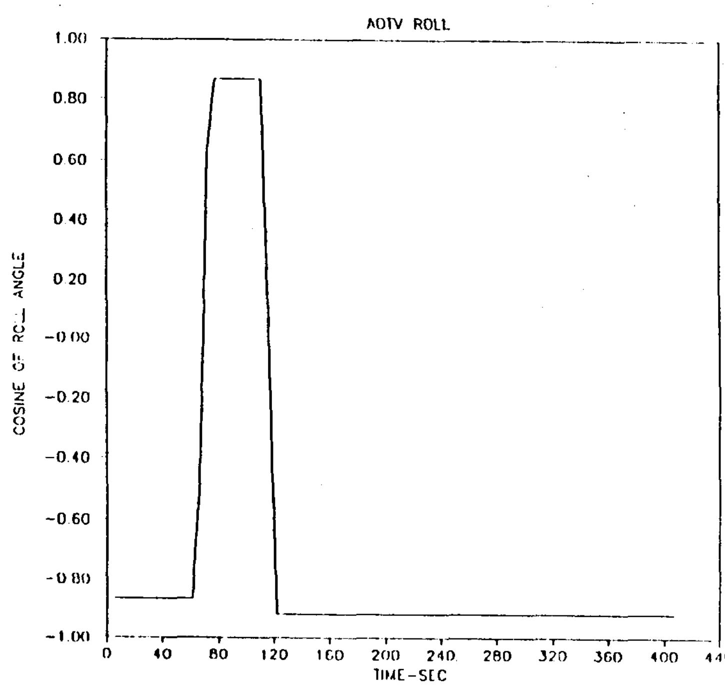
In the oscillator equation above, the selection of damping ratio, ζ, and natural frequency, ω_N, are equavalent to specifying the manner in which the AOTV system will react. The appearance of H_{COM} in the equation allows targeting to a specific altitude on the entry phase and assures that the altitude rate will be nulled at that altitude. For the exit phase, this same form can be used with different system characteristics.

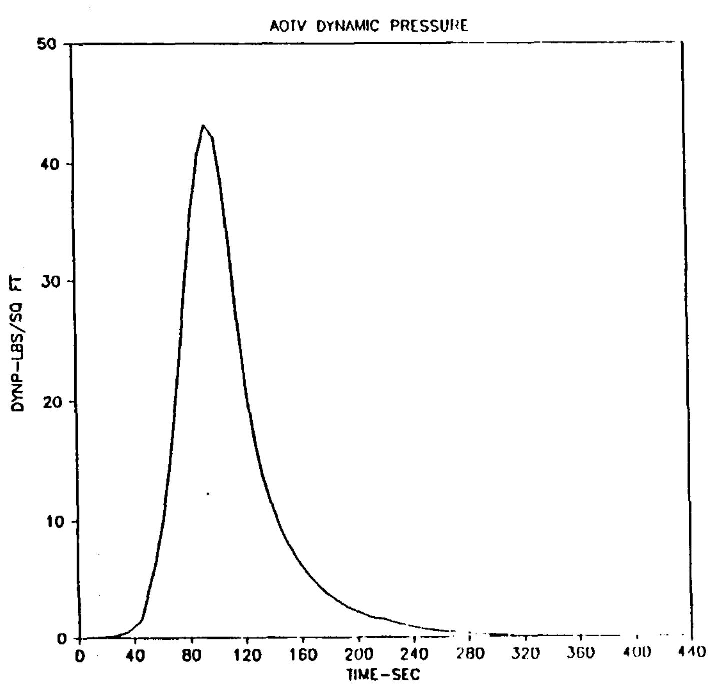
$$COS(\phi)_{COM} = \frac{2 M}{C_L S \rho V_R^2} [(\frac{d^2H}{dt^2})_{COM} + G - \frac{V^2}{R}]$$

The outstanding benefits of the guidance scheme listed above is that it is fast (with no iteration), it allows altitude targeting, and the same form of guidance can be used in the entry phase and the exit phase with appropriate changes in the system characteristics.

The figures shown below represent the trajectory shape for the atmospheric phase, with the attendant dynamic pressure, and a roll cosine profile. The roll cosine does not exhibit the "ratcheting" which the roll angle does as the "ratcheting" is due to sign reversals on the sine function.







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