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# FINAL REPORT ON NASA GRANT NO. NAG-8-755,
## OPTIMAL TRAJECTORIES FOR THE
## AEROASSISTED FLIGHT EXPERIMENT, 1988-89

by

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RICE UNIVERSITY

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Abstract. This paper summarizes the research on optimal trajectories for the aeroassisted flight experiment, performed by the Aero-Astronautics Group of Rice University during the period 1988-89. This research includes the following topics: equations of motion in an Earth-fixed system; equations of motion in an inertial system; formulation of the optimal trajectory problem; results on the optimal trajectory problem; guidance implications.

Key Words. Flight mechanics, equations of motion, hypervelocity flight, atmospheric flight, aeroassisted flight experiment, aeroassisted orbital transfer, guidance.

## 1.   Introduction

The objective of this research is to study optimal trajectories for the aeroassisted flight experiment (AFE). This flight experiment simulates a GEO-to-LEO transfer by an aeroassisted orbital transfer vehicle (AOTV), to be flown on board of the space shuttle in 1994.

During the atmospheric pass, the angle of attack of the AFE vehicle is kept constant, $\alpha = 17$ deg, and the angle of bank $\mu$ is controlled in such a way that the total characteristic velocity is minimized, subject to two major constraints: (a) after the atmospheric pass, the AFE spacecraft must ascend to a specified low Earth orbit (h = 178 NM), where the motion is circularized; and (b) the exit orbital plane of the AFE spacecraft is identical with the entry orbital plane, which in turn is identical with the shuttle orbital plane. With reference to (a), two possible maneuvers are considered: (IA) indirect ascent to a 178 NM orbit via a 197 NM apogee; and (DA) direct ascent to a 178 NM orbit.

The methods of optimal control theory have been employed in conjunction with the sequential gradient-restoration algorithm (SGRA) in order to minimize the total characteristic velocity, subject to the specified constraints.

## 2.   Research Results

The research undertaken  with the present grant has led
to the publication of four Aero-Astronautics Reports (Refs. 1-4)
and one paper, presented at the 40th Congress of the International
Astronautical Federation, Malaga, Spain, 1989 (Ref. 5).

References 1-2 are introductory in nature and deal with
the derivation of the equations of motion for the AFE spacecraft
in both an Earth-fixed system (Ref. 1) and an inertial system
(Ref. 2).

References 3-5 deal with the problem of the optimal trajectories
of the AFE spacecraft. The major findings are summarized below.

As explained, two possible transfers are considered: (IA)
indirect ascent to a 178 NM perigee via a 197 NM apogee; and (DA)
direct ascent to a 178 NM apogee.  For both transfers, two cases
are investigated: (i) the bank angle is continuously variable;
and (ii) the trajectory is divided into segments along which
the bank angle is constant.  For case (ii), the following
subcases are studied: two segments, three segments, four segments,
and five segments; because the time duration of each segment is
optimized, the above subcases involve  four, six, eight, and ten
parameters, respectively.  For comparison purposes and only for
Transfer (IA), a reference trajectory is also considered: this
is a five-segment trajectory, close to the nominal trajectory given
in Ref. 6.

From the extensive numerical computations, the following
conclusions arise:

(i)    The optimal trajectories are two-subarc trajectories, with the bank angle constant in each subarc; hence, the control is bang-bang.

(ii)    In the atmospheric entry phase, the bank angle is near 180 deg, yielding a positive projected lift $L_p$, which in turn causes the path inclination to increase gradually from the entry negative value to nearly zero value.

(iii)    In the atmospheric exit phase, the bank angle is near 0 deg, yielding a negative projected lift $L_p$, which offsets the centrifugal force effects due to the curvature of the Earth, so as to ensure exit conditions compatible with the desired apogee requirement.

(iv)    The lateral component of the lift during the atmospheric entry phase and the lateral component of the lift during the atmospheric exit phase have the same sign and the same order of magnitude; they are directed in such a way that they nearly offset the effects due to the Earth's rotation. In this way, the instantaneous orbital plane is almost identical with the initial orbital plane, meaning that the wedge angle $\eta$ is nearly zero during the atmospheric pass.  This means that, for efficient flight, the motion of the AFE spacecraft is nearly planar in an inertial space; in other words, one must avoid energy dissipation associated with the lateral motion.

(v)    Comparison of the optimal trajectories and the reference trajectory shows that the OTs are superior to the RT in terms of the main quantities of interest, namely, the characteristic

velocity, the peak dynamic pressure, the peak heating rate, and the peak wedge angle. In particular, for Transfer (IA), the characteristic velocity is $\Delta V$ = 98.0 m/sec for the RT and $\Delta V$ = 81.9 m/sec for the OT.  For Transfer (DA), the characteristic velocity of the OT is 72.0 m/sec.

(vi)    The results on optimal trajectories have important guidance implications. They suggest the idea of developing a new guidance scheme based on the following precepts: to control both the angle of attack (near 17 deg) and the angle of bank; and to utilize a single switch of the bank angle, so as to have $L_p$ > 0 in the entry phase and $L_p$ < 0 in the exit phase.  This new guidance system is promising, and it appears to be an improvement of the existing guidance scheme in the control of the lateral motion of the AFE spacecraft.

For the abstracts of Refs. 1-5, see Section 3.

For more information on the guidance implications of the results on optimal trajectories, see Section 4.  These guidance implications are not only of interest within the frame of the AFE vehicle, but are also important within the frame of Mars penetration vehicles, Mars return vehicles, and lunar return vehicles.

3.   <u>Abstracts of Publications</u>

3.1. MIELE, A., ZHAO, Z. G., and LEE, W.Y., <u>Optimal Trajectories</u>

<u>for the Aeroassisted Flight Experiment, Part 1, Equations of</u>

<u>Motion in an Earth-Fixed System</u>, Rice University, Aero-

Astronautics Report No. 238, 1989.

<u>Abstract</u>. This report is the first of a series dealing with

the determination of optimal trajectories for the aeroassisted

flight experiment (AFE).  The AFE refers to the study of the

free flight of an autonomous spacecraft, shuttle-launched and

shuttle-recovered. Its purpose is to gather atmospheric entry

environmental data for use in designing aeroassisted orbital

transfer vehicles (AOTV).

It is assumed that: the spacecraft is a particle of constant

mass; the Earth is rotating with constant angular velocity;

the Earth is an oblate planet, and the gravitational potential

depends on both the radial distance and the latitude; however,

harmonics of order higher than four are ignored; the atmosphere

is at rest with respect to the Earth.

Under the above assumptions, the equations of motion for

hypervelocity atmospheric flight (which can be used not only for

AFE problems, but also for AOT problems and space shuttle problems)

are derived in an Earth-fixed system.  Transformation relations

are supplied which allow one to pass from quantities computed in

an Earth-fixed system to quantities computed in an inertial

system, and viceversa.

3.2. MIELE, A., ZHAO, Z. G., and LEE, W.Y., <u>Optimal Trajectories</u>

<u>for the Aeroassisted Flight Experiment, Part 2, Equations</u>

<u>of Motion in an Inertial System</u>, Rice University, Aero-

Astronautics Report No. 239, 1989.

<u>Abstract</u>. This report is the second of a series dealing with

the determination of optimal trajectories for the aeroassisted

flight experiment (AFE).  The AFE refers to the study of the free

flight of an autonomous spacecraft, shuttle-launched and shuttle-

recovered.  Its purpose is to gather atmospheric entry environmental

data for use in designing aeroassisted orbital transfer vehicles

(AOTV).

It is assumed that: the spacecraft is a particle of constant

mass; the Earth is rotating with constant angular velocity; the

Earth is an oblate planet, and the gravitational potential depends

on both the radial distance and the latitude;however, harmonics

of order higher than four are ignored; the atmosphere is at rest

with respect to the Earth.

Under the above assumptions,the equations of motion for

hypervelocity atmospheric flight (which can be used not only for

AFE problems, but also for AOT problems and space shuttle problems)

are derived in an inertial system.  Transformation relations are

supplied which allow one to pass from quantities computed in an

inertial system to quantities computed in an Earth-fixed system,

and viceversa.

3.3. MIELE, A., WANG, T., LEE, W.Y., and ZHAO, Z. G., <u>Optimal</u>

<u>Trajectories for the Aeroassisted Flight Experiment, Part 3</u>,

<u>Formulation, Results, and Analysis</u>, Rice University, Aero-

Astronautics Report No. 242, 1989.

<u>Abstract</u>. This report is the third of a series dealing with

the determination of optimal trajectories for the aeroassisted

flight experiment (AFE).  The intent of this experiment is to

simulate a GEO-to-LEO transfer, where GEO denotes a geosynchronous

Earth orbit and LEO denotes a low Earth orbit. Specifically,

the AFE spacecraft is released from the space shuttle and is

accelerated by means of a solid rocket motor toward Earth, so as

to achieve atmospheric entry conditions identical with those of

a spacecraft returning from GEO.  During the atmospheric pass,

the angle of attack is kept constant, and the angle of bank is

controlled in such a way that the following conditions are satisfied:

(a) the atmospheric velocity depletion is such that, after

exiting, the AFE spacecraft first ascends to a specified apogee

and then descends to a specified perigee; and (b) the exit orbital

plane is identical with the entry orbital plane. The final maneuver,

not analyzed here, includes the rendezvous with and the capture

by the space shuttle.

In this report, the trajectories of an AFE spacecraft are

analyzed in a 3D-space, employing the full system of 6 ODEs describing

the atmospheric pass. The atmospheric entry conditions are given,

and the atmospheric exit conditions are adjusted in such a way that

requirements (a) and (b) are met, while simultaneously minimizing

the total characteristic velocity, hence the propellant consumption

required for orbital transfer.  Two possible transfers are considered: (IA) indirect ascent to a 178 NM perigee via a 197 NM apogee; and (DA) direct ascent to a 178 NM apogee.

For both transfers, two cases are investigated: (i) the bank angle is continuously variable; and (ii) the trajectory is divided into segments along which the bank angle is constant. For case (ii), the following subcases are studied: two segments, three segments, four segments, and five segments; because the time duration of each segment is optimized, the above subcases involve four, six, eight, and ten parameters, respectively.

A surprising result of the analysis is that the optimal trajectories of cases (i) and (ii) coalesce into a single trajectory: a two -subarc trajectory, with the bank angle constant in each subarc (bang-bang control).  Specifically, the bank angle is near 180 deg in the atmospheric entry phase (positive lift projection phase) and is near 0 deg in the atmospheric exit phase (negative lift projection phase).  Another surprising result is that, during the atmospheric pass, the peak values of the changes of the orbital inclination and the longitude of the ascending node are nearly zero; hence, the peak value of the wedge angle (angle between the instantaneous orbital plane and the initial orbital plane) is nearly zero.  This means that the motion of the spacecraft is nearly planar in an inertial space.

The guidance implications of the above results are discussed.

3.4. MIELE, A., WANG, T., LEE, W.Y., WANG, H., and WU, G. D.,

Optimal Trajectories for the Aeroassisted Flight Experiment,

Part 4, Data, Tables, and Graphs, Rice University, Aero-

Astronautics Report No. 243, 1989.

Abstract. This report is the fourth of a series dealing

with the determination of optimal trajectories for the aero-

assisted flight experiment (AFE). It presents data, tables, and

graphs relative to the following transfers: (IA) indirect ascent

to a 178 NM perigee via a 197 NM apogee; and (DA) direct ascent

to a 178 NM apogee.

For both transfers, two cases are investigated: (i) the

bank angle is continuously variable; and (ii) the trajectory is

divided into segments along which the bank angle is constant.

For case (ii), the following subcases are studied: two segments,

three segments, four segments, and five segments; because the

time duration of each segment is optimized, the above subcases

involve four, six, eight, and ten parameters, respectively.

To sum up, this report presents systematic data on ten

optimal trajectories (OT), five for Transfer (IA) and five for

Transfer (DA). For comparison purposes and only for Transfer

(IA), a reference trajectory (RT) is also considered: this is a

five-segment trajectory, close to the nominal trajectory given

in Ref. 6.

3.5. MIELE, A., WANG, T., LEE, W. Y., and ZHAO, Z. G., <u>Optimal</u>

   <u>Trajectories for the Aeroassisted Flight Experiment</u>, Paper

   No. IAF-89-361, 40th Congress of the International Astronautical

   Federation, Malaga, Spain, 1989.

<u>Abstract</u>. This paper deals with the determination of optimal
trajectories for the aeroassisted flight experiment (AFE). The
intent of this experiment is to simulate a GEO-to-LEO transfer,
where GEO denotes a geosynchronous Earth orbit and LEO denotes
a low Earth orbit.  Specifically, the AFE spacecraft is released
from the space shuttle and is accelerated by means of a solid
rocket motor toward Earth, so as to achieve atmospheric entry
conditions identical with those of a spacecraft returning from
GEO. During the atmospheric pass, the angle of attack is kept
constant, and the angle of bank is controlled in such a way that
the following conditions are satisfied: (a) the atmospheric
velocity depletion is such that, after  exiting, the AFE spacecraft
first ascends to a specified apogee and then descends to a
specified perigee; and (b) the exit orbital plane is identical
with the entry orbital plane. The final maneuver, not analyzed
here, includes the rendezvous with and the capture by the space
shuttle.

   In this paper, the trajectories of an AFE spacecraft are
analyzed in a 3D-space, employing the full system of 6 ODEs
describing the atmospheric pass.  The atmospheric entry conditions
are given, and the atmospheric exit conditions are adjusted in
such a way that requirements (a) and (b) are met, while

simultaneously minimizing the total characteristic velocity, hence
the propellant consumption required for orbital transfer. Two
possible transfers are considered: (IA) indirect ascent to a
178 NM perigee via a 197 NM apogee; and (DA) direct ascent to a
178 NM apogee.

For both transfers, two cases are investigated: (i) the
bank angle is continuously variable; and (ii) the trajectory
is divided into segments along which the bank angle is constant.
For case (ii), the following subcases are studied: two segments,
three segments, four segments, and five segments; because the
time duration of each segment is optimized, the above subcases
involve four, six, eight, and ten parameters, respectively.

It is shown that the optimal trajectories of cases (i)
and (ii) coalesce into a single trajectory: a two-subarc trajectory,
with the bank angle constant in each subarc (bang-bang control).
Specifically, the bank angle is near 180 deg in the atmospheric
entry phase (positive lift projection phase) and is near 0 deg
in the atmospheric exit phase (negative lift projection phase).
It is also shown that, during the atmospheric pass, the peak
values of the changes of the orbital inclination and the longitude
of the ascending node are nearly zero; hence, the peak value
of the wedge angle (angle between the instantaneous orbital plane
and the initial orbital plane) is nearly zero. This means that
the motion of the spacecraft is nearly planar in an inertial space.

4.   Guidance Implications

       The results of Section 2 provide a foundation for developing

a more efficient guidance scheme for the AFE spacecraft.  For

information concerning the existing guidance scheme, see Refs. 6-7.

       First, we recall the basic idea of the existing guidance

scheme.  For the AFE spacecraft, the angle of attack varies from

7 to 27 deg, and the lift coefficient varies from -0.47 to -0.21.

Therefore, if the AFE spacecraft were to be controlled via only

the angle of attack, the lift coefficient range would be $|\Delta C_L| = 0.26$.

To offset the above difficulty, the existing guidance scheme

employs a constant angle of attack $\alpha = 17$ deg, corresponding to

$C_L = -0.37$, coupled with a variable angle of bank.

       Let $L_p = L\cos\mu$ denote the projection of the lift vector in

the vertical direction; let $C_{Lp} = C_L\cos\mu$ denote the projected

lift coefficient.  Because $C_L$ is constant and $\cos\mu$ varies from

-1 to +1, the projected lift coefficient range is $|\Delta C_{Lp}| = 0.74$.

This is nearly triple the lift coefficient range $|\Delta C_L| = 0.26$.

       To sum up, for the AFE spacecraft, the existing guidance

scheme employs constant angle of attack and variable angle of

bank in order to achieve the following goals: for the longitudinal

motion, to dissipate excess velocity so that the spacecraft,

upon exiting the atmosphere, can ascend to a specified apogee;

and for the lateral motion, to keep the instantaneous orbital plane

close to the initial orbital plane, hence to keep the wedge

angle $\eta$ close to zero.  These goals are achieved as follows: for

the longitudinal motion, one controls the modulus of the bank
angle; for the lateral motion, one controls the sign of the bank
angle; thus, whenever the wedge angle exceeds a specified bound,
the sign of the bank angle is reversed.

Unquestionably, the existing guidance scheme has obvious
merits: (a) simplicity; and (b) the fact that the projected lift
coefficient range is three times the lift coefficient range.
However, there are weaknesses associated with the control of the
lateral motion:

(A)   There is no equilibrium point for the control of the
lateral motion.   When $\eta = 0$, it would be desirable to have $\dot{\eta} = 0$,
so that the wedge angle continues to be zero.   However, $\mu$ is
determined from the requirement of longitudinal motion control;
hence, generally speaking, $\dot{\eta} \neq 0$ when $\eta = 0$.   This means that
the system is not stable around $\eta = 0$.

(B)   There is a bank angle error due to noninstantaneous
switches.   The implementation of the existing guidance scheme ideally
requires instantaneous switches in $\text{sign}(\mu)$, so as to keep $\cos\mu$
unchanged.   In practice, this is not possible, since $|\dot{\mu}| \leq 20$ deg/sec.
For example, a switch from $\mu = +170$ to $\mu = -170$ deg requires
$\Delta t = 17$ sec.   If the correct $\mu$-values are $\mu = +170$ and $\mu = -170$ deg,
this means that, during the time interval $\Delta t = 17$ sec, there is
an error in the value of $\mu$ which is required for the control of the
longitudinal motion.

(C)   There is a contradiction between accuracy and stability.
For accurate control of the lateral motion, the wedge angle tolerance

should be small.  On the other hand, if the wedge angle tolerance
is small, the number of switches in sign($\mu$) increases; therefore,
the system stability becomes worse.

To offset the above difficulties, consideration should be
given to developing a new guidance scheme, based on the properties
of the optimal trajectories.  The basic ideas of the new guidance
scheme are: to control both the angle of attack (near 17 deg) and
the angle of  bank; and to utilize a single switch of the bank
angle, consistently with the optimal trajectory properties, so
as to have $L_p > 0$ in the entry phase and $L_p < 0$ in the exit phase;
here, $L_p$ is the projected lift.  The new guidance scheme retains
the basic advantage of the existing guidance scheme, in that
the projected lift coefficient range is three times the lift
coefficient range.  In addition, it has the following advantages:

(A)  There is an equilibrium point for the control of the
lateral motion, due to the fact that both the angle of attack and
the angle of bank are being varied.  Hence, when $\eta = 0$, it
is possible to have $\dot{\eta} = 0$, which means that the system is stable
around $\eta = 0$.

(B)  There is less bank angle error due to noninstantaneous
switches.  For the existing guidance scheme, the effects due to
the noninstantaneous switch from $+\mu$ to $-\mu$ can be serious, since
there are multiple switches and they occur randomly.  For the new
guidance scheme, the effects due to the noninstantaneous switch
from $+\mu$ to $-\mu$ are less serious, owing to the fact that there

is only one switch, which occurs whenever a preselected velocity is achieved.

(C)   There is improved accuracy and stability in the control of the lateral motion.  This is because the lateral motion is no longer controlled by the sign of the bank angle, but by the values of both the bank angle and the angle of attack.

(D)   The new guidance scheme is based on the properties of the optimal trajectories.  Hence, it preserves the good properties of the optimal trajectories concerning the characteristic velocity, the peak dynamic pressure, the peak heating rate, and the peak wedge angle.

(E)   The new guidance scheme uses the same hardware (AFE configuration, measurements, sensors, and reaction control system) as the existing guidance scheme.  The only difference is in the software (computer code).  Therefore, if acceptable, a change from the existing guidance scheme to the new guidance scheme would be of limited cost.

Finally, it must be stressed that the development of a new guidance scheme is not only of interest within the frame of the AFE vehicle, but is also important within the frame of Mars penetration  vehicles, Mars return vehicles, and lunar return vehicles.

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