NASA Technical Memorandum 102606

Use of Random Martian Atmosphere to Evaluate Potential Entry Guidance Schemes

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January 1990

NASA
National Aeronautics and
Space Administration

Langley Research Center
Hampton, VA 23665

(NASA-TM-102606) USE OF RANDOM MARTIAN ATMOSPHERE TO EVALUATE POTENTIAL ENTRY GUIDANCE SCHEMES (NASA) 29 p CSCL 22B

N90-20122

Unclas
G3/18 0275328

ABSTRACT

A random Martian atmosphere was developed and was used with three guidance schemes to determine the effect of random density variations on the guidance. This random atmosphere was shown to be useful for testing the robustness of guidance schemes for vehicles encountering random disturbances during aerobraking for capture into planetary orbit. Levels of disturbance that could be tolerated and areas where performance could be improved were established. The need for Monte Carlo studies to define the excursion boundaries of capture orbit parameters was indicated.

INTRODUCTION

Since weight reduction is absolutely necessary for an extended mission, such as the Manned Mars Mission (MMM), new methods for reducing a spacecraft's weight are always being sought. Aerobraking, which uses aerodynamic drag to produce the required velocity decrements, as opposed to firing retro-rockets, is one of the most effective ways to reduce the size and mass of a Mars mission. When aerobraking is used to allow the spacecraft to be captured into an elliptical orbit about a planet, the procedure is called aerocapture. When using aerobraking, the preferred method of guidance is bank angle steering. This procedure requires that the vehicle be rolled in order to decrease the portion of the lift vector which opposes gravity. This study is concerned with computer modeling of these control maneuvers.

The program that was used to simulate Martian trajectories was the Program to Optimize Simulated Trajectories (POST) (reference 1). The 3D version of POST, which was originally developed in the early 1970's to optimize Space Shuttle trajectories, is a generalized point mass, discrete parameter targeting and optimization program. The program is capable of simulating and optimizing trajectories for a wide variety of aerospace vehicles operating in the vicinity of a single planetary body. This manned Mars mission study had two main goals. The first goal was to implement a variety of control laws in the POST simulation, using bank angle steering to guide the vehicle in order to achieve an elliptical orbit around Mars with a smooth altitude profile. The second goal was to implement a stochastically random atmosphere model and to test a variety of trajectories in this atmosphere.

This paper will discuss the implementation of a random Martian atmosphere model in POST and the use of this model to test the adaptability of several guidance techniques during a Mars entry simulation. First, guidance techniques will be developed using a deterministic atmosphere and then runs will be made with the random atmosphere to see which techniques survive.

SYMBOLS

A	area, square feet
C_D	drag coefficient
D	drag force, pounds
h_p	predicted perigee altitude, nautical miles
h_T	target perigee altitude, nautical miles
L	lift force, pounds
k	feedback gain
M	mass, slugs
S_c	current vehicle state
S_N	vehicle state from baseline trajectory
ϕ	commanded bank angle, degrees
ϕ_N	bank angle from baseline trajectory, degrees

ABBREVIATIONS

ALTITO	altitude, feet
BNKANG	bank angle, degrees
DENS	density, slugs/ft^3
ENERGY	energy per unit mass, ft^2/sec^2
nm	nautical miles
POST	program to optimize simulated trajectories
TIME	time, seconds
VELI	velocity, ft/sec

APPROACH

This section will first discuss the development and the implementation of several guidance schemes. Next, the development and the implementation of the random Martian atmosphere will be presented.

Data from reference 2 showed that, for trajectories with entry flight path angles near the center of the entry window, only one or two commanded bank angle changes were required for Martian aerocapture of a vehicle with an L/D of .5. For the vehicle characterized in Table I, a capture trajectory that required only two bank commands was developed. The vehicle entered the atmosphere at the first commanded bank angle which remained constant. The second bank angle commanded was to attain its commanded value at the edge of the atmosphere. The bank angle changed at a constant rate until the commanded value was reached. This trajectory had a minimum altitude of 115,456 ft (19 nm), a maximum acceleration of 2.8 gravity units, and captured into an orbit with a period of 2.83 hours (fig. 1). An open loop guidance scheme which makes use of these two bank angle commands will be defined as the baseline guidance for this report. The baseline trajectory parameters will be called nominal parameters

Adaptive Guidance 1

Once an acceptable baseline trajectory was developed, techniques for following this target trajectory were considered. The baseline trajectory was followed by adjusting the bank angle using a control law of the form

$\phi = \phi_N + k * (s_c - s_N)$ where ϕ is the commanded bank angle, ϕ_N is the nominal bank angle, k is the feedback gain, s_c is the current state, and s_N is the nominal state. Two decisions were required. First, was the selection of a variable to use as an index so that comparisons with the nominal state could be made at a specific condition. Energy, time, and velocity were considered as candidates. Second was the selection of what state to follow. Altitude, energy, and velocity were considered as candidates. A number of cases were run with various combinations of index and follow parameters. Using velocity as the index and energy as the parameter to follow seemed the most promising combination. In this paper guidance 1 will use velocity as an index and at any specific velocity the current energy will be compared with the nominal energy and the bank angle changed to try to return the orbital energy to the nominal.

Adaptive Guidance 2

A second guidance technique predicted the altitude of perigee based on current conditions and then changed the bank angle to try to attain a desired perigee altitude. The form of the bank angle correction equation is $\phi = \phi_N + k * (h_T - h_p)$ where ϕ is the commanded bank angle, ϕ_N is the bank angle from the baseline trajectory, k is the feedback gain, h_T is the target perigee altitude, and h_p is the predicted perigee altitude. Once perigee was reached, the vehicle was rolled to a specified bank angle until a velocity of 16400 ft/sec (approximate capture velocity for Mars) was attained, and then the vehicle was rolled to a bank angle of 0° for exit from the atmosphere. A more sophisticated version of this approach is given in reference 3, but the guidance described here is sufficient to demonstrate the effect of the random atmosphere.

The guidance schemes implemented were not optimal but were developed to determine the effect on representative guidance systems of random atmospheric disturbances encountered during a Martian entry.

Random Martian Atmosphere

Earlier Martian entry studies were made using fixed atmospheric models. A number of models for various conditions have been assembled by David Pitts, et al., at Johnson Space Center, and several of these are tabulated in reference 2. A randomly varying atmosphere was constructed so that the robustness of guidance techniques in the presence of atmospheric variations could be tested. This randomly varying atmosphere reflected the possible variations in density seen in the Martian atmospheric models. The basic structure for this random atmosphere was a model for the Earth that had been developed and implemented into POST (ref. 4). Density, pressure, and temperature data from a nominal Martian atmosphere (north-summer) were fitted into this structure. The result was a random Martian atmosphere that was compatible with POST.

Details of the generation of the Martian random atmosphere follow. The Earth random atmosphere program models the Earth's atmosphere as a stochastic process. This program was modified to get the Martian random atmosphere model. One important aspect of this model is that a correlation function is used to limit gradients in the random variables. The density, pressure, and temperature at a given point have values close to those of the density, pressure, and temperature at a nearby point. This correlation function was used in the Martian atmosphere model. Because the amount of information about the Martian atmosphere is sparse, it was necessary to use the standard deviation tables that were used in the Earth simulation. Since the Martian atmosphere is known to be quite different from the Earth's atmosphere, (i.e., stronger winds and composed of over 90 percent CO_2), a provision was included to amplify the standard deviations, if required, to make the model more realistic. This was done through the use of multipliers on the standard deviation tables to change the sizes of perturbations from the mean. For the runs used in this report Table II shows the maximum percent variation in density for various multipliers on the standard deviations. Since the density variation is random not all runs will show this maximum variation. This model enables the testing of guidance techniques in Martian atmospheres with any magnitude of density variations that might be desired.

RESULTS AND DISCUSSION

The initial step in this investigation was to run the baseline open loop guidance with and without the random Martian atmosphere. The variations in density due to the random atmosphere were increased until the vehicle did not capture into an acceptable orbit. For the purposes of this study any entry trajectory that captured into an elliptical orbit and had a minimum altitude during the initial aeropass greater than 18 nm was considered acceptable.

The preliminary results with a limited number of cases indicated that, for variations of 50 percent, the baseline guidance was successful 90 percent of the time. For variations of 86 percent, all of the runs using the baseline open loop guidance failed. The random atmosphere, with 50 percent and 86 percent density variations, was then used to check the adaptive guidance techniques to see if they could give acceptable capture trajectories.

Adaptive guidance technique 1 was run with the random atmosphere using 86 percent variations and with a deterministic atmosphere for comparison. A trajectory run with the nominal Martian atmosphere and two commanded bank angles is the baseline. The results of several successful runs are shown as figures 2 and 3. The density comparison between the nominal density profile and the random profile with 86 percent variation is shown as part of figures 2 and 3.

The figures also show the effect of different gains. With high gains the bank angle time history showed many large variations, but the resulting capture was good. When gains were reduced so that the bank angle time history was more acceptable for a manned vehicle, the actual energy was not as close to the nominal as with the higher gains, but the resulting capture was still acceptable. For both gains, the perigee altitude was within 5 percent of the baseline. With the higher gain the eccentricity of the capture orbit was within 1 percent of the baseline, while for the lower gain the capture orbit had an eccentricity that was 20 percent less than the baseline; however, the period was 4.4 hours and was considered acceptable. The tradeoffs between gain, bank angle time history, and energy following will require additional investigation.

The density deviations from the random atmosphere resulted in the acceleration and bank angle time histories seen as parts of figures 2 and 3. In spite of significantly different forces acting on the vehicle when the 86 percent random atmosphere was used, the guidance system was able to adjust the bank angle so that a majority of entries were successful. However, when adaptive guidance technique 1 was used with 50 percent variations, all of the runs were successful. Typical runs are shown as figures 4 and 5. The figures show entries using two different gains compared with a baseline entry generated using a deterministic atmosphere. For both gains the perigee altitude was within 5 percent of the baseline. The high gain case resulted in a capture trajectory that was 11 percent more eccentric than the baseline.

The low gain case was 30 percent more eccentric than the baseline. Although the period of the orbit was 18 hours, the vehicle was still captured. All of the above results are for a limited sample and the extremes for capture orbits at any given density variation are not known. A Monte Carlo analysis must be run to establish a percent of successful runs and boundaries of orbital eccentricity and period for the successful cases.

The effects of the random Martian atmosphere on adaptive guidance 2 were also investigated. First, the guidance was run with a deterministic atmosphere to obtain a baseline trajectory to be used for comparison with runs made using the random atmosphere. In general, when the deterministic atmosphere was used, the capture orbit tended to have perigee altitudes below the target perigee altitude. As a result, the capture orbits were less eccentric and had smaller periods than the capture orbits when adaptive guidance 1 was used.

The initial runs made using the random atmosphere and adaptive guidance 2 had a density variation of 50 percent. A typical run, with the random atmosphere compared with a run using the deterministic atmosphere, is shown as figure 6. The runs using the random atmosphere tended to lose more energy than the run using the deterministic atmosphere, but all runs were successful. For the example of figure 6, the eccentricity of the capture orbit flown through the random atmosphere decreased by 11 percent from the eccentricity of the capture orbit flown through the deterministic atmosphere, but the period of the capture orbit flown through the random atmosphere was 3.41 hours.

When the density variation was increased to 86 percent, all the runs using adaptive guidance 2 were still successful. A typical run using the random atmosphere compared with the deterministic atmosphere run is shown as figure 7. The eccentricity decreased by 28 percent when compared to the baseline, but the period of the capture orbit was 2.84 hours, and the capture was successful. Regardless of the density variation used, the difference in perigee altitude was less than 5 percent from the perigee altitude obtained with the deterministic atmosphere.

Refinements in the accuracy of attaining the desired perigee altitude and in the gain of adaptive guidance 2 could possibly improve its performance. Also, additional runs will be required to better define the variation of capture orbit parameters for the various random atmospheres.

CONCLUSIONS

A random Martian atmosphere was developed based on a nominal Martian atmosphere. This random atmosphere was used with three guidance schemes to determine the effect of random density variations on the guidance. Multipliers in POST enabled the random atmosphere routine to simulate density variations of up to 100 percent. The three guidance schemes used were one open loop and two adaptive techniques that used state feedback.

When density variations of 86 percent were used, 100 percent of the open loop guidance runs failed. However, the majority of the adaptive guidance 1 and all of the adaptive guidance 2 runs were successful. When density variations of 50 percent were used, approximately 90 percent of the open loop guidance runs were successful and all of the runs using adaptive guidance 1 and adaptive guidance 2 were successful.

The random Martian atmosphere developed was shown to be useful for testing the robustness of guidance schemes for vehicles encountering random disturbances during aerobraking for capture into planetary orbit. Levels of disturbance that various schemes could tolerate were determined. Areas where refinement of the different guidance schemes could improve their performance were outlined. The need for Monte Carlo studies to define success rates of the guidance schemes and excursion boundaries of capture orbit parameters was clearly indicated.

REFERENCES

1. Brauer, G. L.; Cornick, D. E.; and Stevenson, R.: Capabilities and Applications of the Program to Optimize Simulated Trajectories (POST). NASA CR-2770, February 1977.

2. Tartabini, Paul V.; and Suit, William T.: Aerobraking Characteristics for Several Potential Manned Mars Entry Vehicles. NASA TM-101669, November 1989.

3. Fuhry, Douglas P.: A Design Study of Onboard Navigation and Guidance During Aerocapture at Mars. The Charles Stark Draper Laboratory, CSDL - T - 986, May 1988.

4. Queen, Eric M.; and O'Mara, Thomas M.: Comparison of Effects of Copropagated and Precomputed Atmosphere Profiles on Monte Carlo Trajectory Simulation. NASA TM-102600, January 1990.

Table I. Vehicle Characteristics

Mass (M)	= 15515.2 slugs
Drag Coefficient (C_D)	= 1.35
Area (A)	= 1963.5 ft^2
Ballestic Coefficient ($M/ C_D{}^* A$)	= 5.85 $slug/ft^2$

Table II. Density Variation Magnitude

Multiplier	Maximum Random Density Variation
0	Baseline
1	6 %
3	16 %
6	30 %
10	50 %
20	86 %
30	95 %

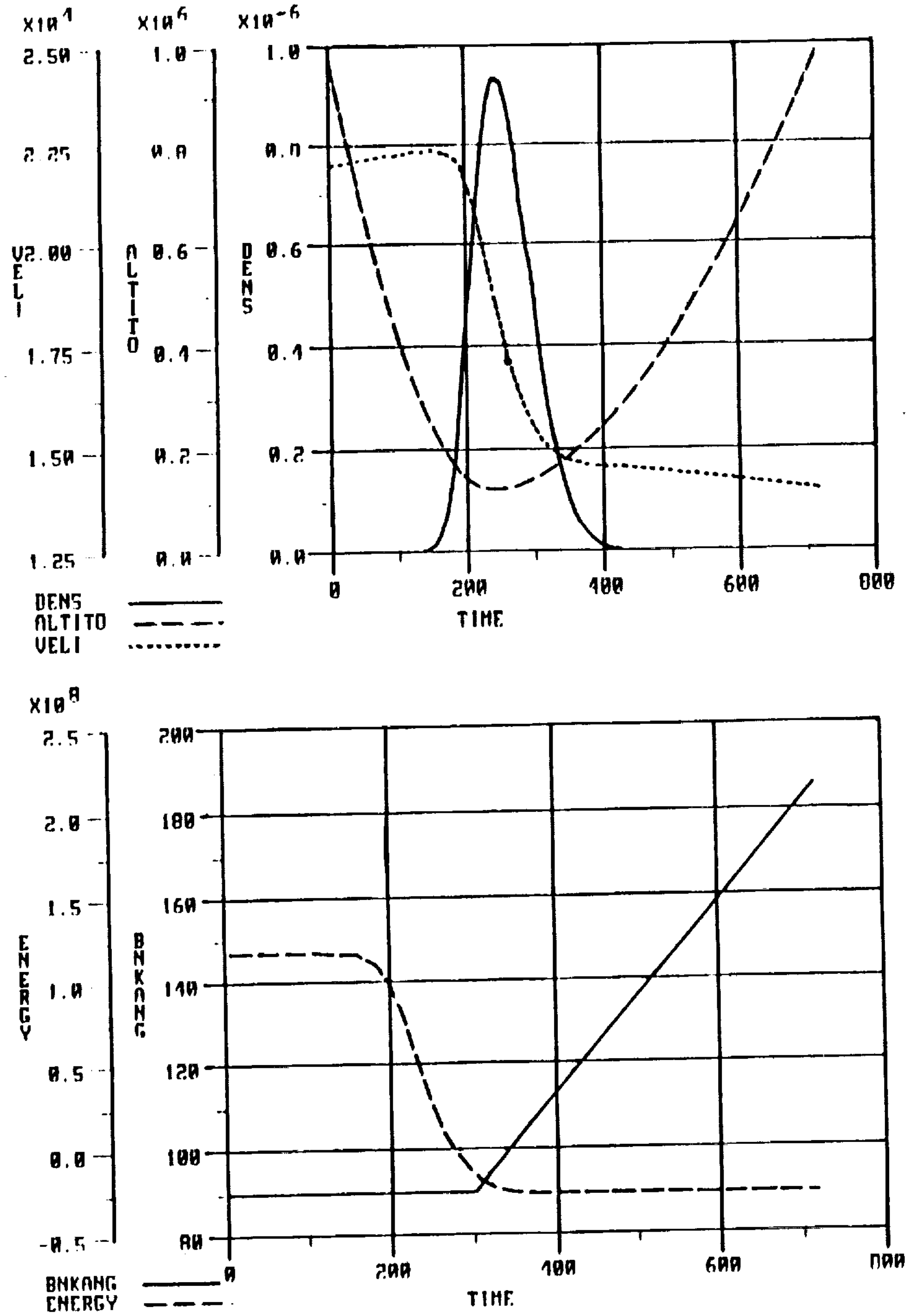


Figure 1. Baseline trajectory showing Martian aerocapture using two bank angle commands and flying through a deterministic atmosphere.

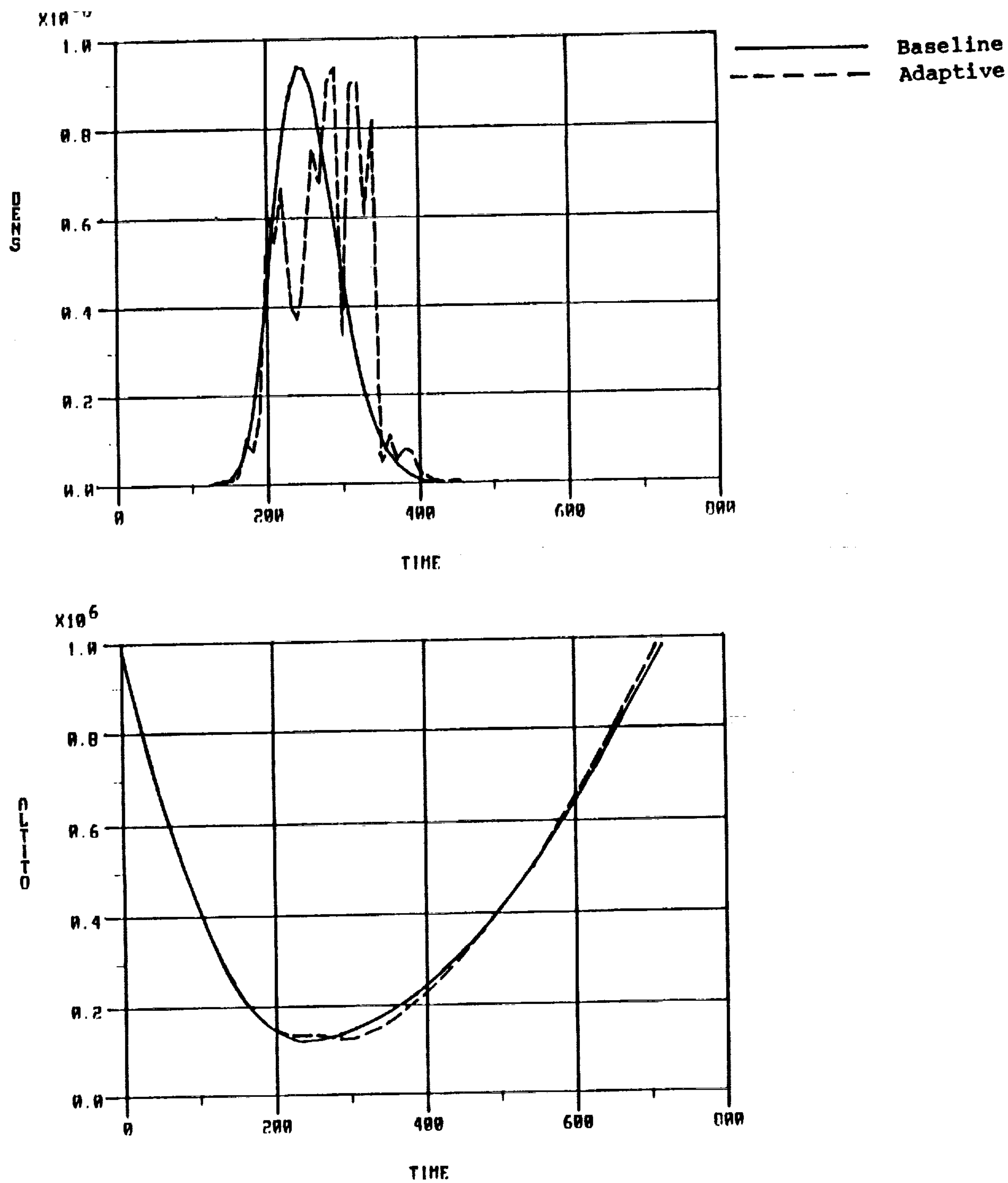
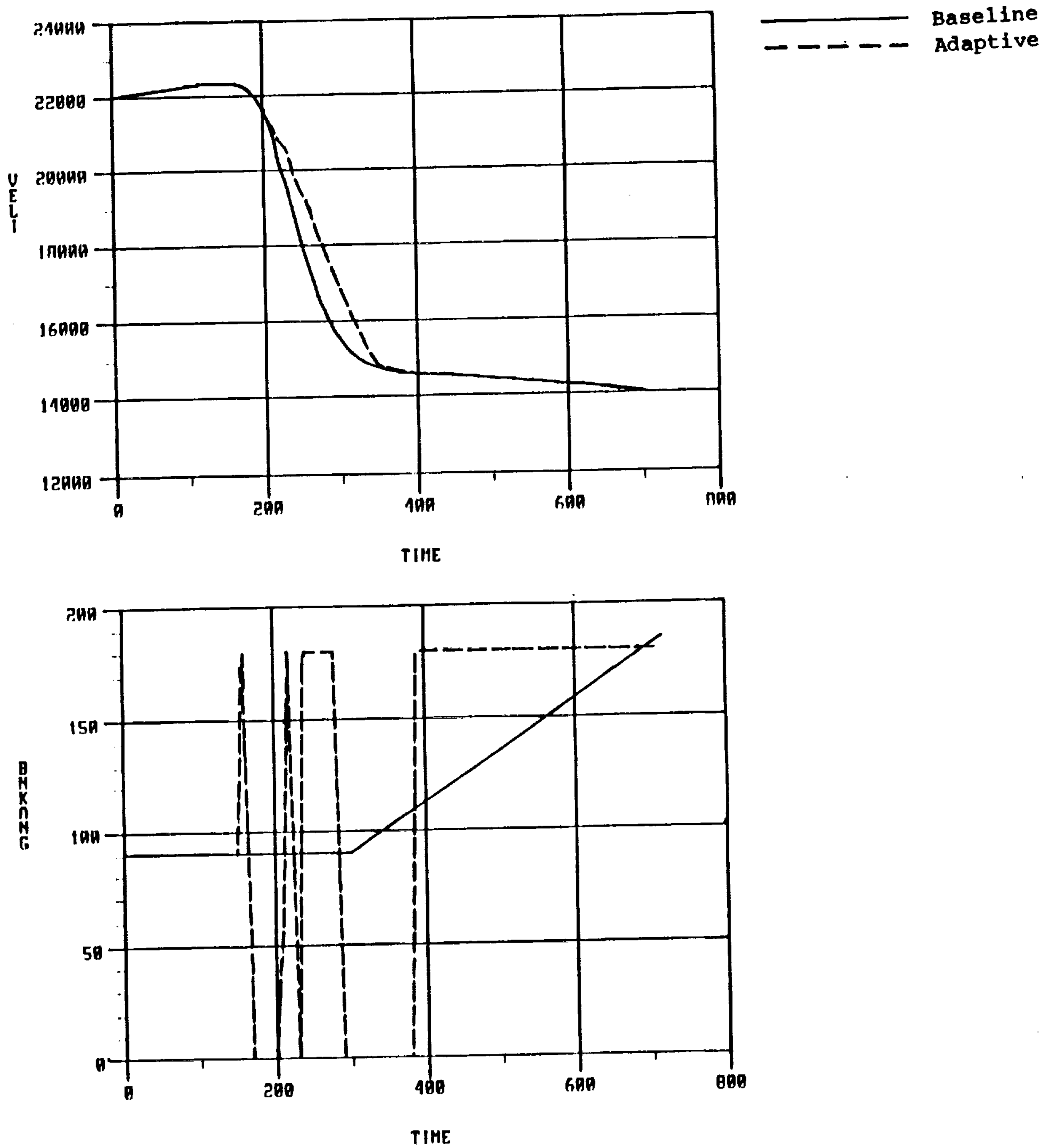


Figure 2. State and atmosphere time histories for a Martian aerocapture using adaptive guidance 1, with a gain of .1, flying through a random atmosphere with maximum density variations of 86 percent and for the baseline trajectory.



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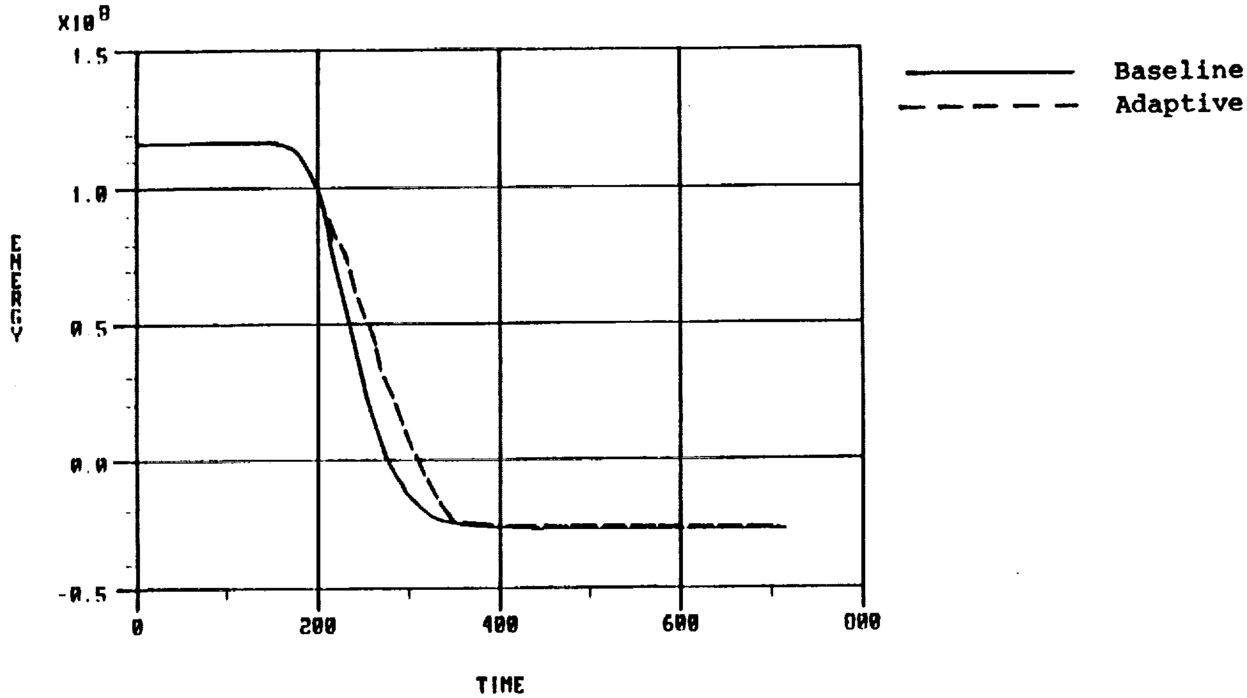

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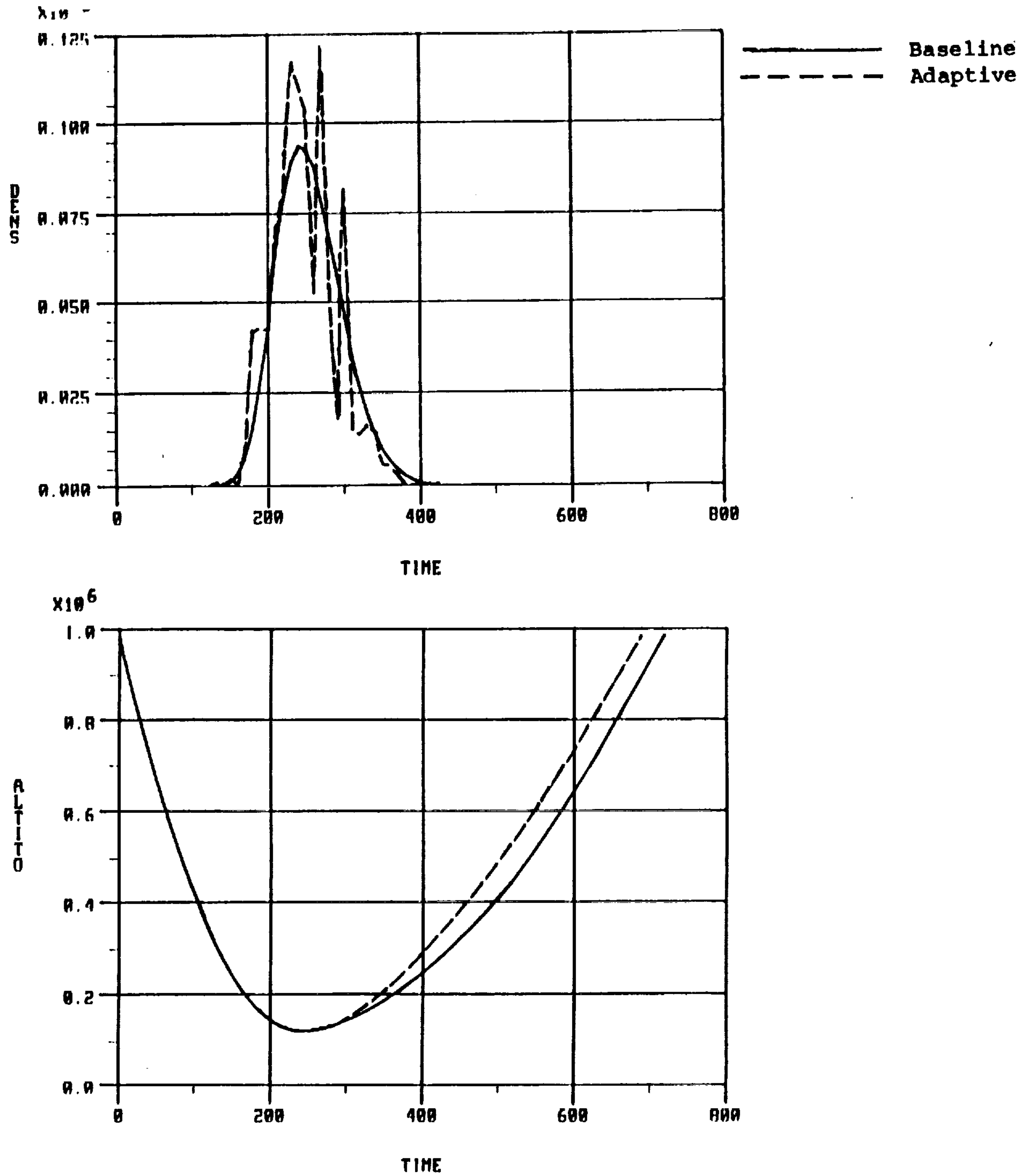
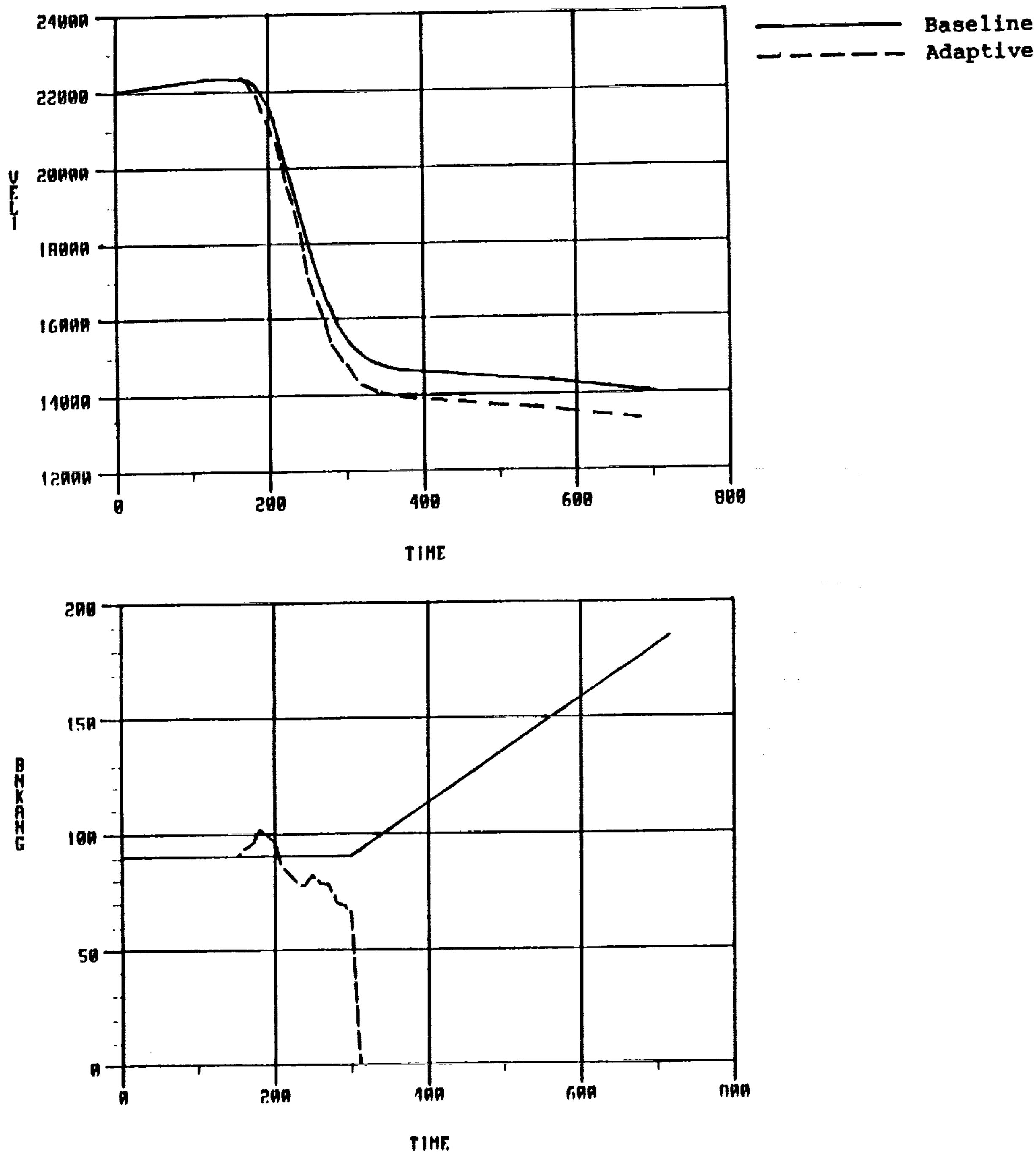


Figure 3. State and atmosphere time histories for a Martian aerocapture using adaptive guidance 1, with a reduced gain of $1x10^{-4}$, flying through a random atmosphere with maximum density variations of 86 percent and for the baseline trajectory.



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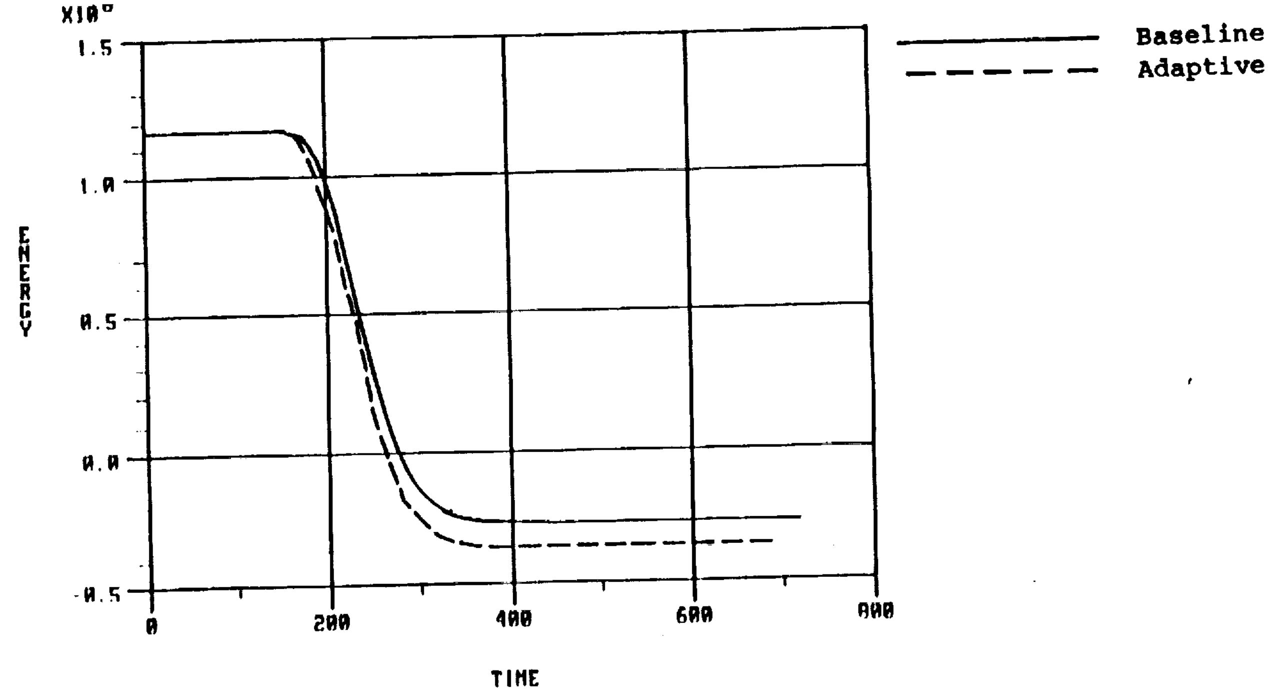

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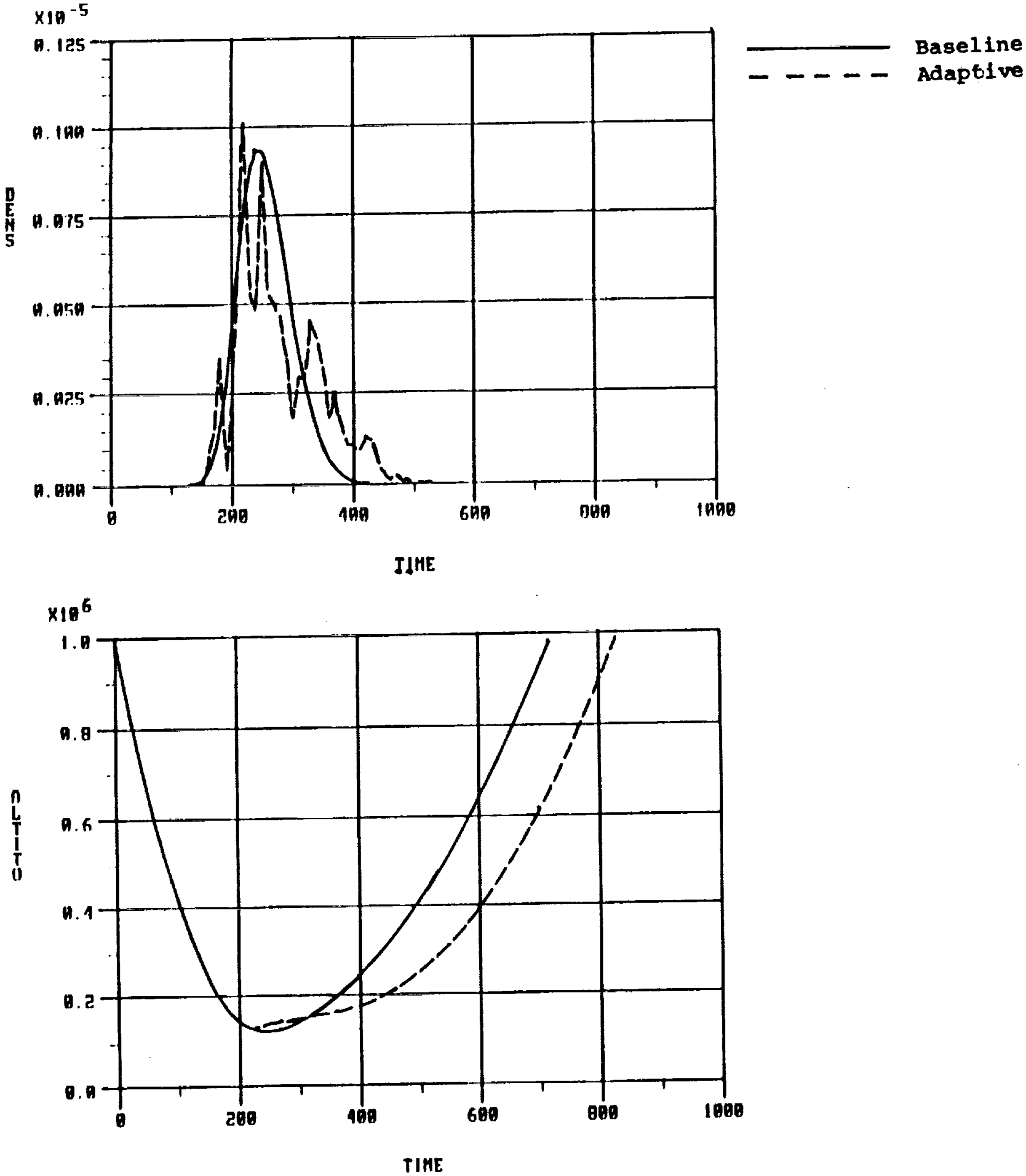
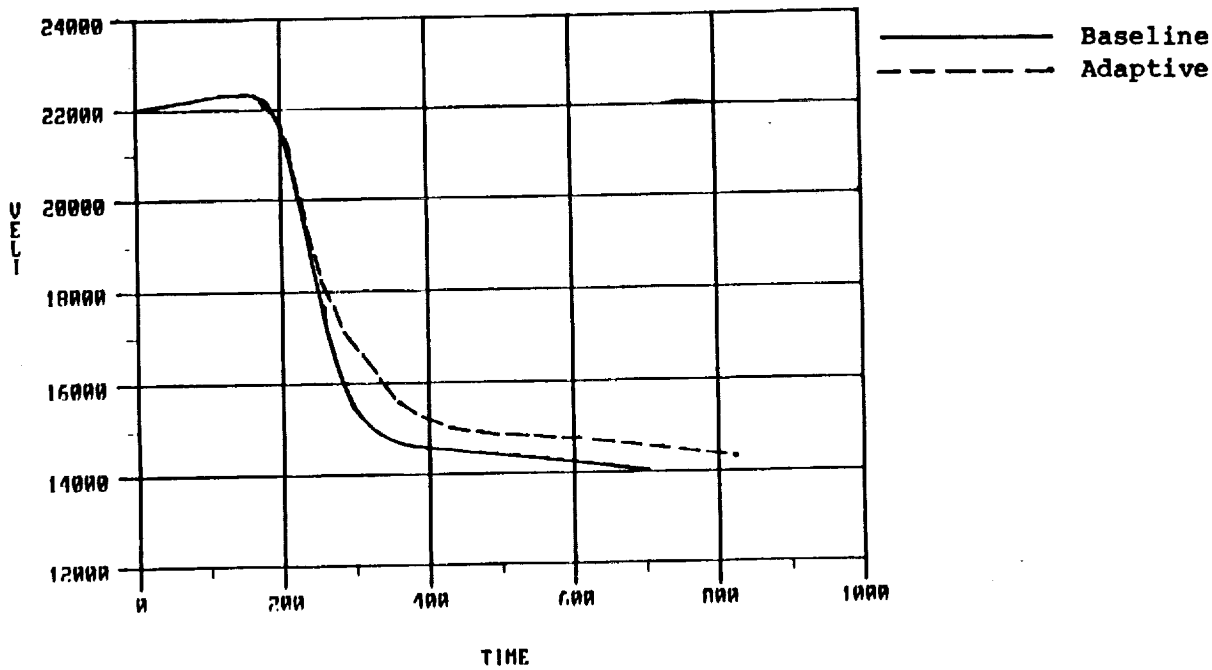


Figure 4. State and atmosphere time histories for a Martian aerocapture using adaptive guidance 1, with a gain of .1, flying through a random atmosphere with maximum density variations of 50 percent and for the baseline trajectory.


Baseline
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16000
14000
12000
VELI
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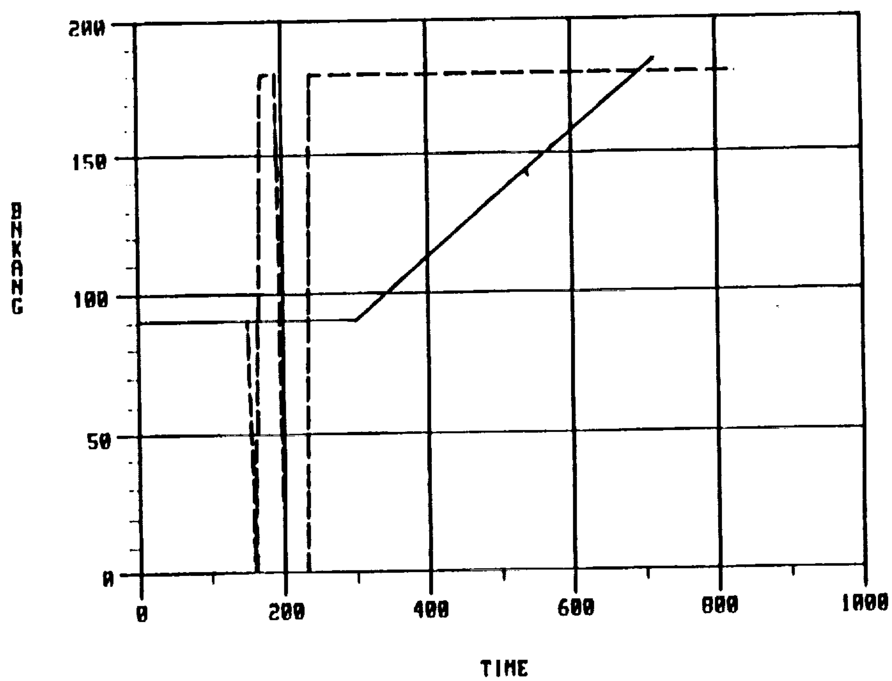
1000
TIME


200
150
100
50
0
BNKANG
0
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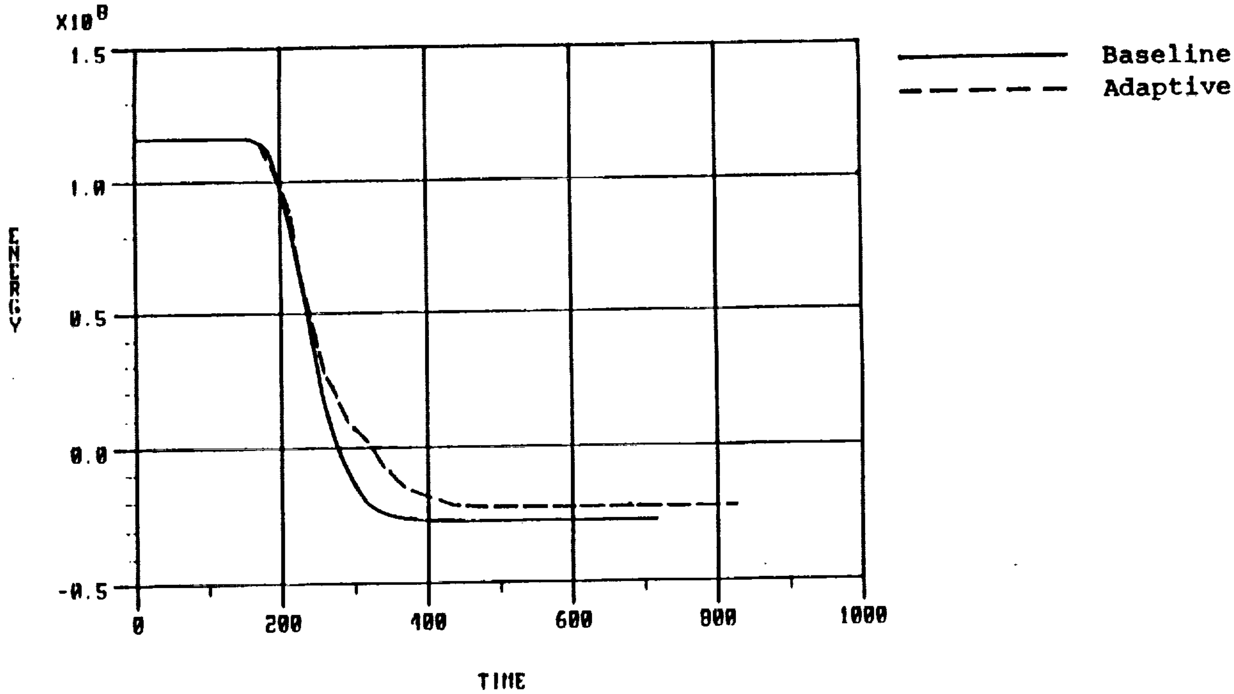
400
600
800
1000
TIME

4. Continued


X10^8
1.5
1.0
0.5
0.0
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200
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1000
TIME
Baseline
Adaptive

4. Concluded.

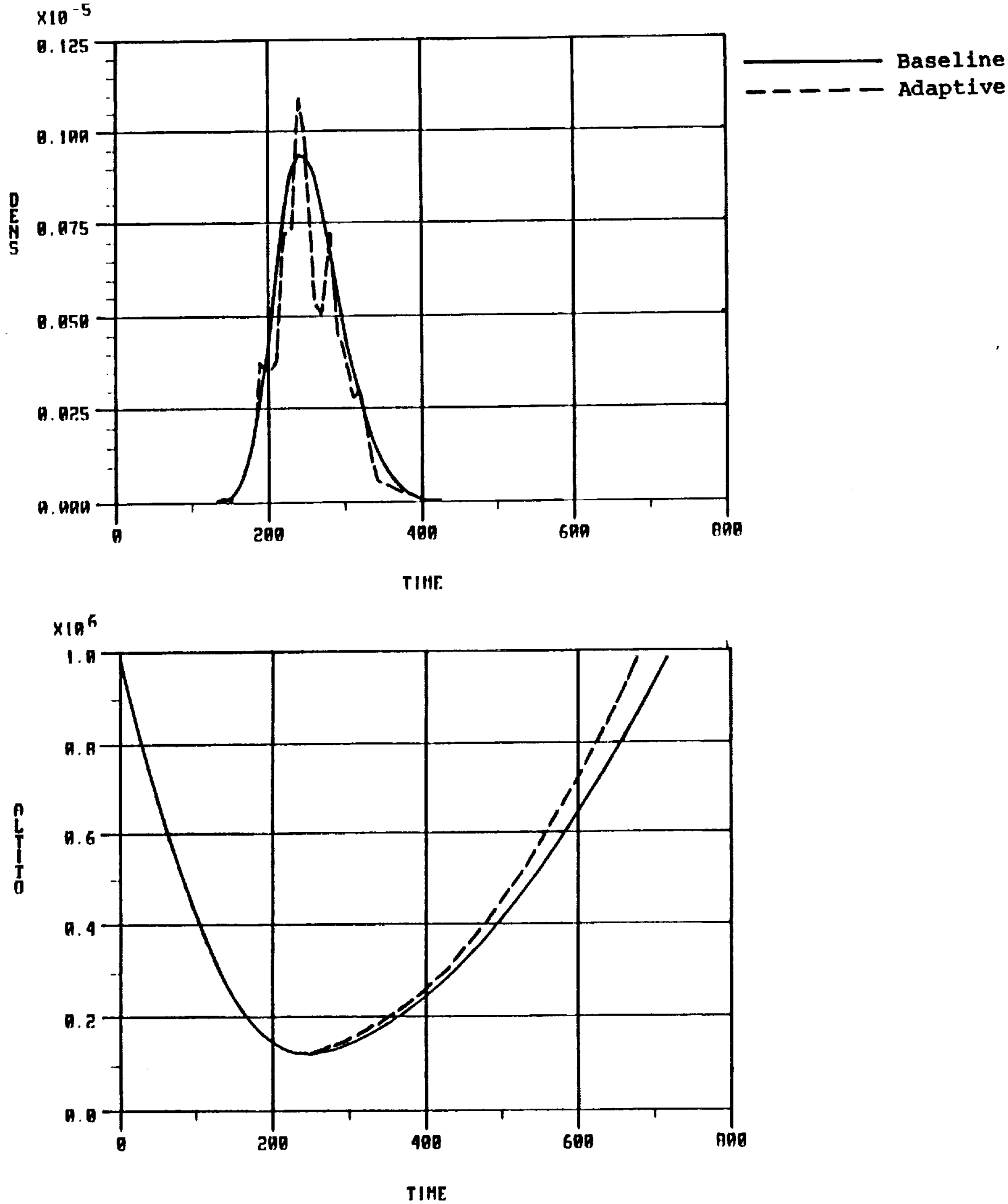
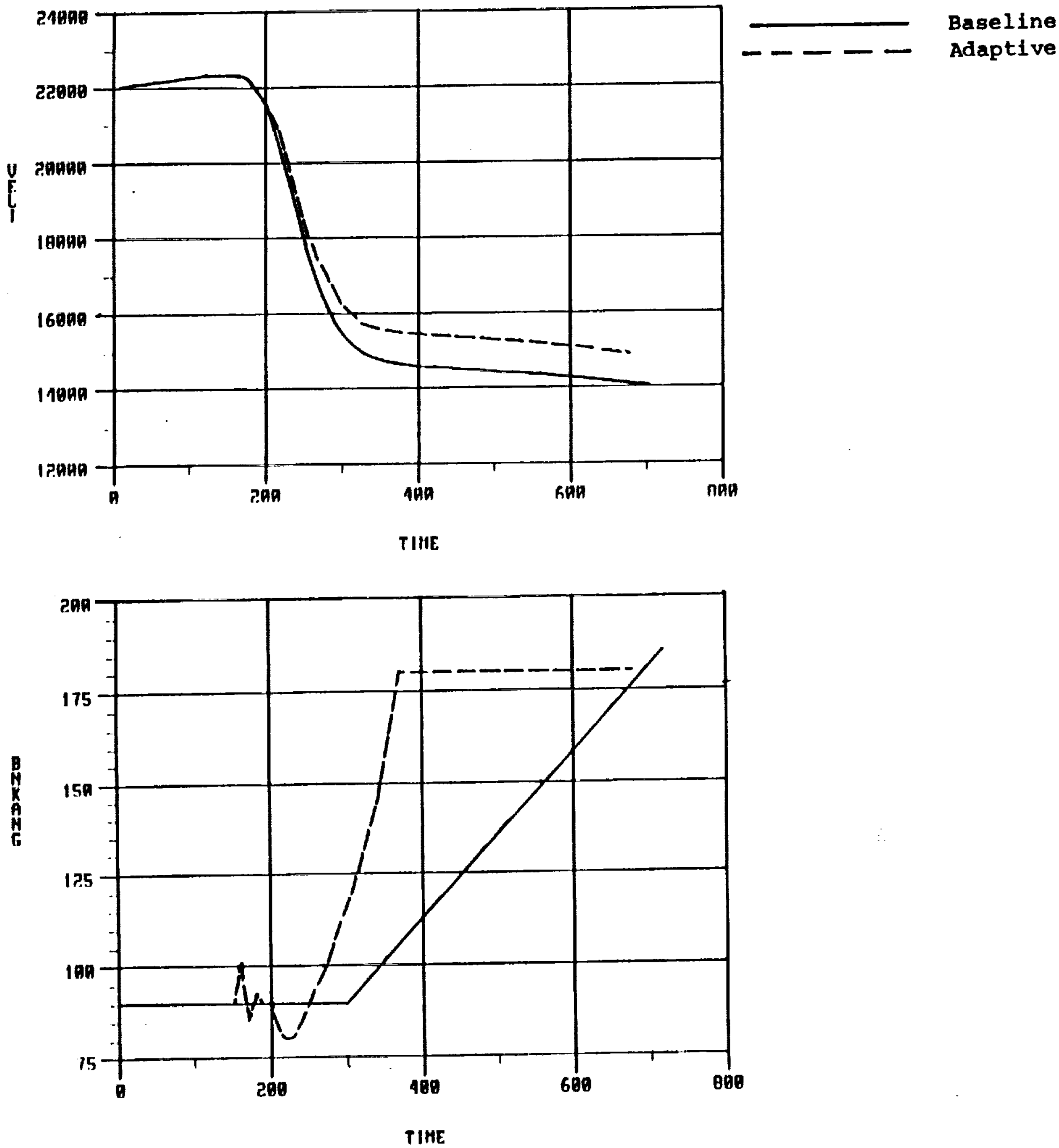


Figure 5. State and atmosphere time histories for a Martian aerocapture using adaptive guidance 1, with a reduced gain of 1×10^{-4}, flying through a random atmosphere with maximum density variations of 50 percent and for the baseline trajectory.



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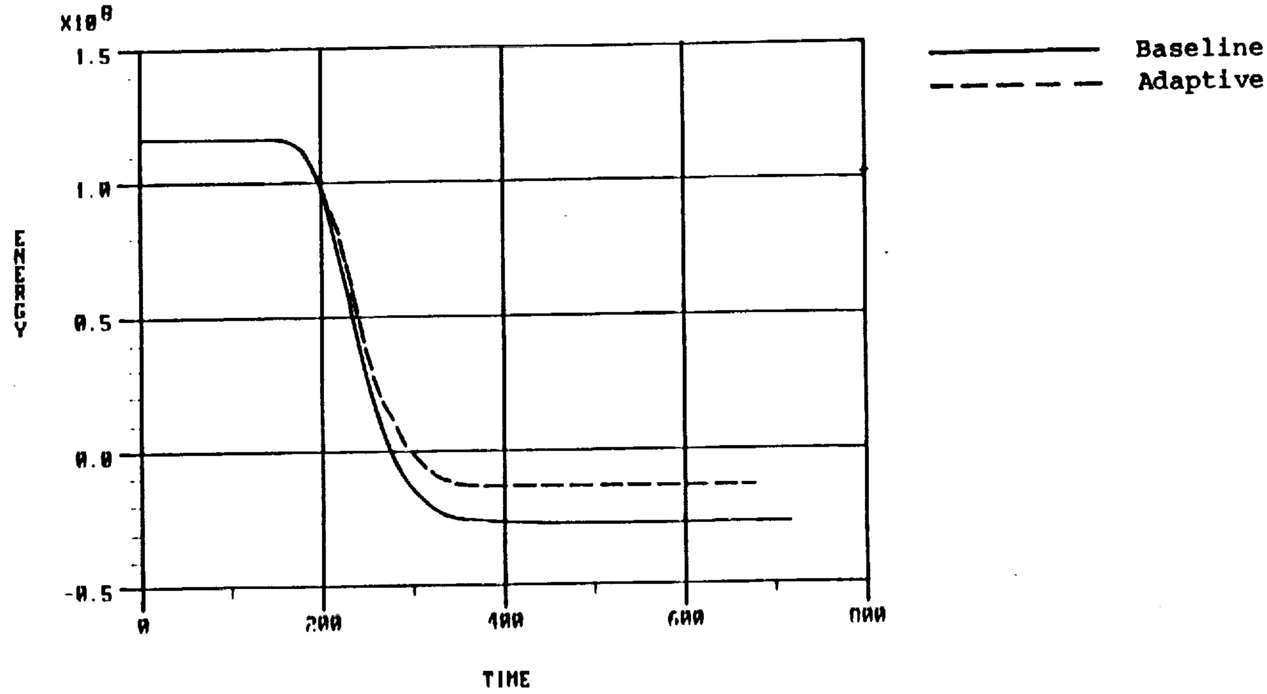

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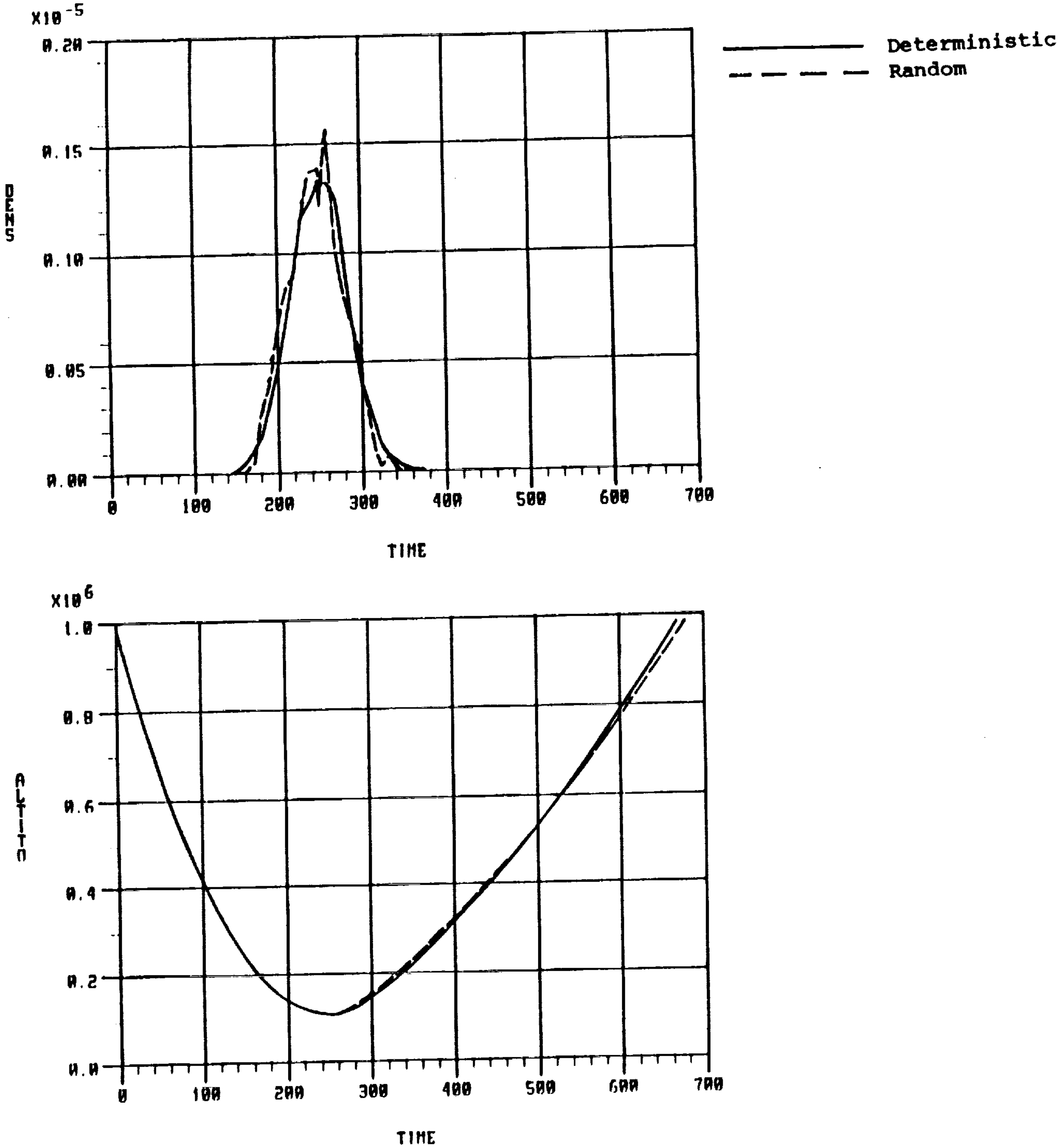
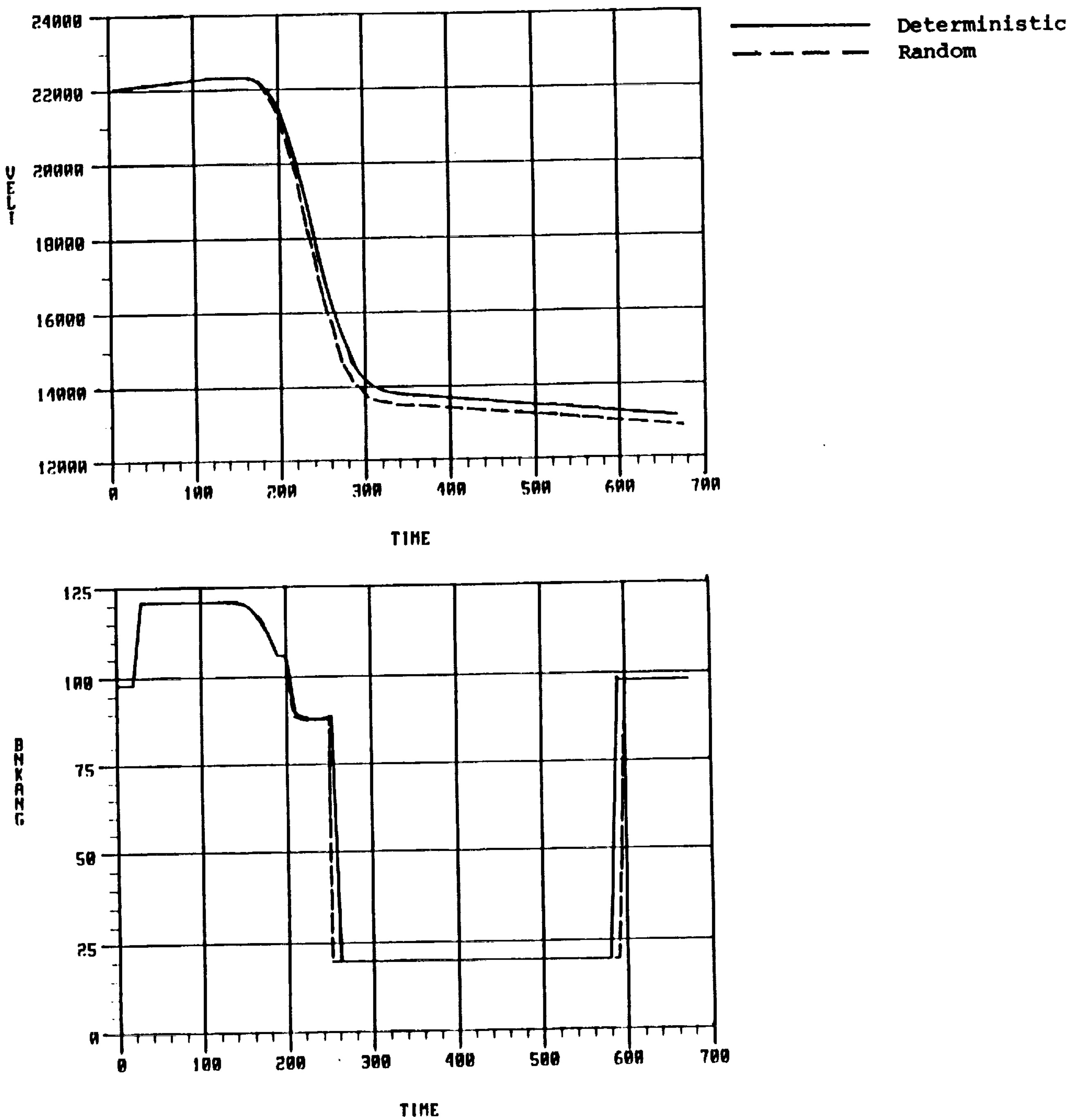


Figure 6. State and atmosphere time histories for a Martian aerocapture using adaptive guidance 2, flying through a random atmosphere with maximum density variations of 50 percent and for a deterministic atmosphere.



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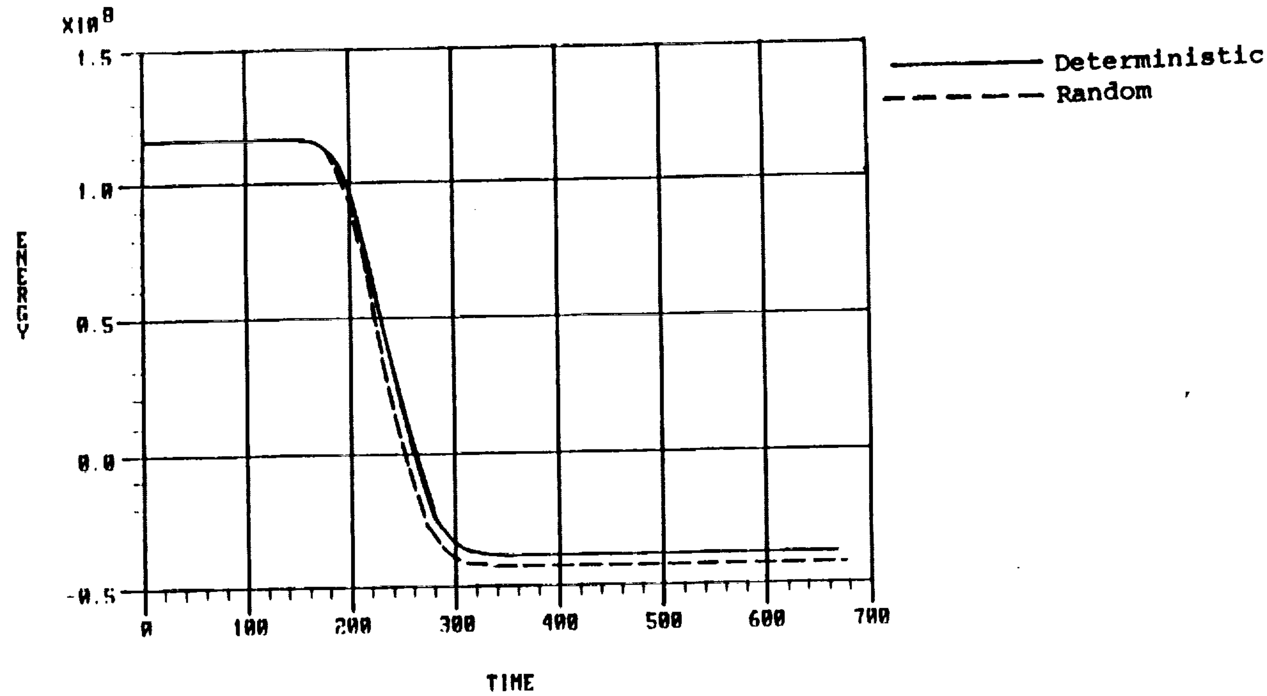

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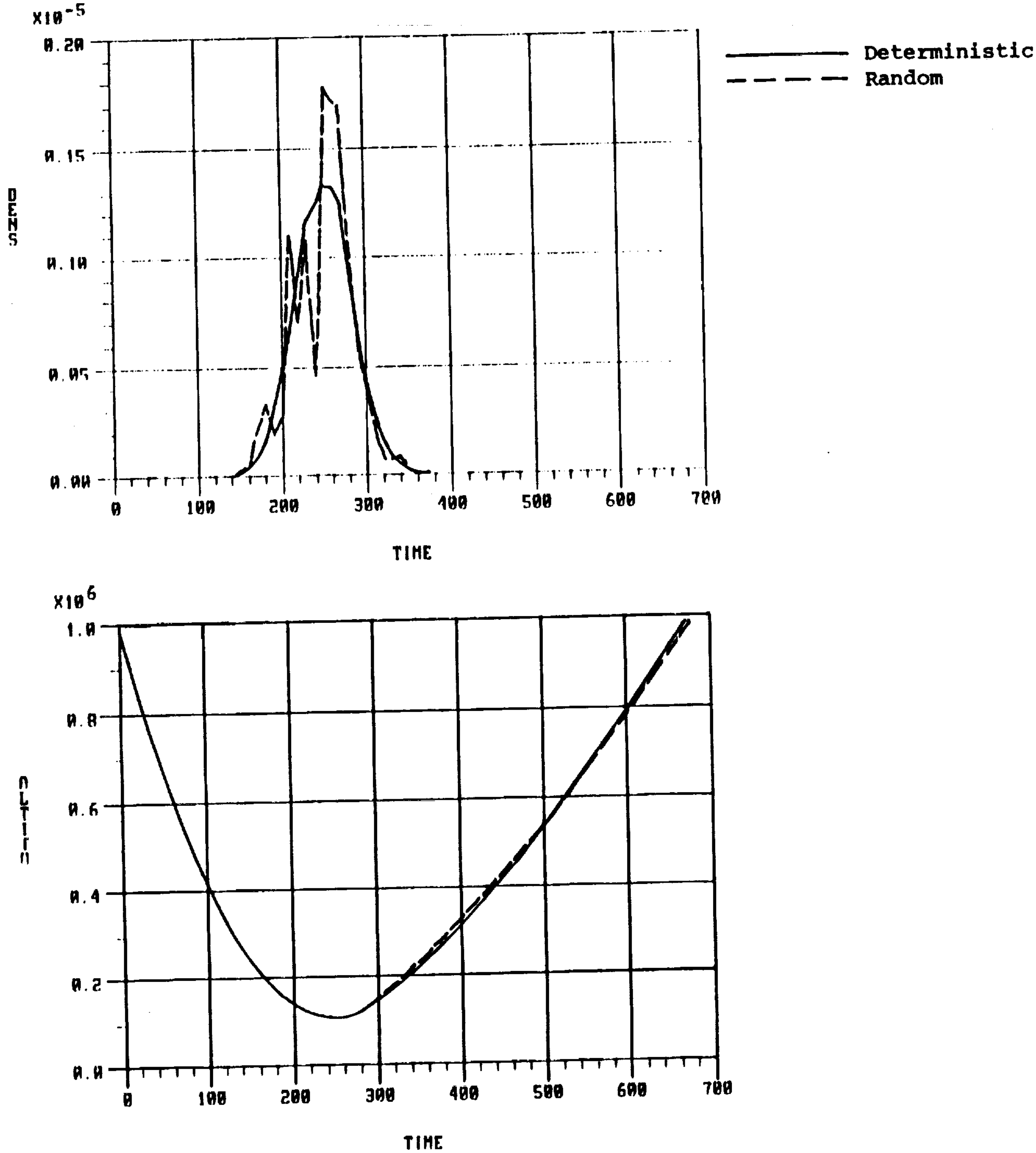
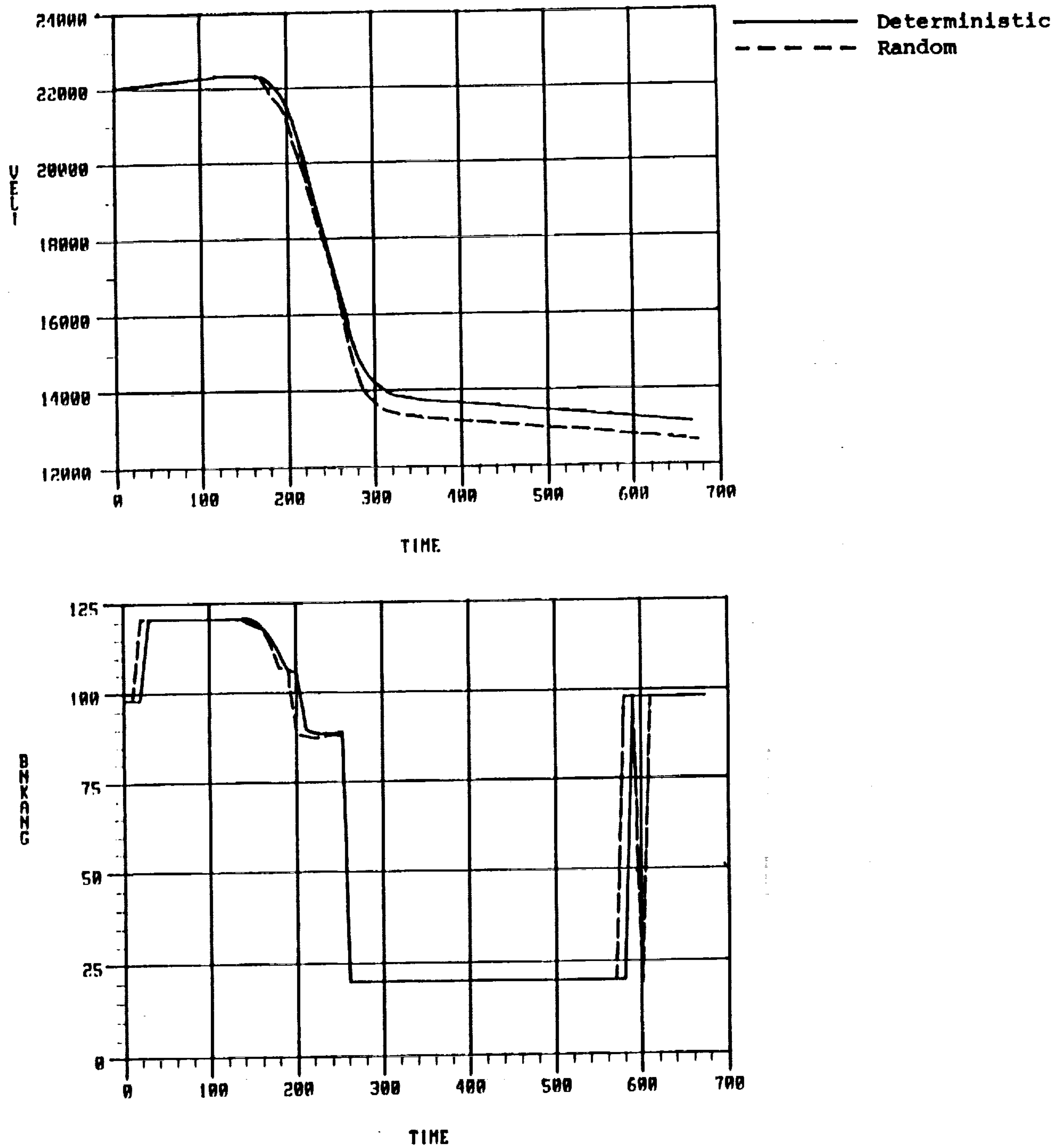


Figure 7. State and atmosphere time histories for a Martian aerocapture using adaptive guidance 2, flying through a random atmosphere with maximum density variations of 86 percent and for a deterministic atmosphere.



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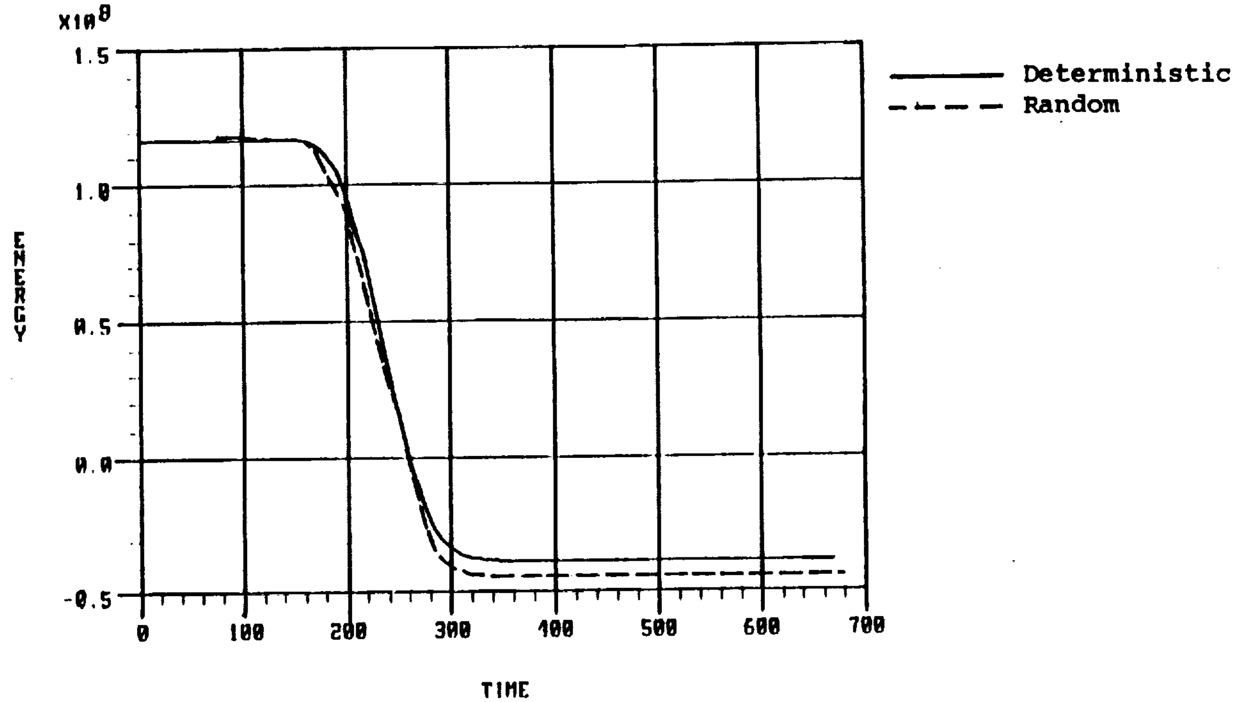

Figure 7. Concluded.

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National Aeronautics and Space Administration

Report Documentation Page

1. Report No.	2. Government Accession No.	3. Recipient's Catalog No.
NASA TM-102606		

4. Title and Subtitle	5. Report Date
Use of Random Martian Atmosphere to Evaluate Potential Entry Guidance Schemes	January 1990
	6. Performing Organization Code
7. Author(s)	8. Performing Organization Report No.
Barbara S. Tomlinson and William T. Suit	
	10. Work Unit No. 506-46-21-01
9. Performing Organization Name and Address NASA Langley Research Center Hampton, VA 23665-5225	11. Contract or Grant No.
	13. Type of Report and Period Covered Technical Memorandum
12. Sponsoring Agency Name and Address National Aeronautics and Space Administration Washington, DC 20546-0001	14. Sponsoring Agency Code

15. Supplementary Notes

16. Abstract

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17. Key Words (Suggested by Author(s))	18. Distribution Statement
Spacecraft Guidance Aeroassist Spacecraft Maneuvers Manned Mars Mission	Unclassified - Unlimited Subject Category 18

19. Security Classif. (of this report)	20. Security Classif. (of this page)	21. No. of pages	22. Price
Unclassified	Unclassified	28	A03

NASA FORM 1626 OCT 86 For sale by the National Technical Information Service, Springfield, VA 22161-2171