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Application of Fuzzy Logic-Neural Network Based Reinforcement Learning to Proximity and Docking Operations

Special Approach/Docking Testcase Results

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Togai InfraLogic, Inc.

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Cooperative Agreement NCC 9-16
Research Activity No. AR.06:
Reinforcement Learning Based on Fuzzy Logic and Neural Networks

NASA Johnson Space Center
Information Systems Directorate

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Research Institute for Computing and Information Systems
University of Houston-Clear Lake

TECHNICAL REPORT

The RICIS Concept

The University of Houston-Clear Lake established the Research Institute for Computing and Information Systems (RICIS) in 1986 to encourage the NASA Johnson Space Center (JSC) and local industry to actively support research in the computing and information sciences. As part of this endeavor, UHCL proposed a partnership with JSC to jointly define and manage an integrated program of research in advanced data processing technology needed for JSC's main missions, including administrative, engineering and science responsibilities. JSC agreed and entered into a continuing cooperative agreement with UHCL beginning in May 1986, to jointly plan and execute such research through RICIS. Additionally, under Cooperative Agreement NCC 9-16, computing and educational facilities are shared by the two institutions to conduct the research.

The UHCL/RICIS mission is to conduct, coordinate, and disseminate research and professional level education in computing and information systems to serve the needs of the government, industry, community and academia. RICIS combines resources of UHCL and its gateway affiliates to research and develop materials, prototypes and publications on topics of mutual interest to its sponsors and researchers. Within UHCL, the mission is being implemented through interdisciplinary involvement of faculty and students from each of the four schools: Business and Public Administration, Education, Human Sciences and Humanities, and Natural and Applied Sciences. RICIS also collaborates with industry in a companion program. This program is focused on serving the research and advanced development needs of industry.

Moreover, UHCL established relationships with other universities and research organizations, having common research interests, to provide additional sources of expertise to conduct needed research. For example, UHCL has entered into a special partnership with Texas A&M University to help oversee RICIS research and education programs, while other research organizations are involved via the "gateway" concept.

A major role of RICIS then is to find the best match of sponsors, researchers and research objectives to advance knowledge in the computing and information sciences. RICIS, working jointly with its sponsors, advises on research needs, recommends principals for conducting the research, provides technical and administrative support to coordinate the research and integrates technical results into the goals of UHCL, NASA/JSC and industry.

RICIS Preface

This research was conducted under auspices of the Research Institute for Computing and Information Systems by Dr. Yashvant Jani of the Technology Systems Division of Togai InfraLogic, Inc. Dr. Kwok-bun Yue served as the RICIS research coordinator.

Funding was provided by the Information Systems Directorate, NASA/JSC through Cooperative Agreement NCC 9-16 between the NASA Johnson Space Center and the University of Houston-Clear Lake. The original NASA research coordinator for this activity was Dr. Robert N. Lea; later Christopher J. Culbert assumed that role. Both research coordinators are from the Information Systems Directorate NASA/JSC.

DELIVERABLES COVER SHEET

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Title of Task : **Special case of final approach Translational & Attitude Control**

Subcontractor : **Technology Systems Division**
Togai InfraLogic, Inc.
Houston, Texas 77058

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APPLICATION OF FUZZY LOGIC-NEURAL NETWORK BASED REINFORCEMENT LEARNING TO PROXIMITY AND DOCKING OPERATIONS

Deliverable D4
Report on Special Approach/Docking Testcase Results

submitted
to

The Research Institute for Computing and Information Systems
University of Houston-Clear Lake
Houston, Texas 77058-1096

Prepared by

Yashvant Jani
Technology Systems Division
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Houston, Texas 77058

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1.0 Introduction :

As part of the RICIS project # AR.06 activity, the reinforcement learning techniques developed at Ames Research Center are being applied to proximity and docking operations using the Shuttle and Solar Maximum Mission (SMM) satellite simulation. In utilizing these fuzzy learning techniques, we use the Approximate Reasoning based Intelligent Control (ARIC) architecture, and so we use these two terms interchangeably to imply the same. This activity is carried out in the Software Technology Laboratory utilizing the Orbital Operations Simulator (OOS) and programming / testing support from other contractor personnel.

This report is the final deliverable D4 in our milestones and project activity. It provides the test results for the special testcase of approach/docking scenario for the shuttle and SMM satellite. Based on our experience and analysis with the attitude and translational controllers, we have modified the basic configuration of the reinforcement learning algorithm in ARIC. The shuttle translational controller and its implementation in ARIC is described in our deliverable D3. In order to simulate the final approach and docking operations, we have set-up this special testcase as described in section 2. The ARIC performance results for these operations are discussed in section 3 and conclusions are provided in section 4 alongwith the summary for the project.

2.0 Approach/Docking Tetstcase Description

As a part of our third task, we had planned to evaluate the ARIC performance for the final approach and docking operations scenario. Typically, the shuttle approaches the satellite from 50 feet to less than 10 feet and continues to station keep at that distance for a while. The Shuttle robotic arm is maneuvered to grapple the satellite in a short time. Actually, the reach envelope of the robotic arm is around 35 feet, and thus, the arm is maneuvered into proper position during the approach and the satellite is captured during the tail end of the approach and the begining of the station-keeping phase.

To simulate this scenario without the robotic arm, we have designed this testcase with three segments (figure 1). The first segment is a station keeping mode at a distance of 200 feet with a 15 feet range deadband (DB) and 5 ft/sec range rate DB. The shuttle attitude in the LVLH frame is (0, 90, 0) in the roll, pitch and yaw sequence, and remains the same in all three segments. The second segment is an approach from 200 feet to 10 feet distance with a range rate DB of 0.05 ft/sec and 2-10 feet of range DB. Actually, the approach does not use range DB at all. It uses only the range rate DB and performs the approach task by maintaining the desired range rate. At the end of the approach segment at 10 feet distance, the desired range rate is 0.0 ft/sec with a 0.05 ft/sec of deadband. The third segment is station keeping at 10 feet distance with 1.25 ft range DB and 0.05 ft/sec range rate DB. If an automatic ARIC system can maintain this position, (10 feet range with zero elevation and zero azimuth angles and the orientation of 0, 90, 0 in roll, pitch and yaw respectively) within their respective deadbands, then, it is performing proximity operations tasks very well. Please note that the ARIC controller has no constraints on fuel usage.

In order to simulate this scenario, we had initially planned to begin the mission at 50 feet and approach all the way to 2 feet distance from the satellite. When we performed detailed calculations to see what are the effects of attitude deadband at 2 feet, we realized that this distance is very close to the satellite, especially with a medium DB used by the shuttle attitude controller. Considering the size of the SMM, a collision may not be avoided. Thus, we decided to stop at 10 feet distance from the satellite. We could begin the mission at 50 feet distance, however, to stabilize the ARIC weights, particularly, the d's and f's in the Action Selection Network (ASN), a definite amount of learning is required by the ASN.

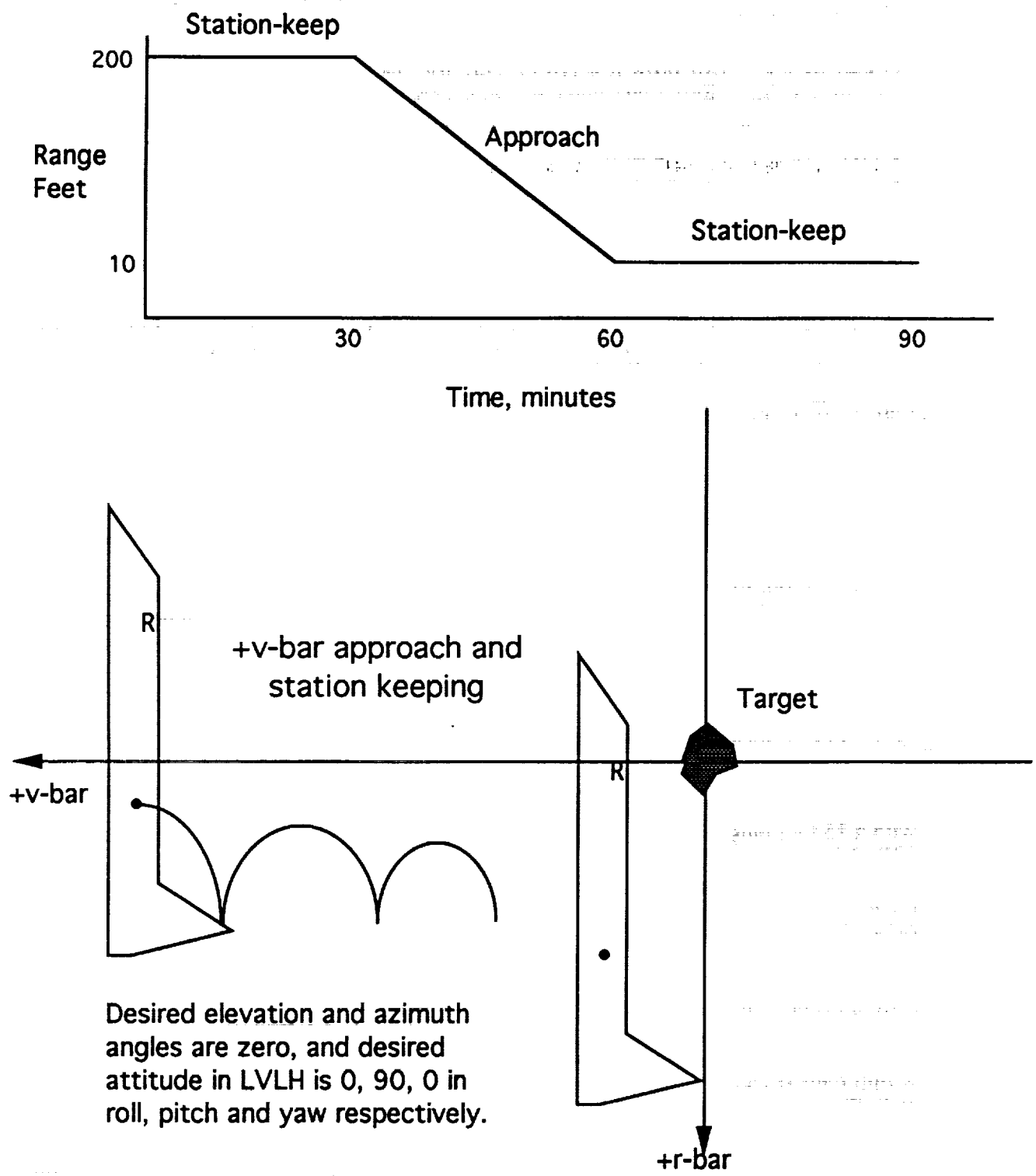


Figure 1. Relative Trajectory for Approach and Docking

Thus, we had to have some station keeping time before we can begin our approach. Since station keeping at 50 feet provides further problem with maintaining the elevation angle, it was best to start the testcase at 200 feet. The radar sensor is located approximately 40 feet from the center of mass of the shuttle, and thus, it would require approximately 14 degrees of elevation angle if proper range deadband is to be maintained. However, the cross-over for the Zero and Positive_Small membership functions of the elevation angle is at 8 degrees. Thus, the elevation controller may violate the range deadband while correcting for high elevation angle and the range controller may violate the elevation deadband. There will be two opposing tasks for two axes of the translational controller both contributing to high fuel usage. To avoid this situation, we decided to start the mission at 200 feet where the elevation angle required is only 7 degrees, less than the cross-over for the elevation angle membership functions. Since the approach task does not use the range DB, there will be no conflict between the range and elevation control.

Several changes and modifications have been made in the fuzzy learning algorithms within the ARIC framework. These changes were determined necessary based on our study so far to properly utilize the fuzzy learning techniques for space operations. The ARIC algorithm with these changes provides us a baseline for total 6 degree of freedom control. This includes attitude as well as translational modules : pitch, yaw, roll axes attitude control, and range, azimuth and elevation control along the line of sight.

a. We have removed the bias input from all modules. Thus all control networks (Action Evaluation Network as well as ASN) will have only two inputs and one output. It is found that the bias term really impedes the learning in these networks.

b. Updates of d's and f's weights in the ASN depend on the belief value of premise as well as consequent part of the rule. Thus, only those weights are updated for which rules fire. If the firing strength of the rule is zero, then, the weights are not updated.

c. All failures in ARIC are crisp failures with protection so that the ASN performance does not degrade below an acceptable level. Our current implementation uses crisp failure, e.g. 0 or -1. at 1.4 DB, but we protect the weight updating from too much punishment.

d. If an action is modified by Stochastic Action Modifier, then, action is changed to no action rather than reverse action.

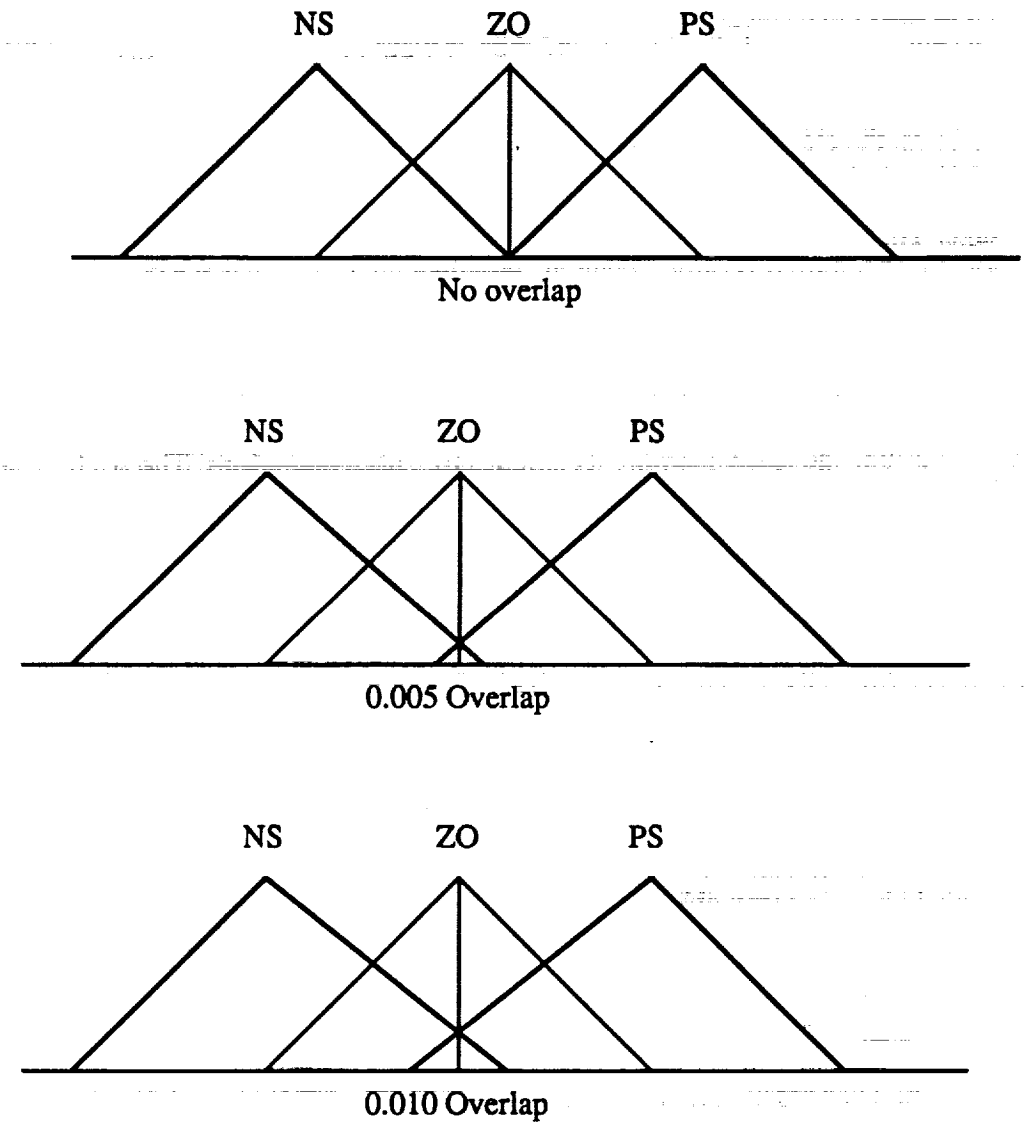
e. There are no changes in computations for measure of confidence in ASN. Currently, the measure of confidence is a function of number of rules. This situation is debatable but for simplicity in our study, we have left it the same.

f. Input parameters are normalized between 0.0 and 1.0.

g. For the attitude controller, we will use overlapping Membership Functions as shown in figure 2. However, we will not utilize such overlap in rate errors for translational controller because we have not analyzed the performance without such overlap. At this time we do not know if a hysterisis exists in the translational control.

3.0 Performance Results

The control tasks during the proximity operations are : 1) maintain the desired range by controlling the thrust along the line of sight, 2) keep the elevation and azimuth angles close to zero with respect to the line of sight, and 3) maintain the desired LVLH attitude within the specified deadband.



Rate Membership Functions Overlap to reduce the fuel usage

Figure 2. Attitude Controller - Overlapping Rate Error MBF's.

It is expected that the attitude controller is performing with desired accuracy in maintaining the desired angle and rate. This assumption is necessary because the translational controller is slaved after the attitude controller in the shuttle proximity operations in manual mode.

Our main results for the approach/docking special testcase are as follows.

1. During the mission, the 6 DOF ARIC performs all required tasks and control for translation as well as rotation axes. In comparison it uses exetremely high amount of fuel. But, it should be noted that the ARIC has no fuel constraints.

2. The orientation and relative position of the shuttle is accurately maintained during all segments of the mission. Figure 3 shows the pitch, yaw and roll angles in the LVLH frame during the mission. Figure 4 shows the x, y and z position in the LVLH frame. The x and z positions maintained at 10 and 45 feet respectively shows that the satellite range from the sensor is 10 feet and the elevation angle is zero because of sensor location on the shuttle. The y position is maintained within one foot distance indicates nearly zero azimuth angle.

3. Roll and yaw rate coupling has high duty cycle and uses too much fuel. Figure 5 shows the body rates of the shuttle, and roll / yaw coupling seems to begin at 2000 seconds in the mission. It is appropriate to investigate the effects of overlap in rate membership functions for these axes.

4. Range rate maintenance uses too much fuel, especially during the last segment of station keeping at 10 feet. This fuel rate could be decreased by changing the range rate DB from 0.05 to 0.1 ft/sec. Figure 6 shows the fuel usage as a function of time, and high fuel usage begins at 3500 seconds in the mission, the beginning of the station keeping phase at 10 feet distance.

5. Azimuth maintenance is acceptable, but the deadband seems to be too tight. Further more the membership functions and ruels require close examination.

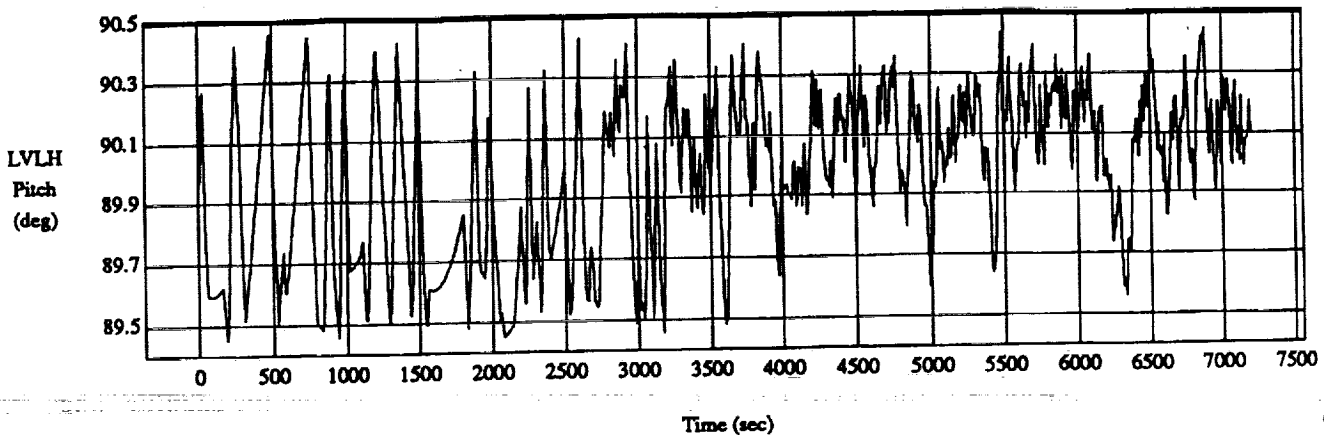
4.0 Conclusions and Summary

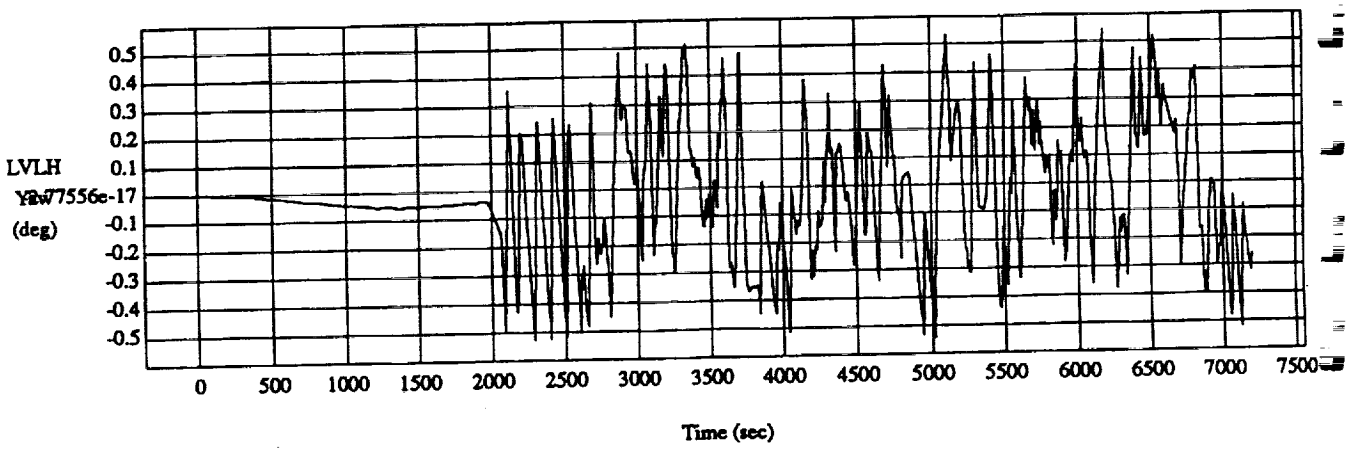
Based on the results obtained so far for the translational control as well as total 6 DOF control, it seems that the ARIC in its current implementation form is not suitable for proximity and docking operations.

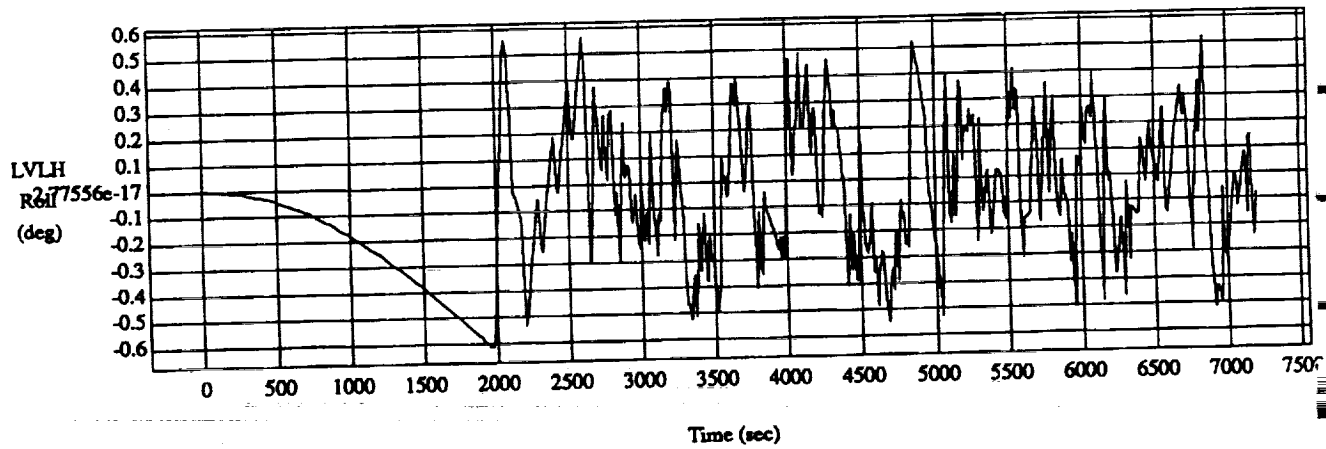
First of all it learns too slow because it does not encounter sufficient number of failures. However, it is also true that the ARIC will never encounter sufficient number of failures for any space operations. Basically, all space operations are designed to be failure-free. Every failure is very costly in space operations. No single point failures are allowed by design. All activities in space are fail-safe, fail-operational, meaning, for all single point failures it has to be operational. Furthermore, the attitude going out of the deadband is never considered a failure. It is just one state that controller is able to control. Similarly, going out of rate deadband is not considered a failure. For use in ARIC acrhitecture, we can consider them as failures, but these are really soft failures. Thus, the failures or the rate of failures expected by the ARIC architecture are not going to occur operationally. It is for this reason, the current ARIC architecture is not suitable.

Second, there is no mechanism in ARIC to sustain performance when two or more failures come in a sequence. There should be an automatic stop on learning and when a normal state is reached, an automatic trigger to learn.

LVLH EULER ATTITUDE TIME HISTORIES







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DATA SAMPLING FREQUENCY: 0.100 Hz

Figure 3. LVLH pitch, yaw and roll angles.

Local Vertical / Local Horizontal - Position

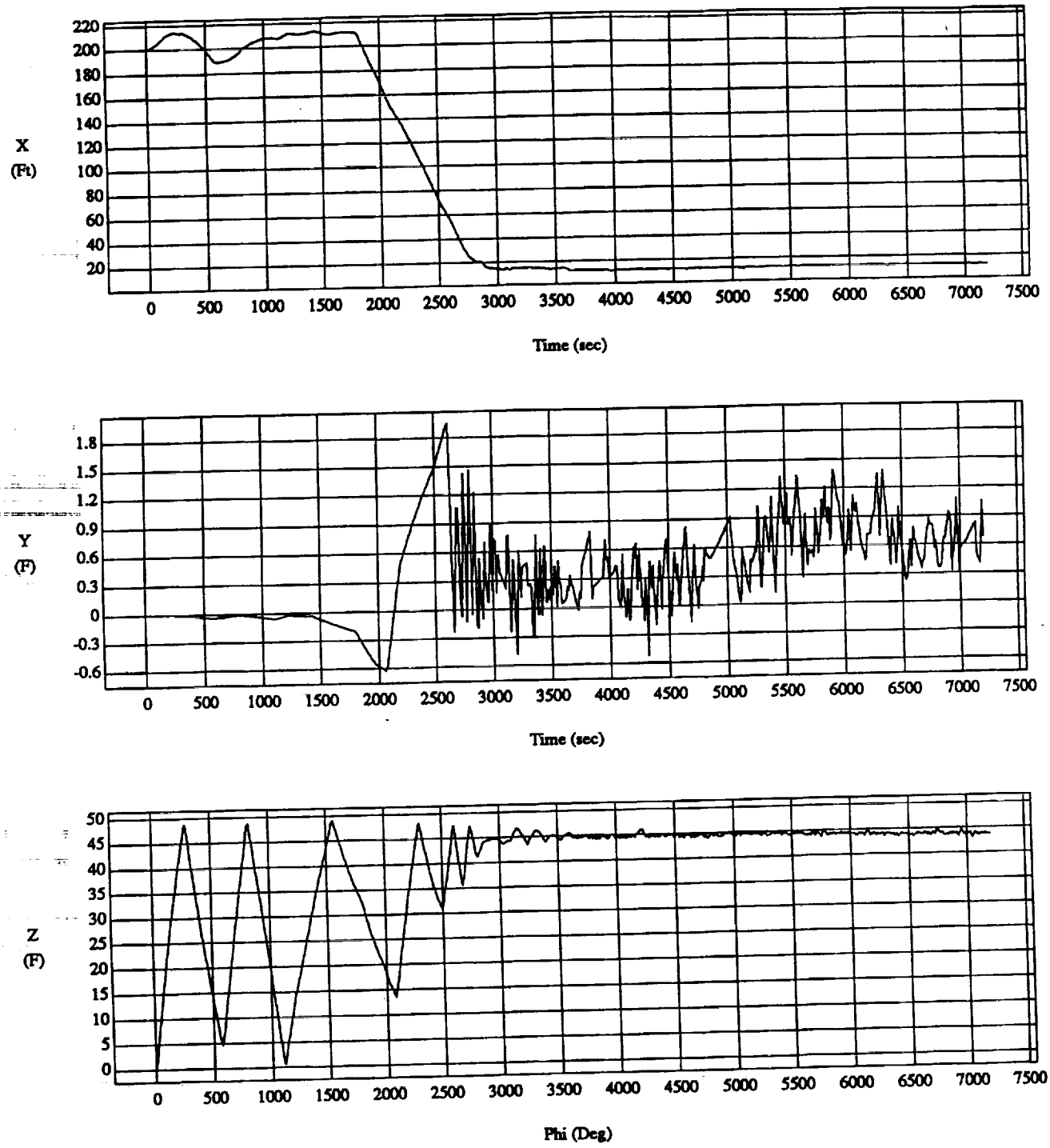

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Figure 4. LVLH x, y and z position.

BODY RATES TIME HISTORIES

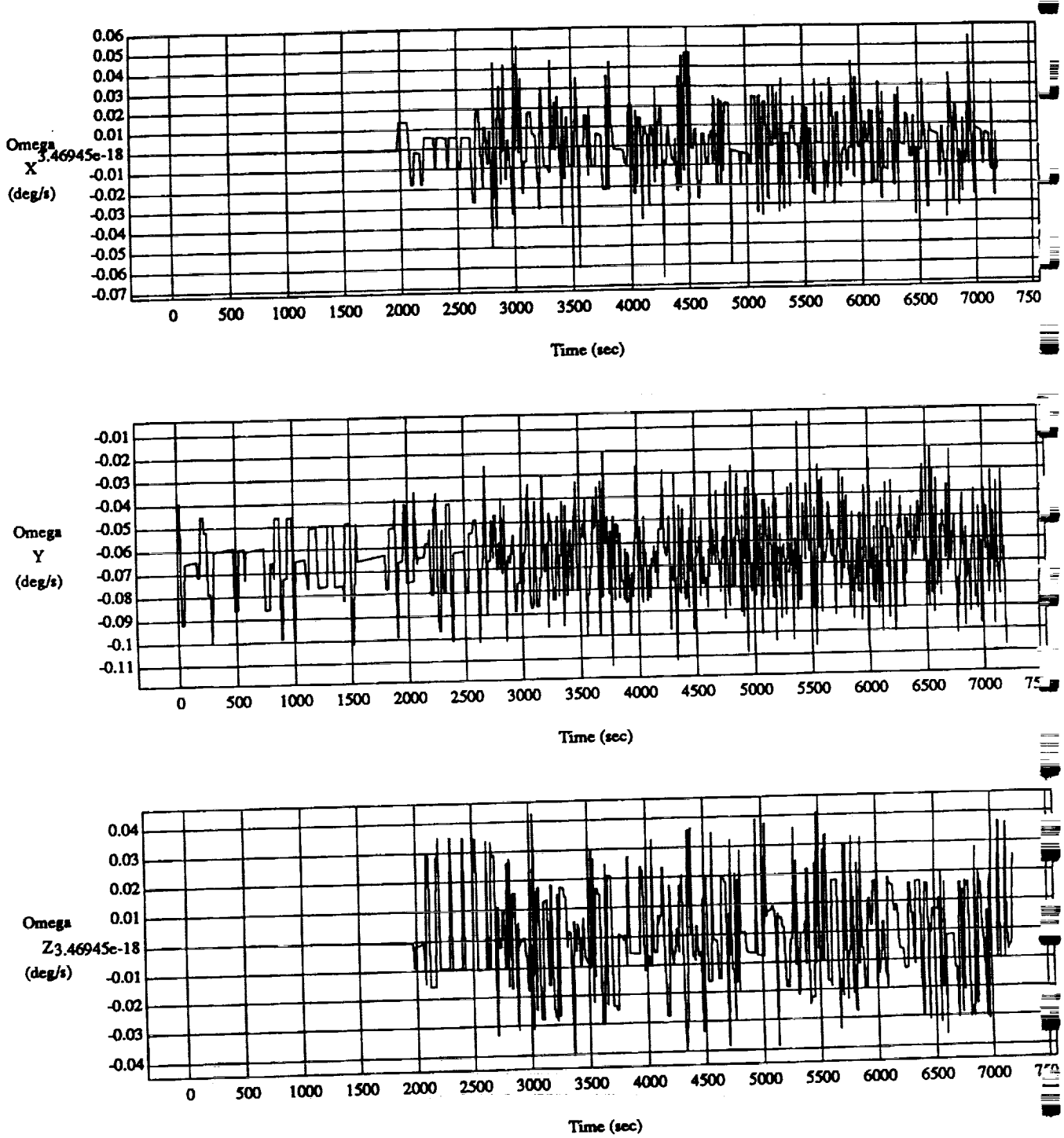

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Figure 5. The shuttle body rates.

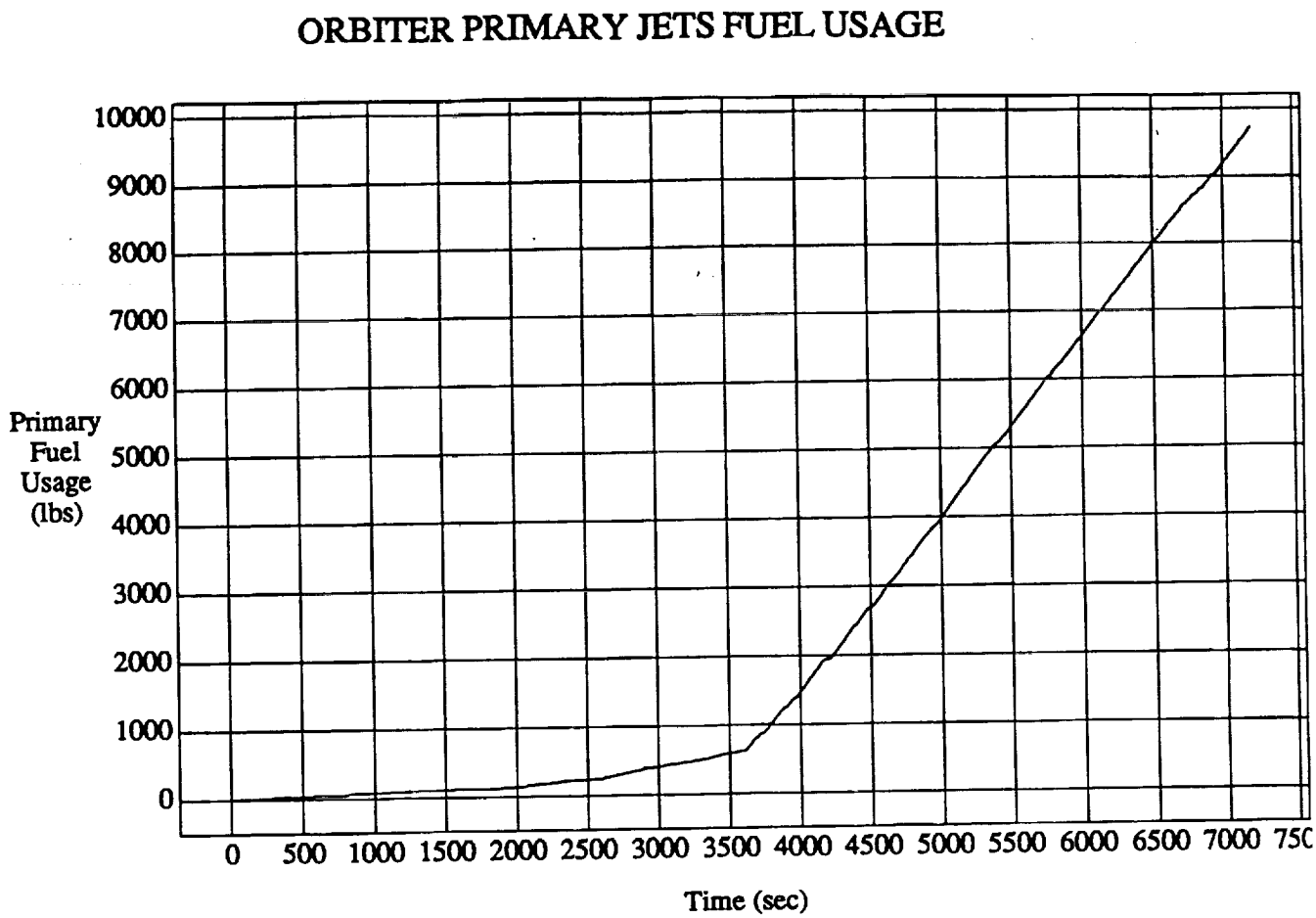

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Figure 6. Fuel usage time history during the mission.

Third, the ARIC architecture must allow soft failures and update weights accordingly. At this time we do not know what exactly is the impact of this change. However, for future testing with ARIC, we propose to implement failure value as shown in figure 7, and if possible, utilize a fuzzy rulebase that can consider fuel usage rate in computing this value.

Fourth, the current membership functions definitions and defuzzification technique does not allow for the inertia coming from the zero rule and zero membership function. Thus, both, the membership functions definitions and the defuzzification method are inadequate.

Fifth, there is no method in ARIC to move the end points of the membership functions. A capability to move these end points is required.

Some of these concerns are taken care of in the new GARIC architecture. Hopefully, it will provide some insight into how to apply learning methods to the space operations.

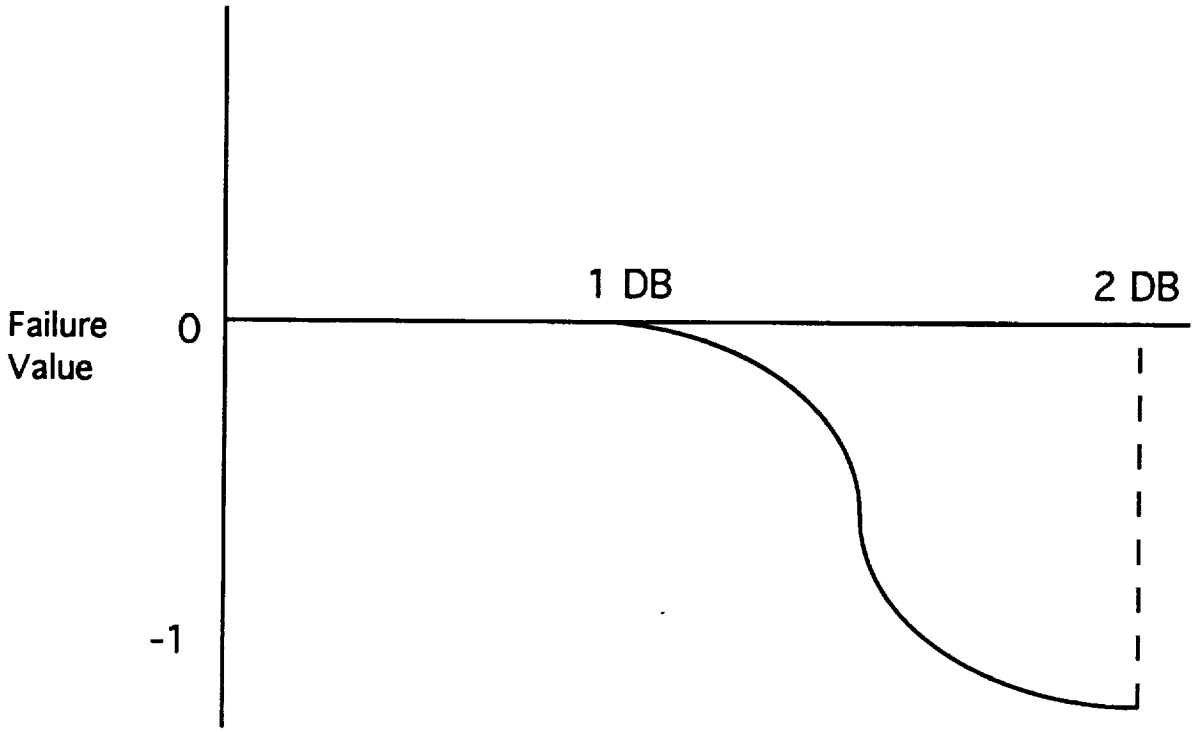
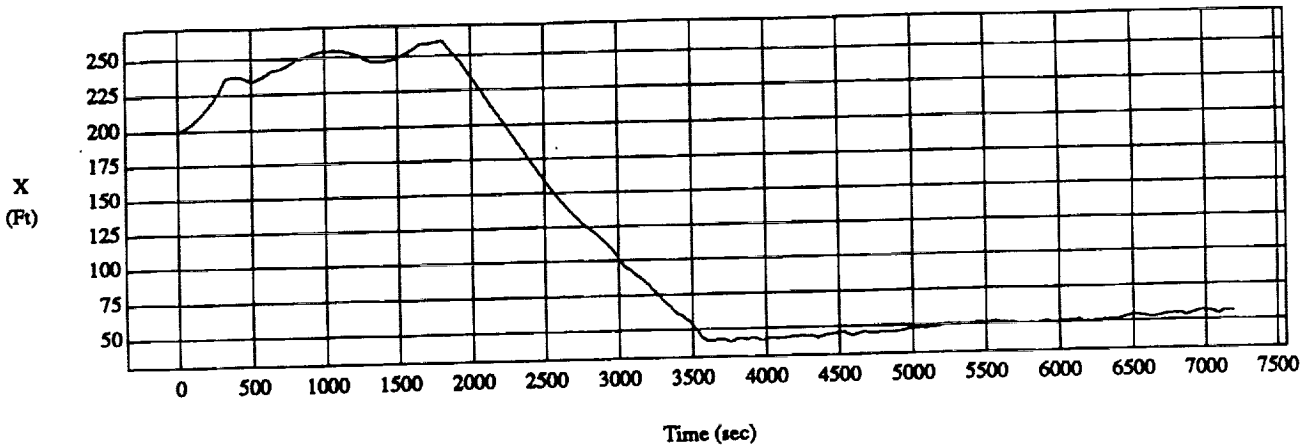


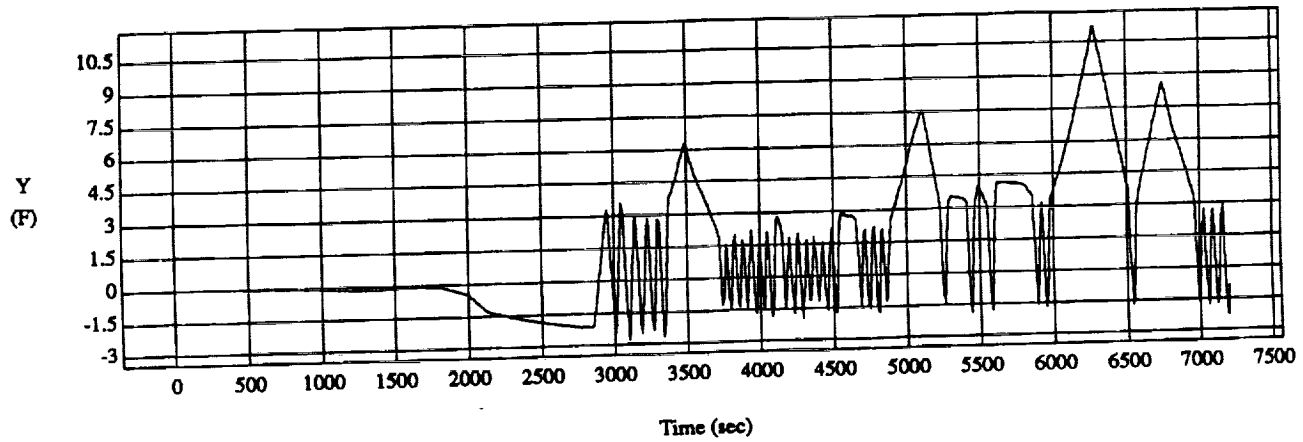
Figure 7. Fost Failure Implementation

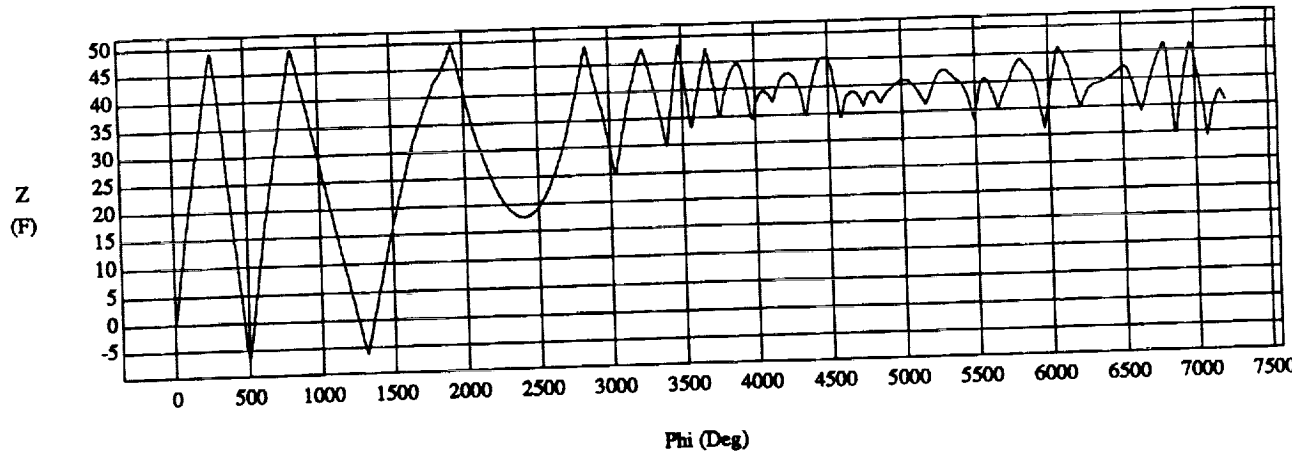
Appendix A.
Plots of Selected Parameters for Shuttle Translational Control

A1. First try with loose range and range rate deadbands.

Local Vertical / Local Horizontal - Position







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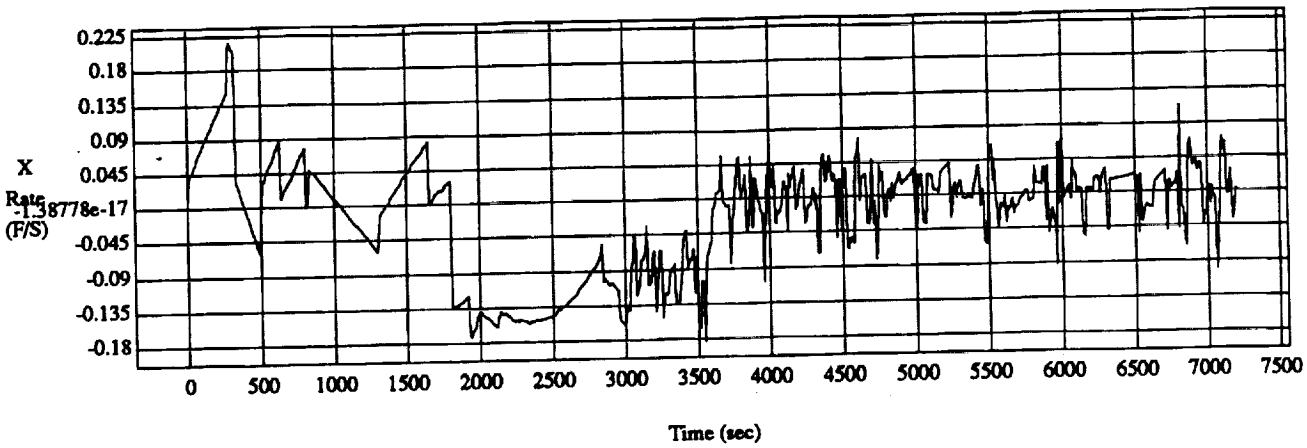
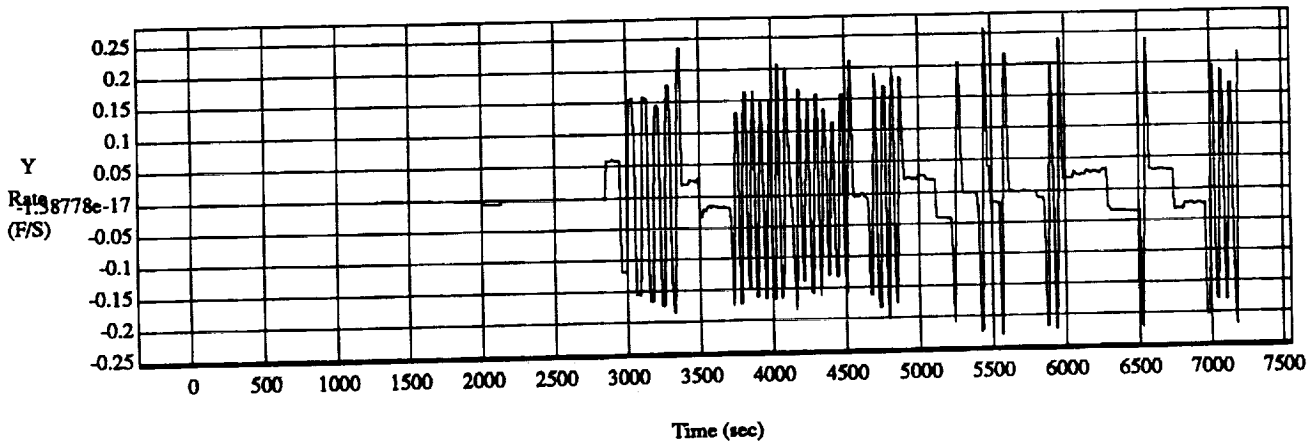
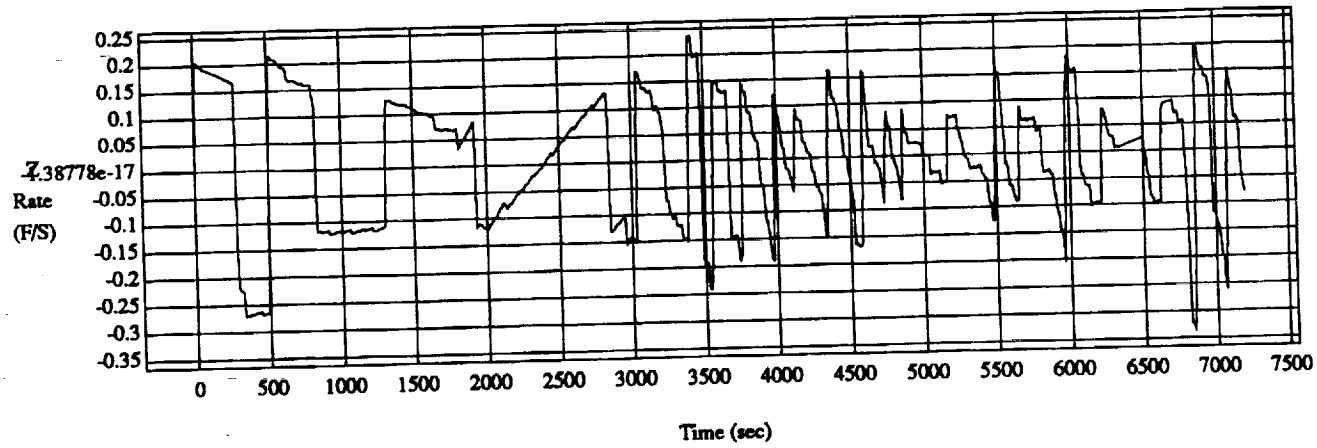
Local Vertical / Local Horizontal - Rate







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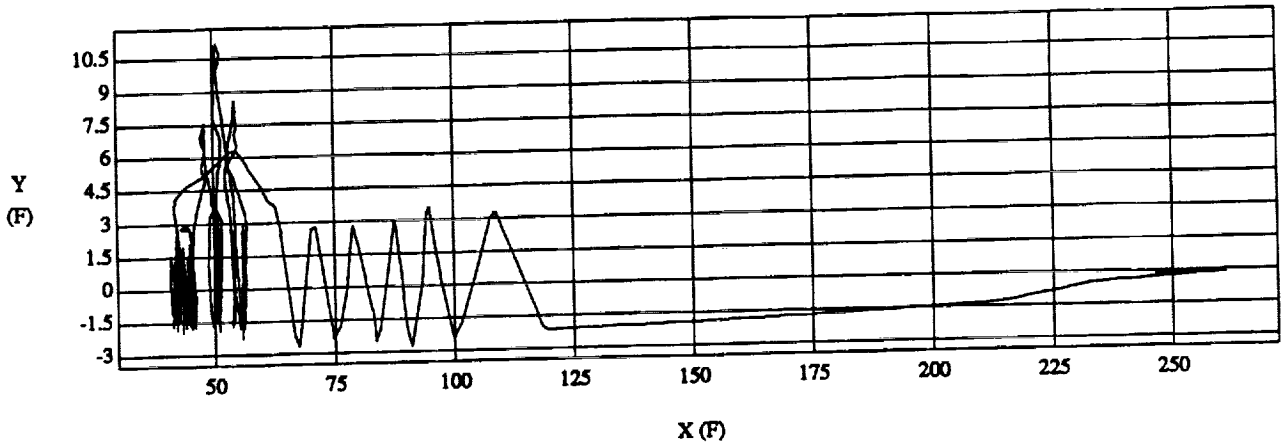

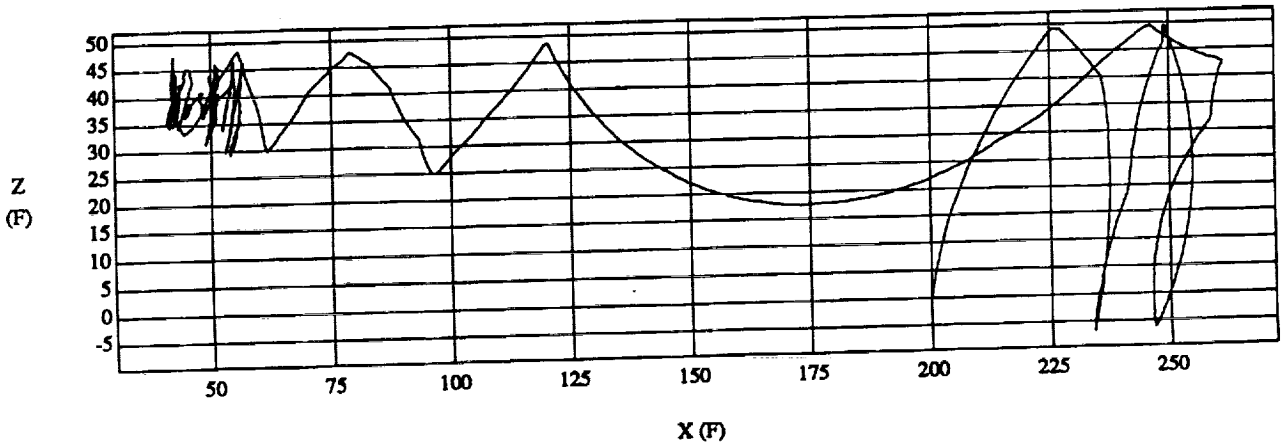

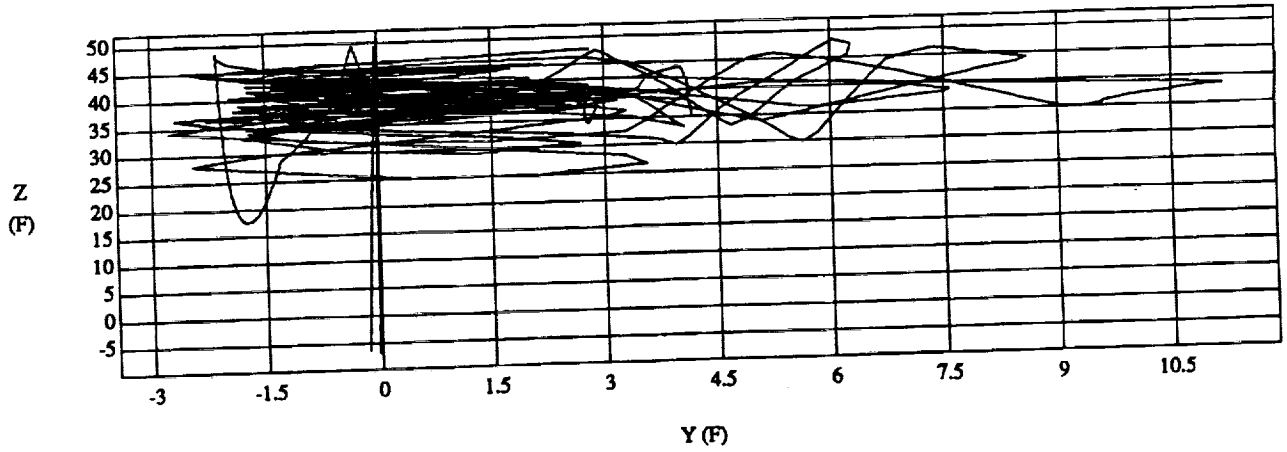

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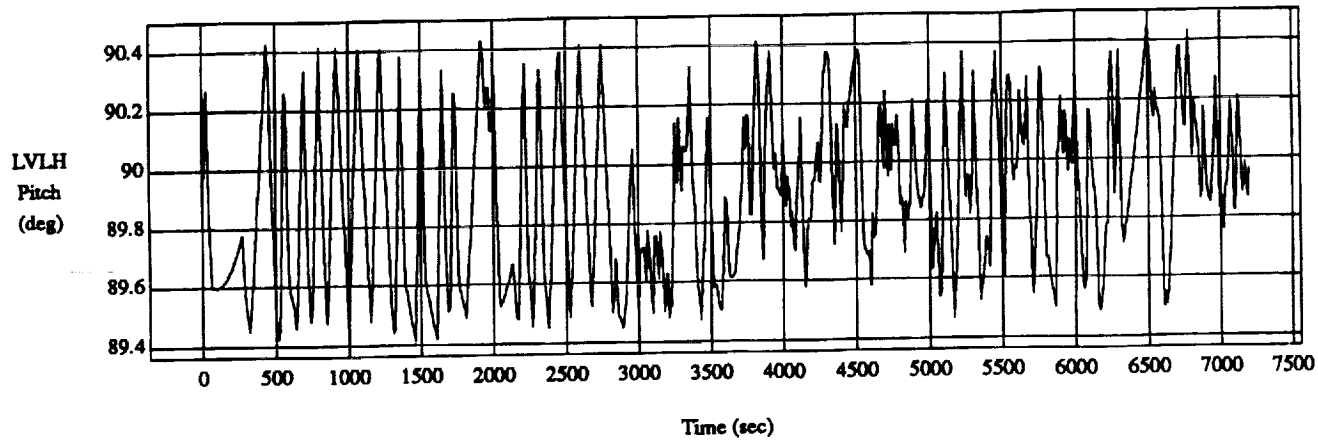
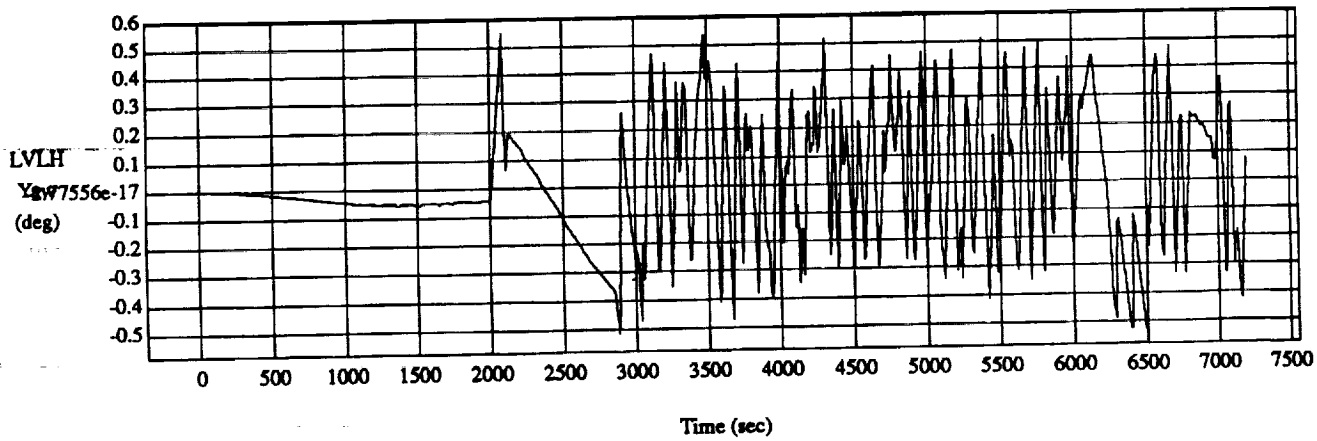
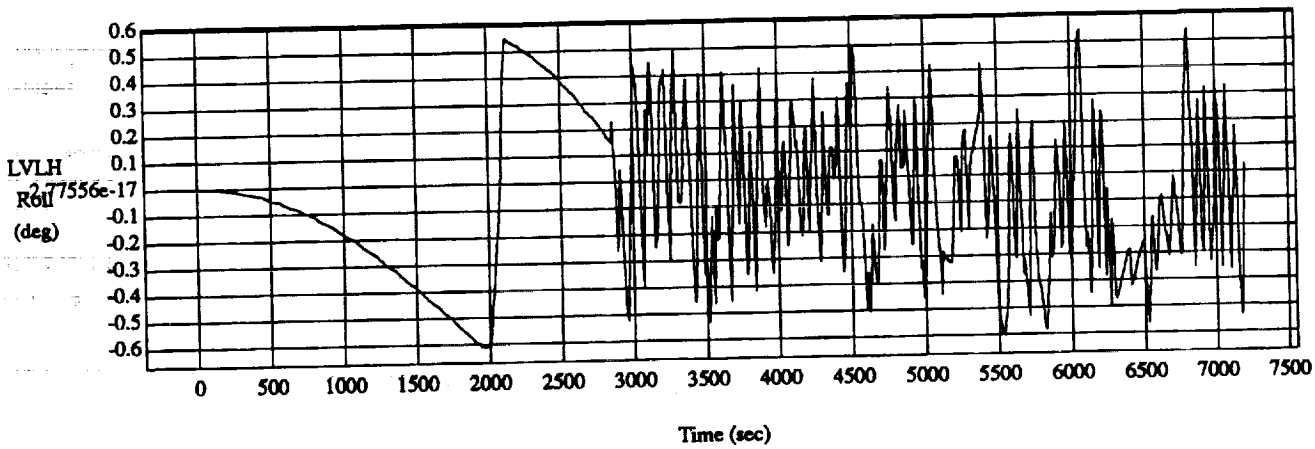
LVLH EULER ATTITUDE TIME HISTORIES







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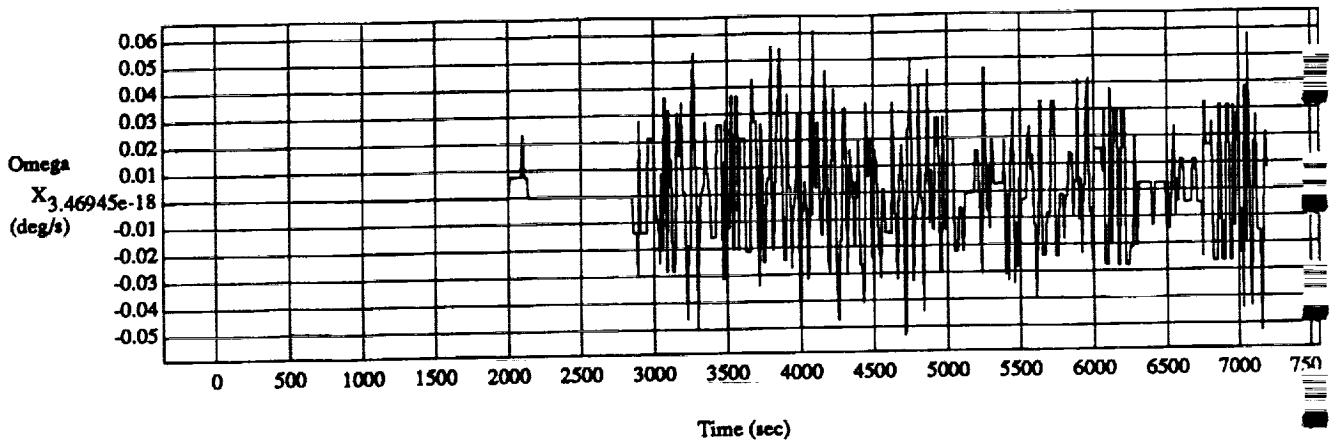
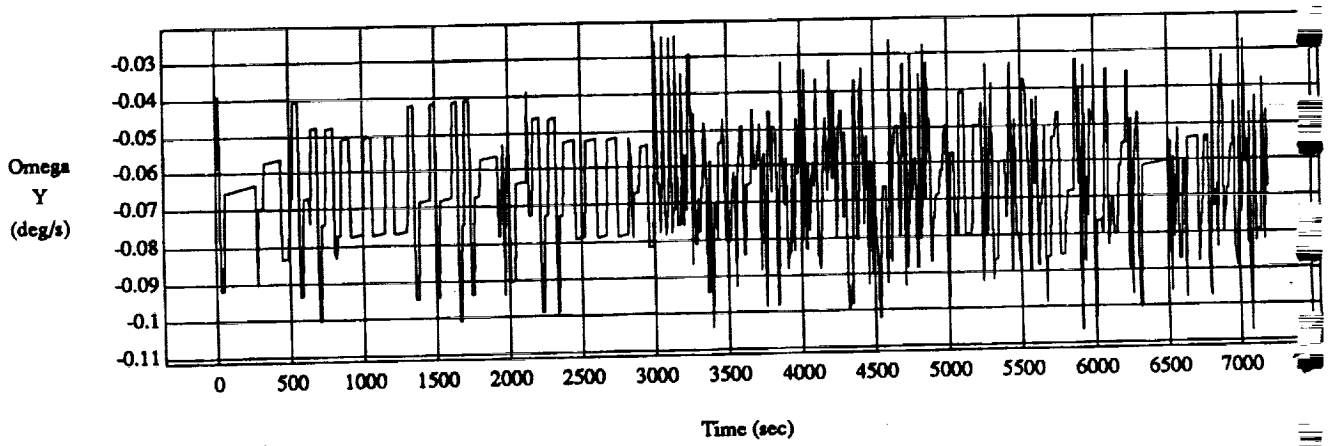
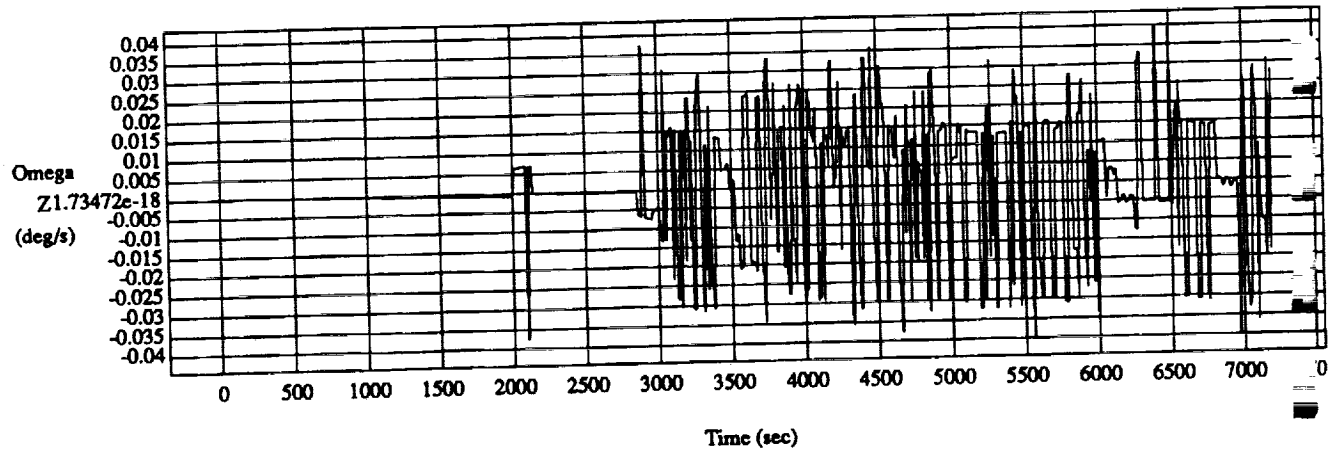
BODY RATES TIME HISTORIES







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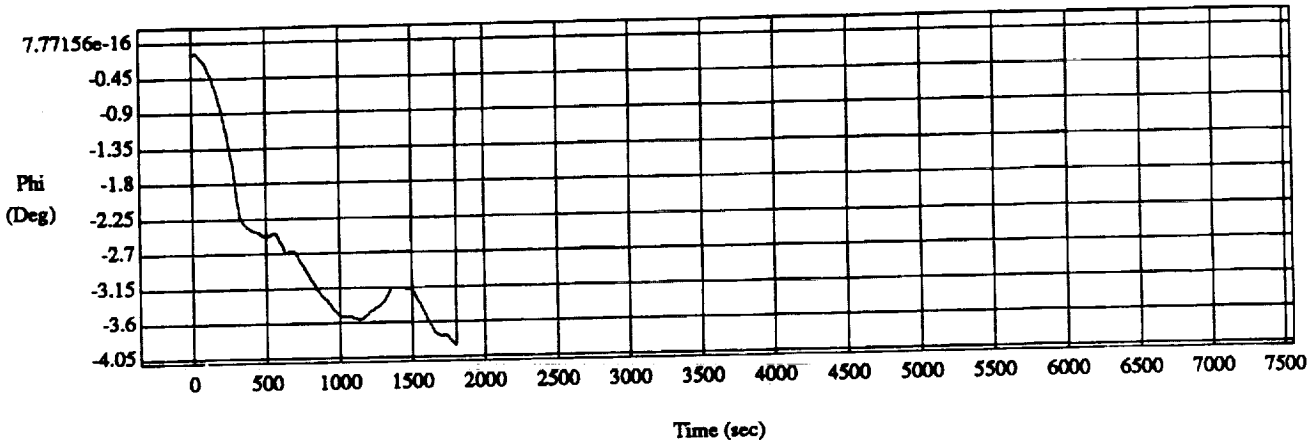
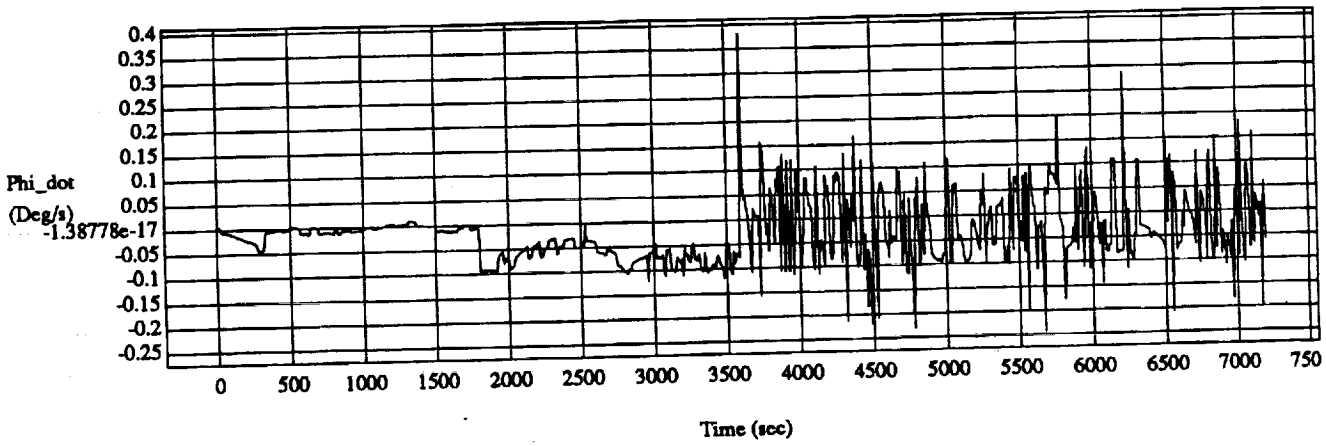
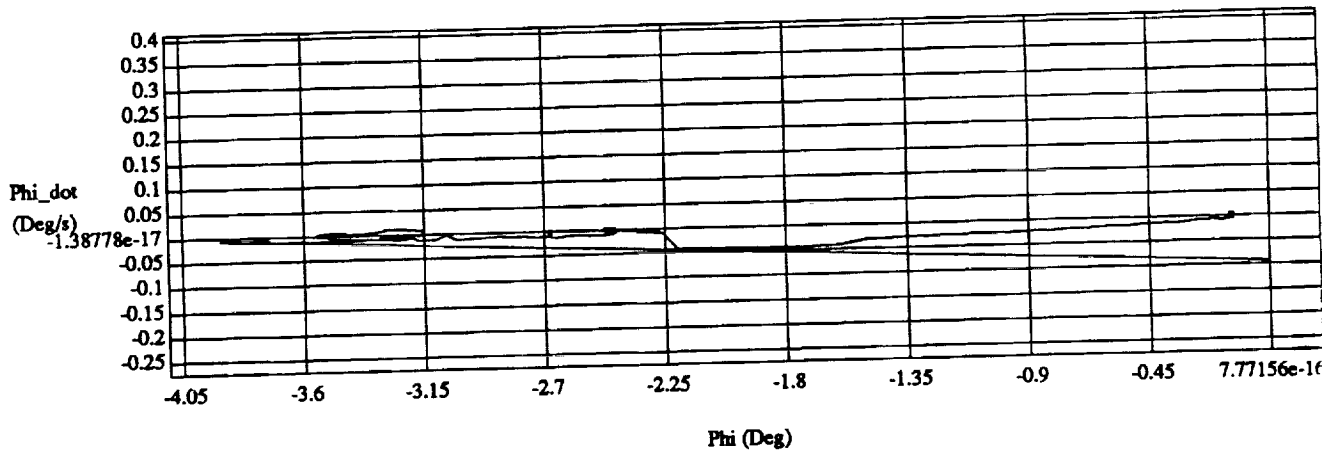
Range ARIC Learning Parameters - Inputs

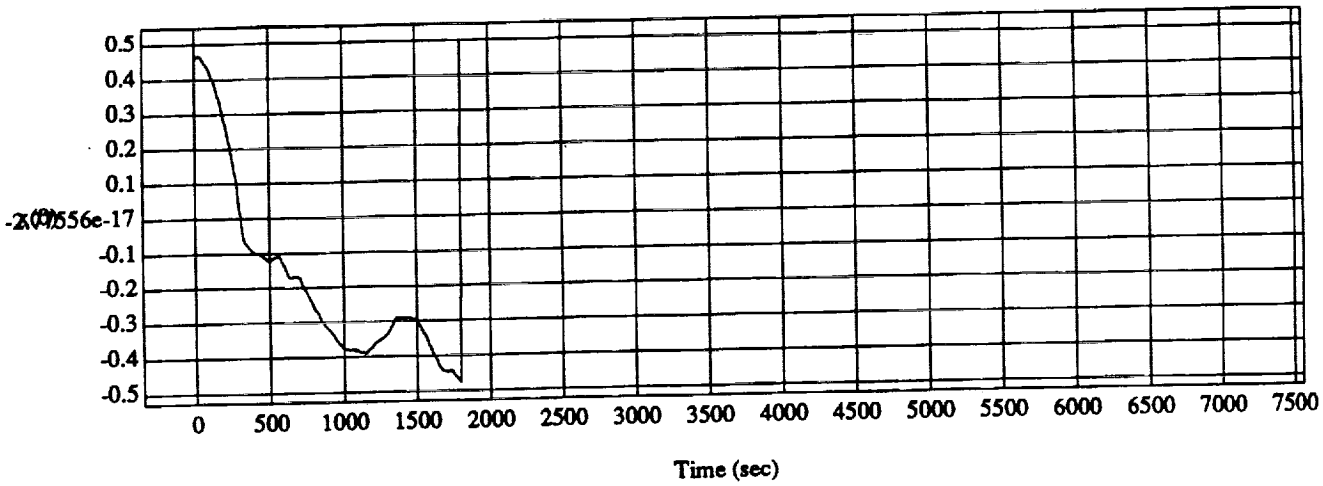


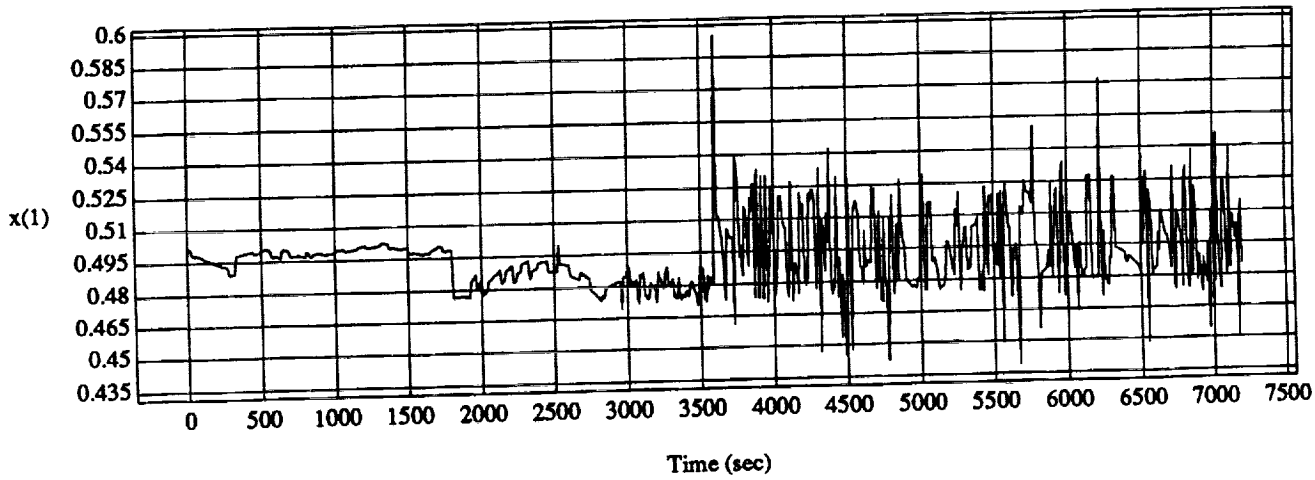




SIMULATION APPLICATION: ARIC Translational Controller Simulation
RUN IDENTIFICATION: 200 SK - Approach 10 - SK
MODEL: ORBITER
DATE: Wed Dec 23 1992 09:33:56 AM
NUMBER OF DATA POINTS: 721
DATA SAMPLING FREQUENCY: 0.100 Hz

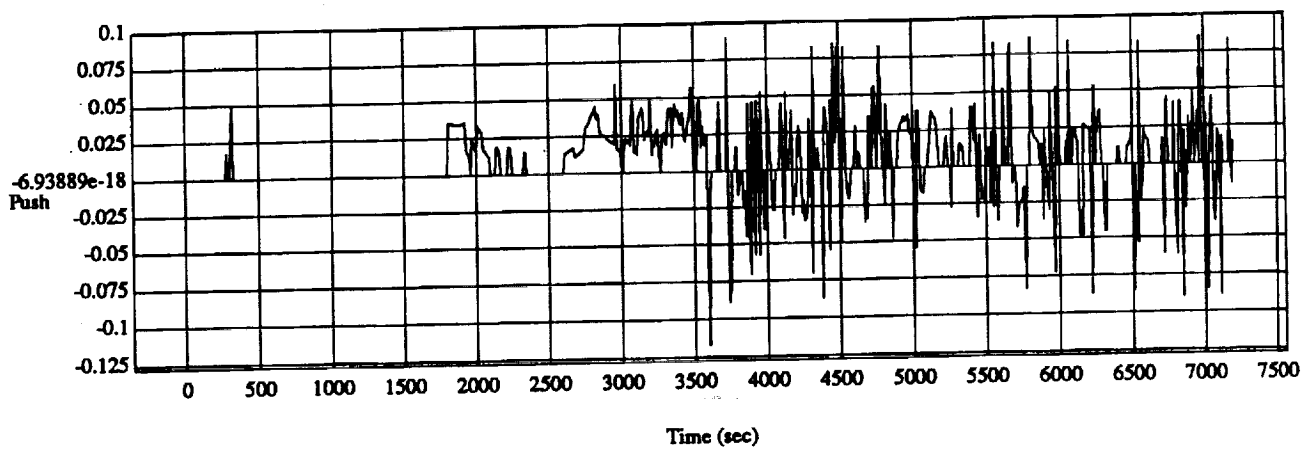
Range ARIC Learning Parameters - Scaled Inputs

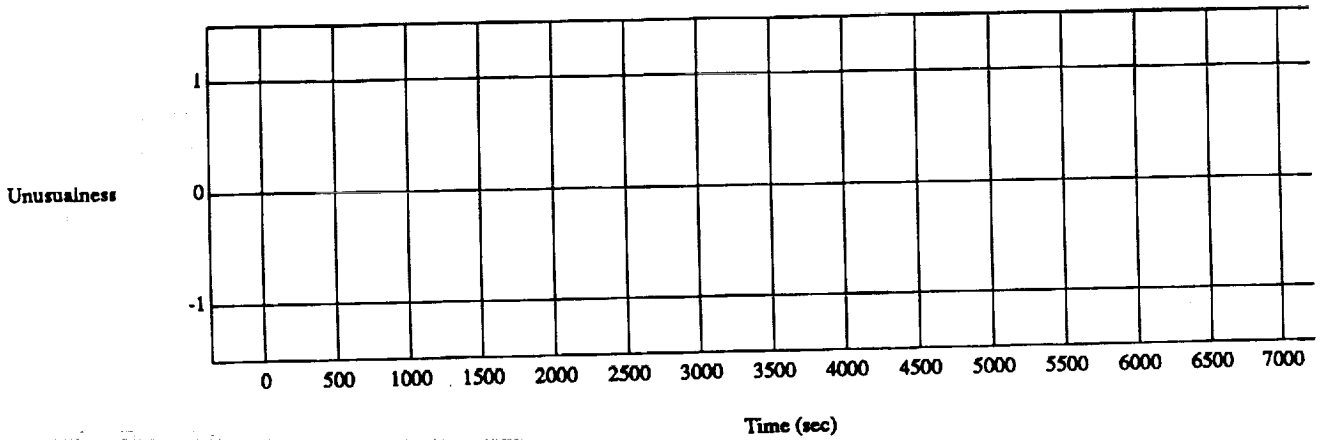


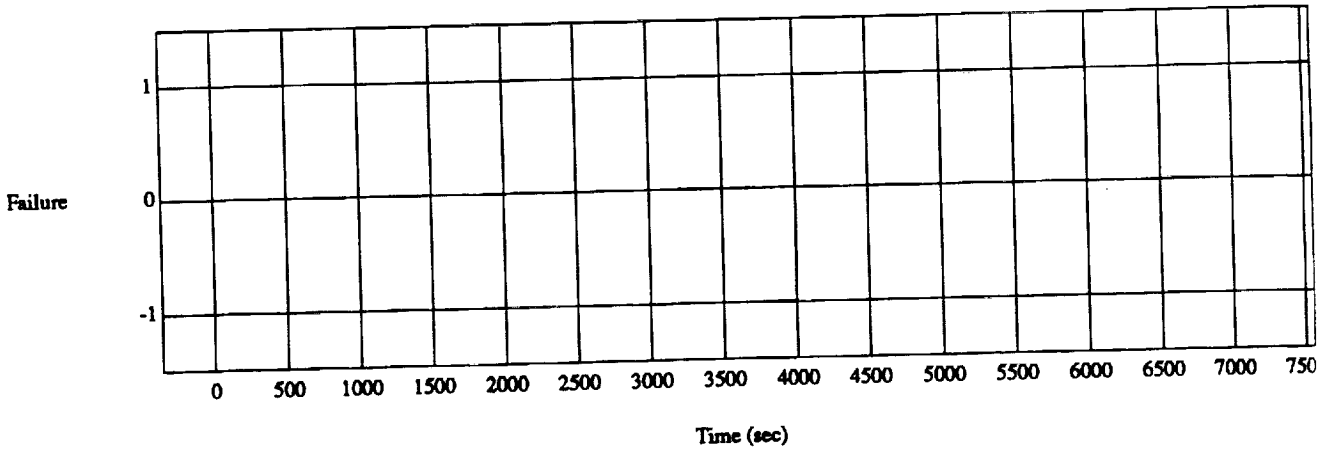


SIMULATION APPLICATION: ARIC Translational Controller Simulation
RUN IDENTIFICATION: 200 SK - Approach 10 - SK
MODEL: ORBITER
DATE: Wed Dec 23 1992 09:33:56 AM
NUMBER OF DATA POINTS: 721
DATA SAMPLING FREQUENCY: 0.100 Hz

Range ARIC Learning Parameters - General Parameters

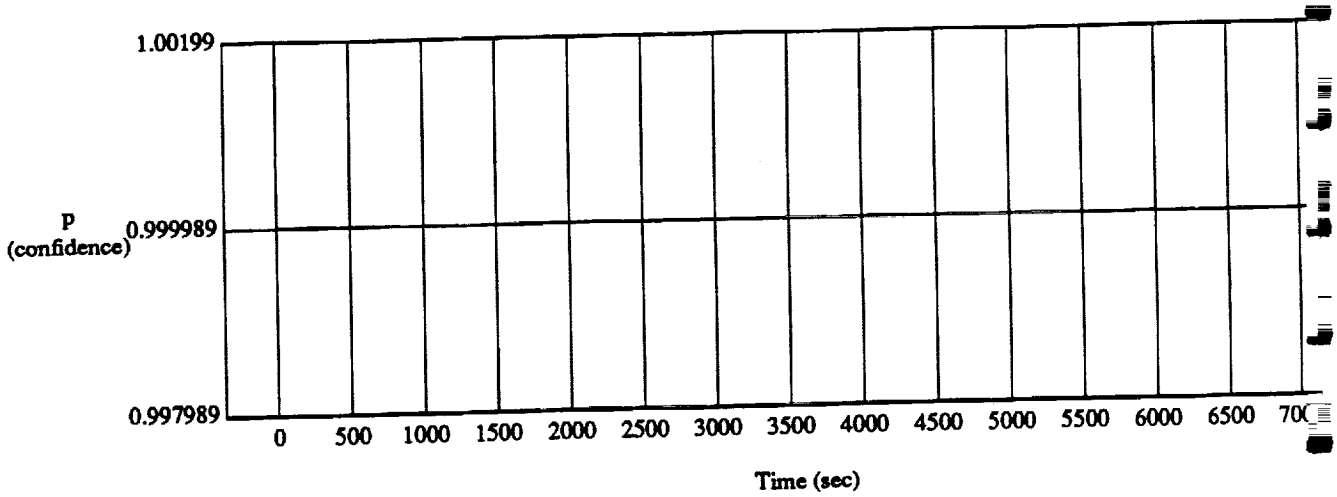


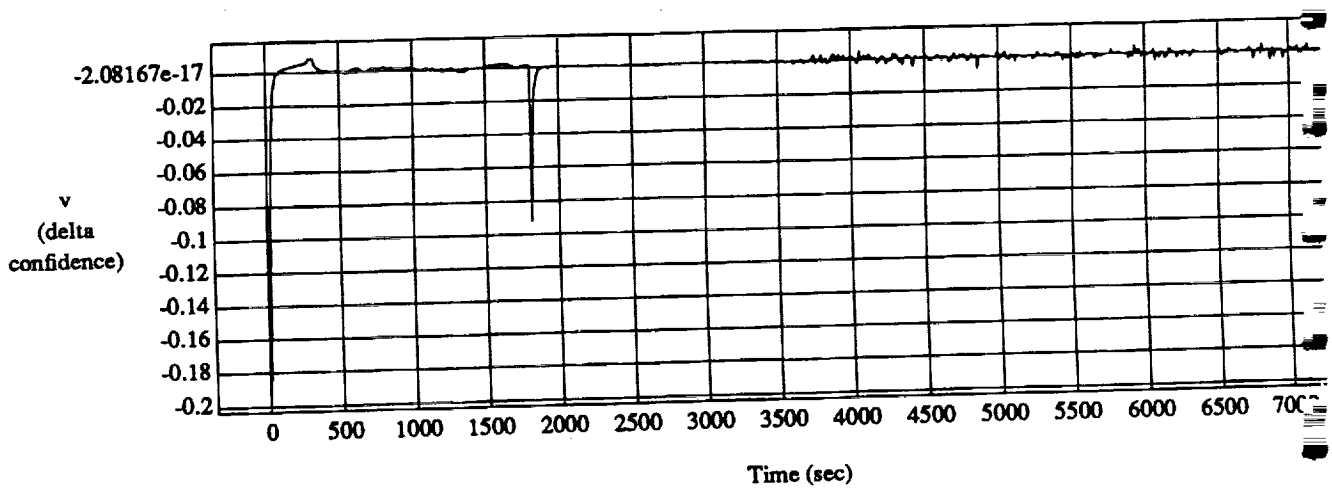




SIMULATION APPLICATION: ARIC Translational Controller Simulation
RUN IDENTIFICATION: 200 SK - Approach 10 - SK
MODEL: ORBITER
DATE: Wed Dec 23 1992 09:33:56 AM
NUMBER OF DATA POINTS: 721
DATA SAMPLING FREQUENCY: 0.100 Hz

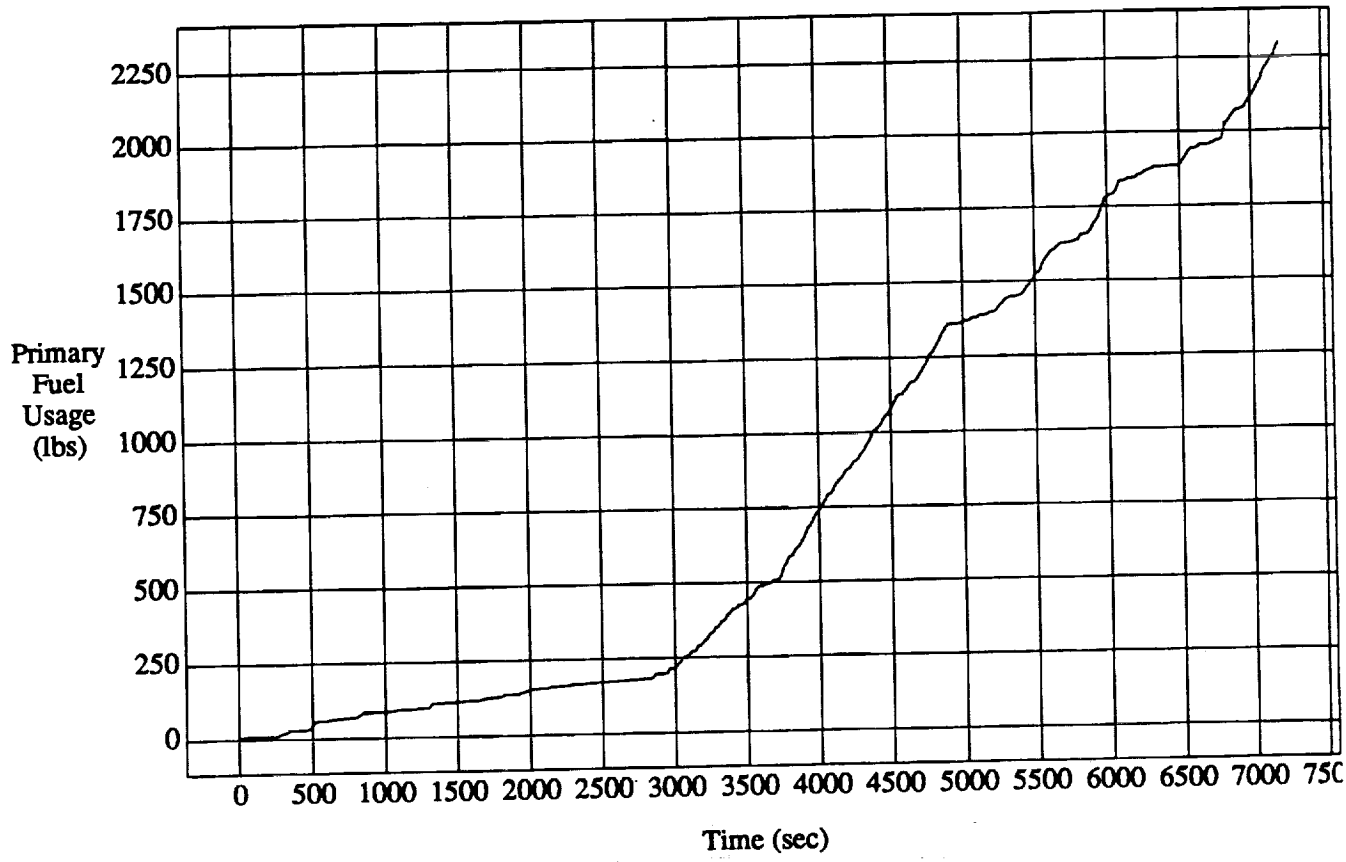
Range ARIC Learning Parameters - Learning Confidence





SIMULATION APPLICATION: ARIC Translational Controller Simulation
RUN IDENTIFICATION: 200 SK - Approach 10 - SK
MODEL: ORBITER
DATE: Wed Dec 23 1992 09:33:56 AM
NUMBER OF DATA POINTS: 721
DATA SAMPLING FREQUENCY: 0.100 Hz

ORBITER PRIMARY JETS FUEL USAGE



SIMULATION APPLICATION: ARIC Translational Controller Simulation
RUN IDENTIFICATION: 200 SK - Approach 10 - SK
MODEL: ORBITER
DATE: Wed Dec 23 1992 09:55:44 AM
NUMBER OF DATA POINTS: 361
DATA SAMPLING FREQUENCY: 0.050 Hz

```
learn_cycle: Failure at 322.000000.
learn_cycle: Failure at 525.760000.
learn_cycle: Failure at 642.400000.
learn_cycle: Failure at 744.560000.
learn_cycle: Failure at 851.680000.
learn_cycle: Failure at 1001.440000.
learn_cycle: Failure at 1153.120000.
learn_cycle: Failure at 1304.800000.
learn_cycle: Failure at 1318.560000.
learn_cycle: Failure at 1460.320000.
learn_cycle: Failure at 1612.000000.
learn_cycle: Failure at 1697.040000.
learn_cycle: Failure at 1805.920000.
learn_cycle: Failure at 2167.600000.
learn_cycle: Failure at 2273.360000.
learn_cycle: Failure at 2378.960000.
learn_cycle: Failure at 2528.640000.
learn_cycle: Failure at 2675.840000.
learn_cycle: Failure at 2823.520000.
learn_cycle: Failure at 2996.320000.
learn_azim: Failure at 3052.800000.
learn_azim: Failure at 3185.280000.
learn_azim: Failure at 3187.200000.
learn_azim: Failure at 3262.080000.
learn_azim: Failure at 3264.000000.
learn_azim: Failure at 3298.560000.
learn_azim: Failure at 3300.480000.
learn_azim: Failure at 3336.960000.
learn_azim: Failure at 3338.880000.
learn_azim: Failure at 3369.600000.
learn_azim: Failure at 3371.520000.
learn_cycle: Failure at 3430.240000.
learn_azim: Failure at 3738.240000.
learn_azim: Failure at 3740.160000.
learn_azim: Failure at 3768.960000.
learn_azim: Failure at 3770.880000.
learn_azim: Failure at 3792.000000.
learn_azim: Failure at 3793.920000.
learn_azim: Failure at 3820.800000.
learn_azim: Failure at 3822.720000.
learn_azim: Failure at 3851.520000.
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learn_azim: Failure at 4047,360000.
learn_azim: Failure at 4078.080000.
learn_azim: Failure at 4080.000000.
learn_azim: Failure at 4104.960000.
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learn_azim: Failure at 4168.320000.
learn_azim: Failure at 4170.240000.
learn_azim: Failure at 4195.200000.
learn_azim: Failure at 4197.120000.
learn_azim: Failure at 4225.920000.
learn_azim: Failure at 4227.840000.
```

```
learn_azim: Failure at 4254.720000.
learn_azim: Failure at 4256.640000.
learn_azim: Failure at 4285.440000.
learn_azim: Failure at 4287.360000.
learn_azim: Failure at 4314.240000.
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learn_azim: Failure at 6566.400000.
learn_azim: Failure at 6568.320000.
learn_cycle: Failure at 6632.800000.
learn_azim: Failure at 6990.720000.
```

```
learn_azim: Failure at 6992.640000.
learn_azim: Failure at 7021.440000.
learn_azim: Failure at 7023.360000.
learn_azim: Failure at 7054.080000.
learn_azim: Failure at 7056.000000.
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learn_azim: Failure at 7117.440000.
learn_azim: Failure at 7119.360000.
learn_azim: Failure at 7152.000000.
learn_azim: Failure at 7153.920000.
learn_azim: Failure at 7182.720000.
learn_azim: Failure at 7184.640000.
        SIMULATION TERMINATED BY 'termin'

SIMULATION START TIME:     0
SIMULATION STOP TIME:      7.2e+03
SIMULATION ELAPSED TIME:   7.2e+03
ACTUAL ELAPSED TIME:       1.32e+03
ACTUAL CPU TIME USED:      1.22e+03
SIMULATION / ACTUAL TIME: 5.45
SIMULATION / CPU TIME:     5.9
CPU TIME FOR INITIALIZATION: 2.16
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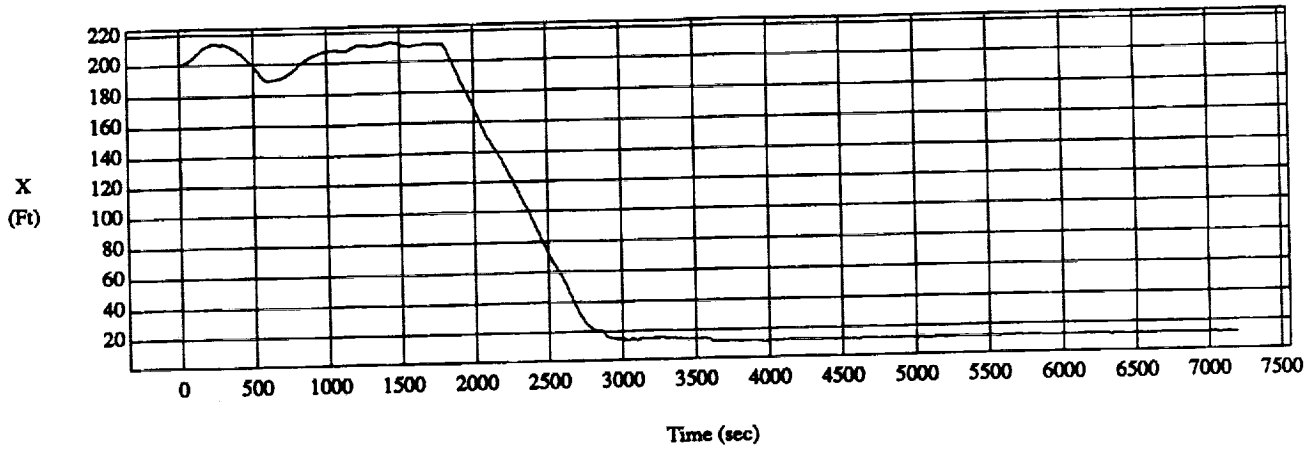
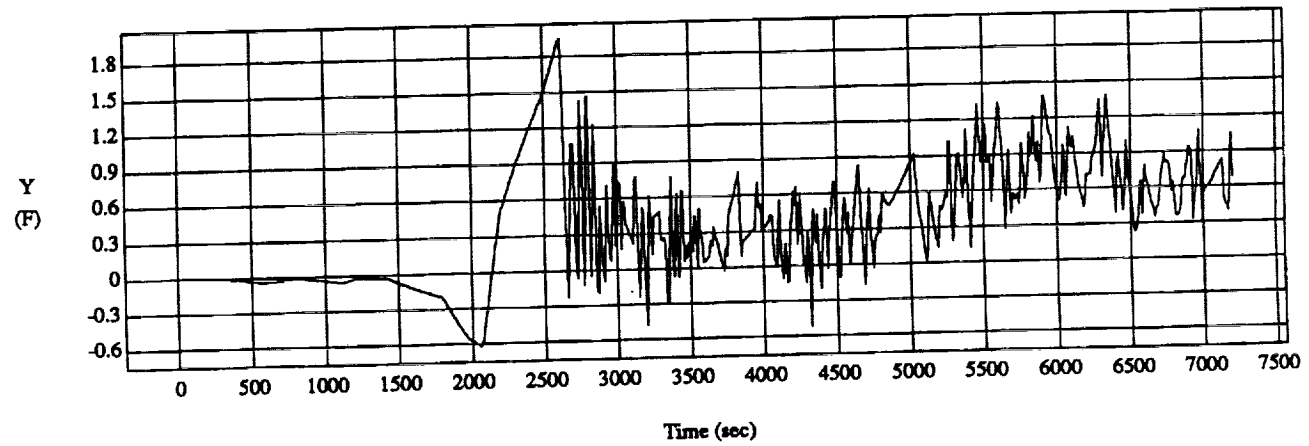
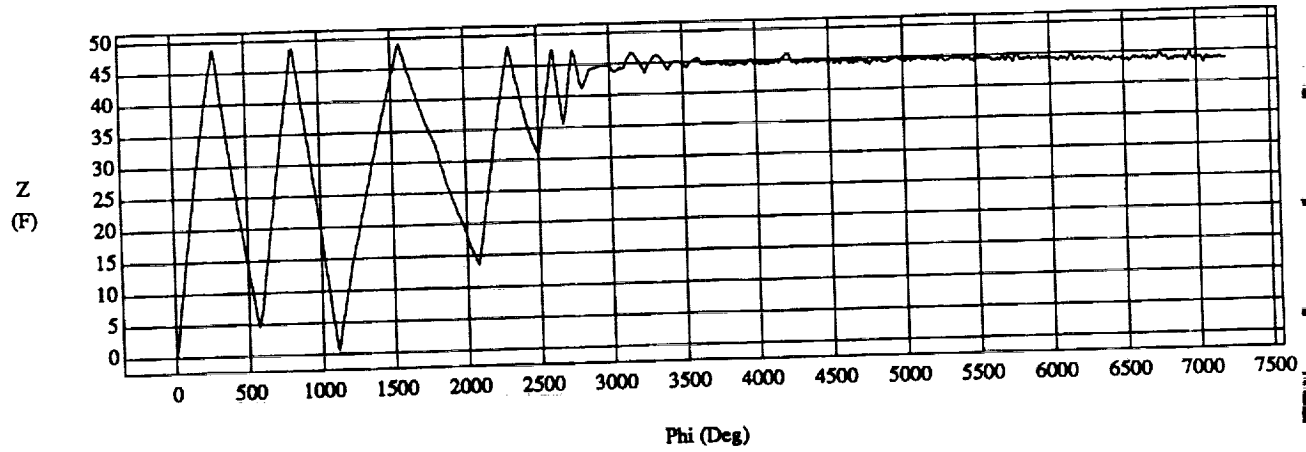
A2. Second try with tight range and range rate deadbands.

Local Vertical / Local Horizontal - Position

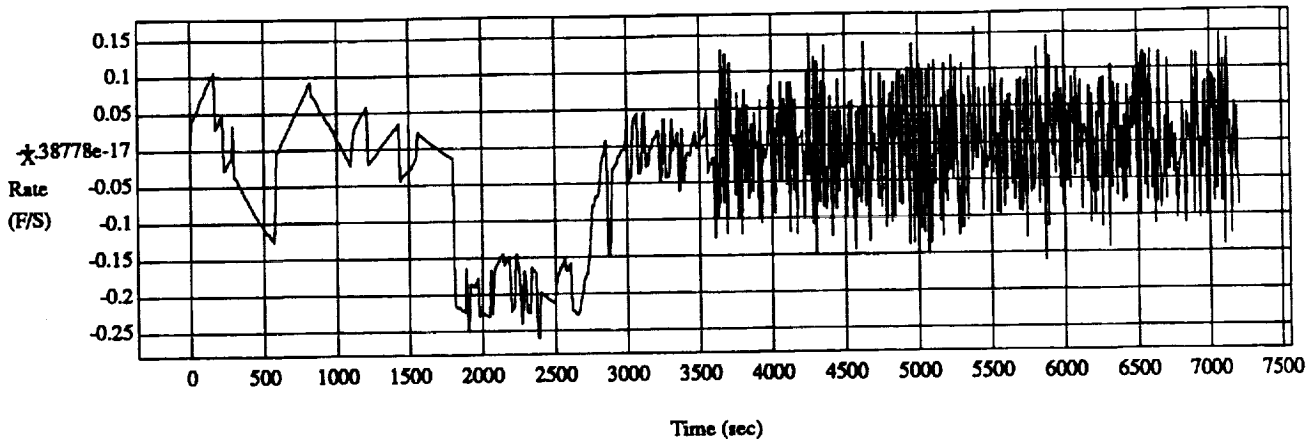


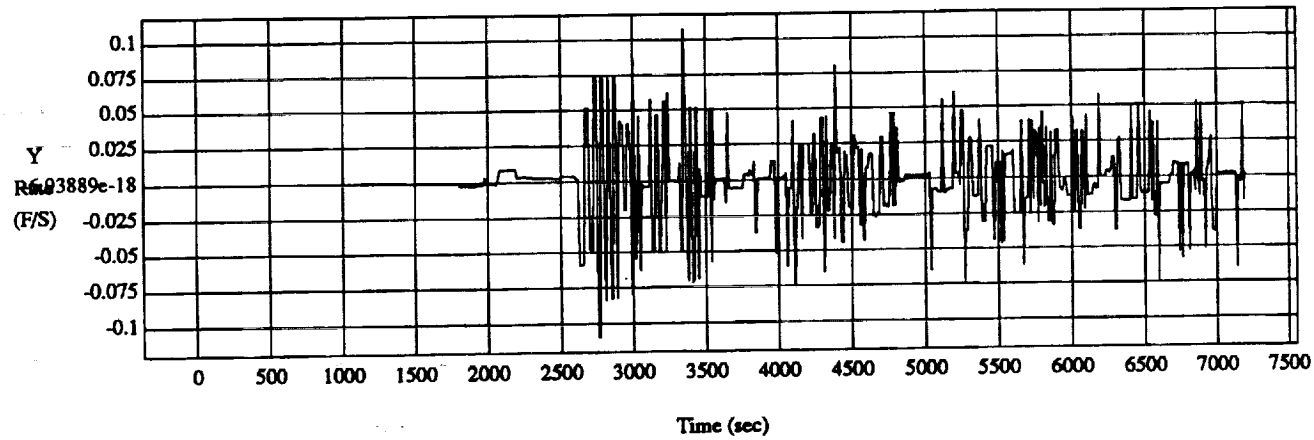


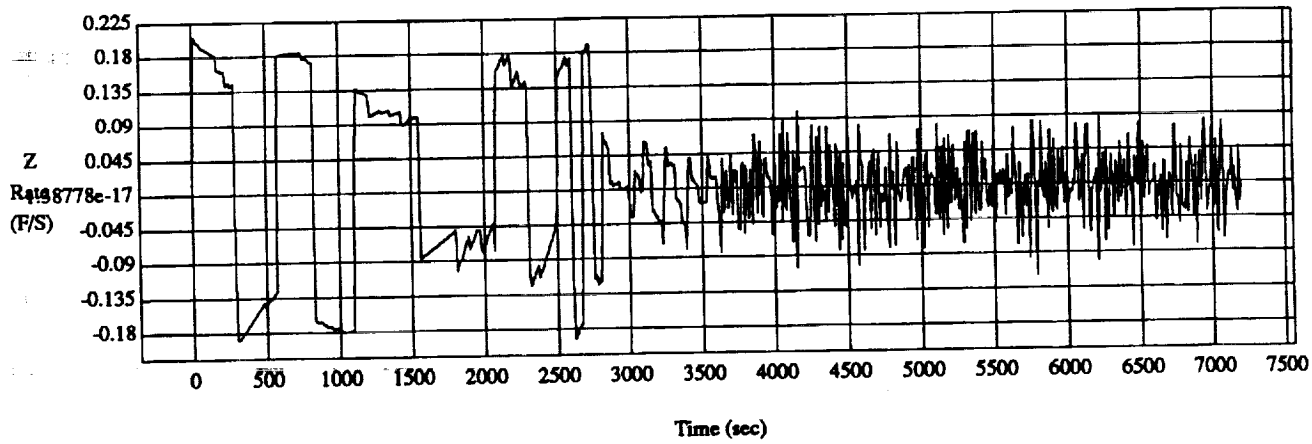


SIMULATION APPLICATION: ARIC Translational Controller Simulation
RUN IDENTIFICATION: 200 SK - Approach 10 - SK
MODEL: ORBITER
DATE: Tue Dec 29 1992 10:05:07 AM
NUMBER OF DATA POINTS: 721
DATA SAMPLING FREQUENCY: 0.100 Hz

Local Vertical / Local Horizontal - Rate

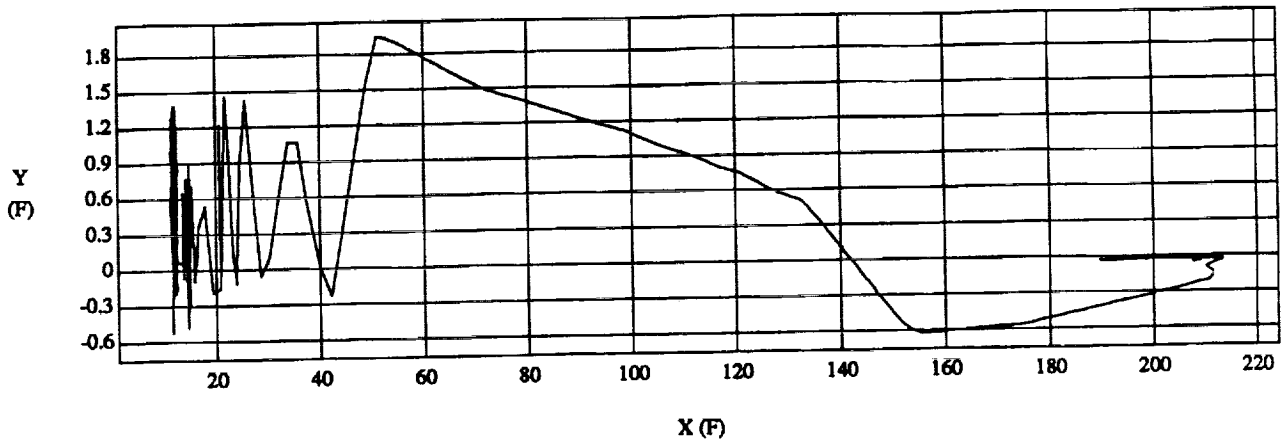


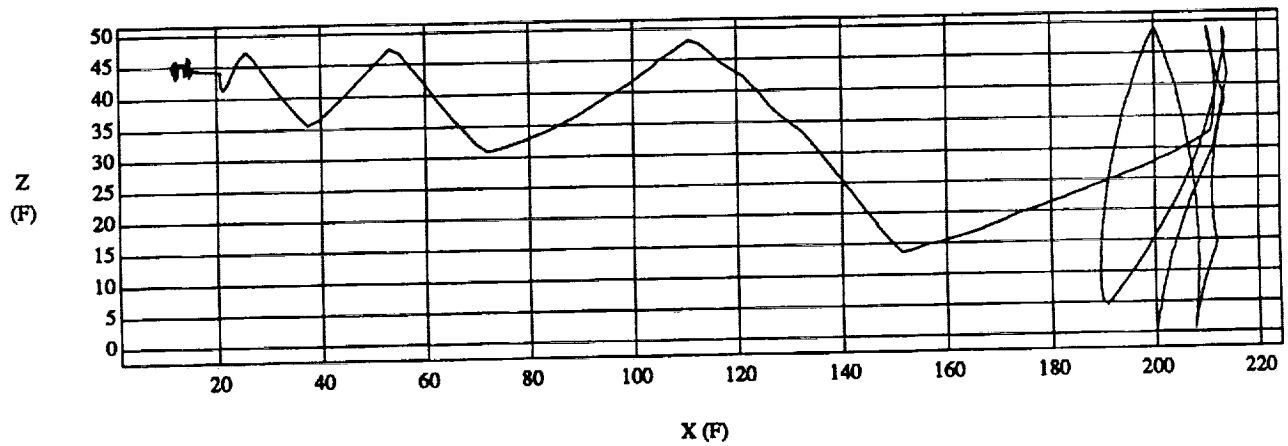


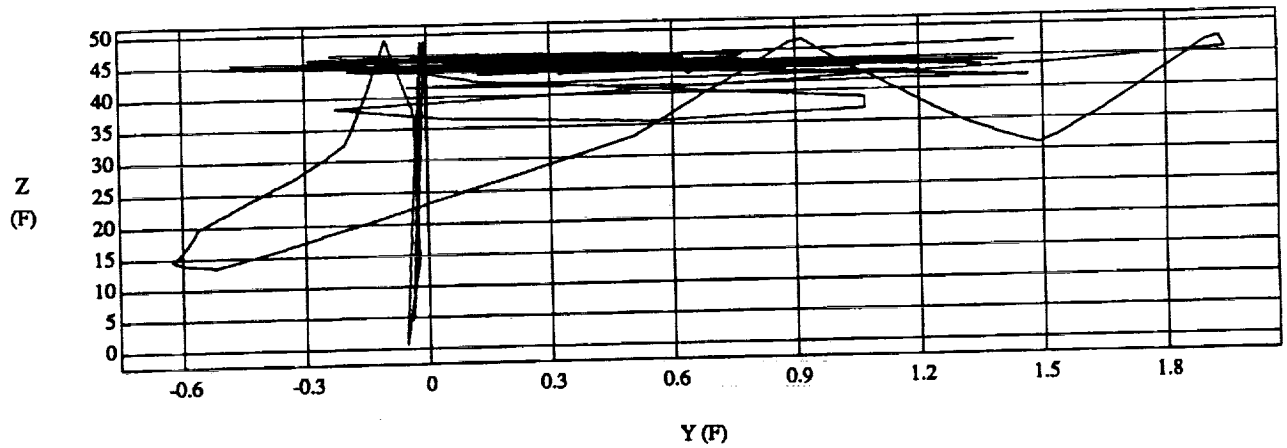


SIMULATION APPLICATION: ARIC Translational Controller Simulation
RUN IDENTIFICATION: 200 SK - Approach 10 - SK
MODEL: ORBITER
DATE: Tue Dec 29 1992 10:05:07 AM
NUMBER OF DATA POINTS: 721
DATA SAMPLING FREQUENCY: 0.100 Hz

Local Vertical / Local Horizontal - Traj

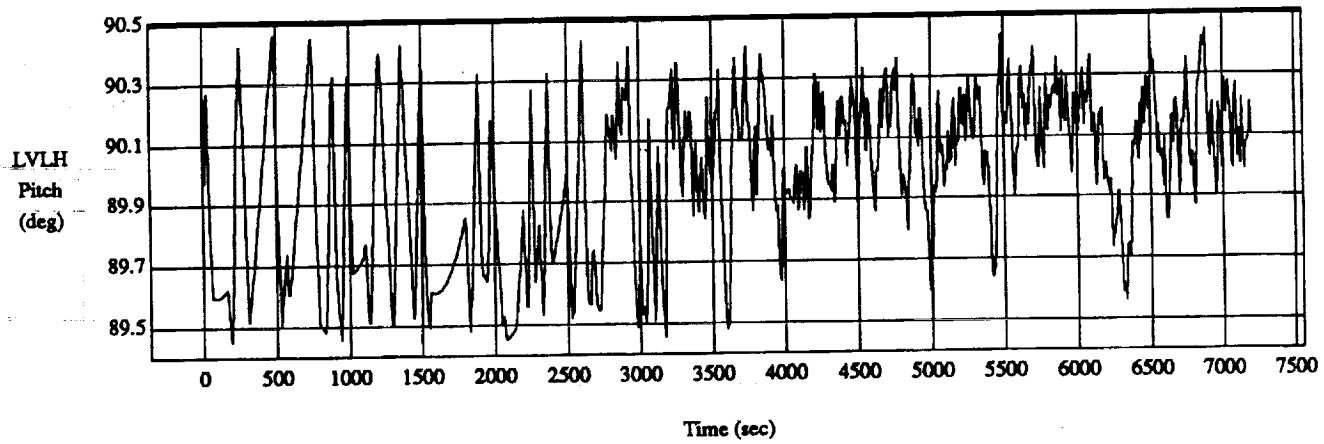


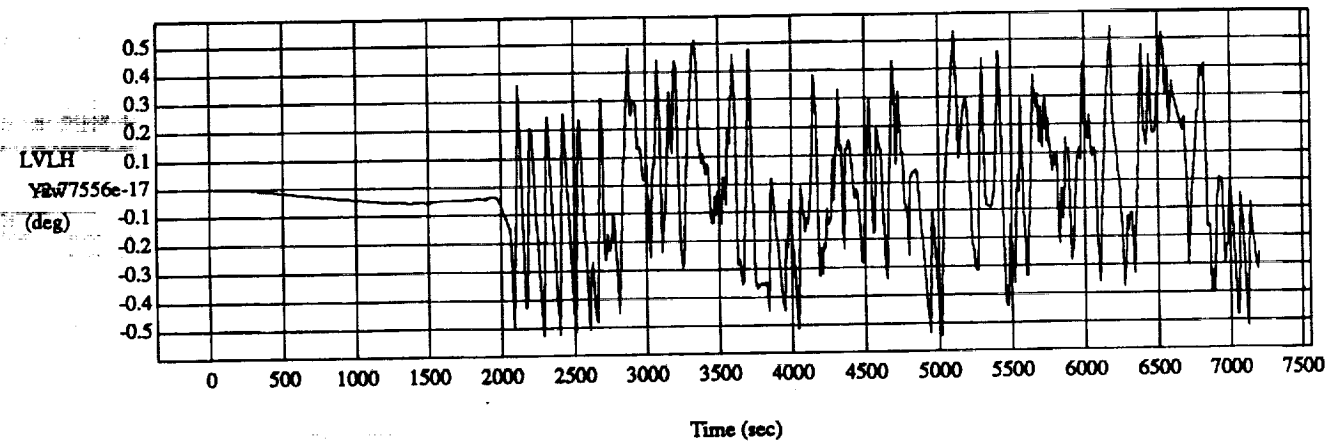


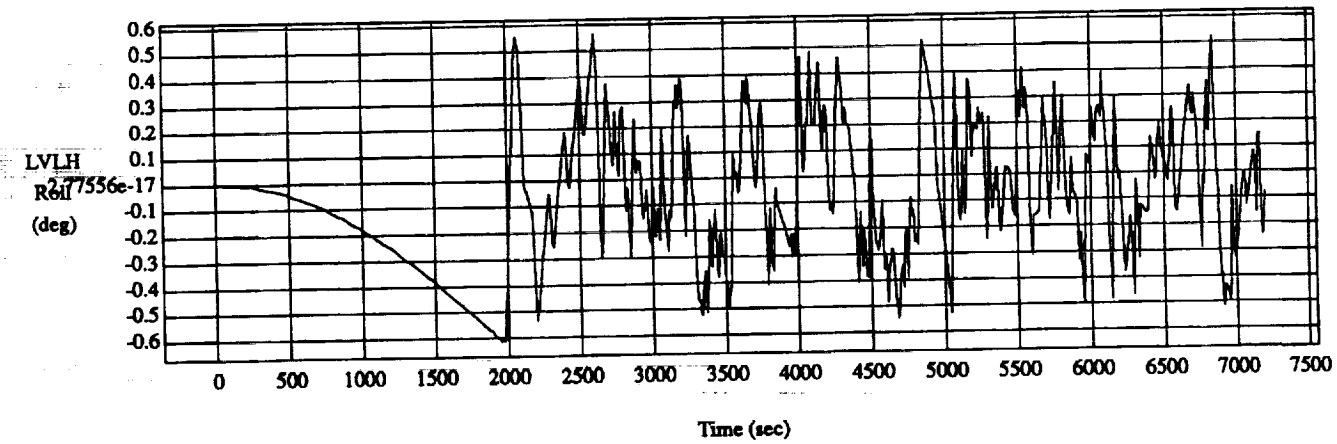


SIMULATION APPLICATION: ARIC Translational Controller Simulation
RUN IDENTIFICATION: 200 SK - Approach 10 - SK
MODEL: ORBITER
DATE: Tue Dec 29 1992 10:05:07 AM
NUMBER OF DATA POINTS: 721
DATA SAMPLING FREQUENCY: 0.100 Hz

LVLH EULER ATTITUDE TIME HISTORIES

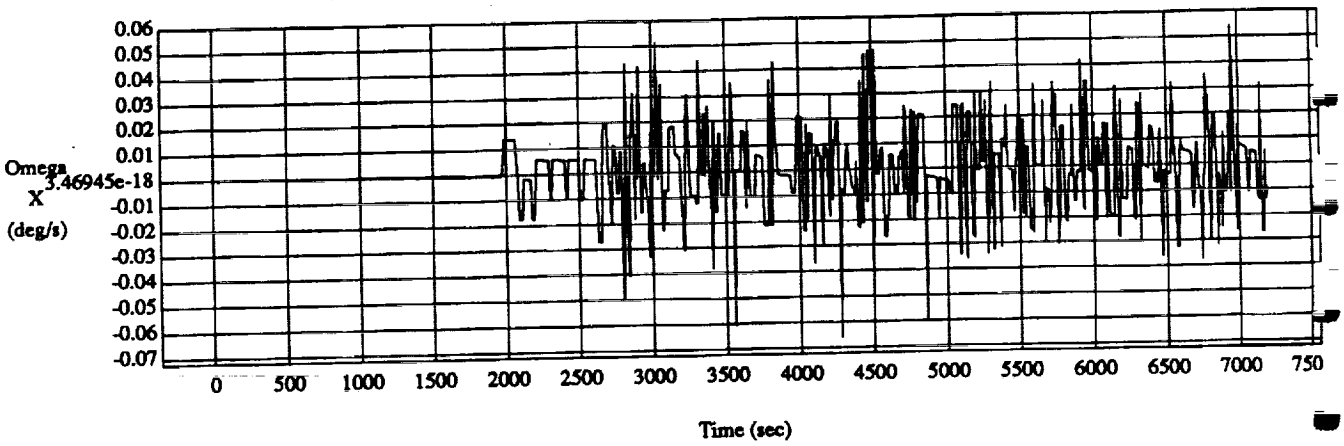


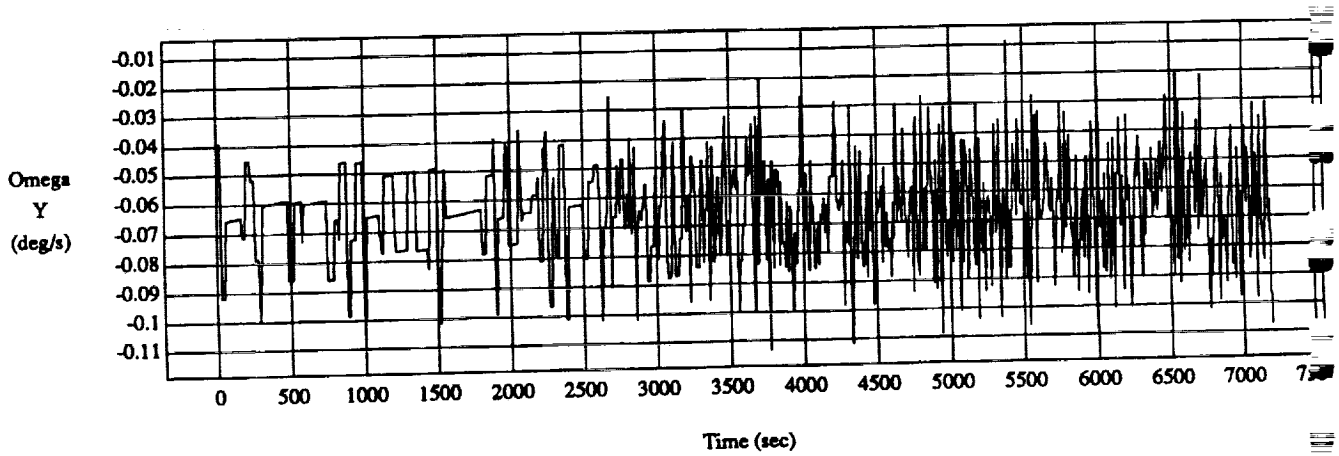


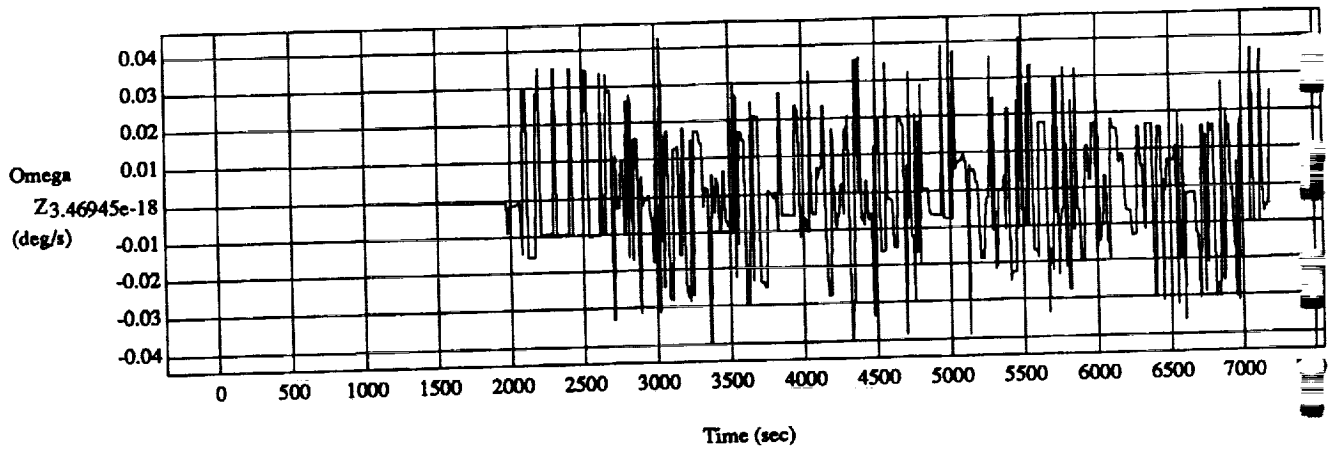


SIMULATION APPLICATION: ARIC Translational Controller Simulation
RUN IDENTIFICATION: 200 SK - Approach 10 - SK
MODEL: ORBITER
DATE: Tue Dec 29 1992 10:47:58 AM
NUMBER OF DATA POINTS: 721
DATA SAMPLING FREQUENCY: 0.100 Hz

BODY RATES TIME HISTORIES

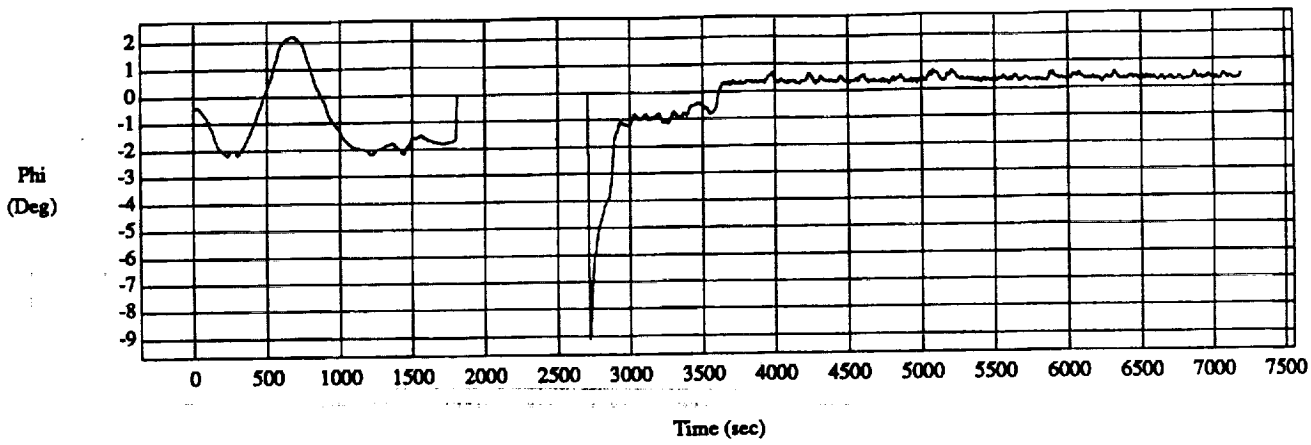


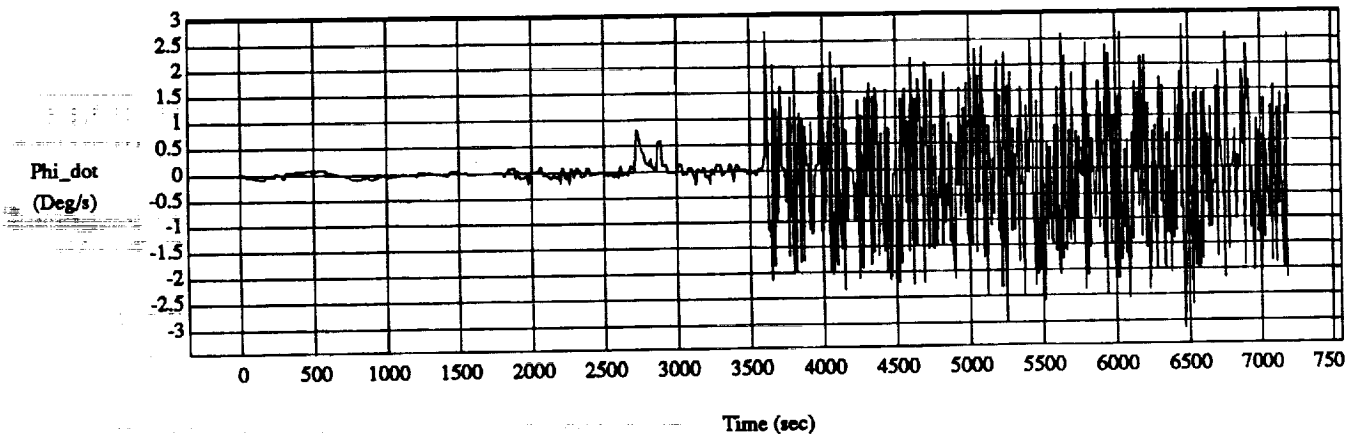


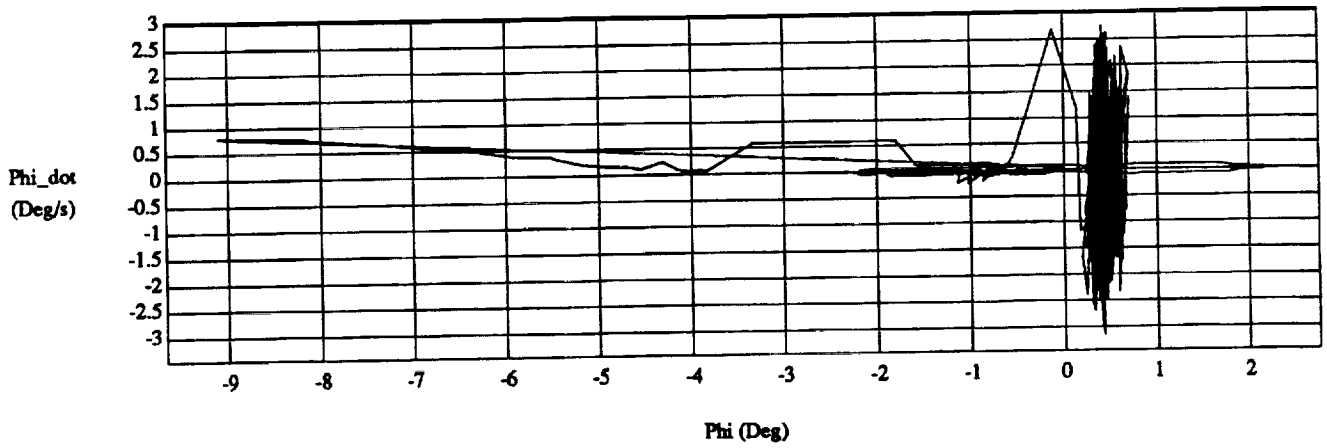


SIMULATION APPLICATION: ARIC Translational Controller Simulation
RUN IDENTIFICATION: 200 SK - Approach 10 - SK
MODEL: ORBITER
DATE: Tue Dec 29 1992 10:47:58 AM
NUMBER OF DATA POINTS: 721
DATA SAMPLING FREQUENCY: 0.100 Hz

Range ARIC Learning Parameters - Inputs

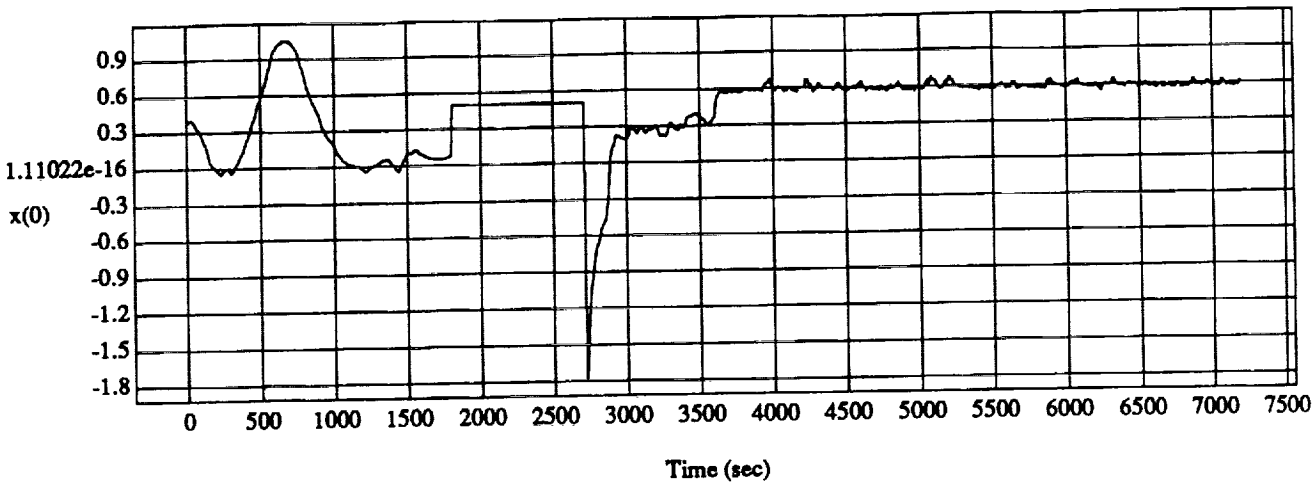


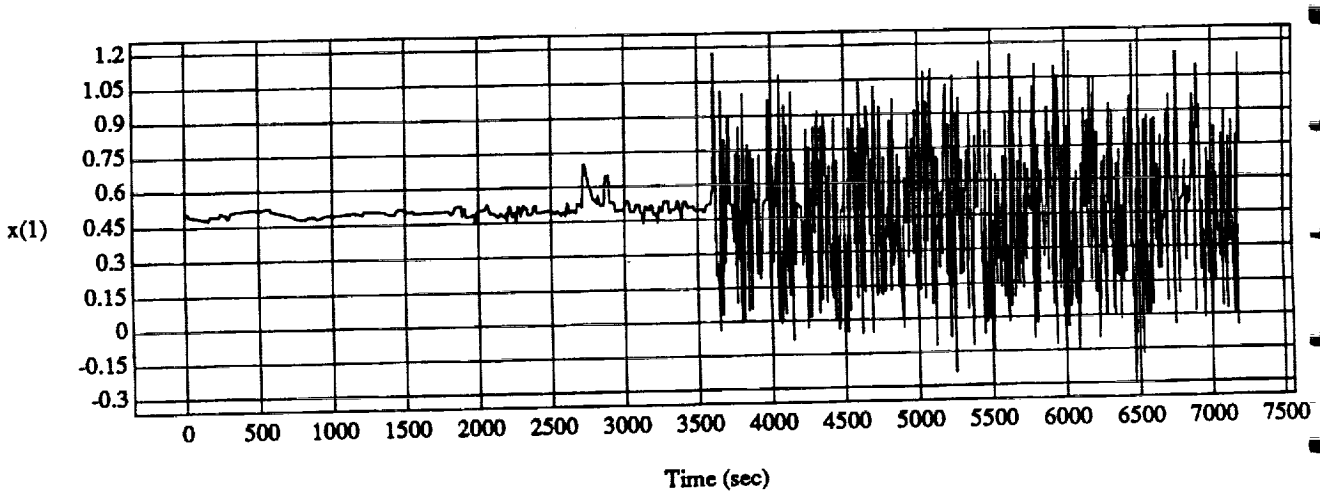




SIMULATION APPLICATION: ARIC Translational Controller Simulation
RUN IDENTIFICATION: 200 SK - Approach 10 - SK
MODEL: ORBITER
DATE: Tue Dec 29 1992 10:06:20 AM
NUMBER OF DATA POINTS: 721
DATA SAMPLING FREQUENCY: 0.100 Hz

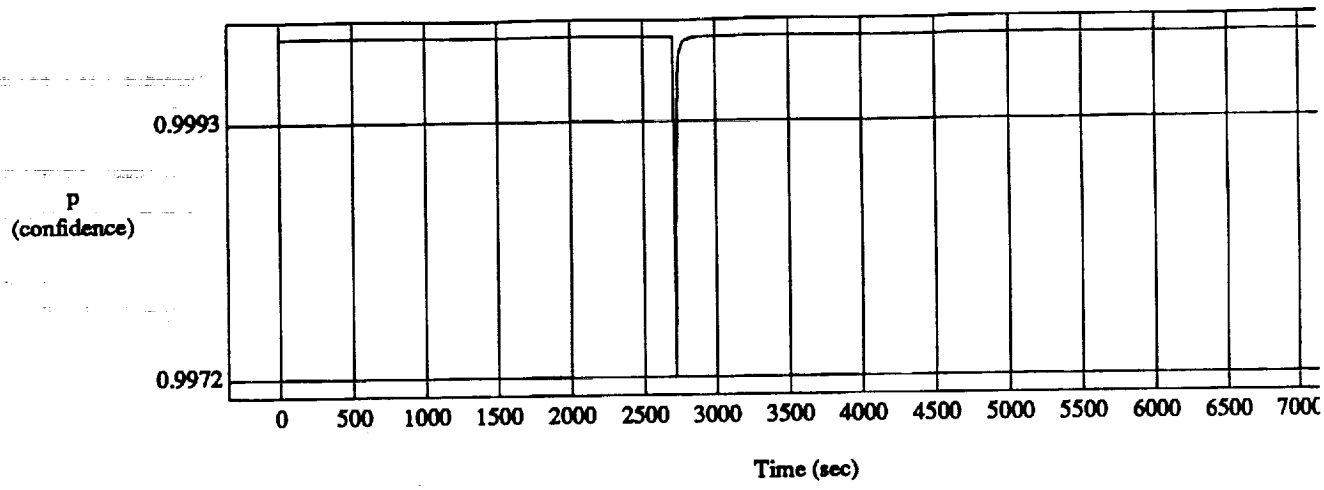
Range ARIC Learning Parameters - Scaled Inputs

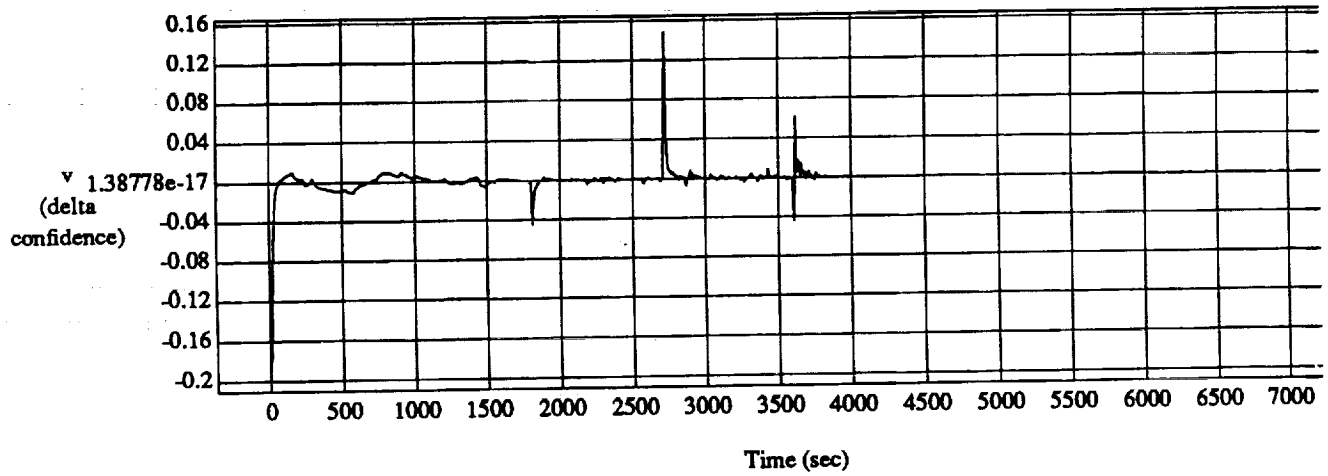




SIMULATION APPLICATION: ARIC Translational Controller Simulation
RUN IDENTIFICATION: 200 SK - Approach 10 - SK
MODEL: ORBITER
DATE: Tue Dec 29 1992 10:06:20 AM
NUMBER OF DATA POINTS: 721
DATA SAMPLING FREQUENCY: 0.100 Hz

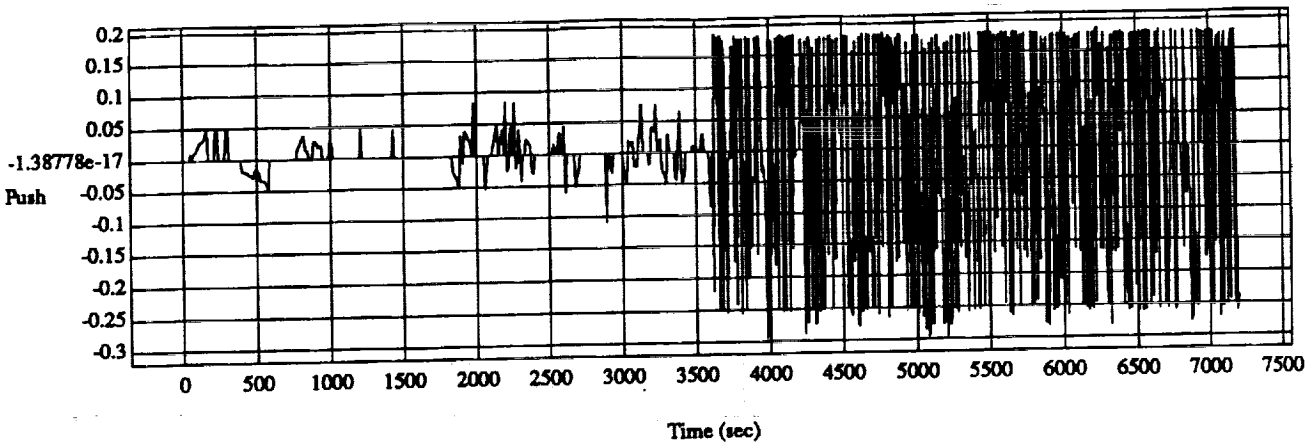
Range ARIC Learning Parameters - Learning Confidence

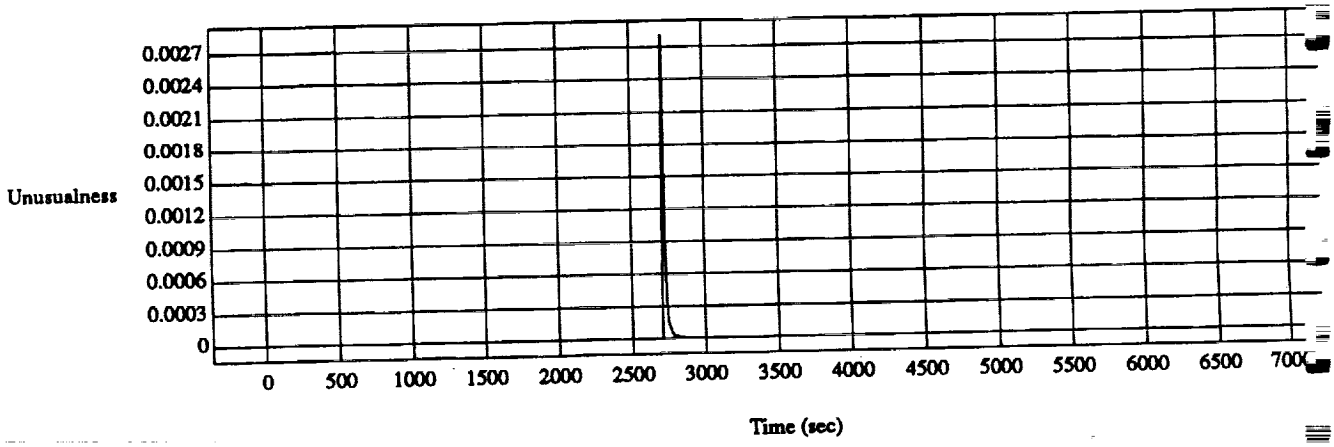


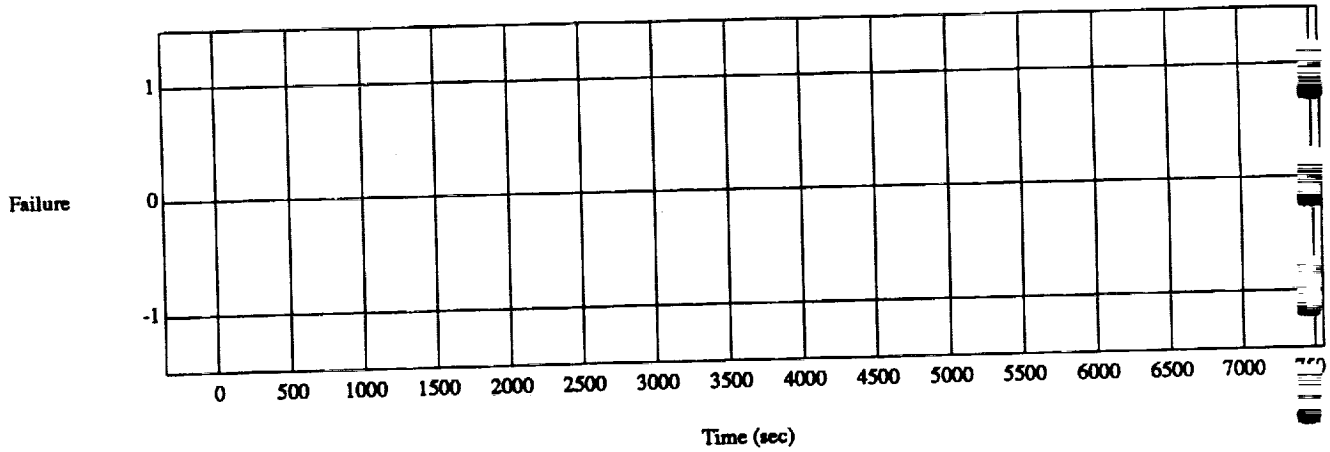


SIMULATION APPLICATION: ARIC Translational Controller Simulation
RUN IDENTIFICATION: 200 SK - Approach 10 - SK
MODEL: ORBITER
DATE: Tue Dec 29 1992 10:06:20 AM
NUMBER OF DATA POINTS: 721
DATA SAMPLING FREQUENCY: 0.100 Hz

Range ARIC Learning Parameters - General Parameters

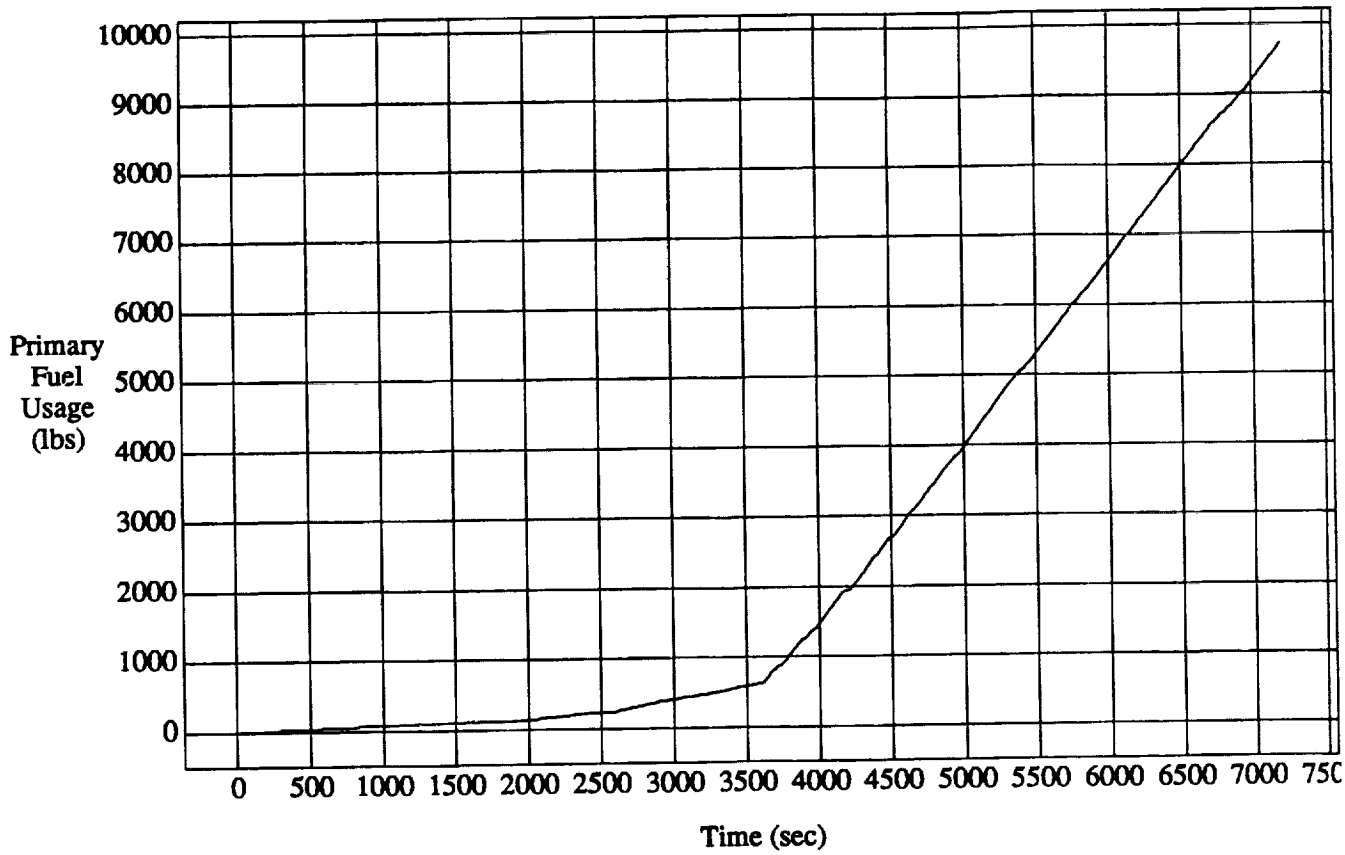






SIMULATION APPLICATION: ARIC Translational Controller Simulation
RUN IDENTIFICATION: 200 SK - Approach 10 - SK
MODEL: ORBITER
DATE: Tue Dec 29 1992 10:06:20 AM
NUMBER OF DATA POINTS: 721
DATA SAMPLING FREQUENCY: 0.100 Hz

ORBITER PRIMARY JETS FUEL USAGE



SIMULATION APPLICATION: ARIC Translational Controller Simulation
RUN IDENTIFICATION: 200 SK - Approach 10 - SK
MODEL: ORBITER
DATE: Tue Dec 29 1992 10:07:39 AM
NUMBER OF DATA POINTS: 361
DATA SAMPLING FREQUENCY: 0.050 Hz