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

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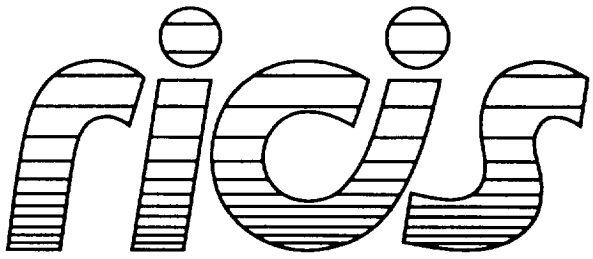

Research Institute for Computing and Information Systems
University of Houston-Clear Lake

INTERIM PROGRESS 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.

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

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 NASA research coordinator for this activity was Dr. Robert N. Lea of the Information Technology Division, NASA/JSC.

Research Activity AR.06

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

Interim Report
submitted
to
The Research Institute for Computing and Information Systems

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1.0 **Introduction** :

As part of the RICIS activity, the reinforcement learning techniques developed at Ames Research Center are being applied to proximity and docking operations using the Shuttle and Solar Max satellite simulation. This activity is carried out in the software technology laboratory utilizing the Orbital Operations Simulator (OOS).

This interim report provides the status of the project after two months of activities and outlines the future plans. Our technical progress is summarized in section 2 and future plans are described in section 3.

2.0 **Summary of Technical Progress** :

Considerable technical progress, as described below, has been achieved during these two months of activities in the project.

1. The source code received from Ames Research Center contained the attitude controller however, the equations of motion still pertained to the inverted pendulum motion. In order to reflect the shuttle motion in the orbital environment, the source code was modified to interface with appropriate routines in the OOS. First, the onorbit digital auto pilot was modified to call the learn cycle in its normal calling sequence. Second, a special OOS structure was created to hold all relevant parameters for input and output. Third, an initialization routine was created to initialize the parameters of the learning algorithms. And, finally, the output of the learn cycle was interpreted and converted to rotational hand controller command. The source code is provided in Appendix A.

2. An attitude hold test case was set up with the shuttle in its normal orbit during its mission. The pitch attitude of the shuttle was set at 45 degrees in the local vertical local horizontal coordinate system. Because of the gravity gradient torques, the shuttle pitch rate starts increasing resulting in an increase in the pitch attitude. As soon as the attitude error (difference between the desired attitude and the current attitude) goes beyond the deadband limit, the fuzzy controller will initiate jet firing. Two neural networks are learning during each cycle and adjusts the parameters as required. The test case was setup to run up to 1000 seconds so there will be at least three attitude firings. For debug and analysis purposes, we initially performed the test case for only 30 seconds. Later, we extended the test case to 1000 and 100,000 seconds to understand the learning process and evaluate the performance of the fuzzy controller and neural networks. Plots for the 1000 seconds test case are included in Appendix B. This is one of the typical tests performed. So far we have performed over 10 test cases with modifications in the source code and changes in the learning parameters. Results and our findings are described separately in this section.

3. During the debug phase, we found several implementation errors. We had to change our structure, interface code and membership functions definitions. Our initial test results showed that the algorithm is holding the rate but not the attitude. We checked for all possible implementation errors, and when we were satisfied that there are no critical implementation errors, we did the test case again.

4. When we found that the results are the same (i.e. no attitude hold), we started analyzing the Tsukamoto's defuzzification method used in the algorithm. In this method, only one side of the triangle is used in computing the output action. In our attitude controller, we have used the max-dot and max-min methods to compute the output, and thus we compared the two methods for any differences. We found that the Tsukamoto's method computes the output with only half the value of the max-dot method. Thus, we changed the interpretation of the learning output for generating the rotational hand controller command. Results of our test indicated that the controller now holds attitude as well as rate. The analysis was involved and we learned a lot about the algorithm.

5. Since our test was successful in holding the rate and attitude, we started analyzing the learning behavior neural networks. Our results indicate that the parameter 'f' that relates to the firing strength varies in the same manner for all rules. The 'd' parameters also show the same variations for all rules. We have discussed the problem with Dr. Berenji at Ames and sent him the source listing as well as plots so that he can compare it with his results and tell us if we are doing something wrong.

6. We have analyzed the effect of the bias term x(2) and have concluded that the its most appropriate value is 0.5. We performed tests with bias values of 0.0 and 1.0 and results were really bad. For these values the controller does not perform its functions and neural networks do not learn.

7. We were invited by the SPIE fuzzy logic and neural network committee to present our initial results at the Orlando conference and special workshop on Fuzzy-Neuro control. We presented our preliminary results at this workshop on April 23, 1992.

3.0 **Future Plans** :

We plan to continue testing of the fuzzy learning algorithms utilizing the attitude hold test case in the orbital operations simulator. Emphasis during this activity is to ensure that the algorithms perform properly and learning by the neural networks in ARIC architecture is achieved in a satisfactory manner. Then we will switch to other attitude control tests such as attitude maneuver, rate hold and rate maneuver. We will perform these tests with proper perturbations typically present during the orbital operations.

As soon as we complete testing the attitude controller with learning, we will implement the translational controller in the simulation and perform proximity

operations test cases. Currently we plan to perform v-bar, r-bar, fly around and station-keeping test cases as we have performed these test cases to check out designs of our translational controller. Finally, we will set up a test case that will simulate docking operations. In this test case, the shuttle will approach the solar max satellite from 50 feet to 2 feet and hold the relative orientation for a specified time at the final distance so that the grappling task can be performed.

4. **Issues and Concerns** :

At this time the project is on schedule and there are no issues or concerns to report in this interim report.

Appendix A. Source Listing of Fuzzy Learning Modules

```
#include <stdio.h>
#include <math.h>
#include <sys/types.h>

      /* EXTERNAL DATA STRUCTURE DEFINITION */
#include "../orb_fuzzy/learn_cycle.h"
int   counter=0;
#define max(x,y)    ( (x >= y) ? x : y )
#define min(x,y)    ( (x < y) ? x : y )
#define Gamma       0.9
#define Beta        0.2
#define Beta_h      0.05
#define Rho         1.0
#define Rho_h       0.2
#define Rho1        2.0
#define Rho_h1      0.4
extern double sgn();
extern double exp();
extern double rnd();

learn_cycle(L)
LEARN_CYCLE * L;      /*IN : */
{
 int i,i1, j, k;
 double match(), calculate_z_array();

 double temp ;


      /* CCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCC */
      /* 11 March 1992 - Alter scaling          */
      /* CCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCC */
      /* L->x[0] = L->Phi/20.0;                 */
           /* L->x[1] = L->Phi_dot/4.0;         */
      /* CCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCC */
      /* 08 April 1992 - Alter scaling          */
      /* CCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCC */
           /* L->x[0] = L->Phi/10.0;            */
           /* L->x[1] = L->Phi_dot/2.0;         */
      /* CCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCC */
           L->x[0] = L->Phi ;
           L->x[1] = L->Phi_dot * 10.0 ;
      /* CCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCC */
      /* 08 April 1992 - Alter Bias             */
      /* CCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCC */
           /* L->x[2] = 1.00 ;                  */
```

```
    /* CCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCC */
    /* 15 April 1992 - Alter Bias                   */
    /* CCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCC */
          L->x[2] = 0.50 ;


          L->failure = 0;

  /* Set up and evaluate the failure criteria */
  if ( (fabs(L->Phi) > 0.7) || (fabs(L->Phi_dot) > 0.07) )
    L->failure = -1.;

/* output: state evaluation */

for (i = 0; i < 31; i++)
 {
  L->sum = 0.0;
  for(j = 0; j < 3; j++)
   {
    L->sum += L->a[i*3+j] * L->x_old[j];
   }
  L->y[i] = 1.0 / (1.0 + exp(-1.0 * L->sum));
 }
L->sum = 0.0;
for(i = 0; i < 31; i++)
 {
  L->sum += L->c[i] * L->y[i];
 }
L->sum1 = 0.0;
for ( j = 0;j < 3; j++)
 {
  L->sum1 += L->b[j] * L->x_old[j];
 }
L->v = L->sum + L->sum1;

/* output: action */
for(i = 0; i < 31; i++)
 {
        i1=i;

  L->w[i] = match(i1,L);
  L->z1[i] = calculate_z_array(i1,L);
 }
L->sum1 = 0.0;
L->denom = 0.0;
for(i = 0; i < 31; i++)
```

```
   {
    L->sum1 += L->w[i] * L->z1[i] *L->f[i] ;
    L->denom += L->w[i]*L->f[i] ;

   }
  L->push = L->sum1 / L->denom;

  /* output: action computations completed */
  for(i = 0; i < 31; i++)
   {

    L->sum = 0.0;

    for (j = 0; j < 3; j++)
     L->sum += L->d[i*3+j] * L->x_old[j];

     L->z[i] = 1.0 / (1.0 + exp(-1.0 * L->sum));
   }
  L->sum2 = 0.0;
  L->sum3 = 0.0;

  for(i = 0; i < 3; i++)
   L->sum2 += L->e[i] * L->x_old[i];

  for (i=0;i < 31; i++)
   L->sum3 += L->f[i] * L->z[i];

 /* CCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCC
C */
 /* 4 May 1992 - Normalize sum3                    */
 /* L->sum4 = L->sum3 +L->sum2;                     */
 /* CCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCC
C */
 L->sum4 = ( L->sum3 / 31.0 ) + L->sum2;

 L->p = 1.0 / (1.0 + exp(-1.0 * L->sum4));

 /* CCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCC
C */
 /* 15 April 1992 - Use temp variable - not push       */
 /* CCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCC
C */
 /* L->push = (rnd() <= L->p) ? L->push : -L->push;     */
 /* L->unusualness = (L->push > 0) ? 1.0 - L->p : -L->p; */
 temp = (rnd() <= L->p) ? L->push : -L->push;
 L->unusualness = (temp > 0) ? 1.0 - L->p : -L->p;
```

```
/*  using new input values and unmodified weights. */
/*  Use y_new and v_new so not to destroy y and v. */
for(i = 0; i < 31; i++)
 {
   L->sum = 0.0;
   for(j = 0; j < 3; j++)
    {
      L->sum += L->a[i*3+j] * L->x[j];
    }
   L->y_new[i] = 1.0 / (1.0 + exp(-1.0 * L->sum));
 }
   L->sum = 0.0;
   L->sum1 = 0.0;
   L->sum2 = 0.0;

for(j = 0; j < 3; j++)
   L->sum1 += L->b[j] * L->x[j];

for(i = 0; i < 31; i++)
   L->sum2 += L->c[i] * L->y_new[i];

L->sum = L->sum1 + L->sum2;
L->v_new = L->sum;

/* action evaluation */
  if (L->failure)
    L->r_hat = L->failure - L->v;
  else
    L->r_hat = L->failure + Gamma * L->v_new - L->v;

/* modification and update to parameters */

    for(i = 0; i < 31; i++)
          {
       L->factor1 = Beta_h * L->r_hat * L->y[i] * (1.0 - L->y[i]) * sgn(L->c[i]);
       L->c[i] += Beta * L->r_hat * L->y[i];

        for(j = 0; j < 3; j++)
                    {
          L->a[i*3+j] += L->factor1 * L->x_old[j];
              }
      }


    for(i = 0; i < 3; i++)
```

```
            L->b[i] += Beta * L->r_hat * L->x_old[i];

    for(i = 0; i < 31; i++)
     {
      L->factor2 = Rho_h * L->r_hat * L->z[i] * (1.0 - L->z[i]) * sgn(L->f[i])*L->unusualnes
s;

       for(j = 0; j < 3; j++)

       L->d[i*3+j] += L->factor2 * L->x_old[j];

     }


    for(i = 0; i < 31; i++)
{

     L->f[i] += Rho * L->r_hat * L->unusualness * L->z[i];
}
    for(i = 0; i < 3; i++)
{

     L->e[i] += Rho * L->r_hat * L->unusualness * L->x_old[i];
}
           L->x_old[0] = L->x[0];
           L->x_old[1] = L->x[1];
           L->x_old[2] = L->x[2];
}
/*************************************************************************/

double sgn(x)
  double x;
{
 if (x < 0.0)
   return (-1.0);
 else if (x > 0.0)
   return (1.0);
 else
   return (0.0);
}


/* zero_one function returns 0 for negative numbers
                    1 for values > 1
                    x for values between 0 and 1 */
double zero_one(x)
```

```
 double x;
{
 if (x < 0)  return (0.0);
 else if (x > 1) return (1.0);
 else return (x);
}


/********** Membership Function for Phi **********************************/

double nb1(x)
double x;
{
 return(min( max((-2-x)/3 , 0.0 ), 1.0 ));
}

double nm1(x)
double x;
{
 if (x <= -2.5)    return (min( max(( x+4)/1.5 , 0.0 ), 1.0 ));
 else  return (min( max(( -x-1)/1.5 , 0.0 ), 1.0 ));
 }
double ns1(x)
double x;
{
 if (x <= -1.0)    return (min( max( x+2.0 , 0.0 ), 1.0 ));
  else  return (min( max( -x , 0.0 ), 1.0 ));
 }
double zo1(x)
double x;
{
 if (x <= 0)    return (min( max( x+1 , 0.0 ), 1.0 ));
 else  return (min( max( -x+1 , 0.0 ), 1.0 ));
 }
double ps1(x)
double x;
{
 if (x <= 1)    return (min( max( x , 0.0 ), 1.0 ));
 else  return (min( max( -x+2 , 0.0 ), 1.0 ));
 }
double pm1(x)
double x;
{
 if (x <= 2.5)    return (min( max(( x-1)/1.5 , 0.0 ), 1.0 ));
 else return (min( max(( -x+4)/1.5 , 0.0 ), 1.0 ));
```

```
 }

double pb1(x)
double x;
{
 return(min( max(( x-2)/3 , 0.0 ), 1.0 ));
}
/****************** Phi_dot Membership Functions ************************/
double nb2(x)
double x;
{
 return(min( max((-.2-x)/.3 , 0.0 ), 1.0 ));
}

double nm2(x)
double x;
{
 if (x <= -.25)    return (min( max(( x+.4)/.15 , 0.0 ), 1.0 ));
 else  return (min( max(( -x-.1)/.15 , 0.0 ), 1.0 ));
 }
double ns2(x)
double x;
{
 if (x <= -.1)    return (min( max(( x+.2)/.1 , 0.0 ), 1.0 ));
 else  return (min( max(( -x/.1) , 0.0 ), 1.0 ));
 }
double zo2(x)
double x;
{
 if (x <= 0)    return (min( max(( x+.1)/.1 , 0.0 ), 1.0 ));
 else  return (min( max(( -x+.1)/.1 , 0.0 ), 1.0 ));
 }
double ps2(x)
double x;
{
 if (x <= .1)    return (min( max(( x/.1) , 0.0 ), 1.0 ));
 else  return (min( max(( -x+.2)/.1 , 0.0 ), 1.0 ));
 }
double pm2(x)
double x;
{
 if (x <= .25)    return (min( max(( x-.1)/.15 , 0.0 ), 1.0 ));
 else return (min( max(( -x+.4)/.15 , 0.0 ), 1.0 ));
 }

double pb2(x)
```

```
double x;
{
 return(min( max(( x-.2)/.3 , 0.0 ), 1.0 ));
}

/****************** Defuzzification Process with Accel Membership Functions ************/

double nm3(x)
double x;
{
 return(-2-x);
}

double ns3(x)
double x;
{
 return(-2*x);
}

double zo3(x)
double x;
{
 return(0.0);
}

double ps3(x)
double x;
{
 return(2*x);
}

double pm3(x)
double x;
{
 return(2+x);
}


double match(i,L)
int i;
LEARN_CYCLE *L;      /*IN : */
{
double temp;
  switch (i) {

   case 0:
```

```
    temp =min( zero_one(nb1(L->Phi)*L->d[i*3+0]), zero_one(zo2(L->Phi_dot)*L->d[i*3+
1]));
/* REMOVE "BIAS" REFERENCE
    temp= min(temp,zero_one(L->x[2]*L->d[i*3+2]));
*/
    return(temp);
  case 1:
    temp=min( zero_one(nb1(L->Phi)*L->d[i*3+0]), zero_one(ns2(L->Phi_dot)*L->d[i*3+
1]));
/* REMOVE "BIAS" REFERENCE
    temp=min(temp,zero_one(L->x[2]*L->d[i*3+2]));
*/
    return(temp);
  case 2:
    temp=min( zero_one(nb1(L->Phi)*L->d[i*3+0]), zero_one(nm2(L->Phi_dot)*L->d[i*3+
1]));
/* REMOVE "BIAS" REFERENCE
    temp=min(temp, zero_one(L->x[2]*L->d[i*3+2]));
*/
    return(temp);
  case 3:
    temp=min( zero_one(nb1(L->Phi)*L->d[i*3+0]), zero_one(nb2(L->Phi_dot)*L->d[i*3+
1]));
/* REMOVE "BIAS" REFERENCE
    temp=min(temp, zero_one(L->x[2]*L->d[i*3+2]));
*/
    return(temp);
  case 4:
    temp=min( zero_one(nm1(L->Phi)*L->d[i*3+0]), zero_one(zo2(L->Phi_dot)*L->d[i*3+
1]));
/* REMOVE "BIAS" REFERENCE
    temp=min(temp, zero_one(L->x[2]*L->d[i*3+2]));
*/
    return(temp);
  case 5:
    temp=min( zero_one(nm1(L->Phi)*L->d[i*3+0]), zero_one(ns2(L->Phi_dot)*L->d[i*3+
1]));
/* REMOVE "BIAS" REFERENCE
    temp=min(temp, zero_one(L->x[2]*L->d[i*3+2]));
*/
    return(temp);
  case 6:
    temp=min( zero_one(nm1(L->Phi)*L->d[i*3+0]), zero_one(nm2(L->Phi_dot)*L->d[i*3
+1]));
/* REMOVE "BIAS" REFERENCE
    temp=min(temp, zero_one(L->x[2]*L->d[i*3+2]));
```

```
*/
    return(temp);
  case 7:
    temp=min( zero_one(nm1(L->Phi)*L->d[i*3+0]), zero_one(nb2(L->Phi_dot)*L->d[i*3+
1]));
/* REMOVE "BIAS" REFERENCE
    temp=min(temp, zero_one(L->x[2]*L->d[i*3+2]));
*/
    return(temp);
  case 8:
    temp=min( zero_one(ns1(L->Phi)*L->d[i*3+0]), zero_one(zo2(L->Phi_dot)*L->d[i*3+
1]));
/* REMOVE "BIAS" REFERENCE
    temp=min(temp, zero_one(L->x[2]*L->d[i*3+2]));
*/
    return(temp);
  case 9:
    temp=min( zero_one(ns1(L->Phi)*L->d[i*3+0]), zero_one(ns2(L->Phi_dot)*L->d[i*3+
1]));
/* REMOVE "BIAS" REFERENCE
    temp=min(temp, zero_one(L->x[2]*L->d[i*3+2]));
*/
    return(temp);
  case 10:
    temp=min( zero_one(ns1(L->Phi)*L->d[i*3+0]), zero_one(nm2(L->Phi_dot)*L->d[i*3+
1]));
/* REMOVE "BIAS" REFERENCE
    temp=min(temp, zero_one(L->x[2]*L->d[i*3+2]));
*/
    return(temp);
  case 11:
    temp=min( zero_one(ns1(L->Phi)*L->d[i*3+0]), zero_one(nb2(L->Phi_dot)*L->d[i*3+
1]));
/* REMOVE "BIAS" REFERENCE
    temp=min(temp, zero_one(L->x[2]*L->d[i*3+2]));
*/
    return(temp);
  case 12:
    temp=min( zero_one(zo1(L->Phi)*L->d[i*3+0]), zero_one(pb2(L->Phi_dot)*L->d[i*3+
1]));
/* REMOVE "BIAS" REFERENCE
    temp=min(temp, zero_one(L->x[2]*L->d[i*3+2]));
*/
    return(temp);
  case 13:
    temp=min( zero_one(zo1(L->Phi)*L->d[i*3+0]), zero_one(pm2(L->Phi_dot)*L->d[i*3+
```

```
1]));
/* REMOVE "BIAS" REFERENCE
    temp=min(temp, zero_one(L->x[2]*L->d[i*3+2]));
*/
    return(temp);
  case 14:
    temp=min( zero_one(zo1(L->Phi)*L->d[i*3+0]), zero_one(ps2(L->Phi_dot)*L->d[i*3+
1]));
/* REMOVE "BIAS" REFERENCE
    temp=min(temp, zero_one(L->x[2]*L->d[i*3+2]));
*/
    return(temp);
  case 15:
    temp=min( zero_one(zo1(L->Phi)*L->d[i*3+0]), zero_one(zo2(L->Phi_dot)*L->d[i*3+
1]));
/* REMOVE "BIAS" REFERENCE
    temp=min(temp, zero_one(L->x[2]*L->d[i*3+2]));
*/
    return(temp);
  case 16:
    temp=min( zero_one(zo1(L->Phi)*L->d[i*3+0]), zero_one(ns2(L->Phi_dot)*L->d[i*3+
1]));
/* REMOVE "BIAS" REFERENCE
    temp=min(temp, zero_one(L->x[2]*L->d[i*3+2]));
*/
    return(temp);
  case 17:
    temp=min( zero_one(zo1(L->Phi)*L->d[i*3+0]), zero_one(nm2(L->Phi_dot)*L->d[i*3+
1]));
/* REMOVE "BIAS" REFERENCE
    temp=min(temp, zero_one(L->x[2]*L->d[i*3+2]));
*/
    return(temp);
  case 18:
    temp=min( zero_one(zo1(L->Phi)*L->d[i*3+0]), zero_one(nb2(L->Phi_dot)*L->d[i*3+
1]));
/* REMOVE "BIAS" REFERENCE
    temp=min(temp, zero_one(L->x[2]*L->d[i*3+2]));
*/
    return(temp);
  case 19:
    temp=min( zero_one(ps1(L->Phi)*L->d[i*3+0]), zero_one(pb2(L->Phi_dot)*L->d[i*3+
1]));
/* REMOVE "BIAS" REFERENCE
    temp=min(temp, zero_one(L->x[2]*L->d[i*3+2]));
*/
```

```
    return(temp);
  case 20:
    temp=min( zero_one(ps1(L->Phi)*L->d[i*3+0]), zero_one(pm2(L->Phi_dot)*L->d[i*3+
1]));
/* REMOVE "BIAS" REFERENCE
    temp=min(temp, zero_one(L->x[2]*L->d[i*3+2]));
*/
    return(temp);
  case 21:
    temp=min( zero_one(ps1(L->Phi)*L->d[i*3+0]), zero_one(ps2(L->Phi_dot)*L->d[i*3+
1]));
/* REMOVE "BIAS" REFERENCE
    temp=min(temp, zero_one(L->x[2]*L->d[i*3+2]));
*/
    return(temp);
  case 22:
    temp=min( zero_one(ps1(L->Phi)*L->d[i*3+0]), zero_one(zo2(L->Phi_dot)*L->d[i*3+
1]));
/* REMOVE "BIAS" REFERENCE
    temp=min(temp, zero_one(L->x[2]*L->d[i*3+2]));
*/
    return(temp);
  case 23:
    temp=min( zero_one(pm1(L->Phi)*L->d[i*3+0]), zero_one(pb2(L->Phi_dot)*L->d[i*3+
1]));
/* REMOVE "BIAS" REFERENCE
    temp=min(temp, zero_one(L->x[2]*L->d[i*3+2]));
*/
    return(temp);
  case 24:
    temp=min( zero_one(pm1(L->Phi)*L->d[i*3+0]), zero_one(pm2(L->Phi_dot)*L->d[i*3
+1]));
/* REMOVE "BIAS" REFERENCE
    temp=min(temp, zero_one(L->x[2]*L->d[i*3+2]));
*/
    return(temp);
  case 25:
    temp=min( zero_one(pm1(L->Phi)*L->d[i*3+0]), zero_one(ps2(L->Phi_dot)*L->d[i*3+
1]));
/* REMOVE "BIAS" REFERENCE
    temp=min(temp, zero_one(L->x[2]*L->d[i*3+2]));
*/
    return(temp);
  case 26:
    temp=min( zero_one(pm1(L->Phi)*L->d[i*3+0]), zero_one(zo2(L->Phi_dot)*L->d[i*3+
1]));
```

```
/* REMOVE "BIAS" REFERENCE
    temp=min(temp, zero_one(L->x[2]*L->d[i*3+2]));
*/
    return(temp);
  case 27:
    temp=min( zero_one(pb1(L->Phi)*L->d[i*3+0]), zero_one(pb2(L->Phi_dot)*L->d[i*3+
1]));
/* REMOVE "BIAS" REFERENCE
    temp=min(temp, zero_one(L->x[2]*L->d[i*3+2]));
*/
    return(temp);
  case 28:
    temp=min( zero_one(pb1(L->Phi)*L->d[i*3+0]), zero_one(pm2(L->Phi_dot)*L->d[i*3+
1]));
/* REMOVE "BIAS" REFERENCE
    temp=min(temp, zero_one(L->x[2]*L->d[i*3+2]));
*/
    return(temp);
  case 29:
    temp=min( zero_one(pb1(L->Phi)*L->d[i*3+0]), zero_one(ps2(L->Phi_dot)*L->d[i*3+
1]));
/* REMOVE "BIAS" REFERENCE
    temp=min(temp, zero_one(L->x[2]*L->d[i*3+2]));
*/
    return(temp);
  case 30:
    temp=min( zero_one(pb1(L->Phi)*L->d[i*3+0]), zero_one(zo2(L->Phi_dot)*L->d[i*3+
1]));
/* REMOVE "BIAS" REFERENCE
    temp=min(temp, zero_one(L->x[2]*L->d[i*3+2]));
*/
    return(temp);
  }
}

double calculate_z_array(i, L)
int i;
LEARN_CYCLE * L;      /*IN : */
{
  switch (i) {
    case 0:
      return(ps3(L->w[0]));
    case 1:
      return(ps3(L->w[1]));
    case 2:
      return(pm3(L->w[2]));
```

```
  case 3:
   return(pm3(L->w[3]));
  case 4:
   return(ps3(L->w[4]));
  case 5:
   return(ps3(L->w[5]));
  case 6:
   return(pm3(L->w[6]));
  case 7:
   return(pm3(L->w[7]));
  case 8:
   return(ps3(L->w[8]));
  case 9:
   return(ps3(L->w[9]));
  case 10:
   return(ps3(L->w[10]));
  case 11:
   return(ps3(L->w[11]));
  case 12:
   return(nm3(L->w[12]));
  case 13:
   return(nm3(L->w[13]));
  case 14:
   return(ns3(L->w[14]));
  case 15:
   return(zo3(L->w[15]));
  case 16:
   return(ps3(L->w[16]));
  case 17:
   return(pm3(L->w[17]));
  case 18:
   return(pm3(L->w[18]));
  case 19:
   return(ns3(L->w[19]));
  case 20:
   return(ns3(L->w[20]));
  case 21:
   return(ns3(L->w[21]));
  case 22:
   return(ns3(L->w[22]));
  case 23:
   return(nm3(L->w[23]));
  case 24:
   return(nm3(L->w[24]));
  case 25:
   return(ns3(L->w[25]));
```

```
    case 26:
      return(ns3(L->w[26]));
    case 27:
      return(nm3(L->w[27]));
    case 28:
      return(nm3(L->w[28]));
    case 29:
      return(ns3(L->w[29]));
    case 30:
      return(ns3(L->w[30]));

  }
}
```

```
/* IDENTIFICATION:        Hana Shehadeh    LinCom Corporation*/
        /*                June 1991        */

/* PURPOSE:*/
#define RAND_MAX 32767

typedef struct {

/*************************************************************************/
/*PARAMETER DECLARATION:                          USAGE BY DRIVER MODULES:*/
/*TYPE   VARIABLE[SIZE]                 <INOUT> DESCRIPTION*/
/*-----------------------------------------------------------------------*/

                                                                        */
int       start_state;          /*        <   >                        */
int       learn_flag;           /*        <   >                        */
int       n1;                   /*        <   >    counter             */
int       n2;                   /*        <   >    counter             */
double    Phi;                  /*deg     <   > angle error
*/
double    Phi_dot;              /*deg     <   > rate error
*/                                                                      */
double  failure ;               /*        <   >                        */
double    x_old[3] ;            /*        <   >                        */
double    y_new[31] ;           /*        <   >                        */
double    z1[31] ;              /*        <   >                        */
double    f1[31] ;              /*        <   >                        */
double    e1[31] ;              /*        <   >                        */
double    w[31];                /*        <   >                        */
double    z[31];                /*        <   >                        */
double    f[31];                /*        <   >                        */
double    x[3];                 /*        <   >
double  a[93];                  /*   <    >     */
double  d[93];                  /*   <    >     */
double    b[3];                 /*        <   >                        */
double    c[31];                /*        <   >                        */
double    e[31];                /*        <   >                        */
double    y[31];                /*        <   >                        */
double    v_new ;               /*        <   >                        */
double    r_hat ;               /*        <   > FORCE APPLIED  */      */
double    push ;                /*        <   >
double    unusualness ;         /*        <   >                        */
double    sum ;                 /*        <   >                        */
double    sum1 ;                /*        <   >                        */
double    sum2 ;                /*        <   >                        */
double    sum3 ;                /*        <   >
```

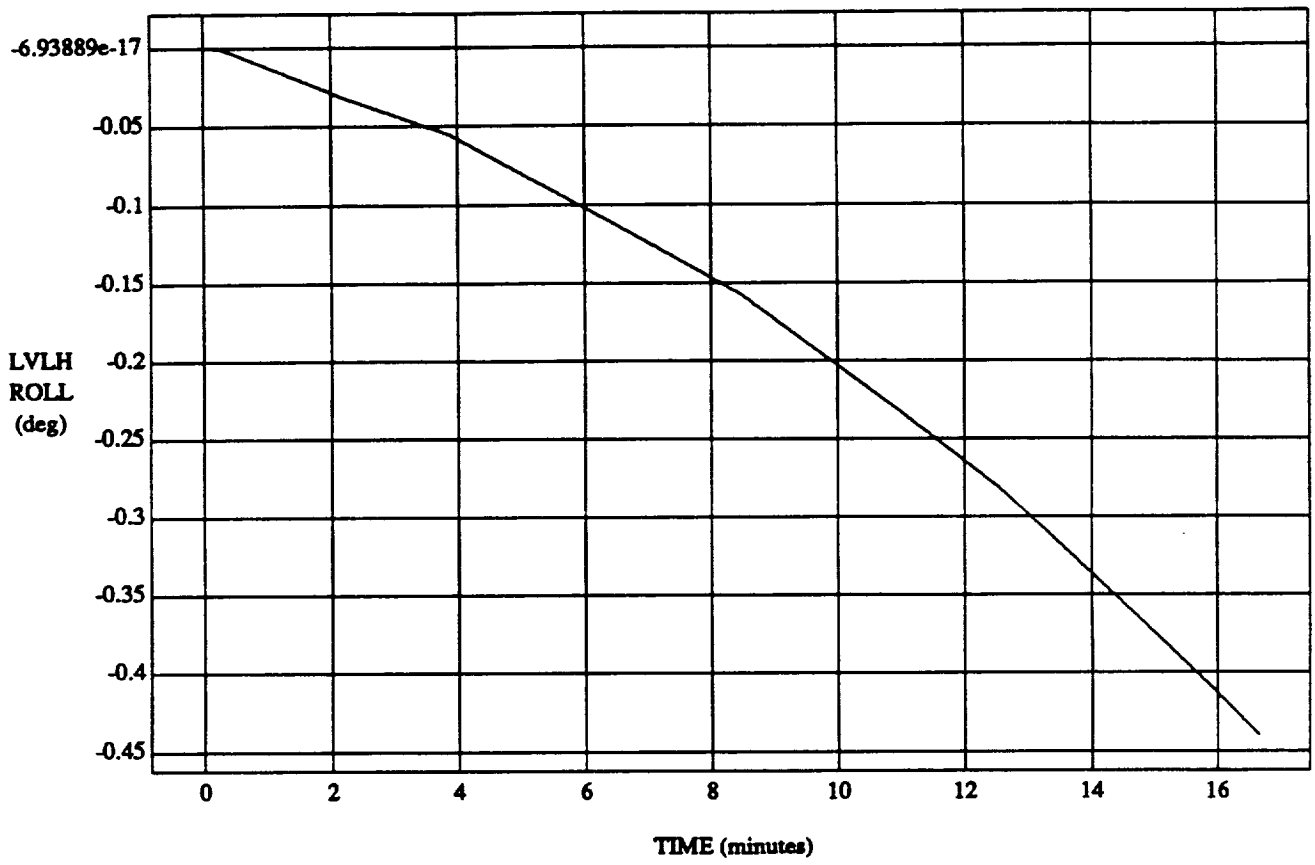
```
double    sum4 ;              /*          <    >                */
double    sumd ;              /*          <    >                */
double    factor1 ;           /*          <    >                */
double    factor2 ;           /*          <    >                */
double    factor3 ;           /*          <    >                */
double    denom ;             /*          <    >                */
double  v;                    /* failure related parameter */
double  p;                    /* failure related parameter */

} LEARN_CYCLE ;
```

```
#include <stdio.h>
#include <math.h>
#include <sys/types.h>
     /* EXTERNAL DATA STRUCTURE DEFINITION */

#include "../orb_fuzzy/learn_cycle.h"


double rnd()          /*  Returns a floating-point between 0 and 1, including 0. */
{
                      /* rand is a number between 0 and 2^31 - 1 */

  return ((double) rand() / (double)(RAND_MAX));
}



set_rnd_weights (L)
LEARN_CYCLE * L;
{
  int i,j;

  for (i = 0; i < 3; i++)
    L->b[i] = rnd() * 0.2 - 0.1;
  for (i = 0; i < 31; i++)
    {
    L->c[i] = rnd() * 0.2 - 0.1;
    L->e[i] = rnd() * 0.2 - 0.1;
    L->f[i] = rnd() * 0.5 + 0.5;
    L->w[i] = 1.0;
    }
            L->x_old[0]= L->x_old[1]= L->x_old[2]=0.0;

  for (j = 0; j < 93; j++)
    {
    L->a[j] = rnd() * 0.2 - 0.1;
    L->d[j] = 1.0;
    }

 }
```

Appendix B. Plots of Attitude-hold Test case

LVLH EULER PYR ROLL vs TIME

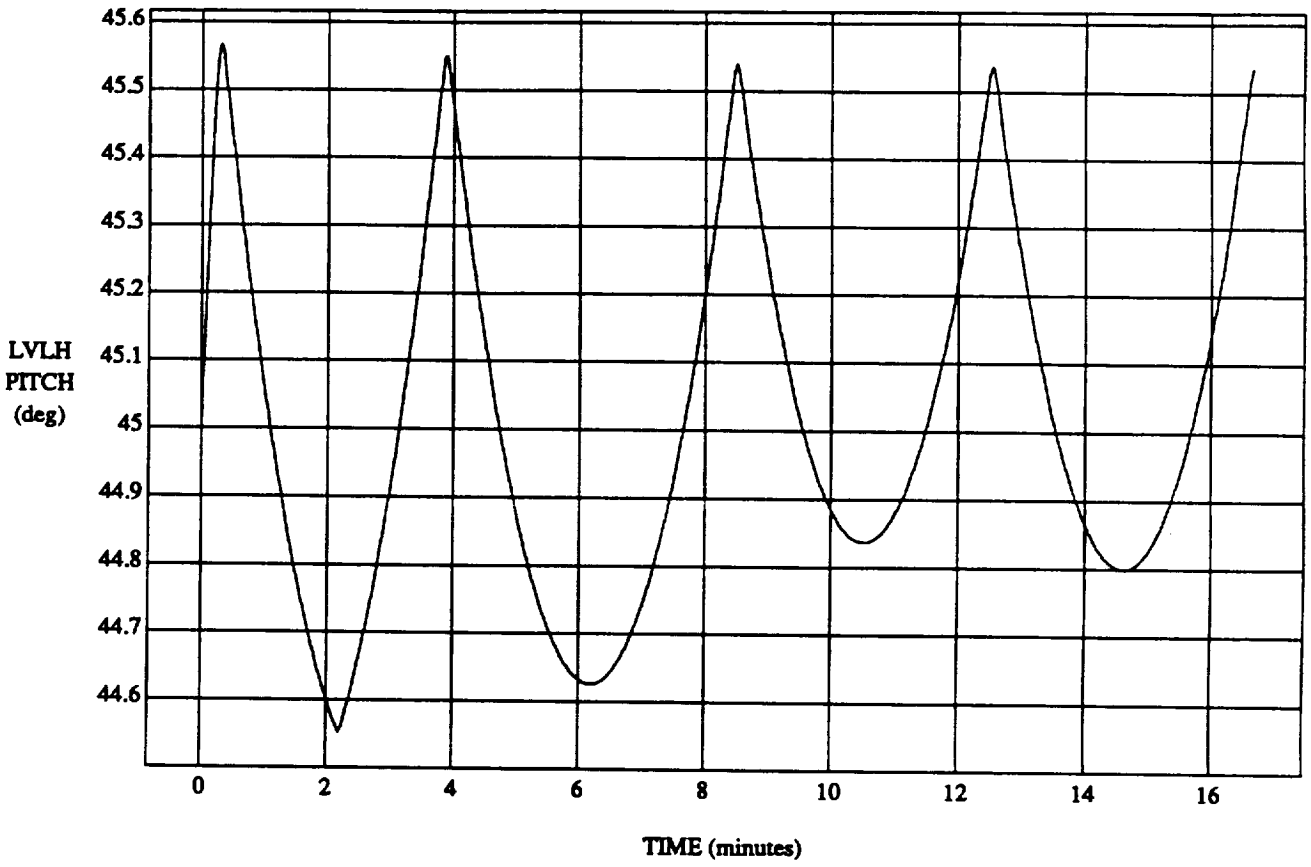
RUN: Att Hold Vernier (Tight DB)



VEHICLE: ORB_FUZZ_BATCH.state
DATA SAMPLING FREQUENCY: 0.500 Hz

LVLH EULER PYR PITCH vs TIME

RUN: Att Hold Vernier (Tight DB)

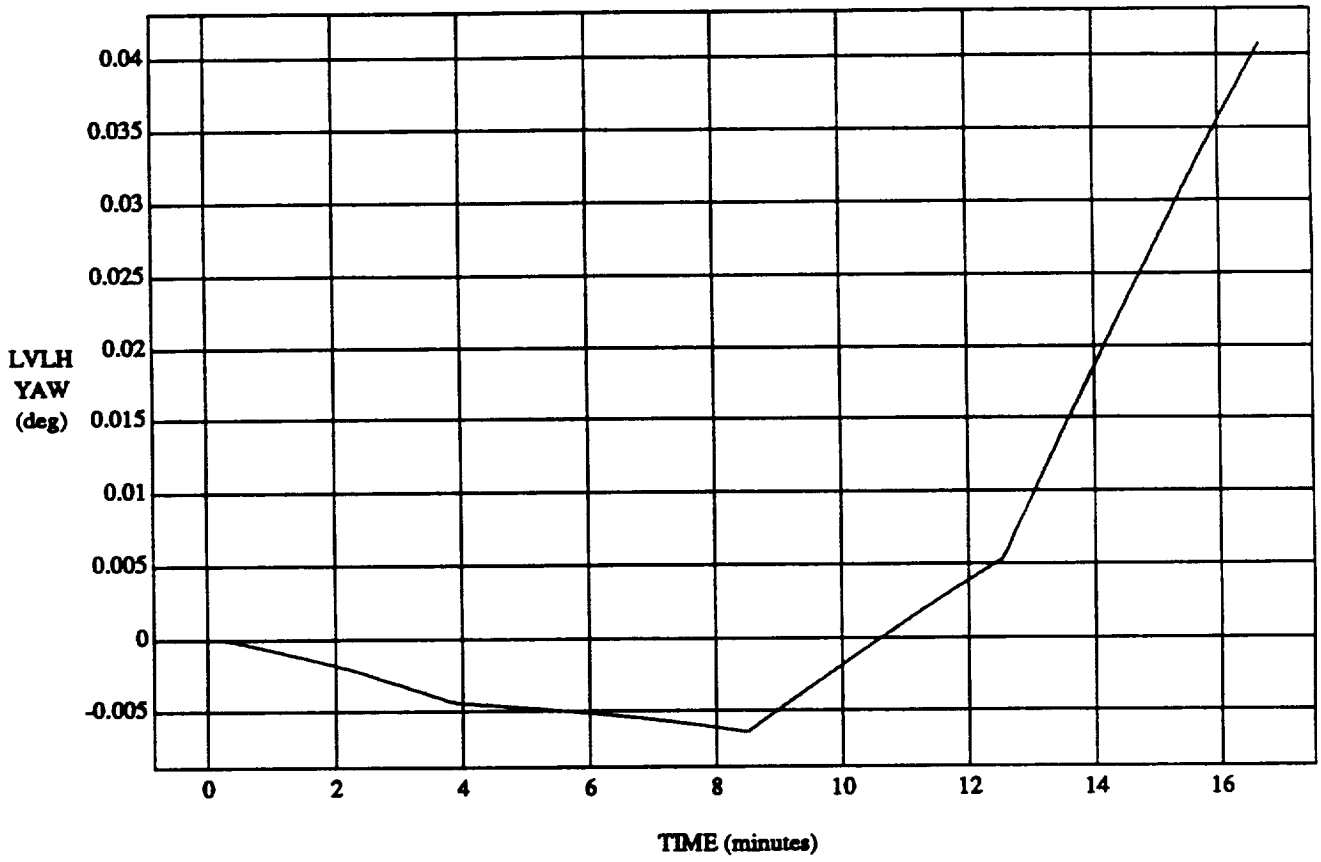


VEHICLE: ORB_FUZZ_BATCH.state

DATA SAMPLING FREQUENCY: 0.500 Hz

LVLH EULER PYR YAW vs TIME

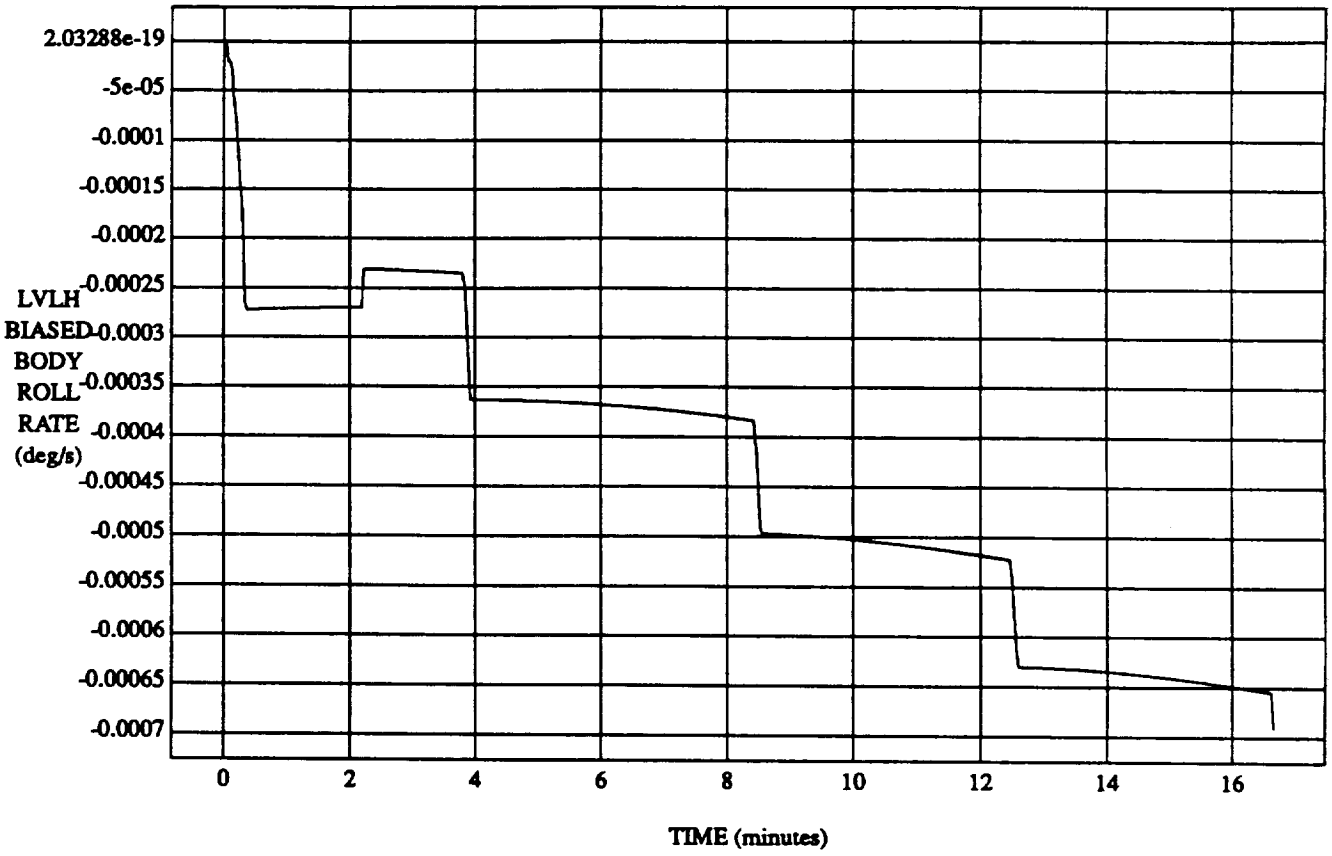
RUN: Att Hold Vernier (Tight DB)



VEHICLE: ORB_FUZZ_BATCH.state
DATA SAMPLING FREQUENCY: 0.500 Hz

LVLH BIASED BODY ROLL RATE vs TIME

RUN: Att Hold Vernier (Tight DB)

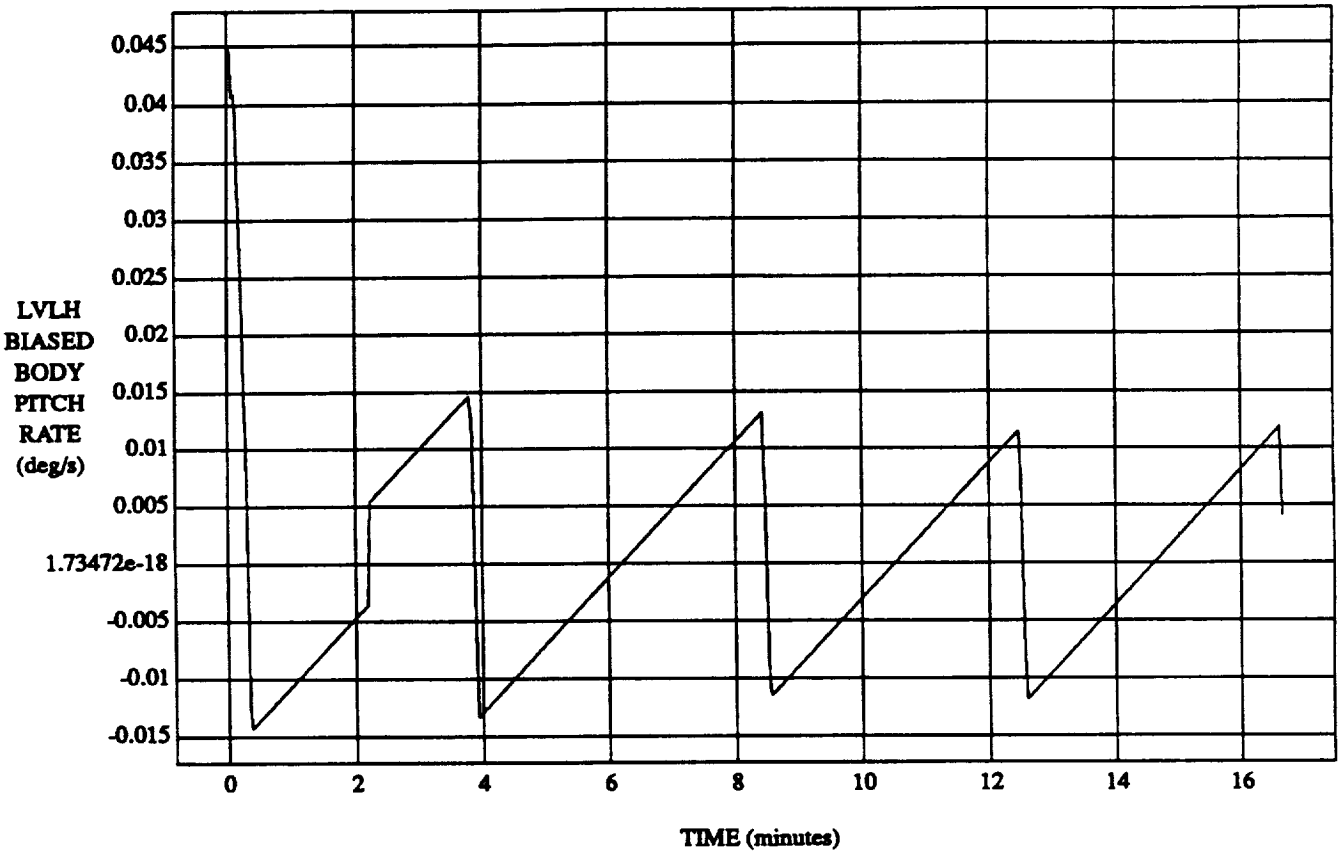


VEHICLE: ORB_FUZZ_BATCH.state

DATA SAMPLING FREQUENCY: 0.500 Hz

LVLH BIASED BODY PITCH RATE vs TIME

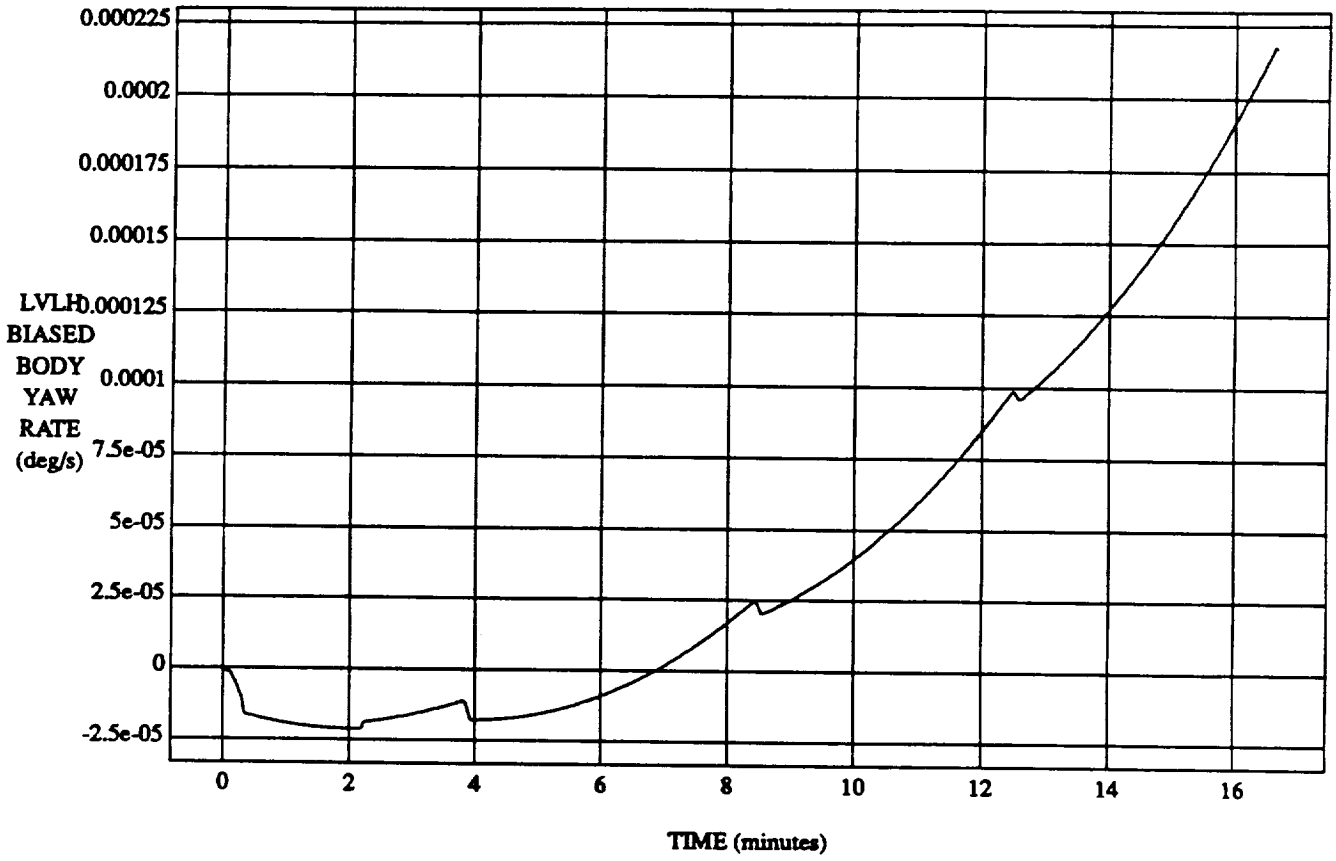
RUN: Att Hold Vernier (Tight DB)



VEHICLE: ORB_FUZZ_BATCH.state
DATA SAMPLING FREQUENCY: 0.500 Hz

LVLH BIASED BODY YAW RATE vs TIME

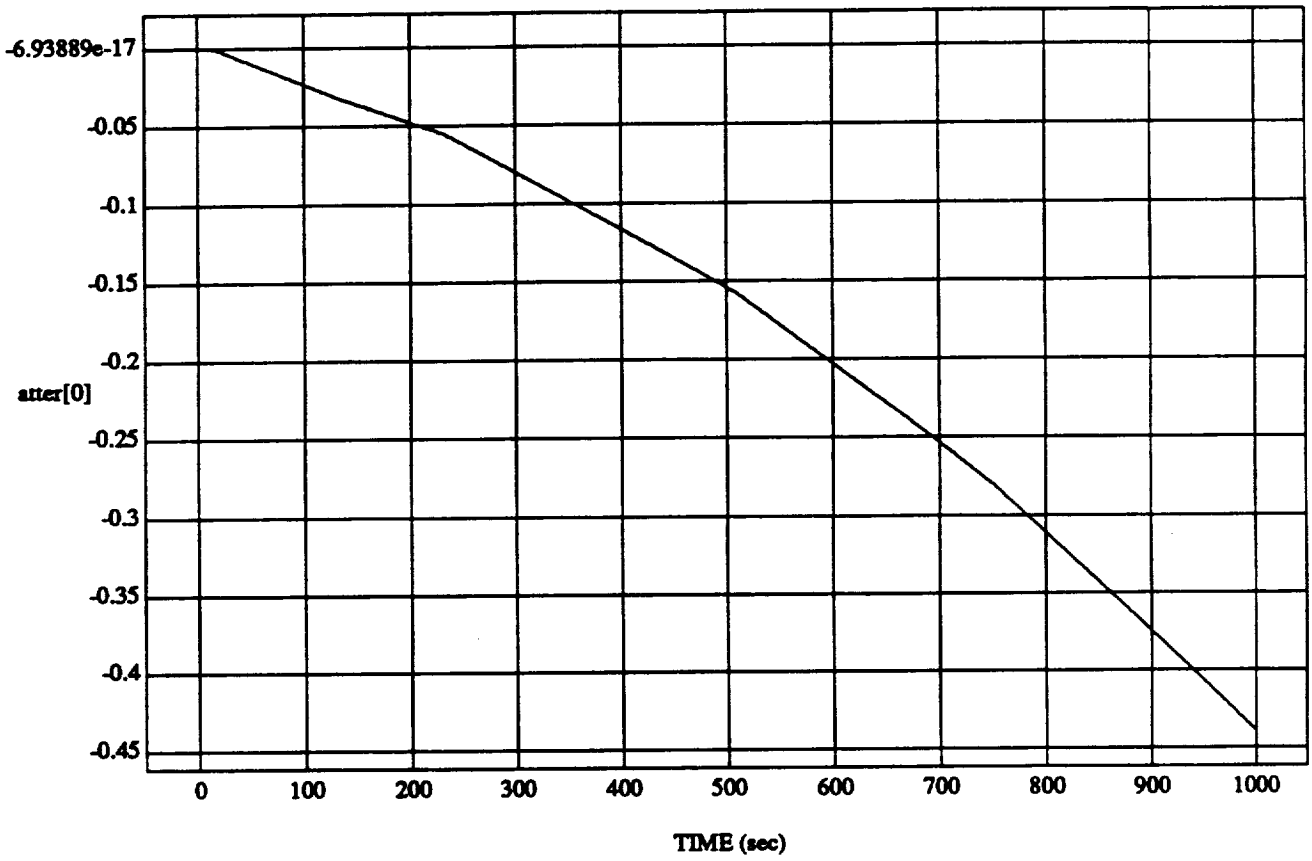
RUN: Att Hold Vernier (Tight DB)



VEHICLE: ORB_FUZZ_BATCH.state
DATA SAMPLING FREQUENCY: 0.500 Hz

atter[0] vs TIME

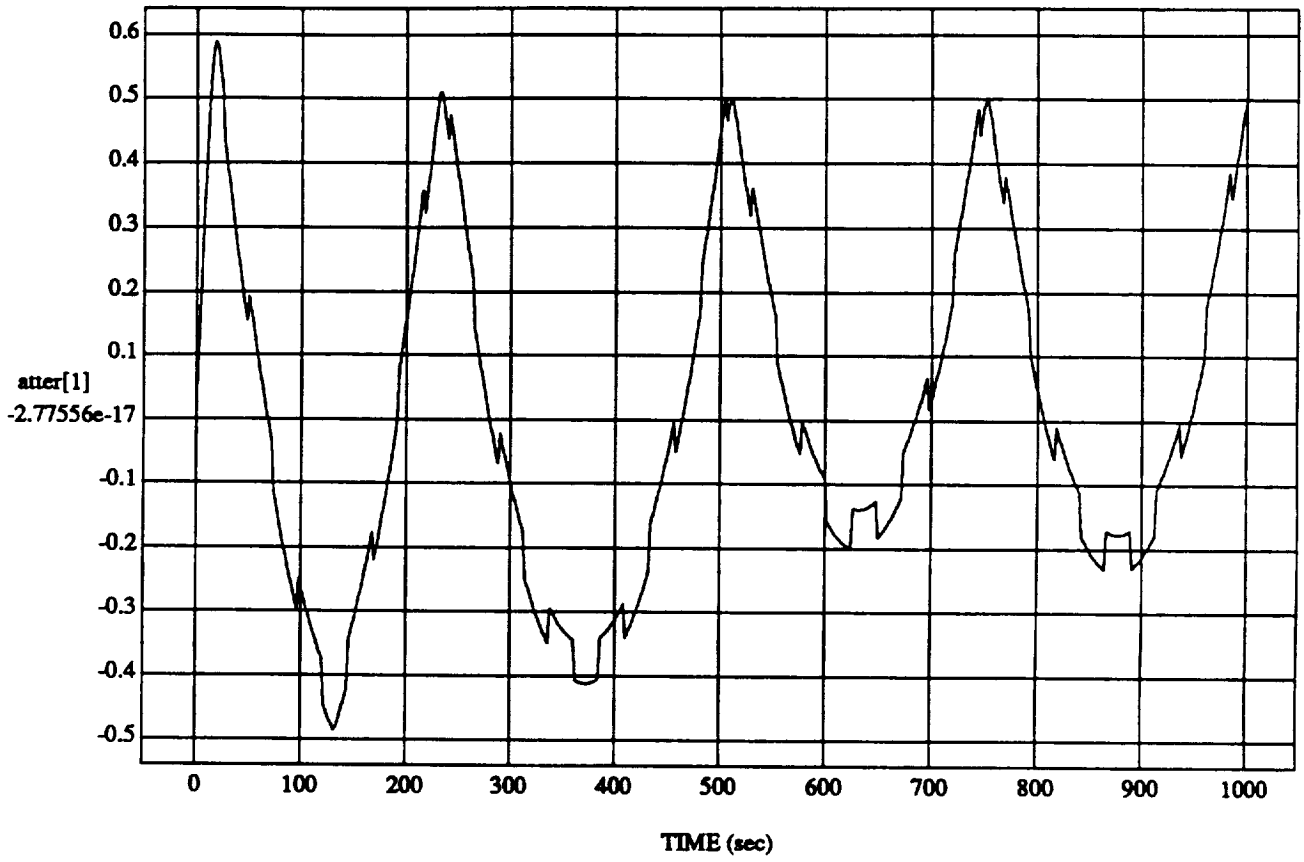
RUN: Att Hold Vernier (Tight DB)



MODULE: ORB_FUZZ_BATCH.fsw
DATA SAMPLING FREQUENCY: 0.500 Hz

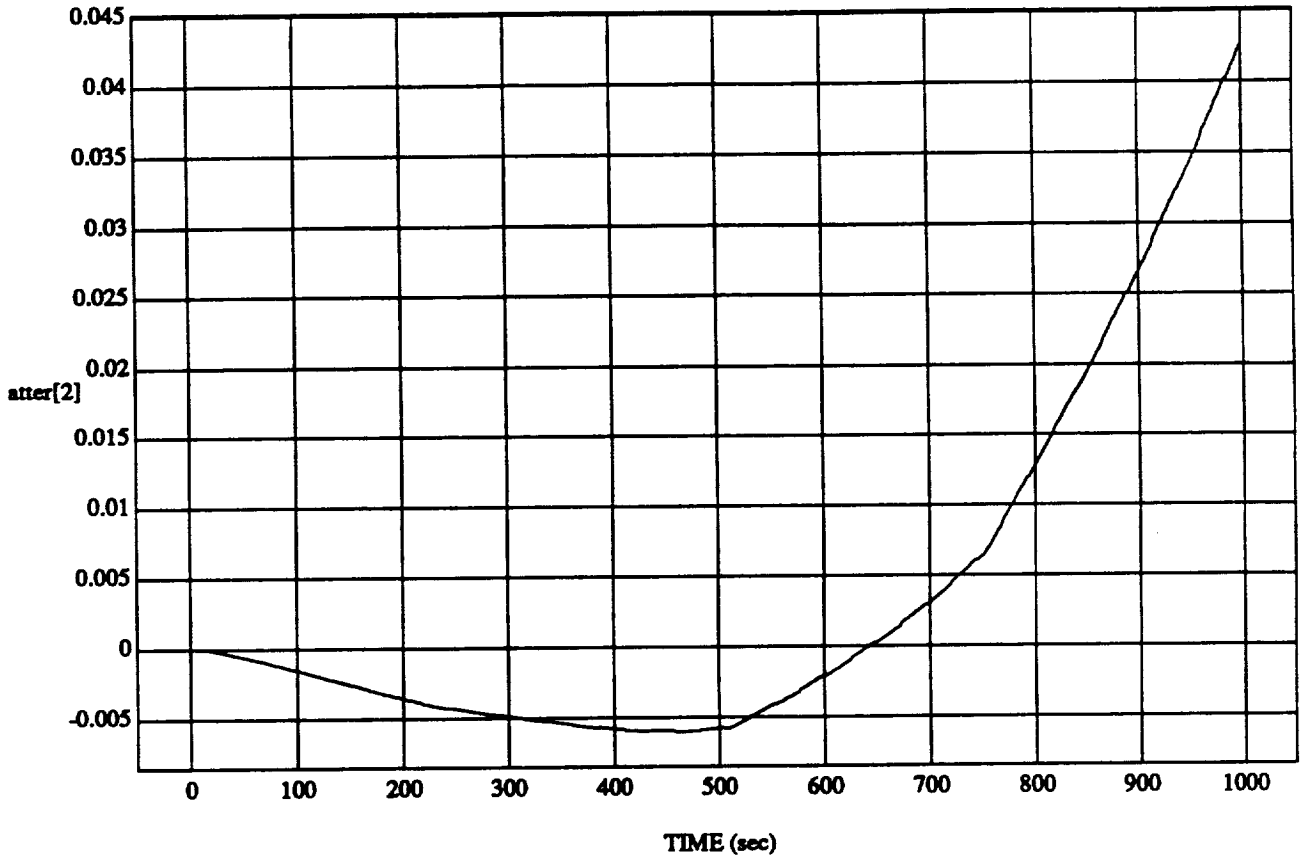
atter[1] vs TIME

RUN: Att Hold Vernier (Tight DB)



MODULE: ORB_FUZZ_BATCH.fsw
DATA SAMPLING FREQUENCY: 0.500 Hz

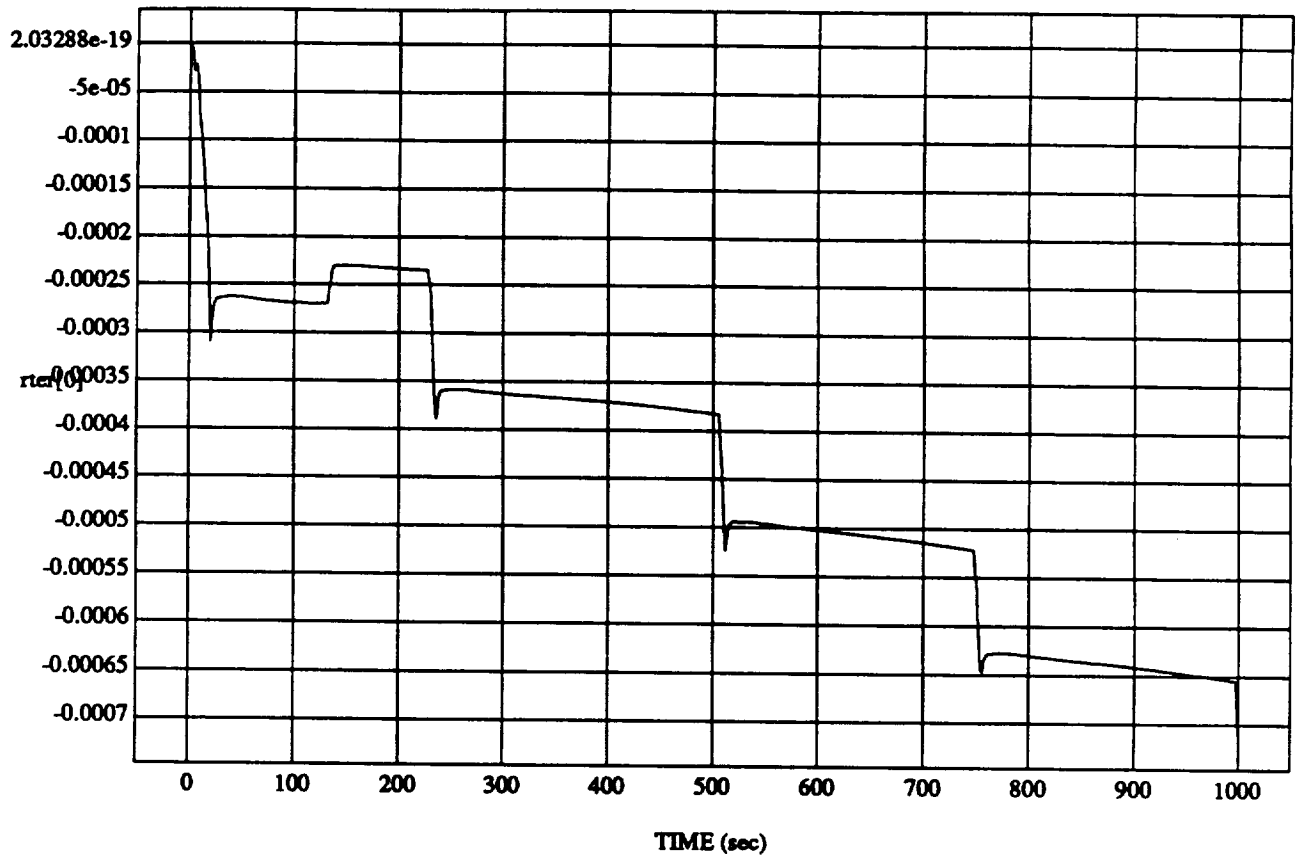
atter[2] vs TIME
RUN: Att Hold Vernier (Tight DB)



MODULE: ORB_FUZZ_BATCH.fsw
DATA SAMPLING FREQUENCY: 0.500 Hz

rter[0] vs TIME

RUN: Att Hold Vernier (Tight DB)

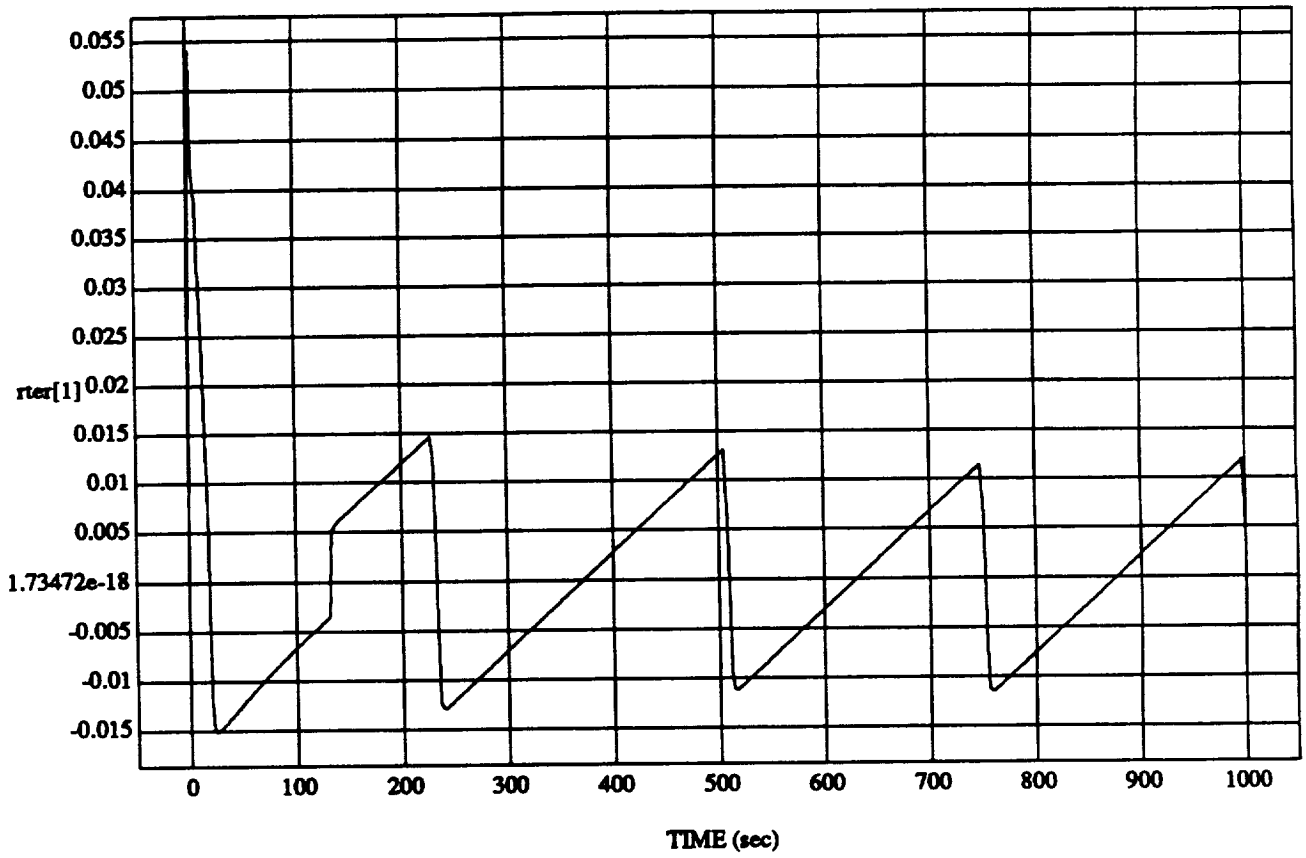


MODULE: ORB_FUZZ_BATCH.fsw

DATA SAMPLING FREQUENCY: 0.500 Hz

rter[1] vs TIME

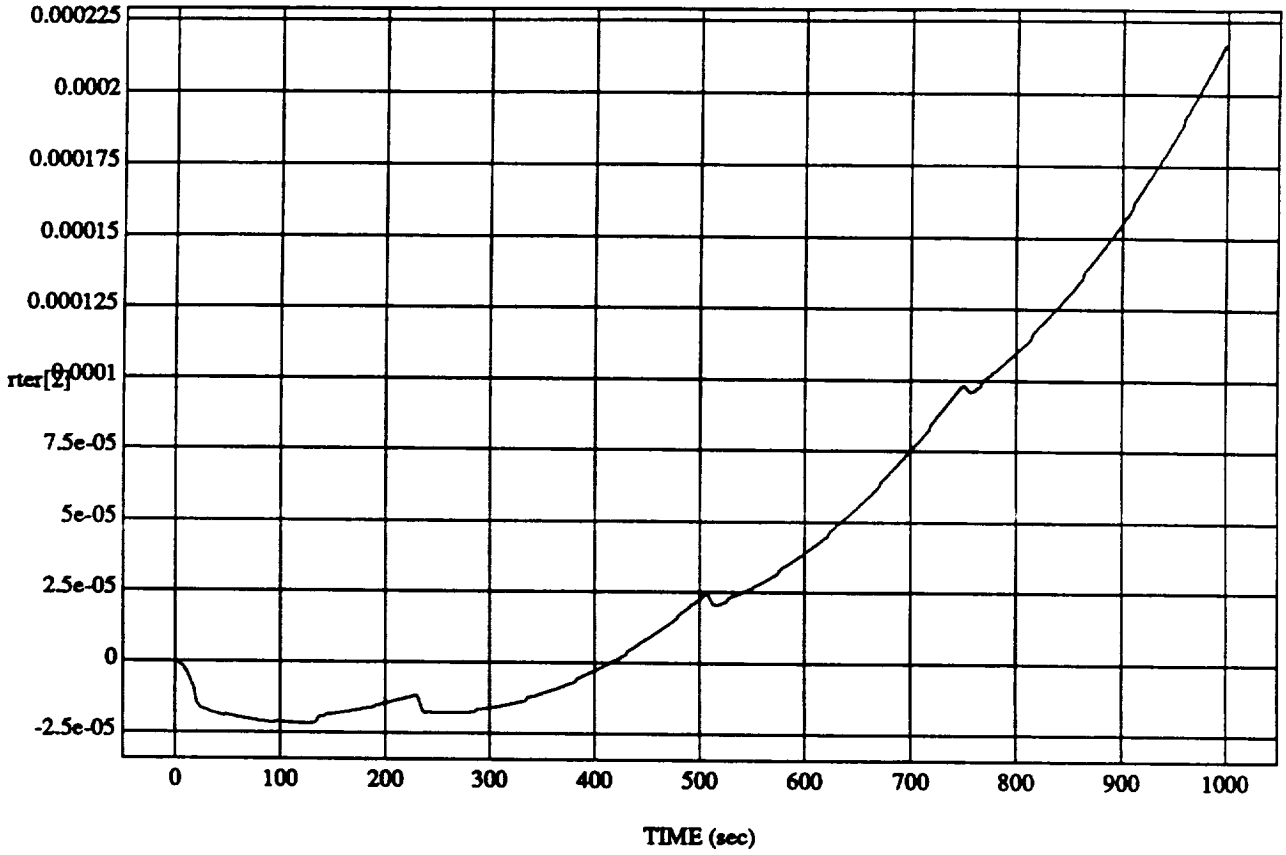
RUN: Att Hold Vernier (Tight DB)



MODULE: ORB_FUZZ_BATCH.fsw
DATA SAMPLING FREQUENCY: 0.500 Hz

rter[2] vs TIME

RUN: Att Hold Vernier (Tight DB)

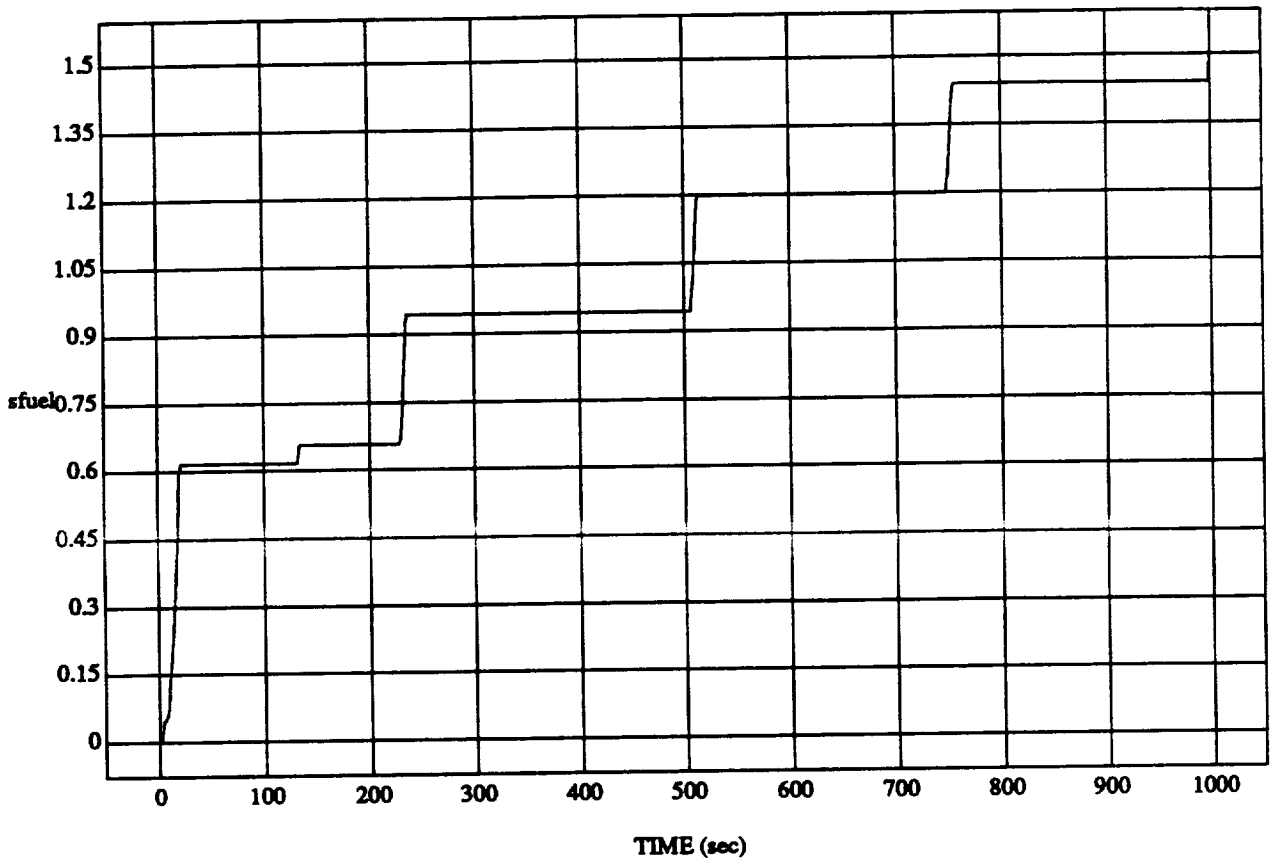


MODULE: ORB_FUZZ_BATCH.fsw
DATA SAMPLING FREQUENCY: 0.500 Hz

SIMULATION APPLICATION: FUZZY ORBITER BATCH APPLICATION (9/14/90)

sfuel vs TIME

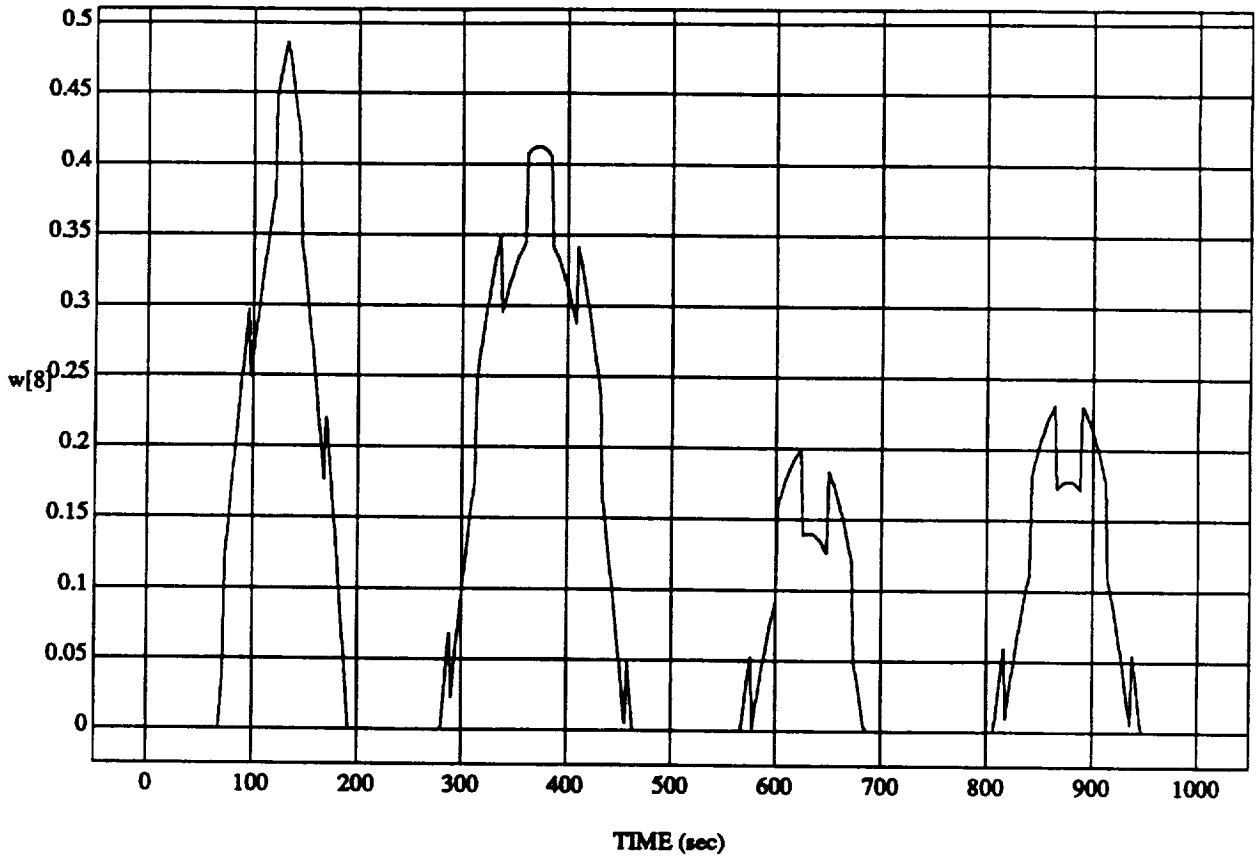
RUN: Att Hold Vernier (Tight DB)



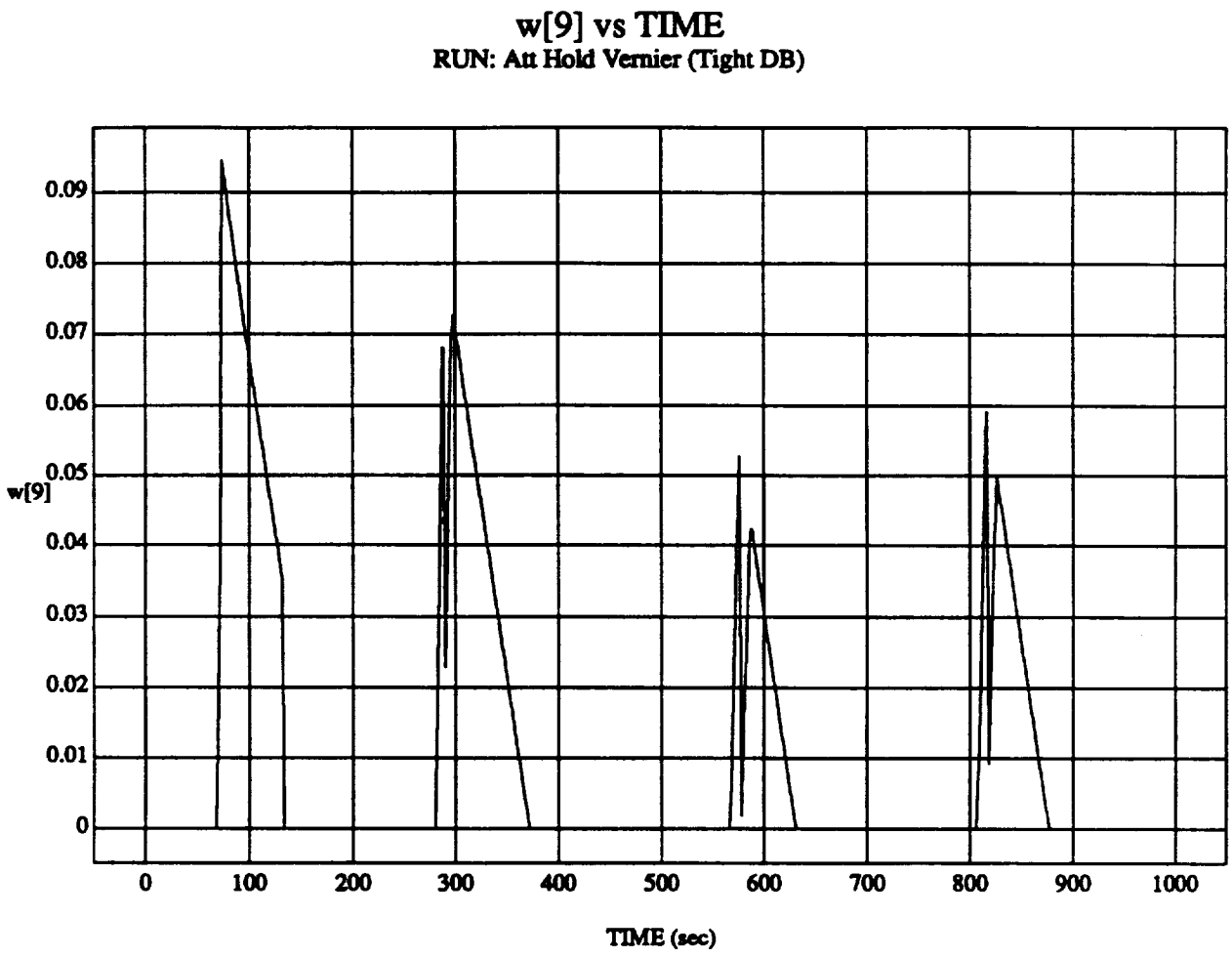
MODULE: ORB_FUZZ_BATCH.vernier
DATA SAMPLING FREQUENCY: 0.500 Hz

w[8] vs TIME

RUN: Att Hold Vernier (Tight DB)



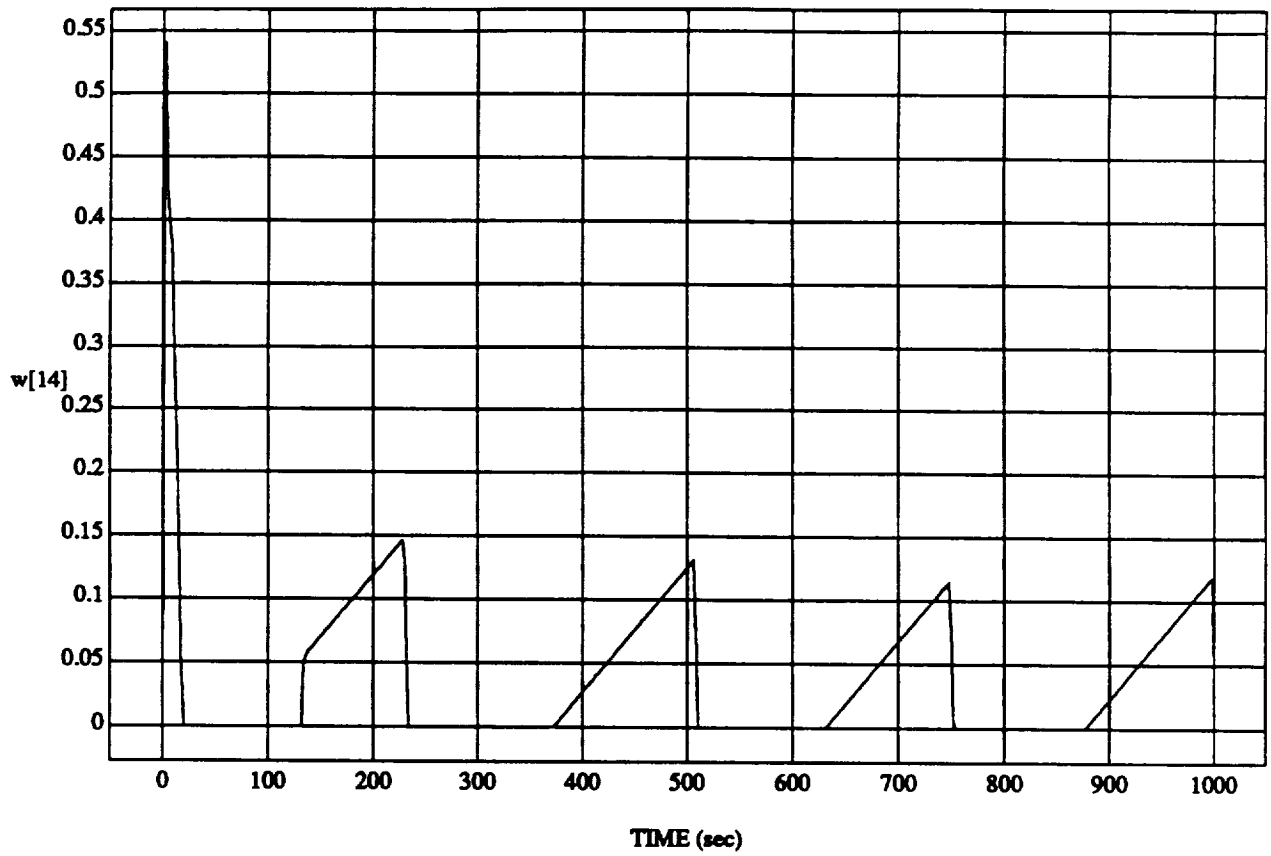
MODULE: ORB_FUZZ_BATCH.learn2
DATA SAMPLING FREQUENCY: 0.500 Hz



MODULE: ORB_FUZZ_BATCH.learn2
DATA SAMPLING FREQUENCY: 0.500 Hz

w[14] vs TIME

RUN: Att Hold Vernier (Tight DB)

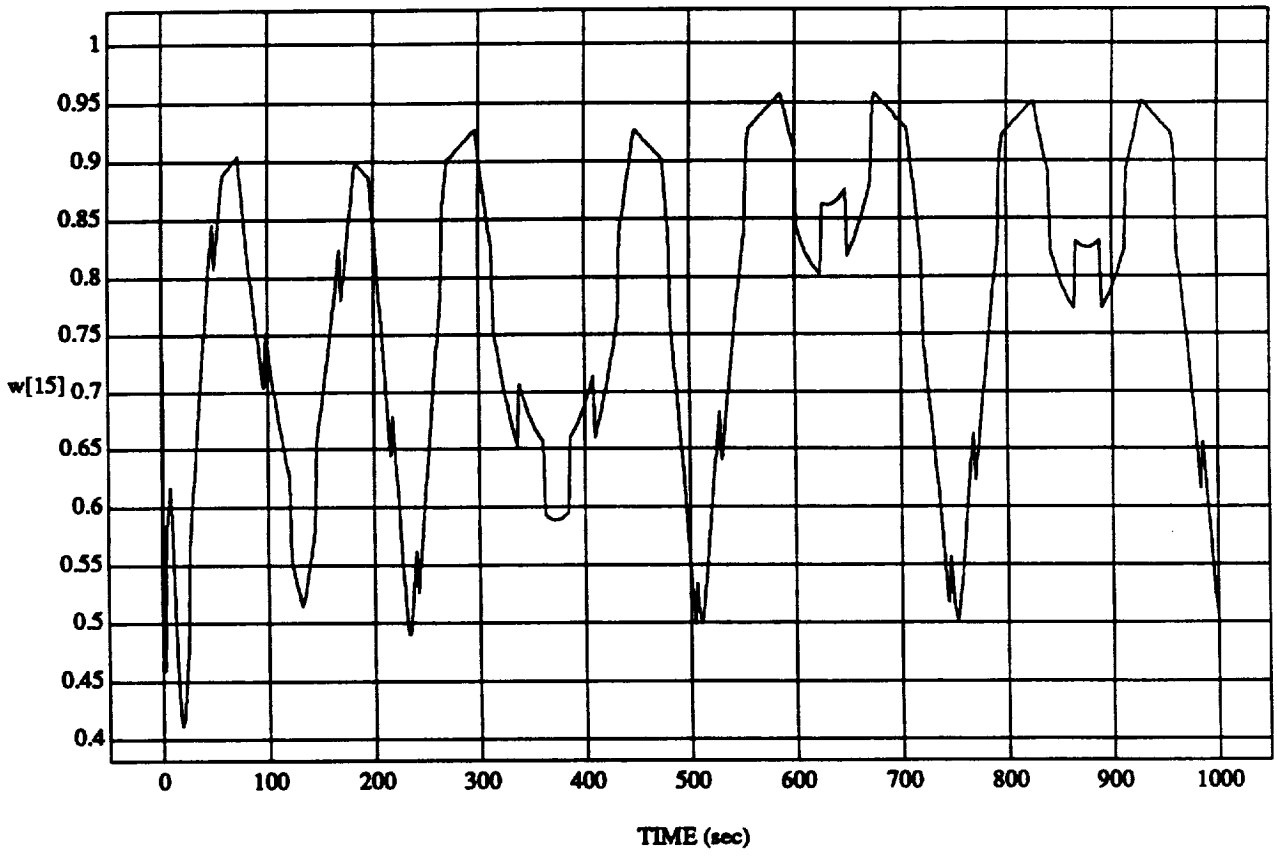


MODULE: ORB_FUZZ_BATCH.learn2

DATA SAMPLING FREQUENCY: 0.500 Hz

w[15] vs TIME

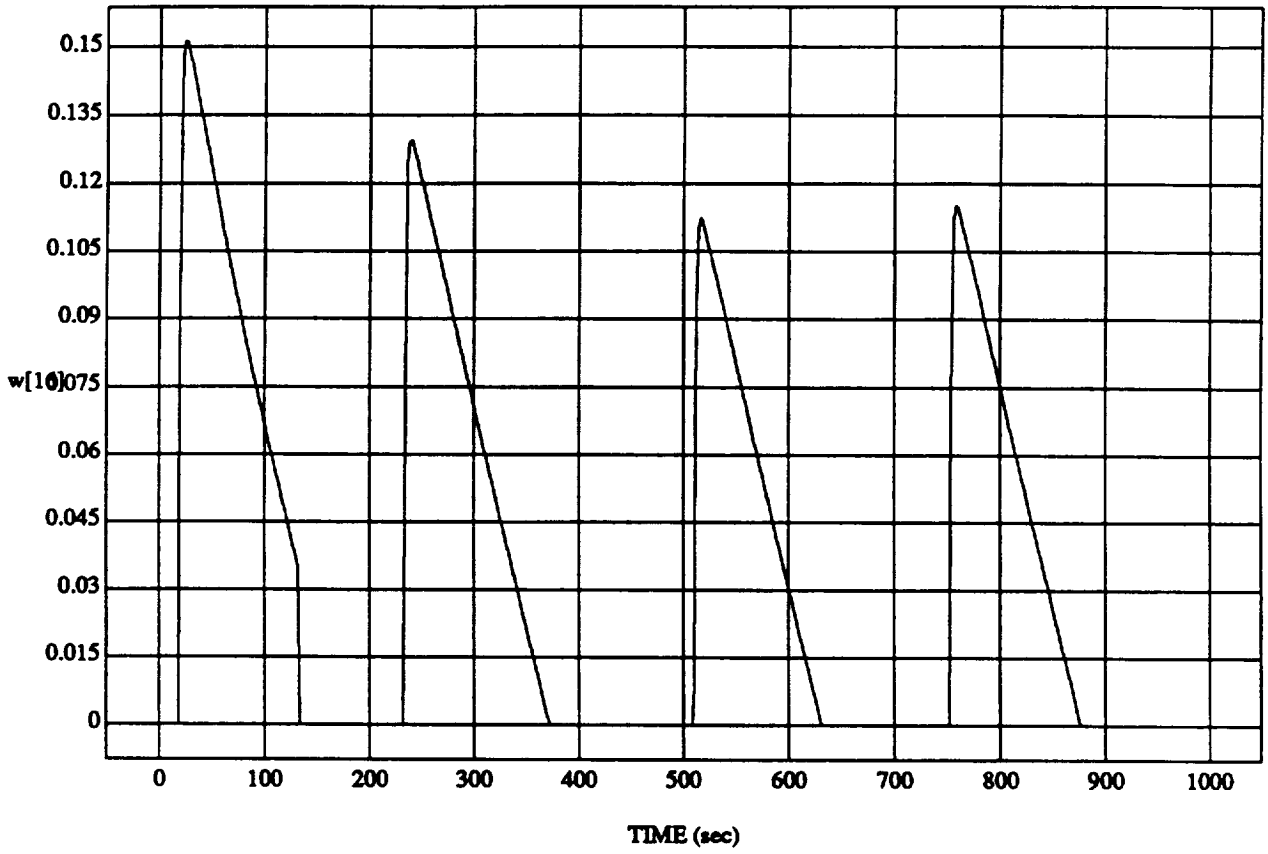
RUN: Att Hold Vernier (Tight DB)



MODULE: ORB_FUZZ_BATCH.learn2
DATA SAMPLING FREQUENCY: 0.500 Hz

w[16] vs TIME

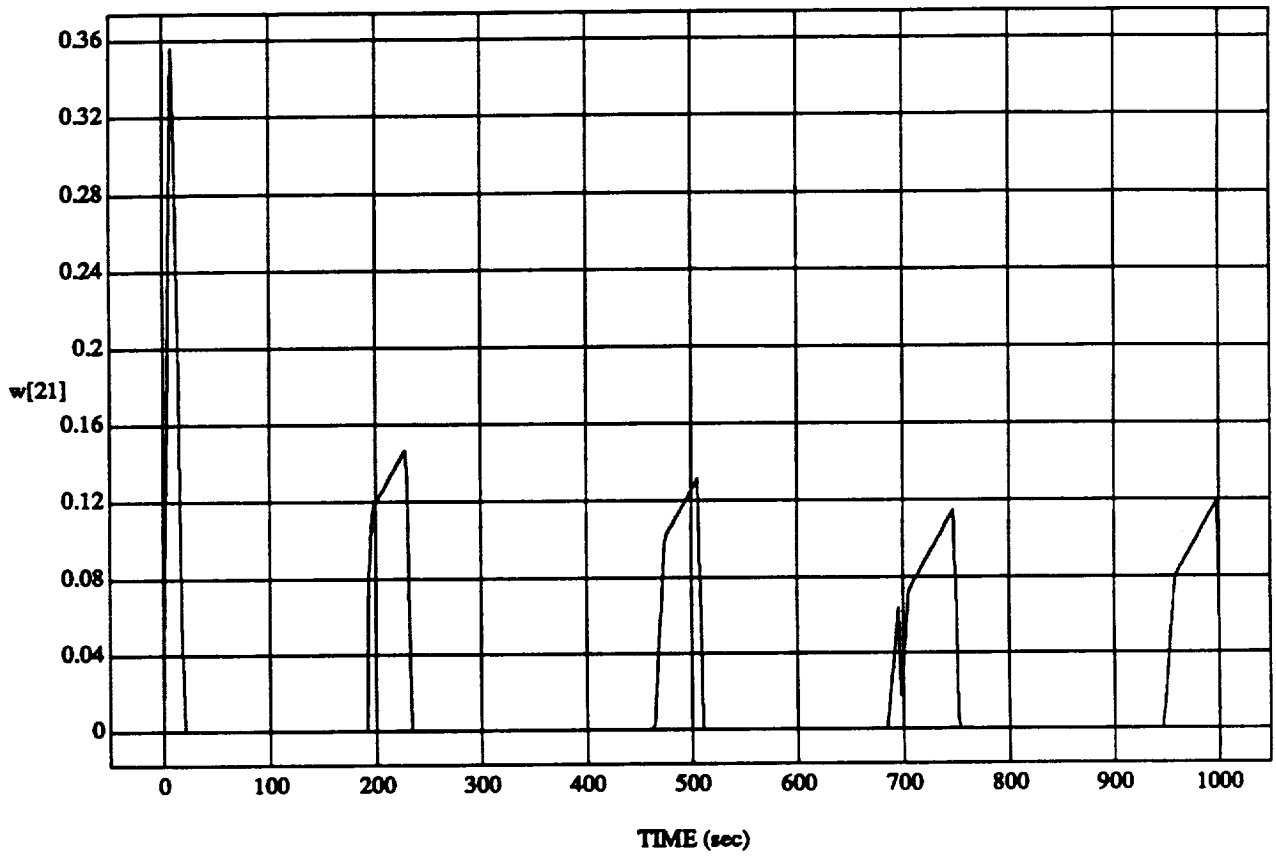
RUN: Att Hold Vernier (Tight DB)



MODULE: ORB_FUZZ_BATCH.learn2
DATA SAMPLING FREQUENCY: 0.500 Hz

w[21] vs TIME

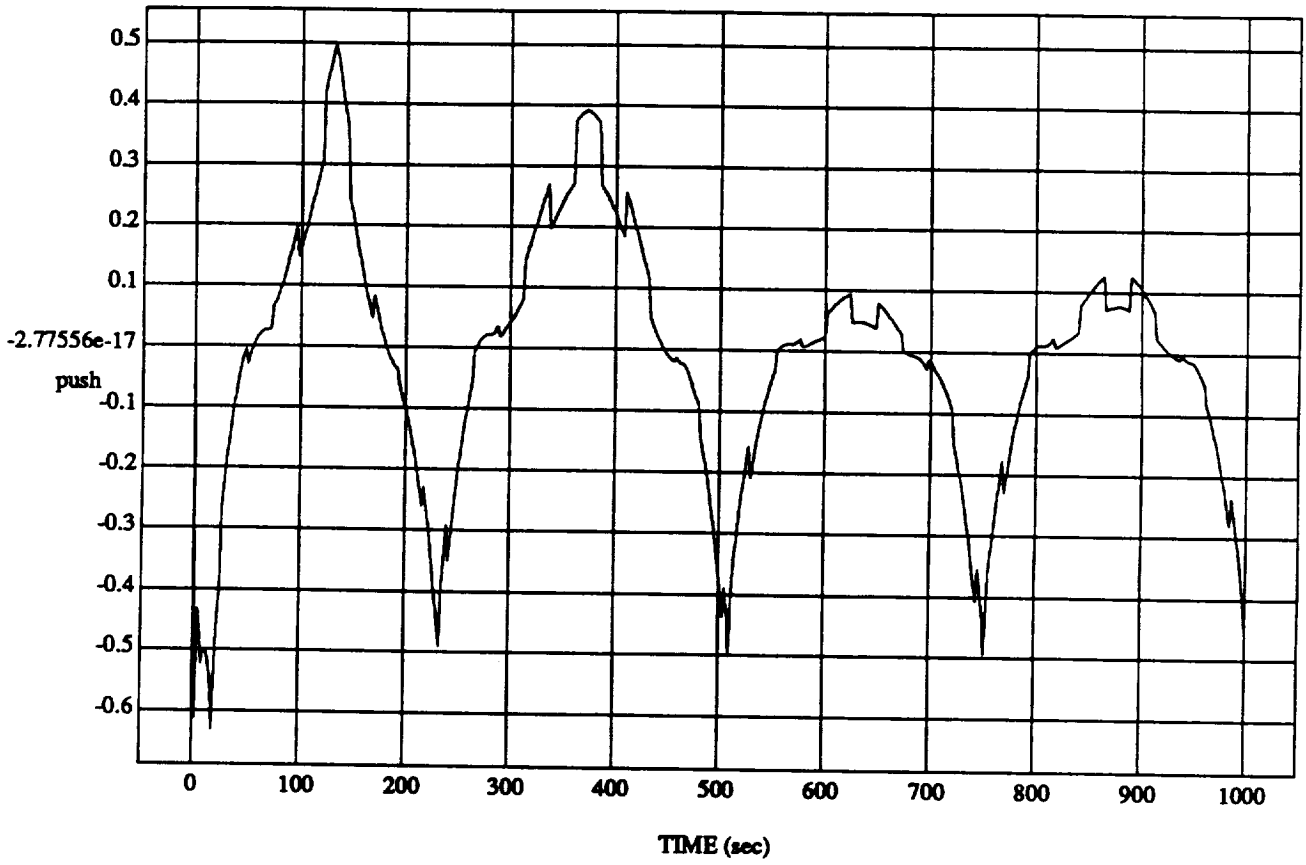
RUN: Att Hold Vernier (Tight DB)



MODULE: ORB_FUZZ_BATCH.learn2
DATA SAMPLING FREQUENCY: 0.500 Hz

push vs TIME

RUN: Att Hold Vernier (Tight DB)

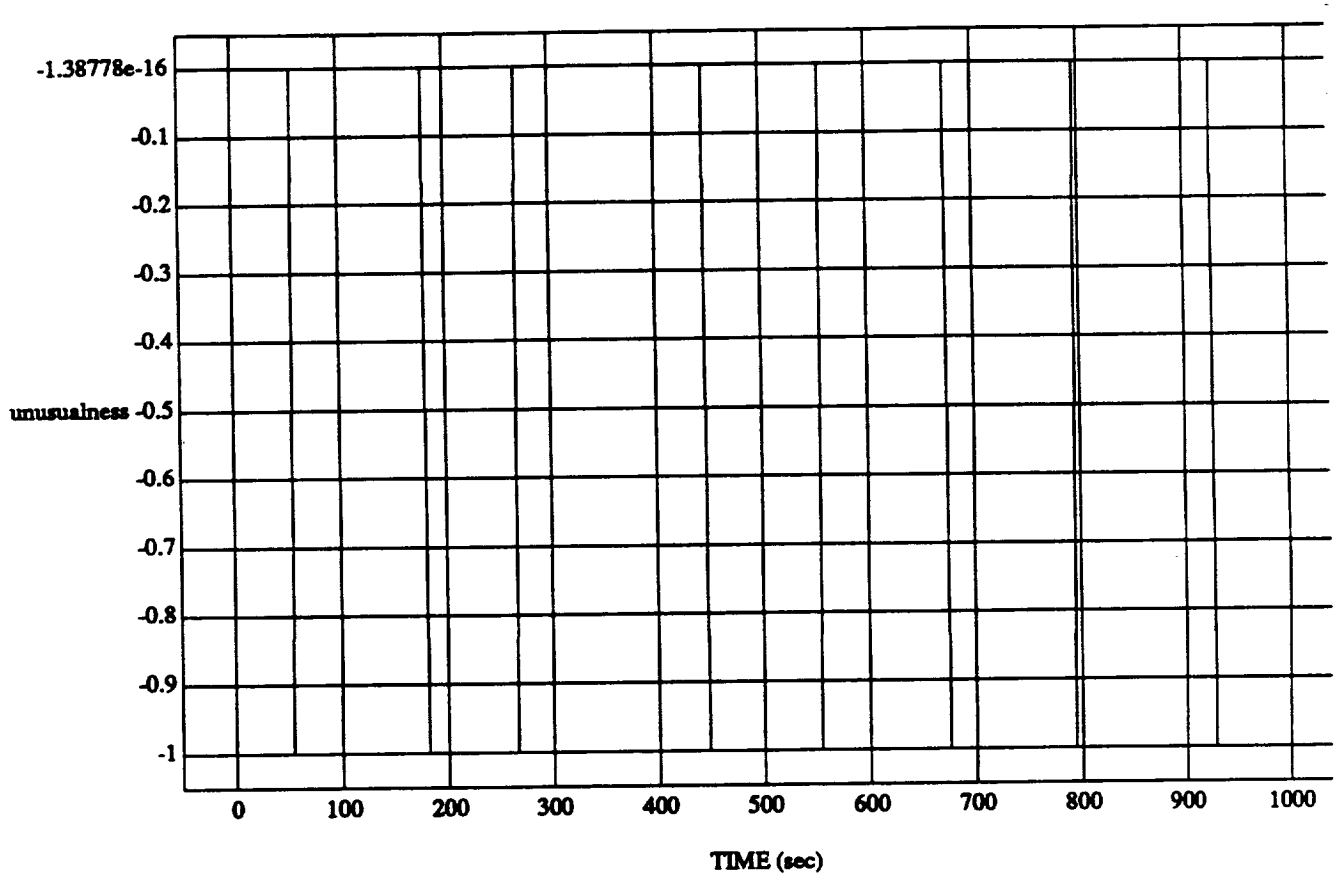


MODULE: ORB_FUZZ_BATCH.learn2

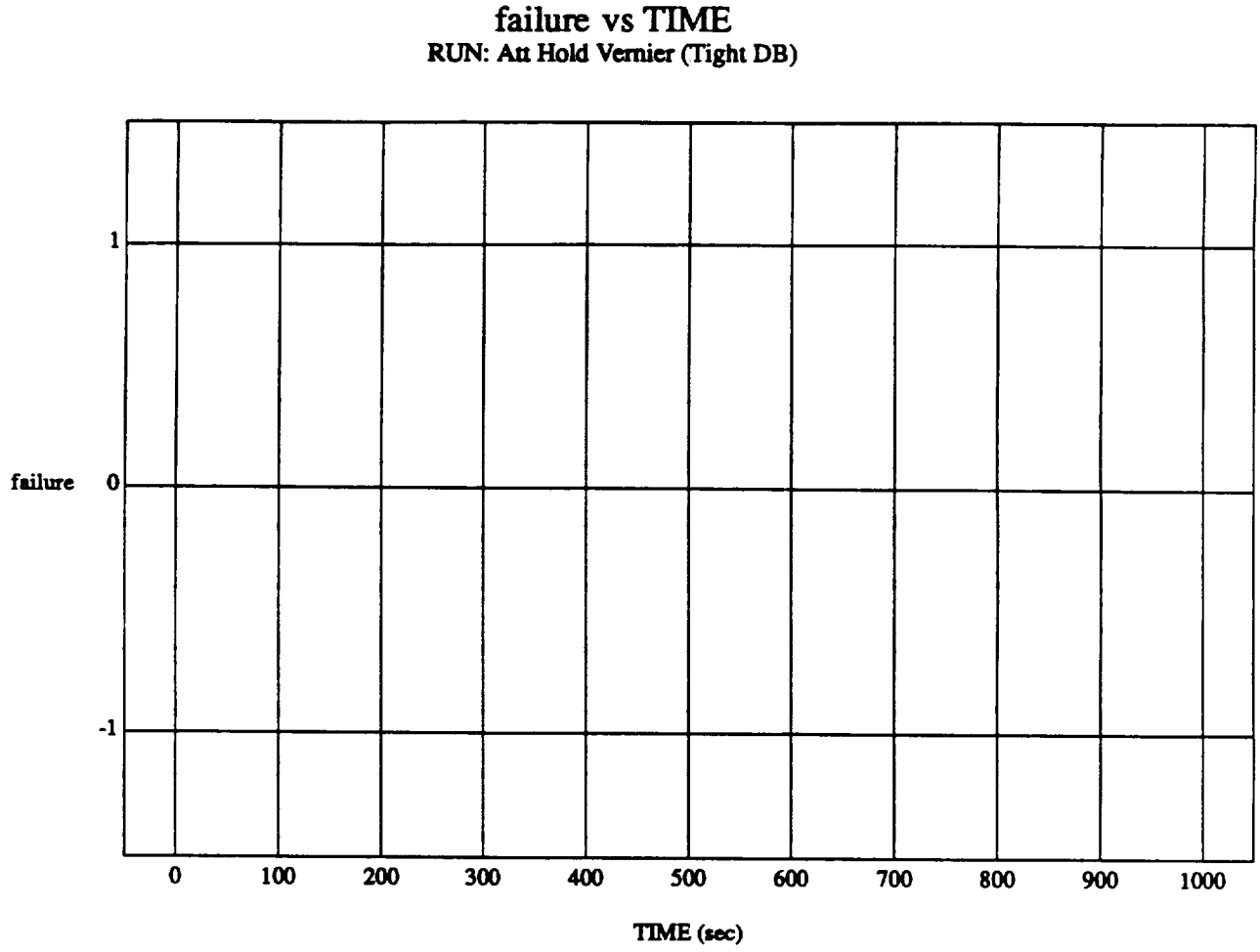
DATA SAMPLING FREQUENCY: 0.500 Hz

unusualness vs TIME

RUN: Att Hold Vernier (Tight DB)



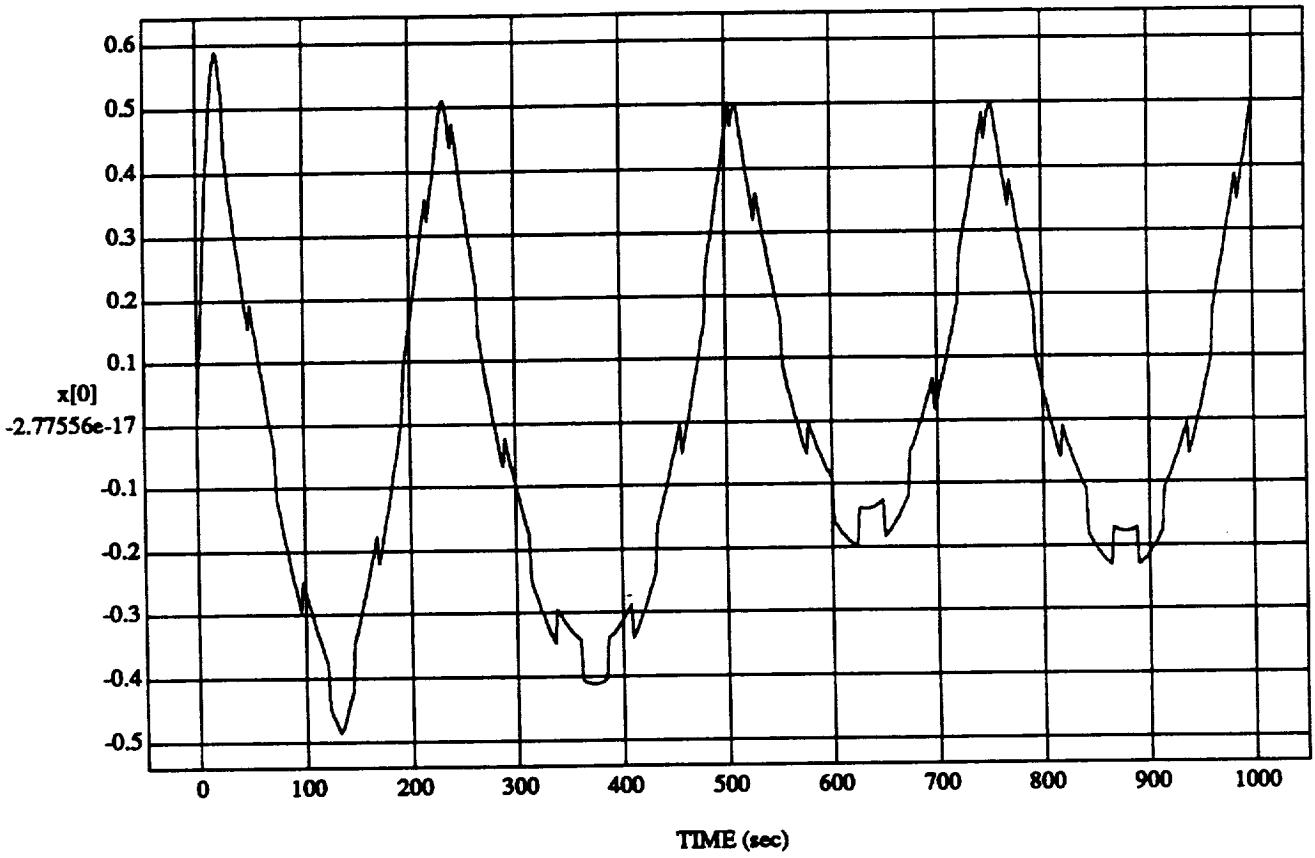
MODULE: ORB_FUZZ_BATCH.learn2
DATA SAMPLING FREQUENCY: 0.500 Hz



MODULE: ORB_FUZZ_BATCH.learn2
DATA SAMPLING FREQUENCY: 0.500 Hz

x[0] vs TIME

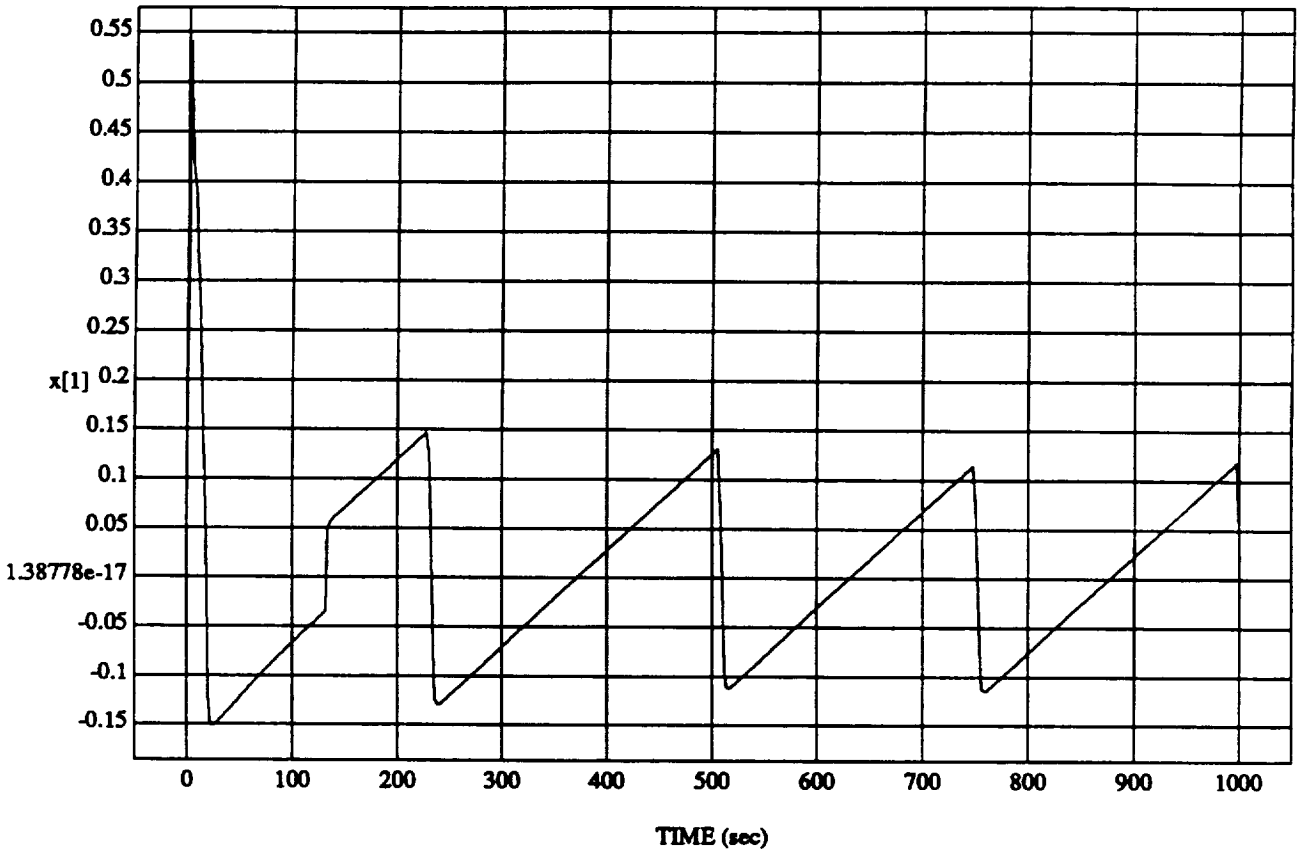
RUN: Att Hold Vernier (Tight DB)



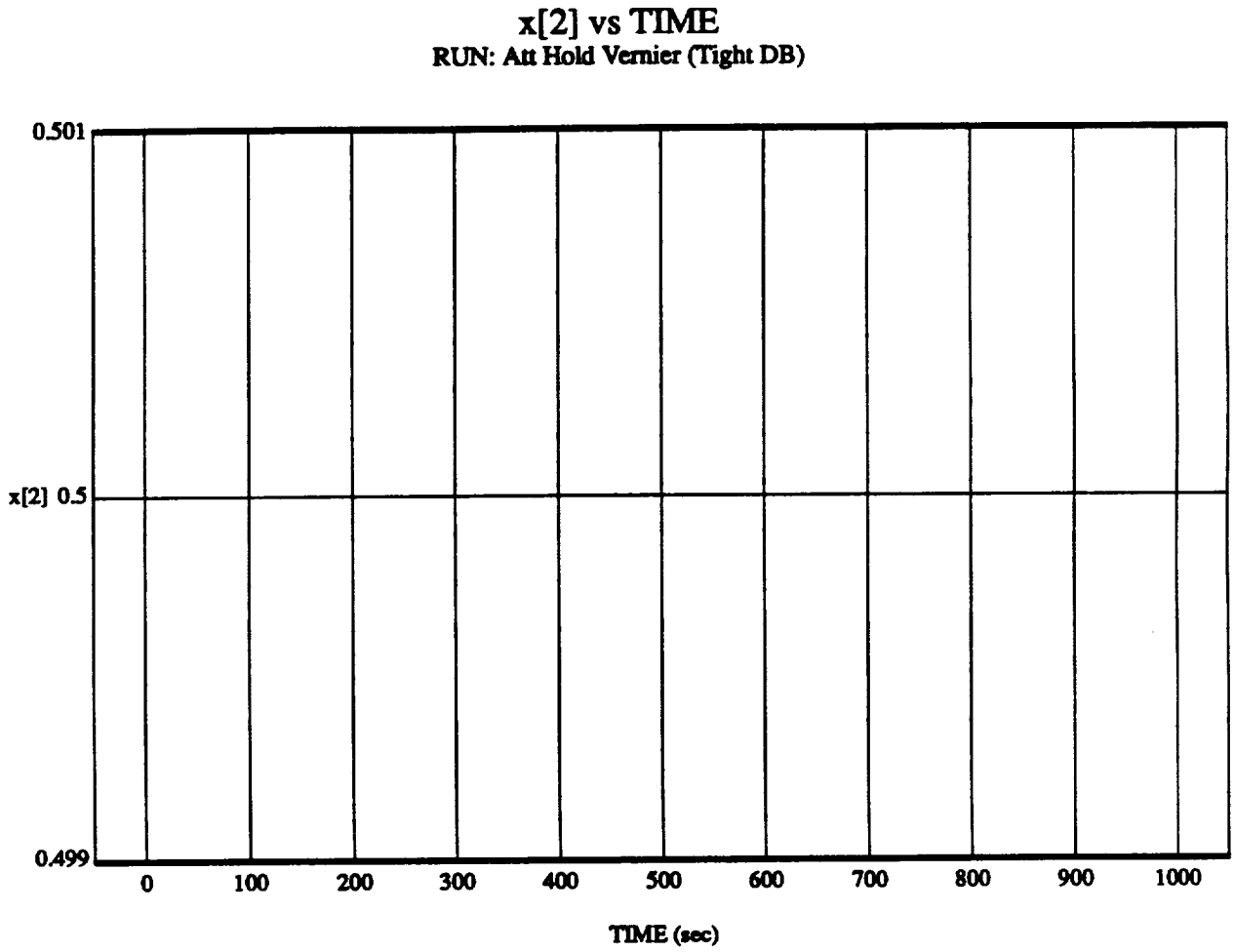
MODULE: ORB_FUZZ_BATCH.learn2
DATA SAMPLING FREQUENCY: 0.500 Hz

x[1] vs TIME

RUN: Att Hold Vernier (Tight DB)



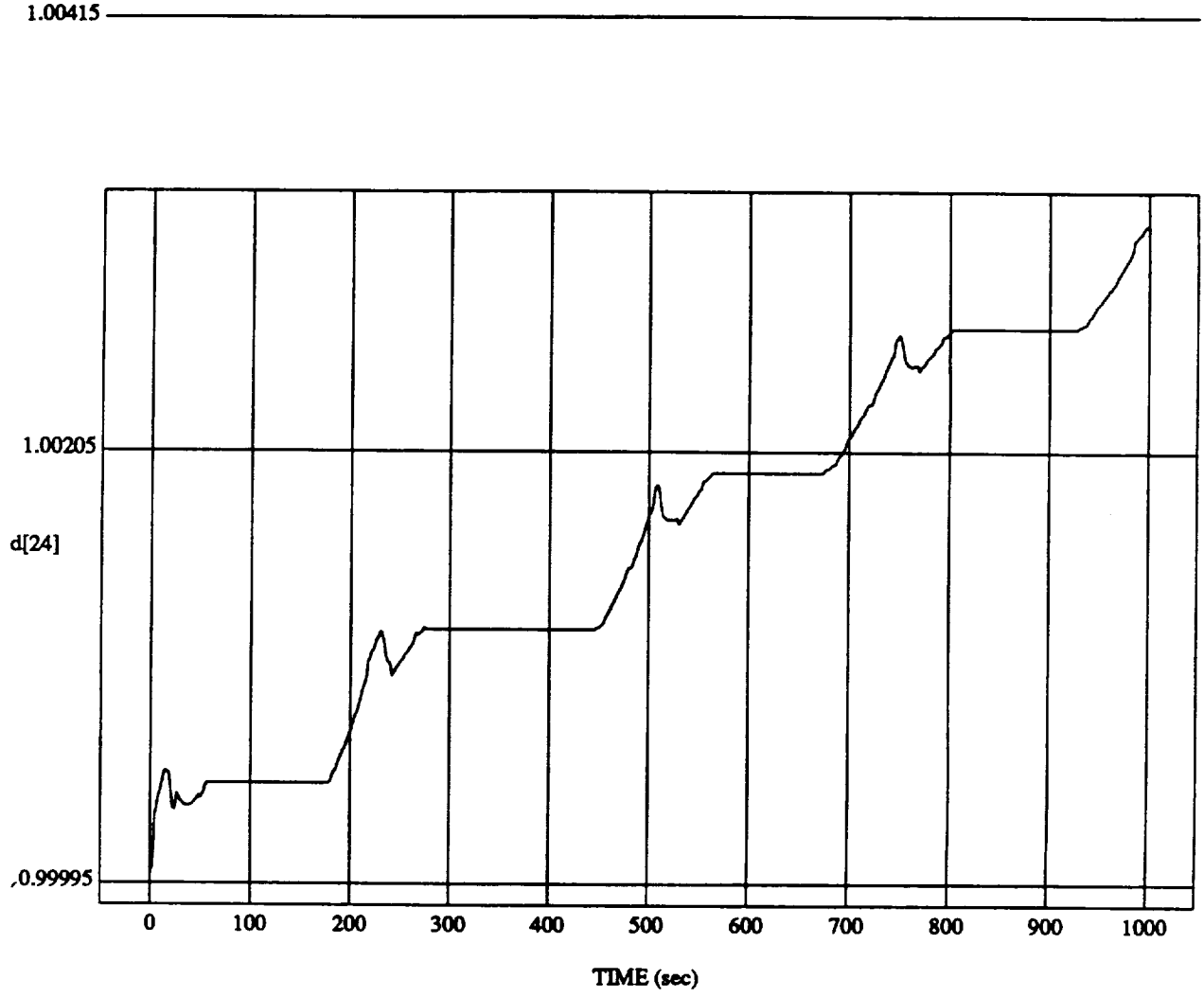
MODULE: ORB_FUZZ_BATCH.learn2
DATA SAMPLING FREQUENCY: 0.500 Hz



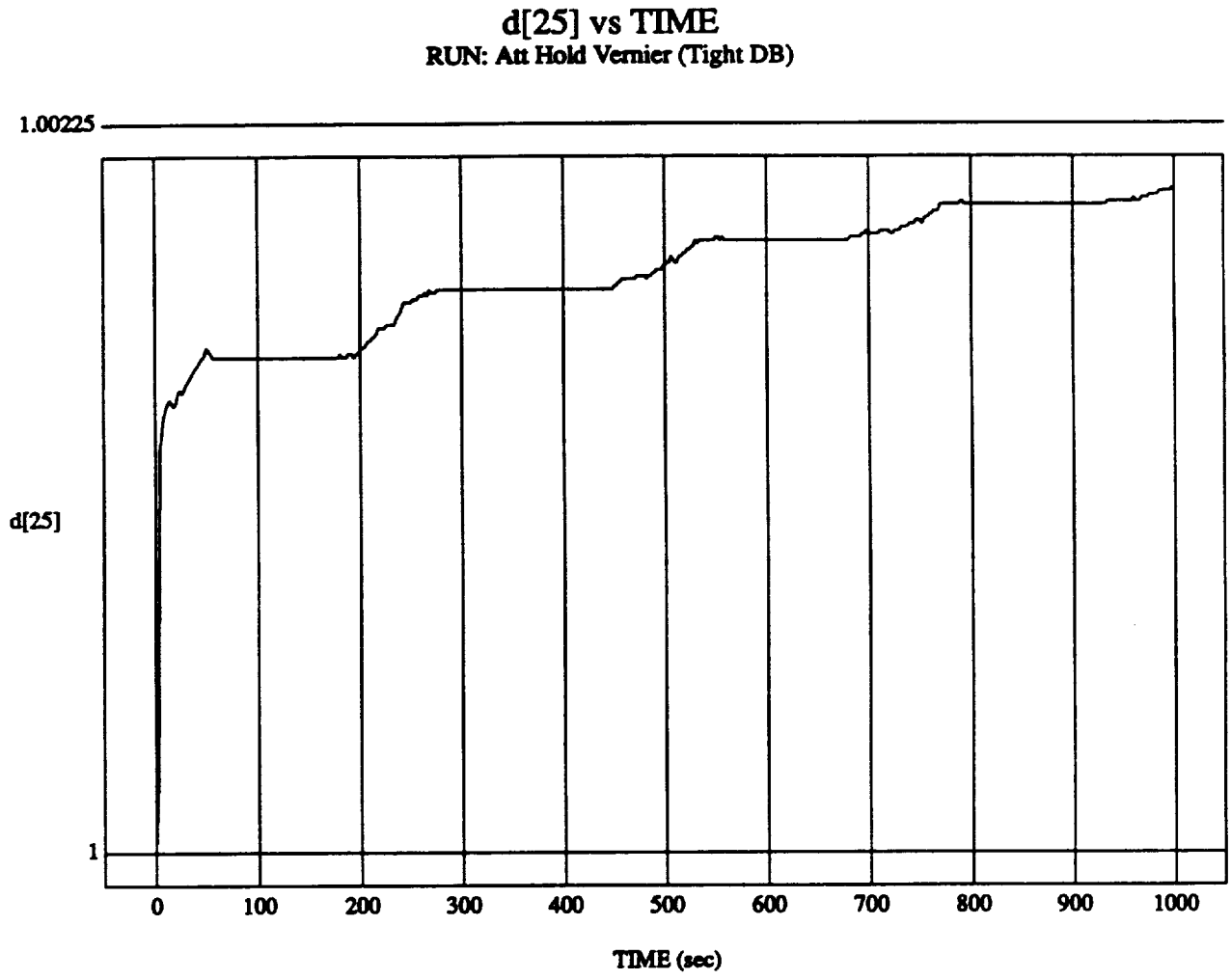
MODULE: ORB_FUZZ_BATCH.learn2
DATA SAMPLING FREQUENCY: 0.500 Hz

d[24] vs TIME

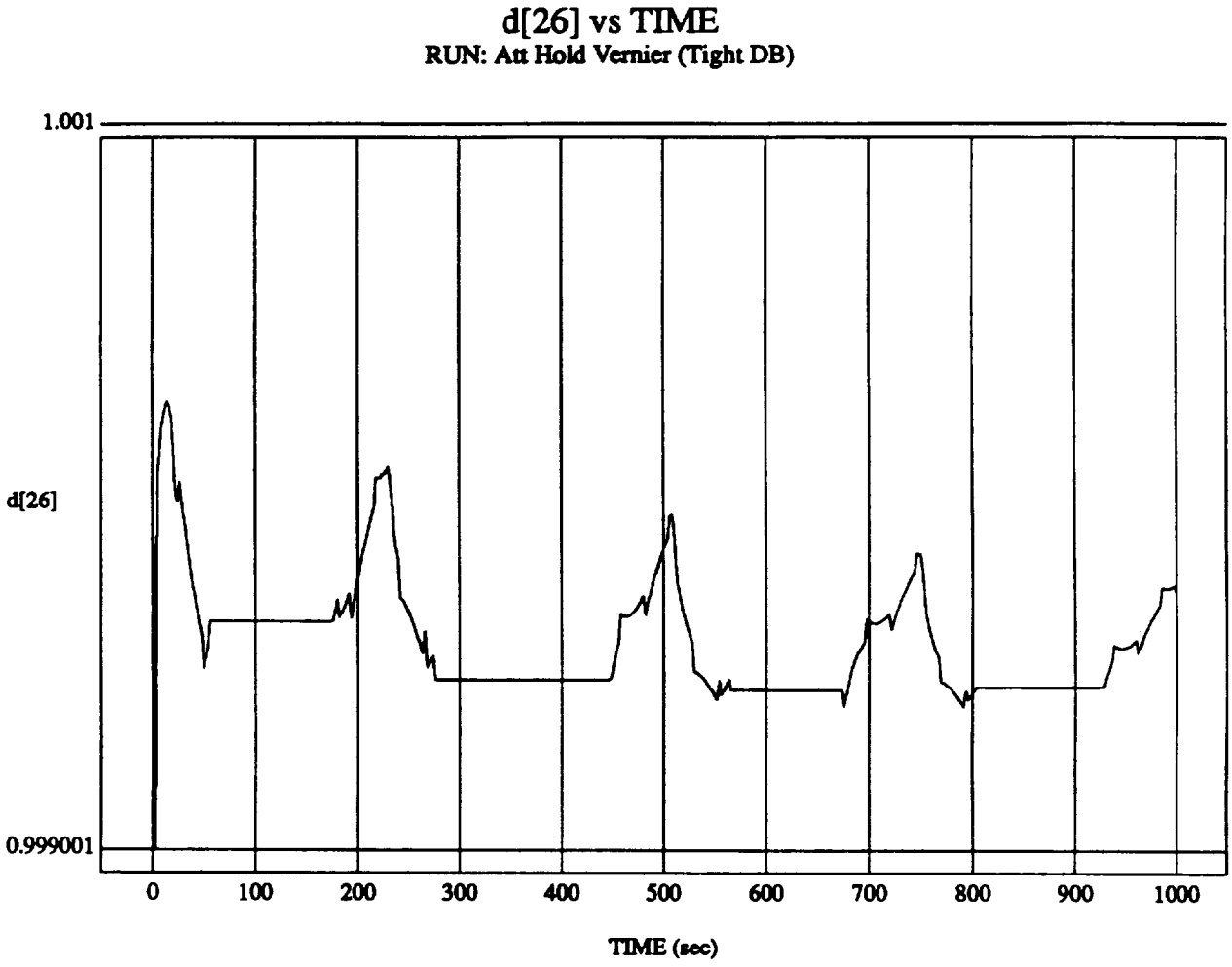
RUN: Att Hold Vernier (Tight DB)



MODULE: ORB_FUZZ_BATCH.learn2
DATA SAMPLING FREQUENCY: 0.500 Hz



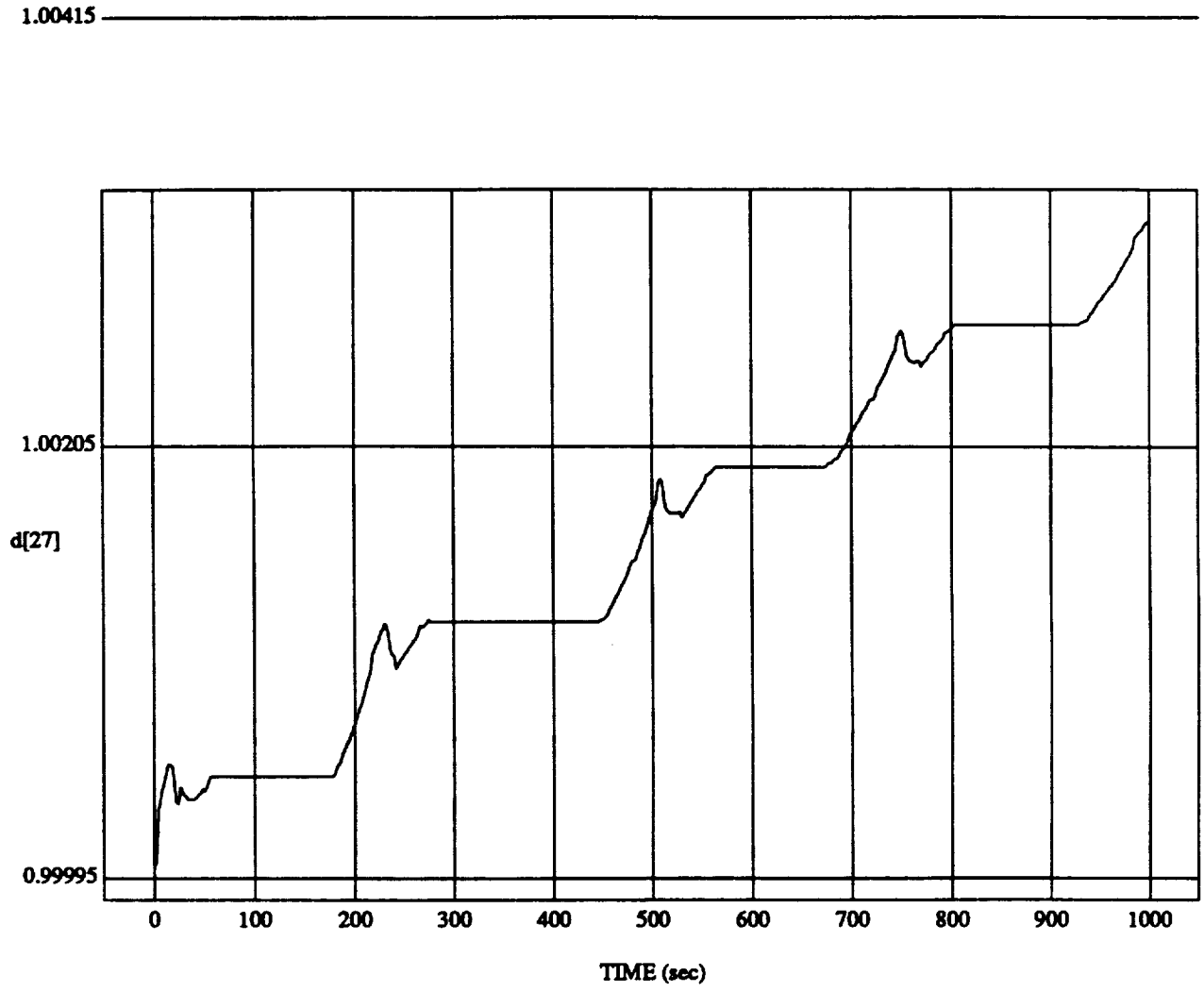
MODULE: ORB_FUZZ_BATCH.learn2
DATA SAMPLING FREQUENCY: 0.500 Hz



MODULE: ORB_FUZZ_BATCH.learn2
DATA SAMPLING FREQUENCY: 0.500 Hz

d[27] vs TIME

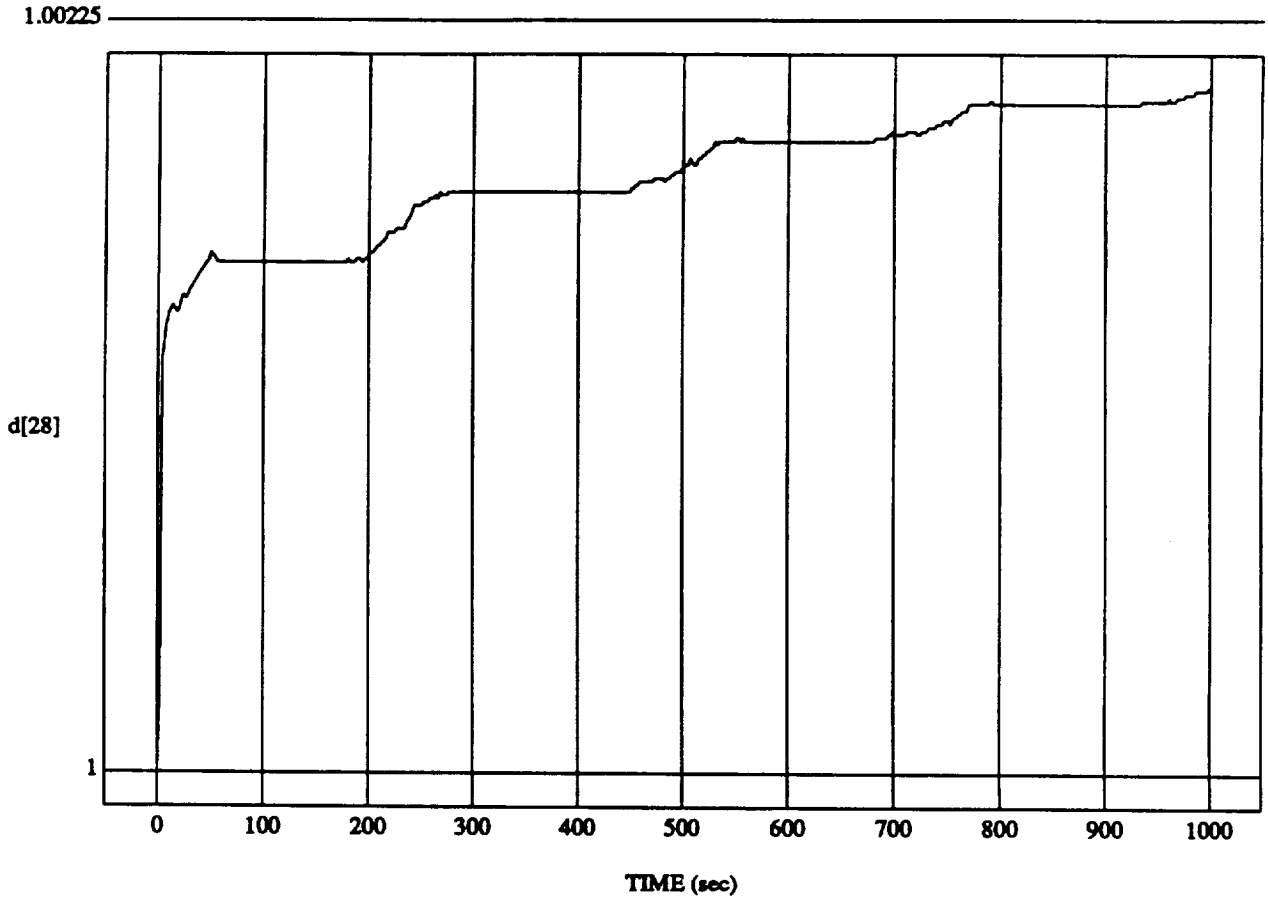
RUN: Att Hold Vernier (Tight DB)



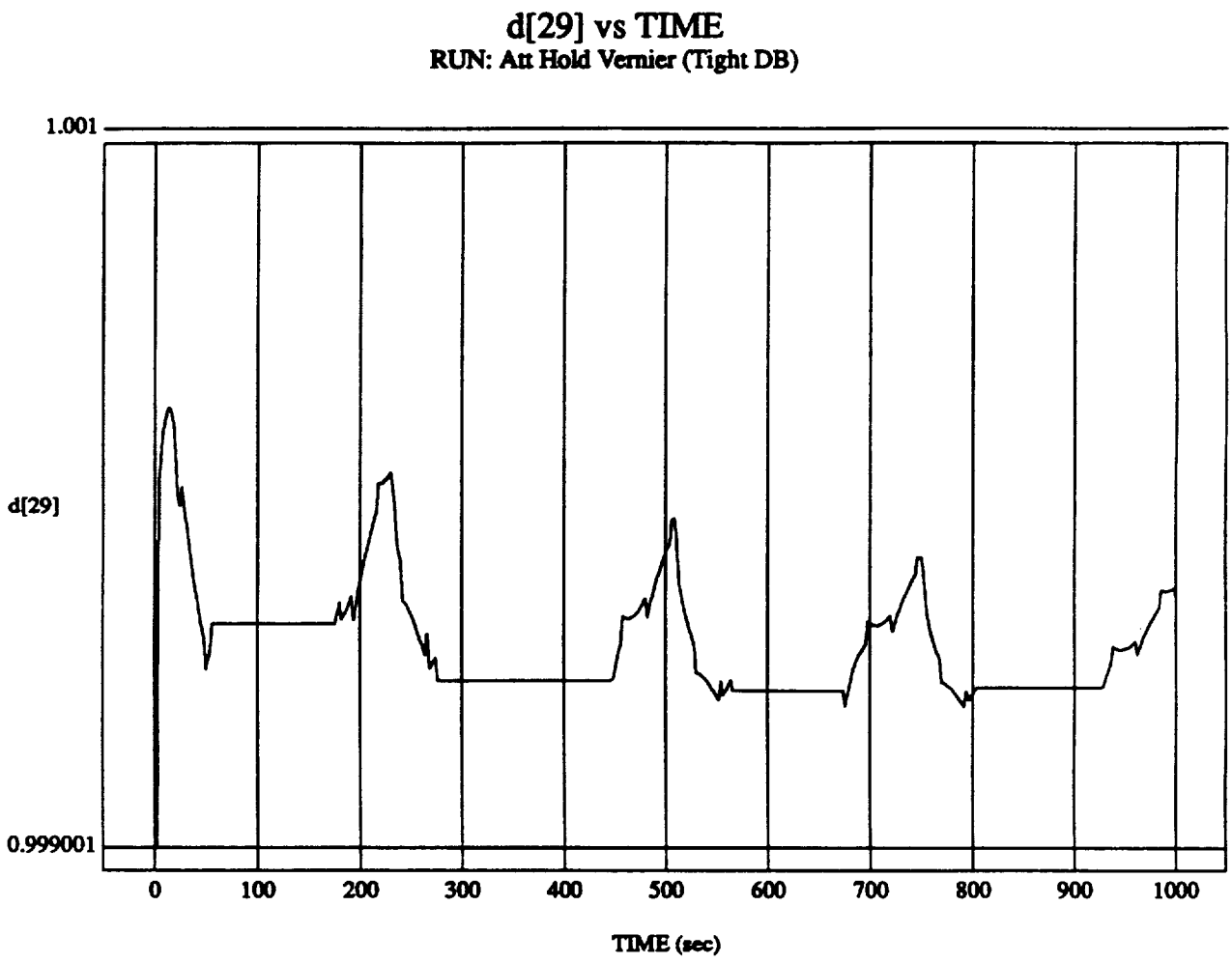
MODULE: ORB_FUZZ_BATCH.learn2
DATA SAMPLING FREQUENCY: 0.500 Hz

d[28] vs TIME

RUN: Att Hold Vernier (Tight DB)



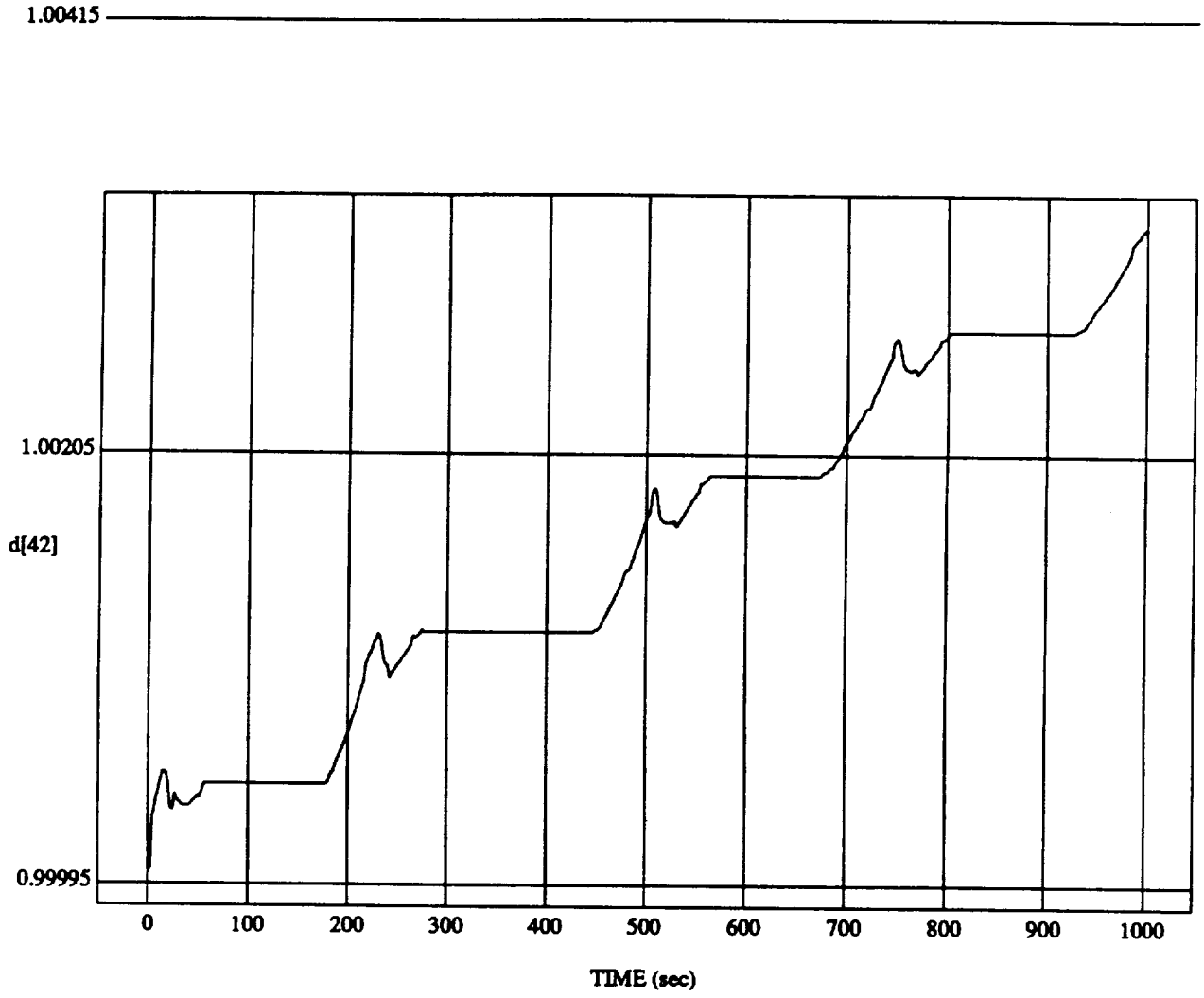
MODULE: ORB_FUZZ_BATCH.learn2
DATA SAMPLING FREQUENCY: 0.500 Hz



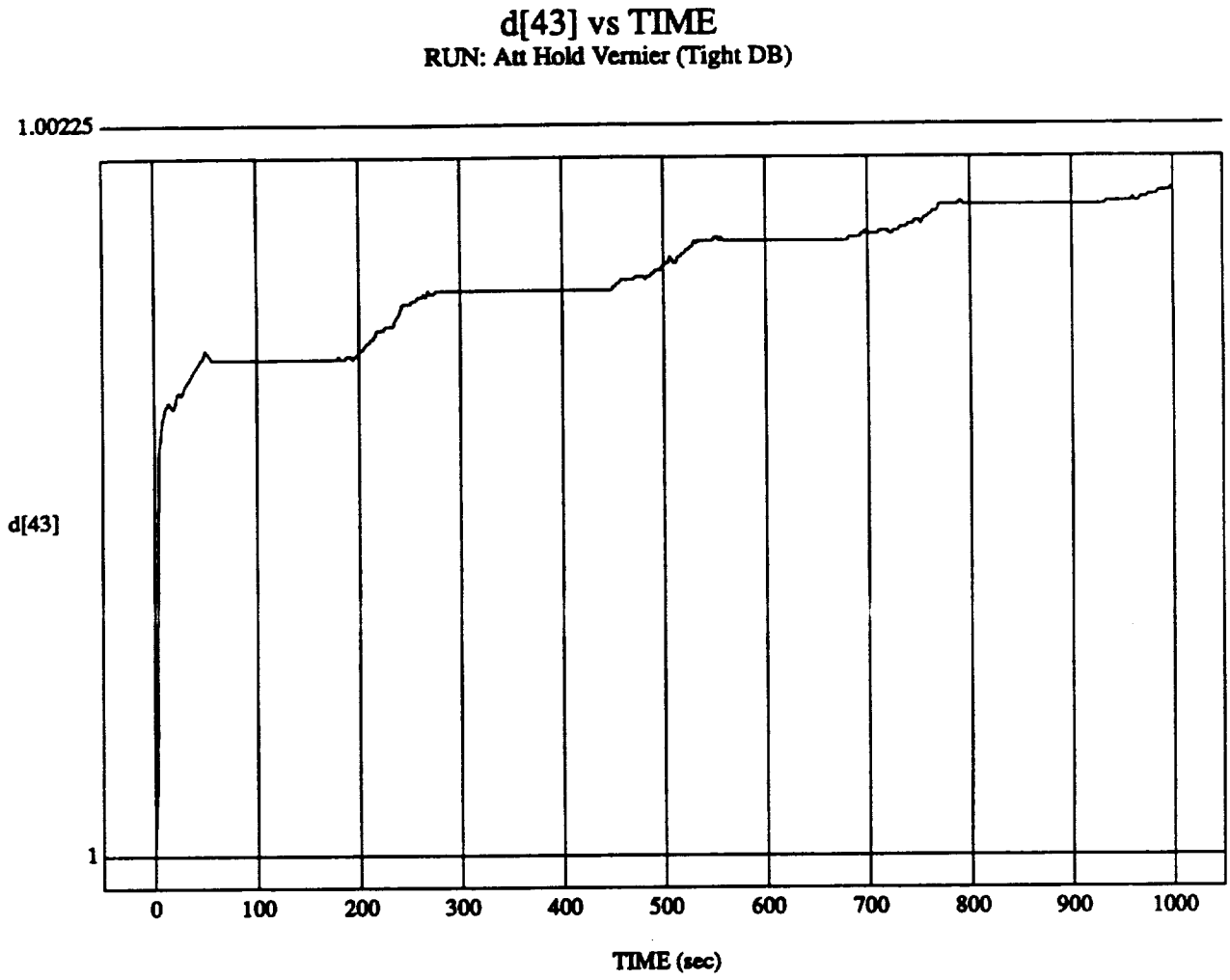
MODULE: ORB_FUZZ_BATCH.learn2
DATA SAMPLING FREQUENCY: 0.500 Hz

d[42] vs TIME

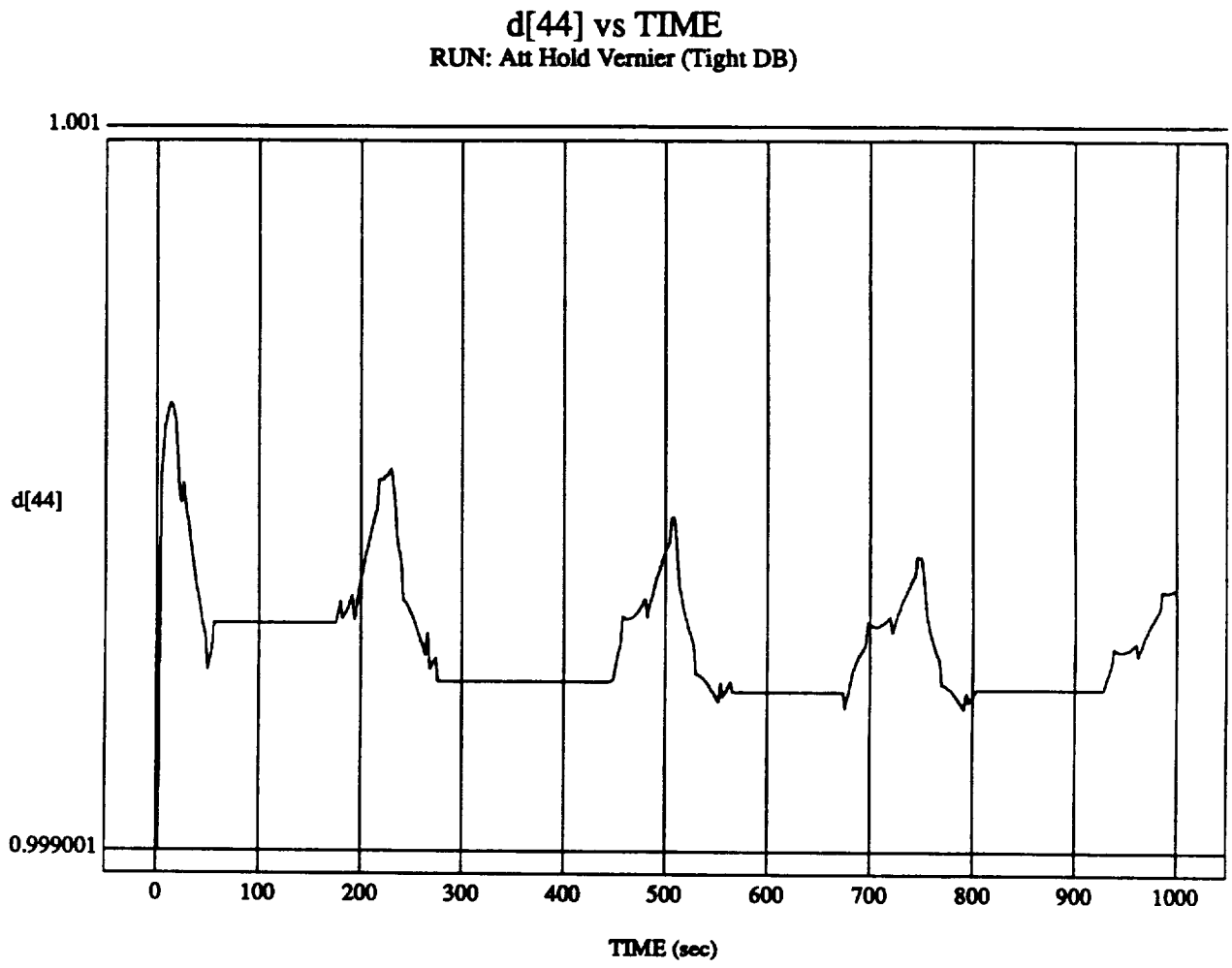
RUN: Att Hold Vernier (Tight DB)



MODULE: ORB_FUZZ_BATCH.learn2
DATA SAMPLING FREQUENCY: 0.500 Hz



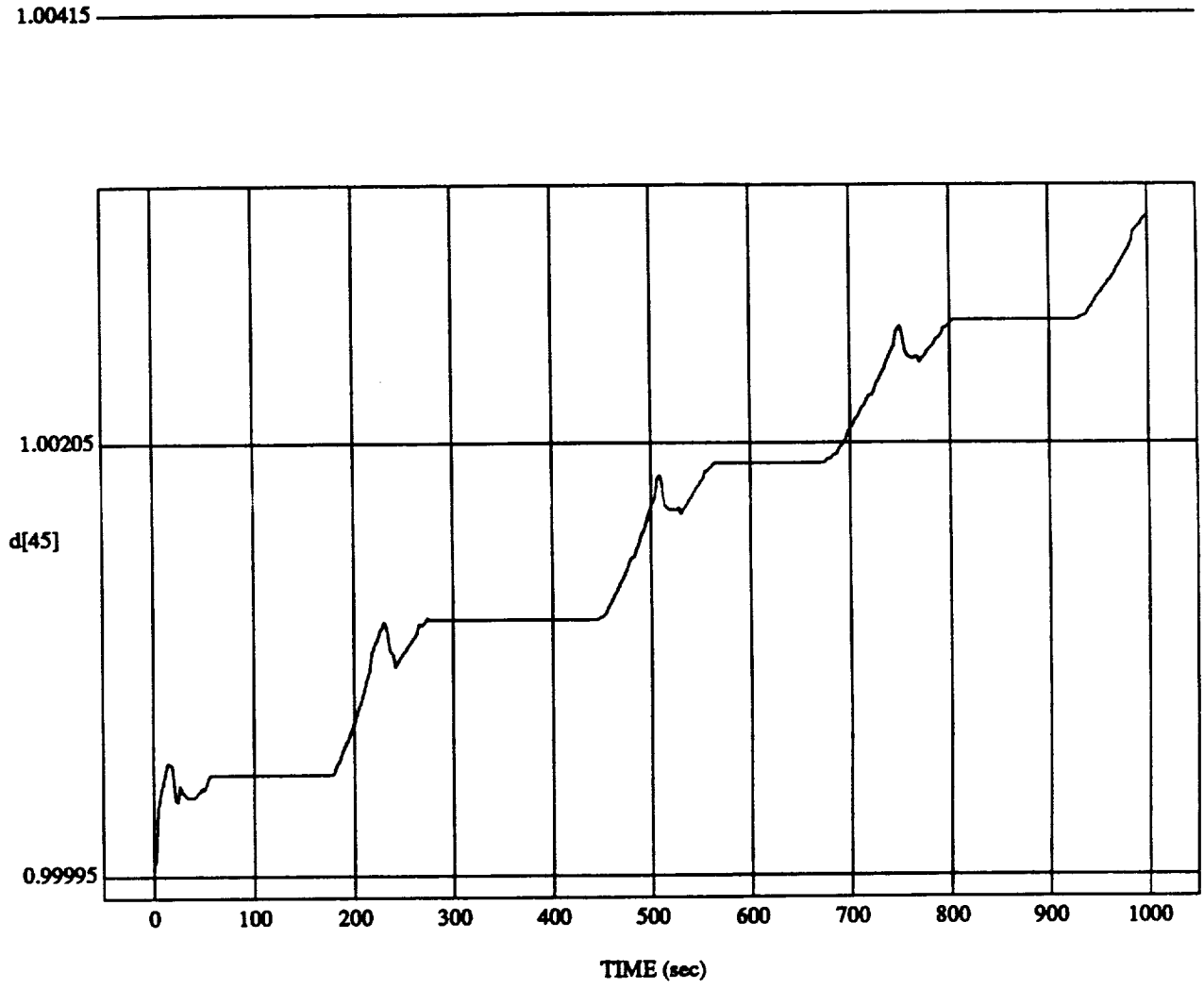
MODULE: ORB_FUZZ_BATCH.learn2
DATA SAMPLING FREQUENCY: 0.500 Hz



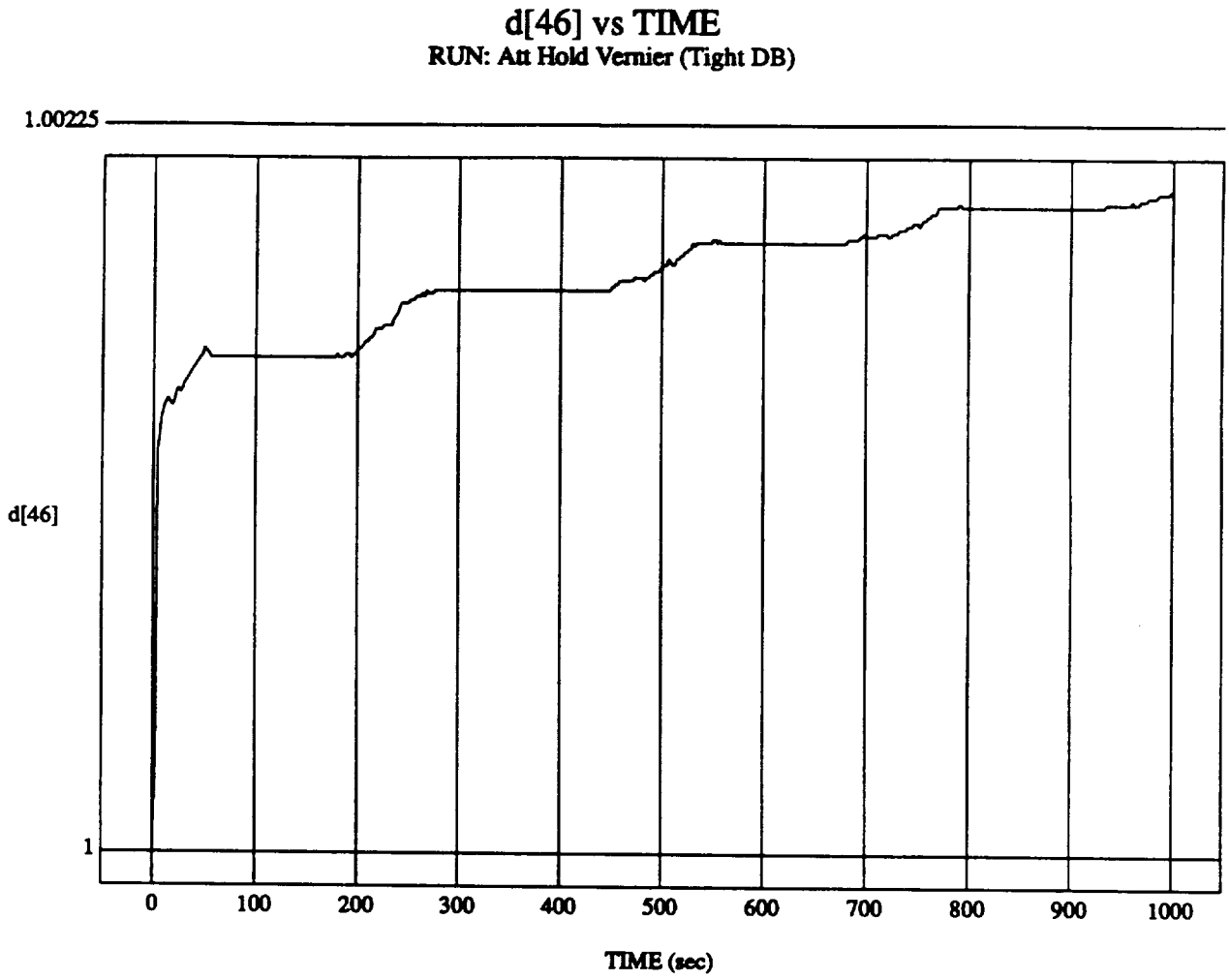
MODULE: ORB_FUZZ_BATCH.learn2
DATA SAMPLING FREQUENCY: 0.500 Hz

d[45] vs TIME

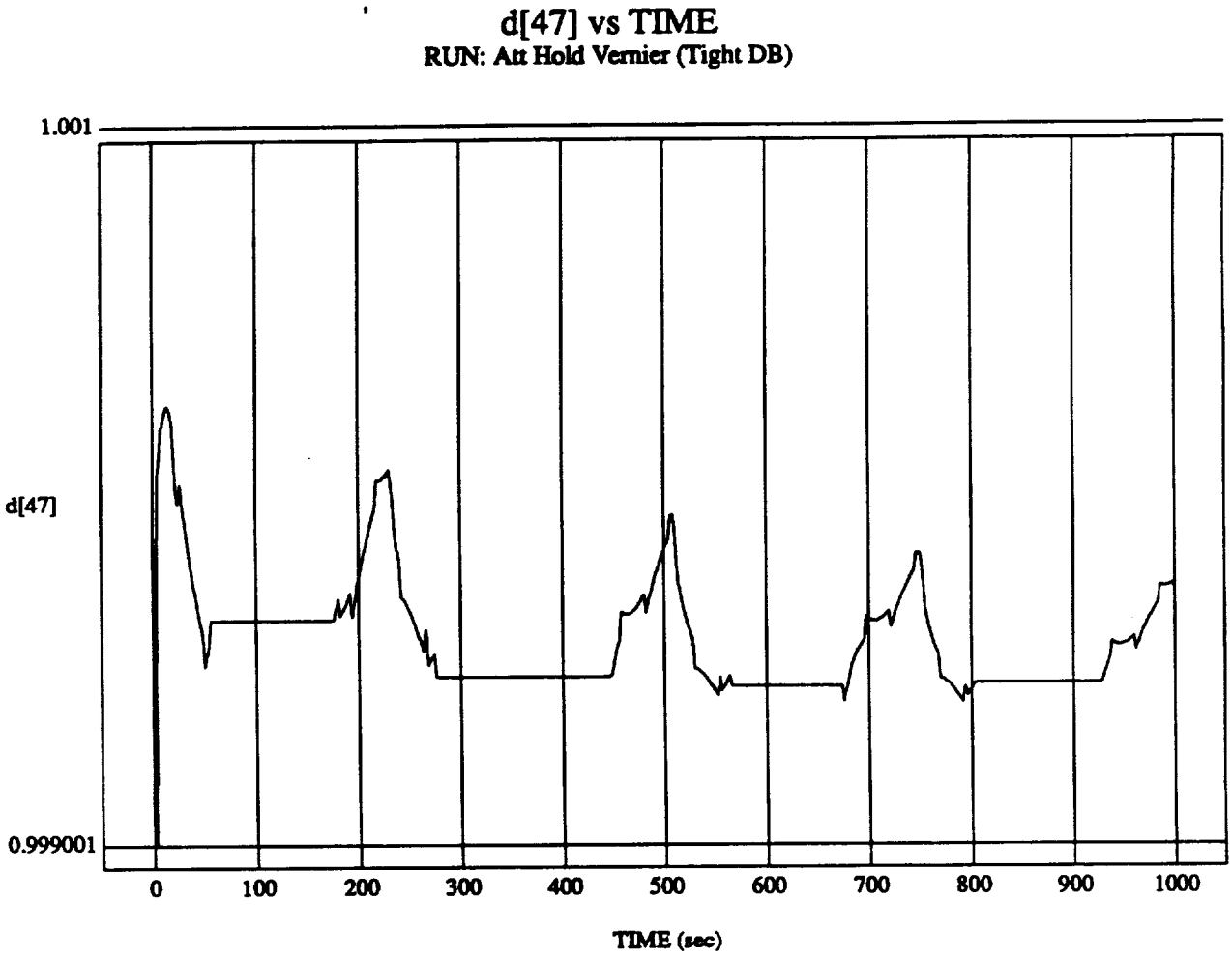
RUN: Att Hold Vernier (Tight DB)



MODULE: ORB_FUZZ_BATCH.learn2
DATA SAMPLING FREQUENCY: 0.500 Hz



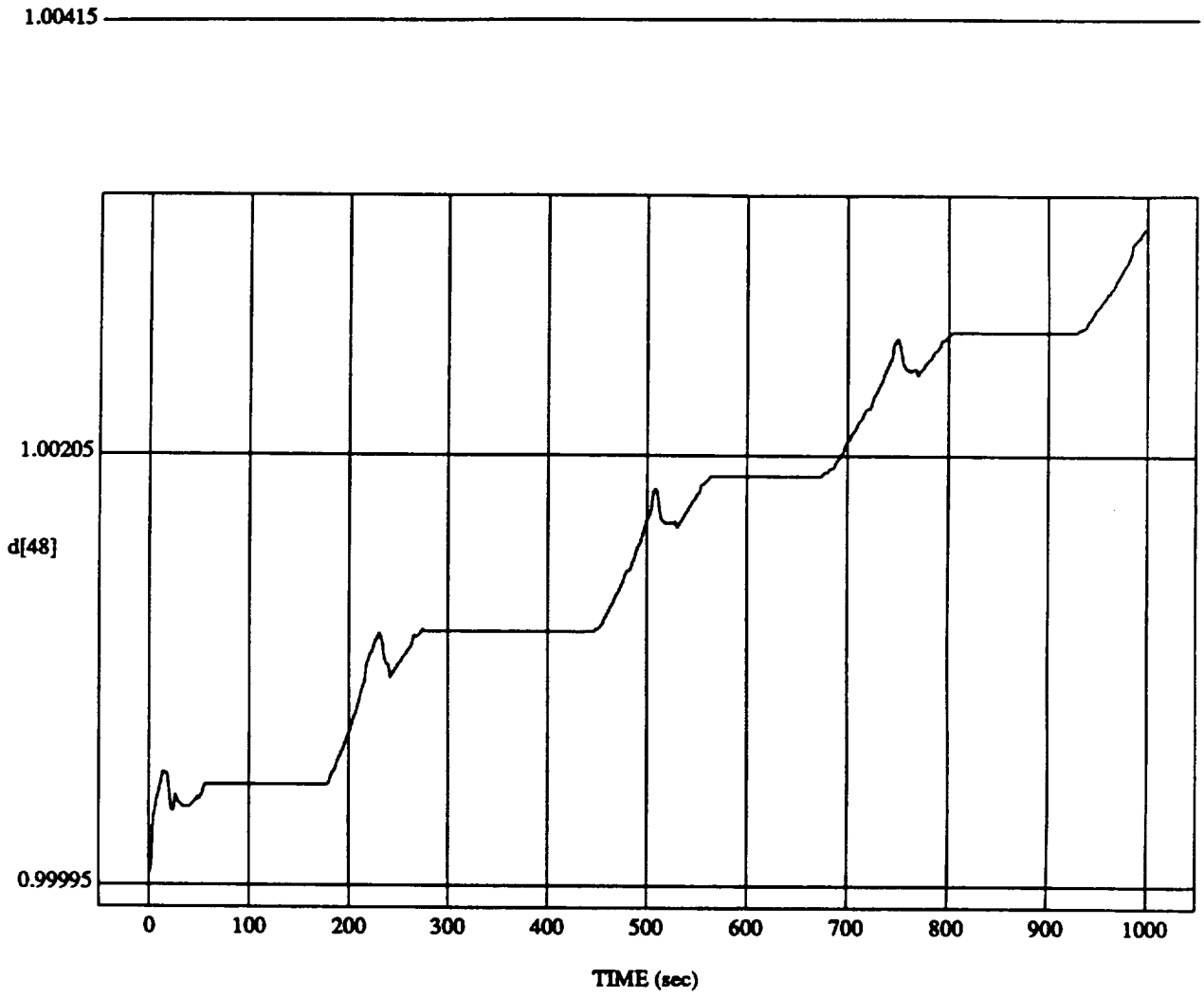
MODULE: ORB_FUZZ_BATCH.learn2
DATA SAMPLING FREQUENCY: 0.500 Hz



MODULE: ORB_FUZZ_BATCH.learn2
DATA SAMPLING FREQUENCY: 0.500 Hz

d[48] vs TIME

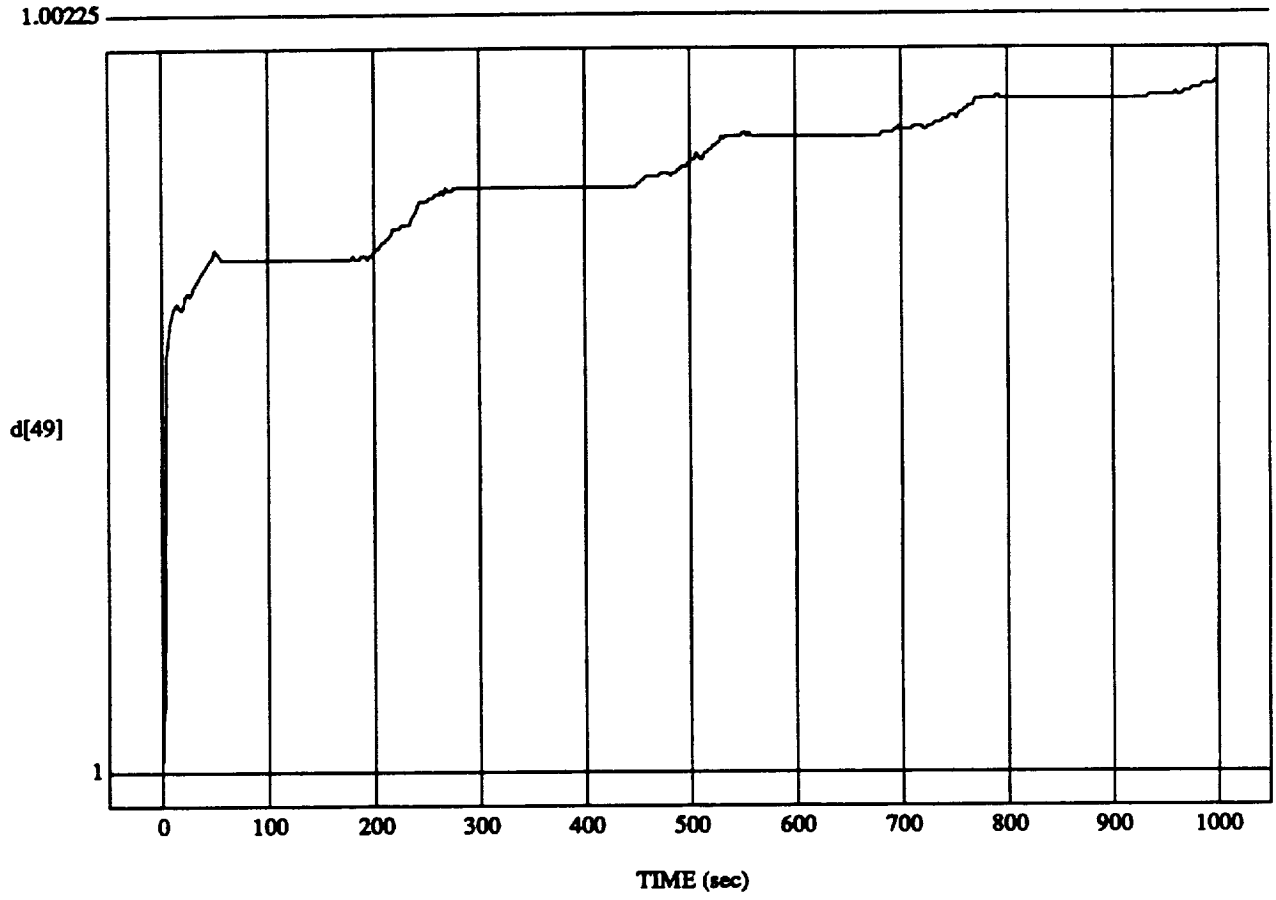
RUN: Att Hold Vernier (Tight DB)



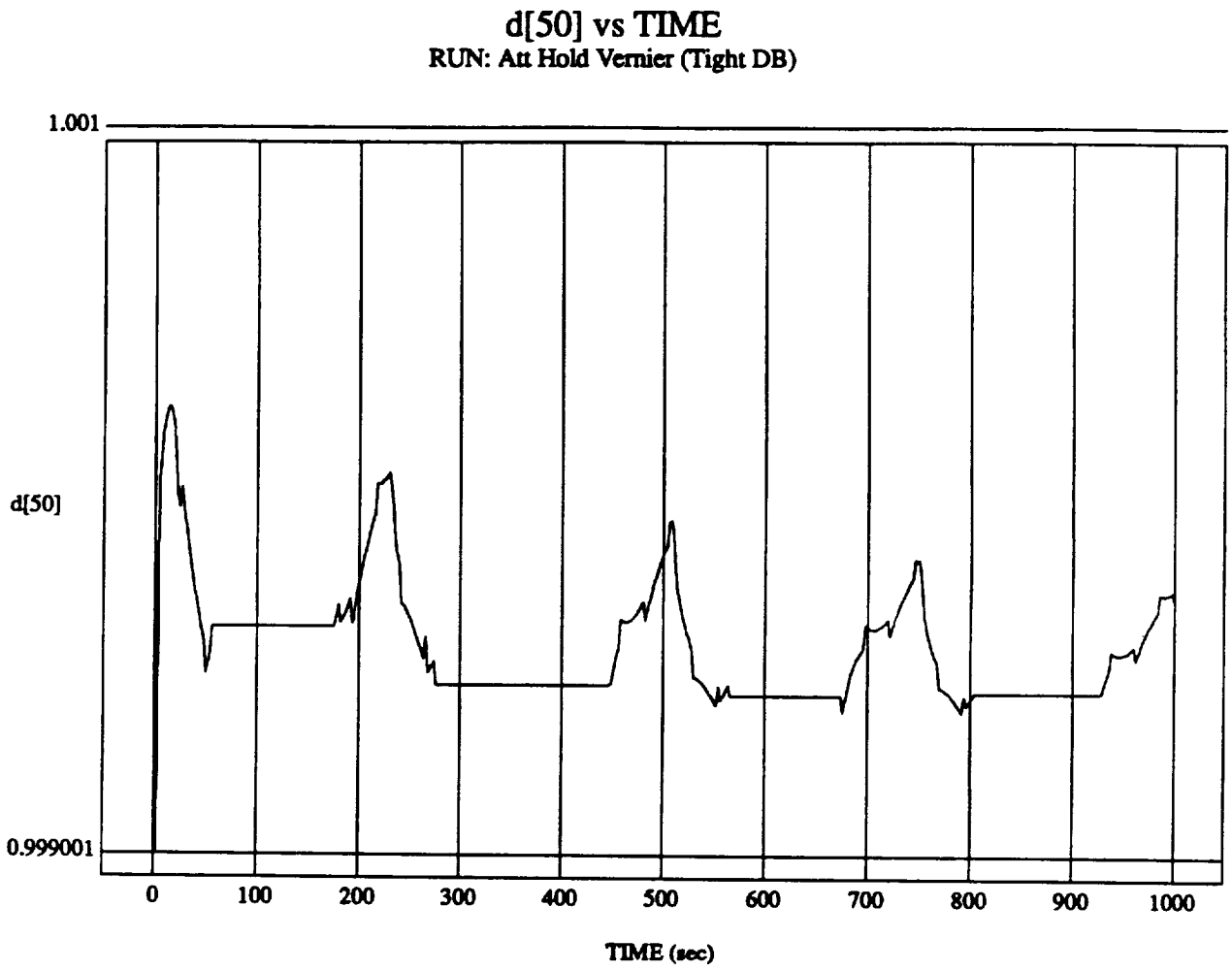
MODULE: ORB_FUZZ_BATCH.learn2
DATA SAMPLING FREQUENCY: 0.500 Hz

d[49] vs TIME

RUN: Att Hold Vernier (Tight DB)



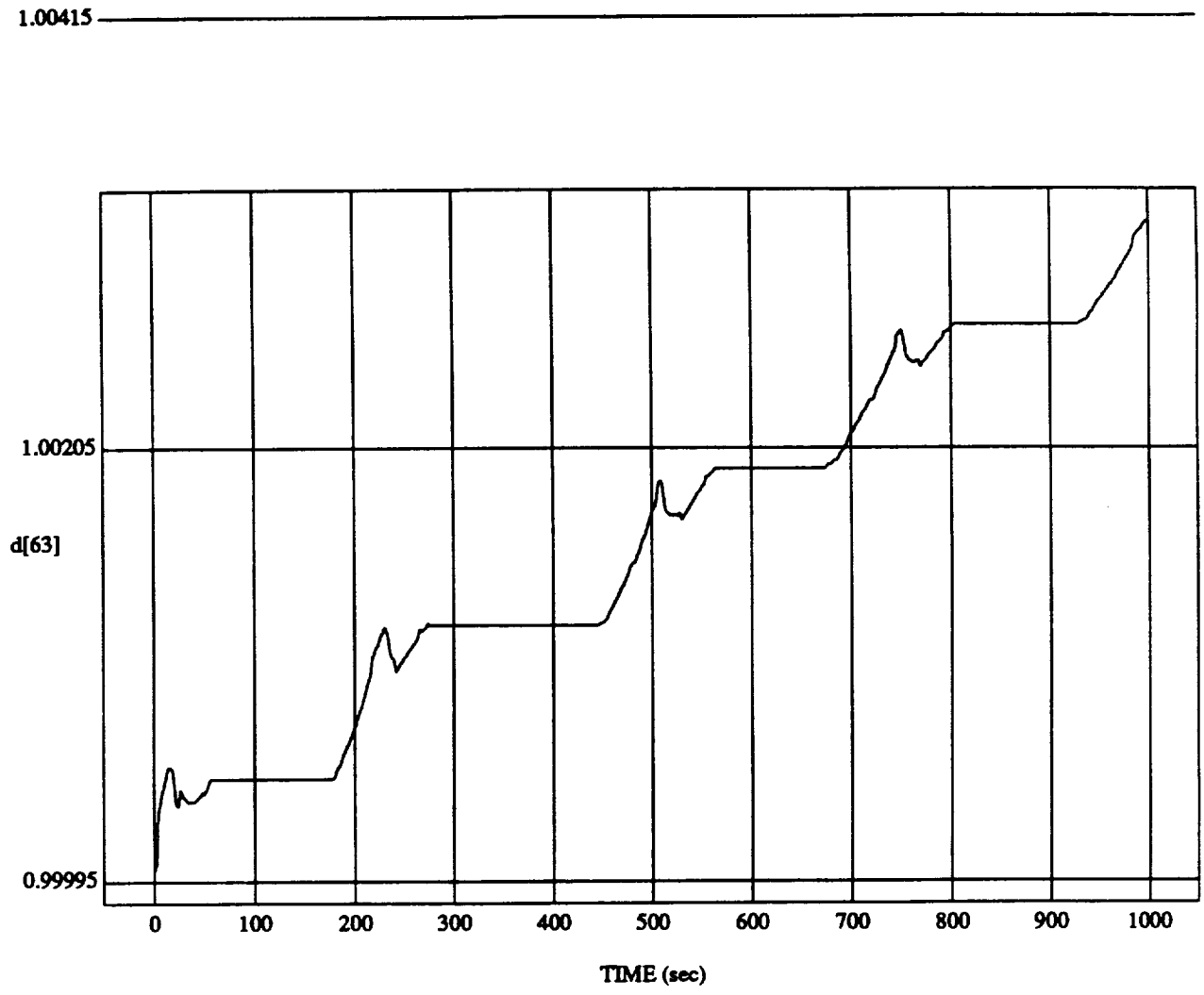
MODULE: ORB_FUZZ_BATCH.learn2
DATA SAMPLING FREQUENCY: 0.500 Hz



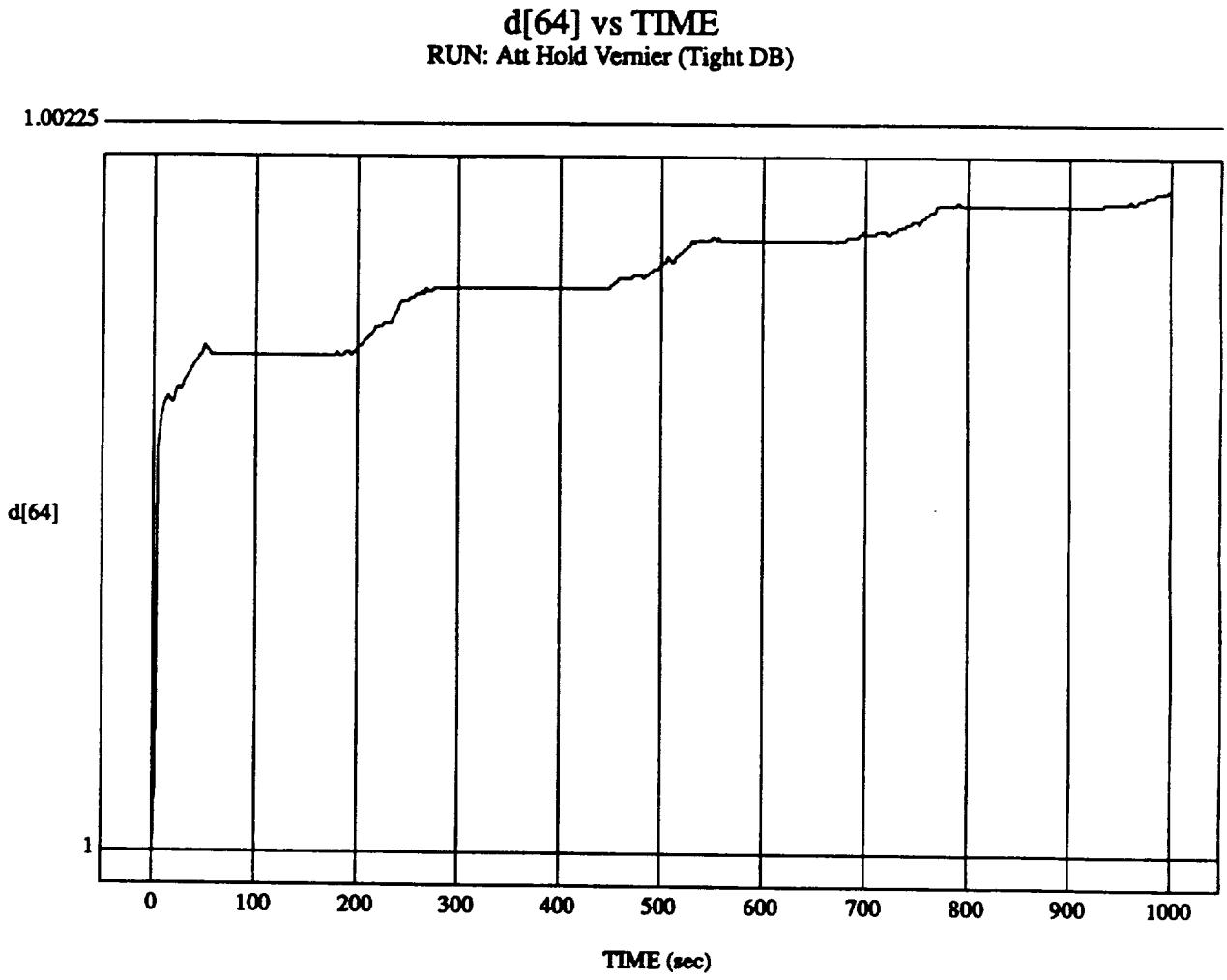
MODULE: ORB_FUZZ_BATCH.learn2
DATA SAMPLING FREQUENCY: 0.500 Hz

d[63] vs TIME

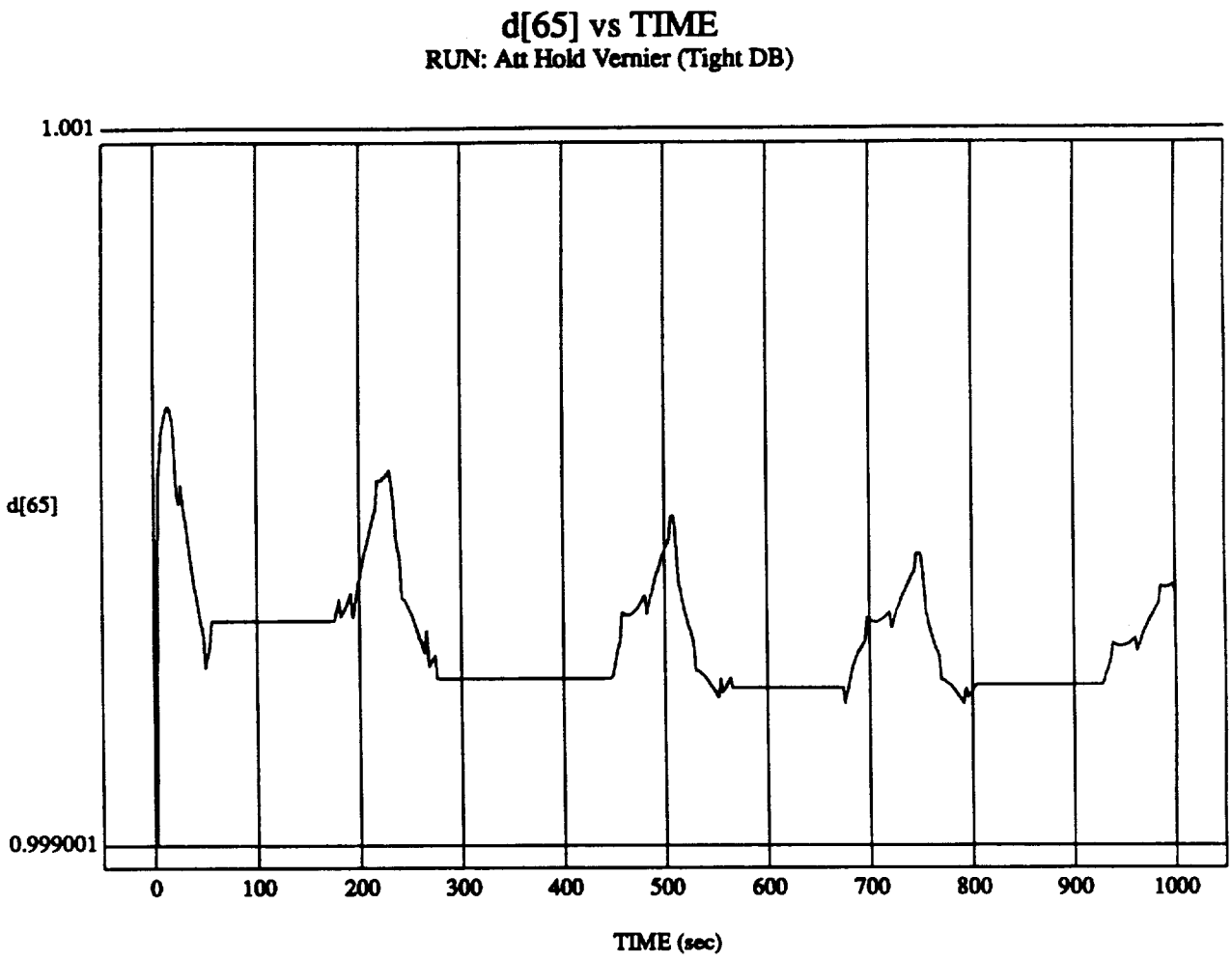
RUN: Att Hold Vernier (Tight DB)



MODULE: ORB_FUZZ_BATCH.learn2
DATA SAMPLING FREQUENCY: 0.500 Hz

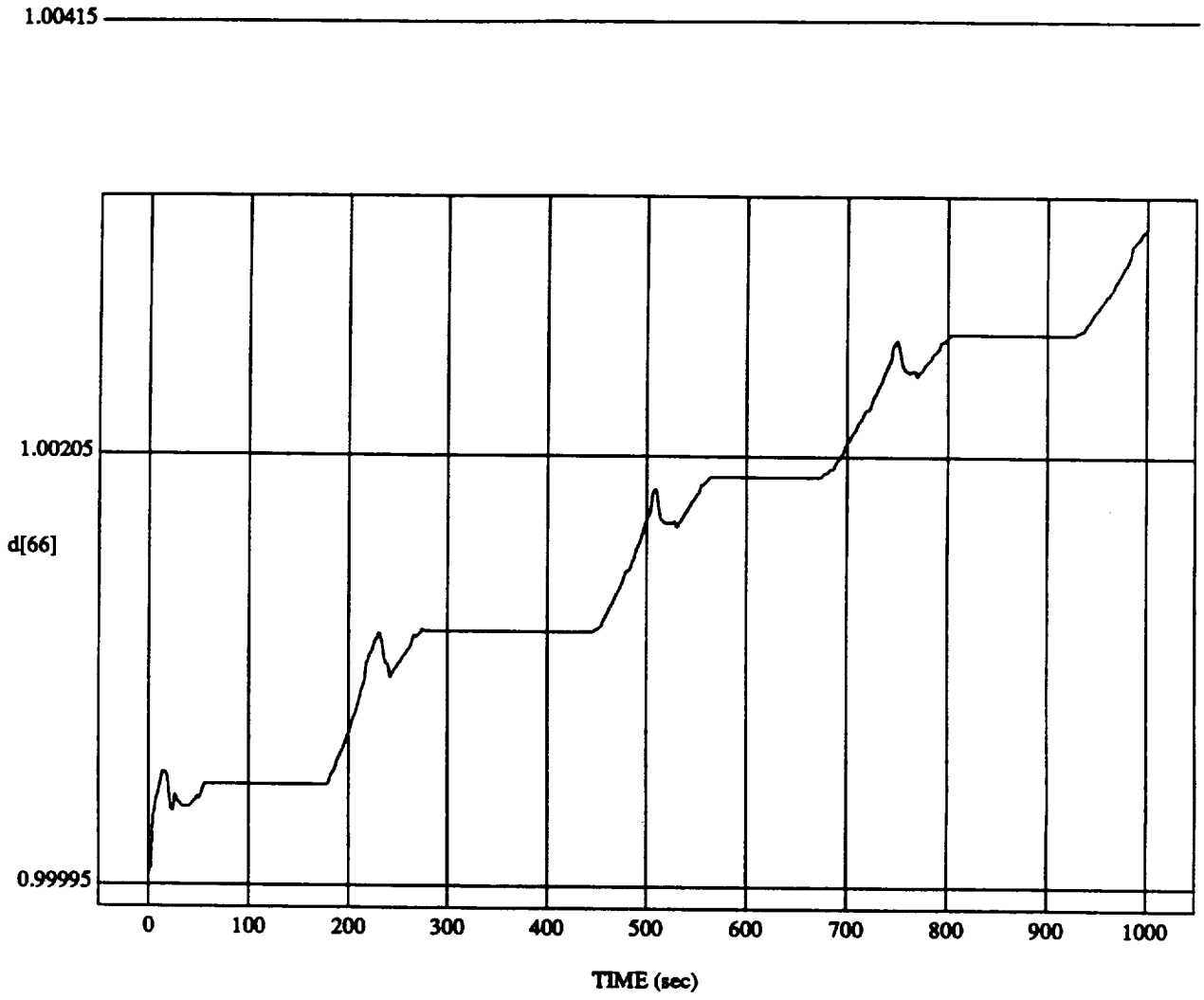


MODULE: ORB_FUZZ_BATCH.learn2
DATA SAMPLING FREQUENCY: 0.500 Hz

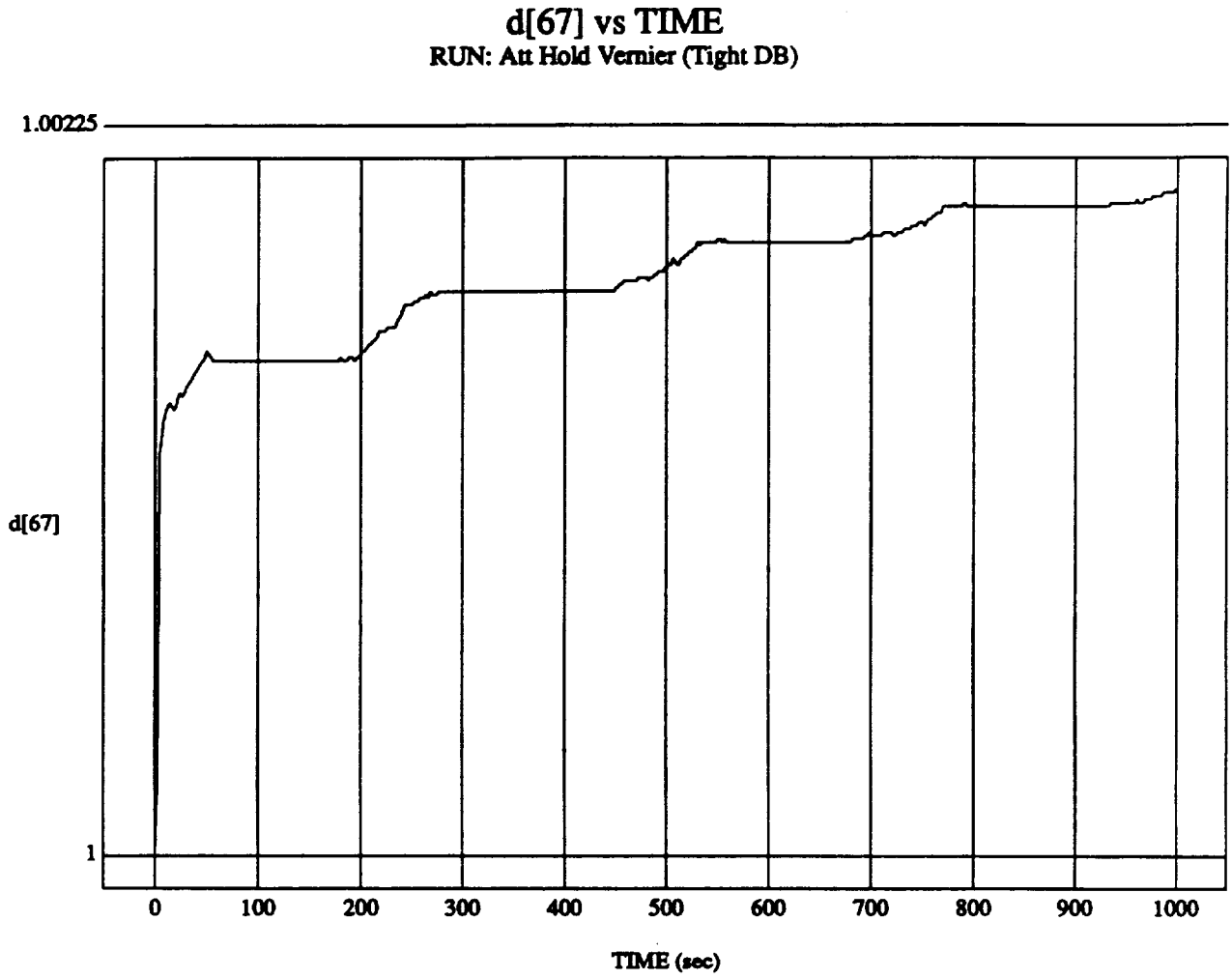


MODULE: ORB_FUZZ_BATCH.learn2
DATA SAMPLING FREQUENCY: 0.500 Hz

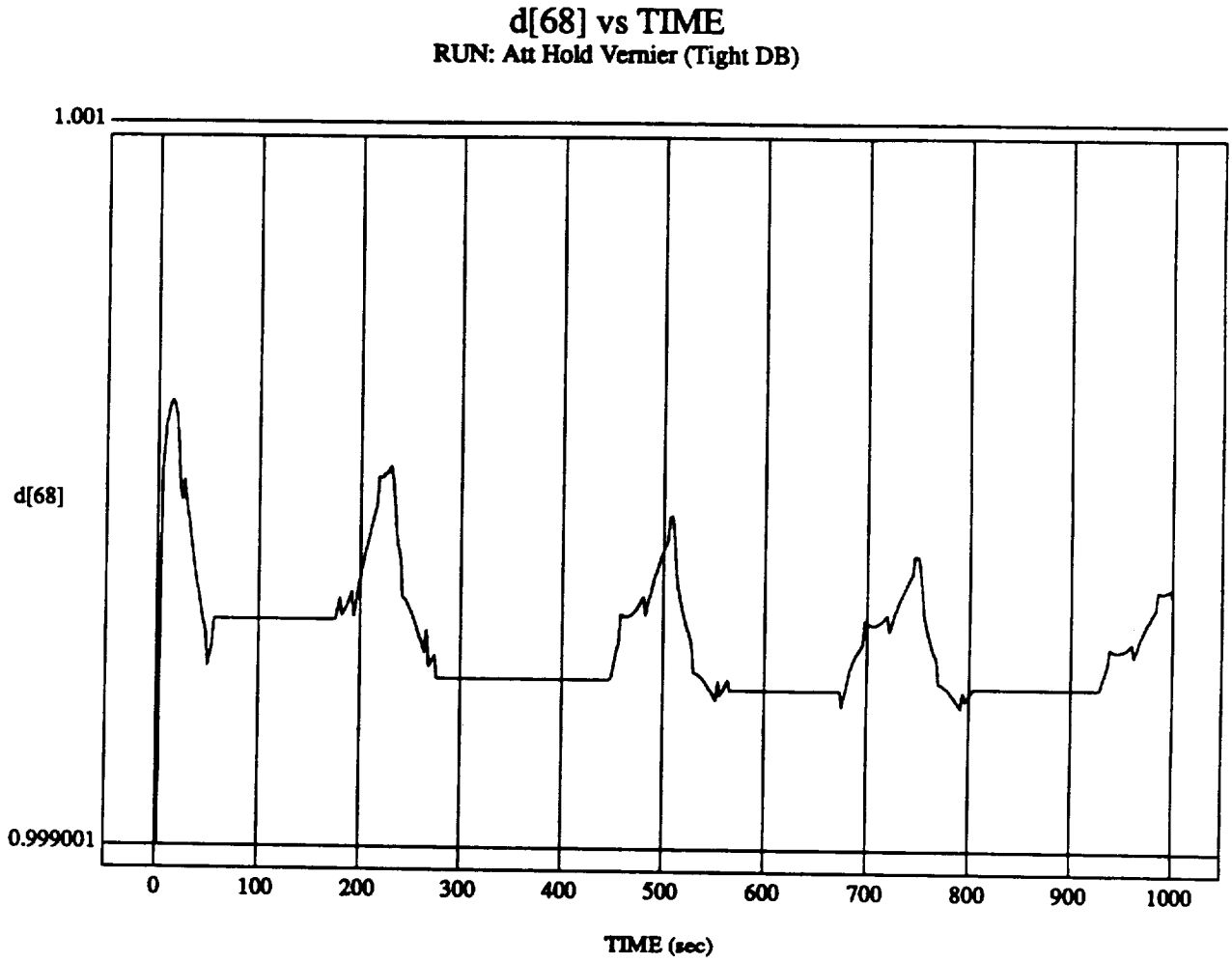
d[66] vs TIME
RUN: Att Hold Vernier (Tight DB)



MODULE: ORB_FUZZ_BATCH.learn2
DATA SAMPLING FREQUENCY: 0.500 Hz

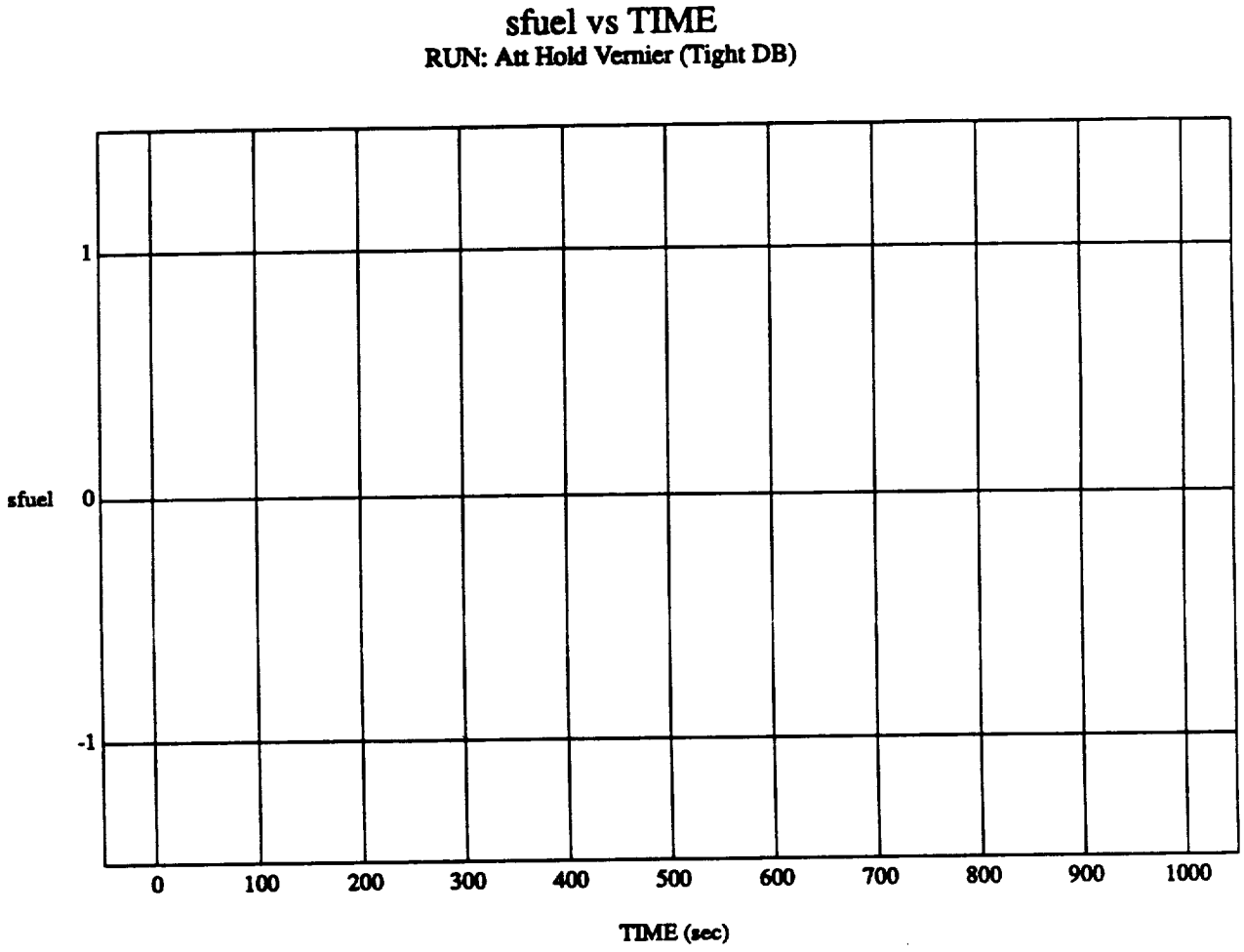


MODULE: ORB_FUZZ_BATCH.learn2
DATA SAMPLING FREQUENCY: 0.500 Hz



MODULE: ORB_FUZZ_BATCH.learn2
DATA SAMPLING FREQUENCY: 0.500 Hz

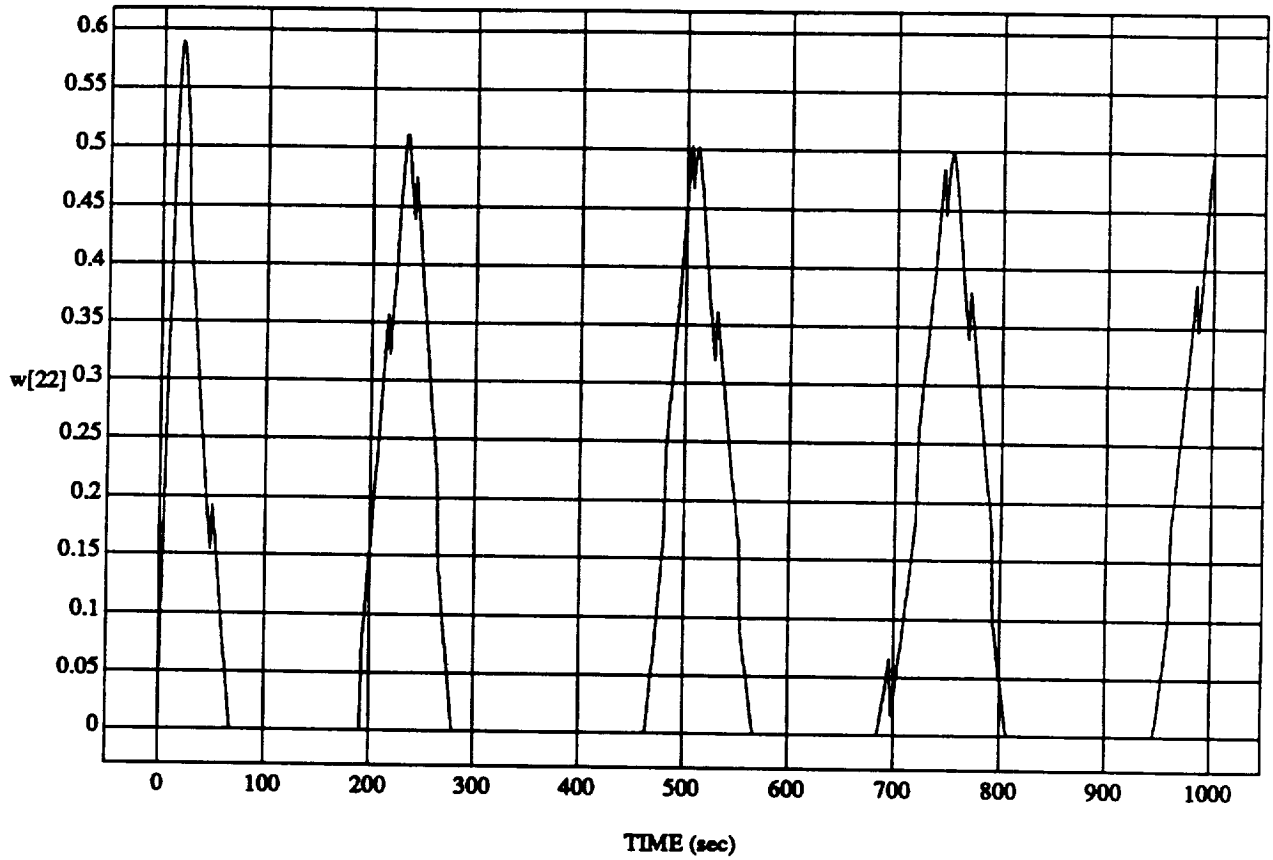
SIMULATION APPLICATION: FUZZY ORBITER BATCH APPLICATION (9/14/90)



MODULE: ORB_FUZZ_BATCH.primary
DATA SAMPLING FREQUENCY: 0.500 Hz

w[22] vs TIME

RUN: Att Hold Vernier (Tight DB)

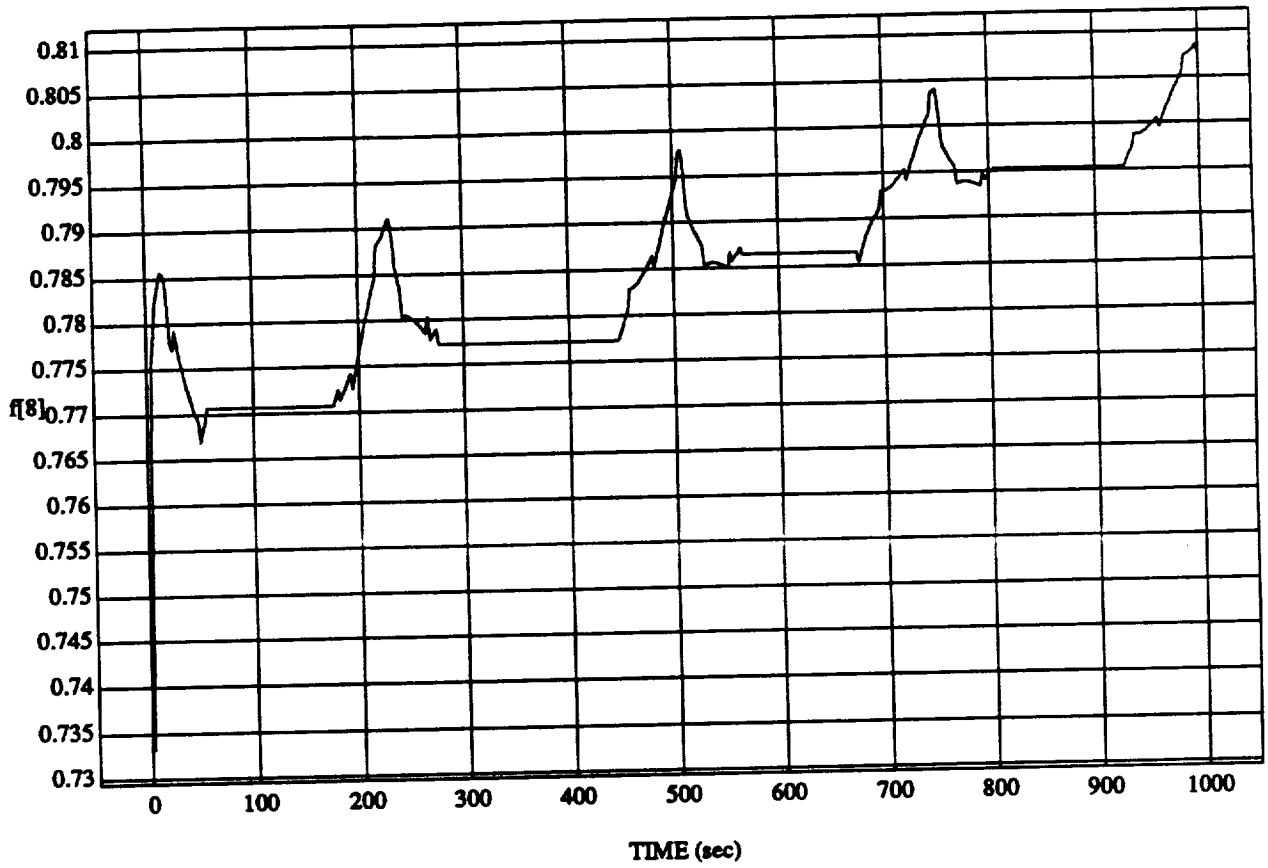


MODULE: ORB_FUZZ_BATCH.learn2
DATA SAMPLING FREQUENCY: 0.500 Hz

SIMULATION APPLICATION: FUZZY ORBITER BATCH APPLICATION (9/14/90)

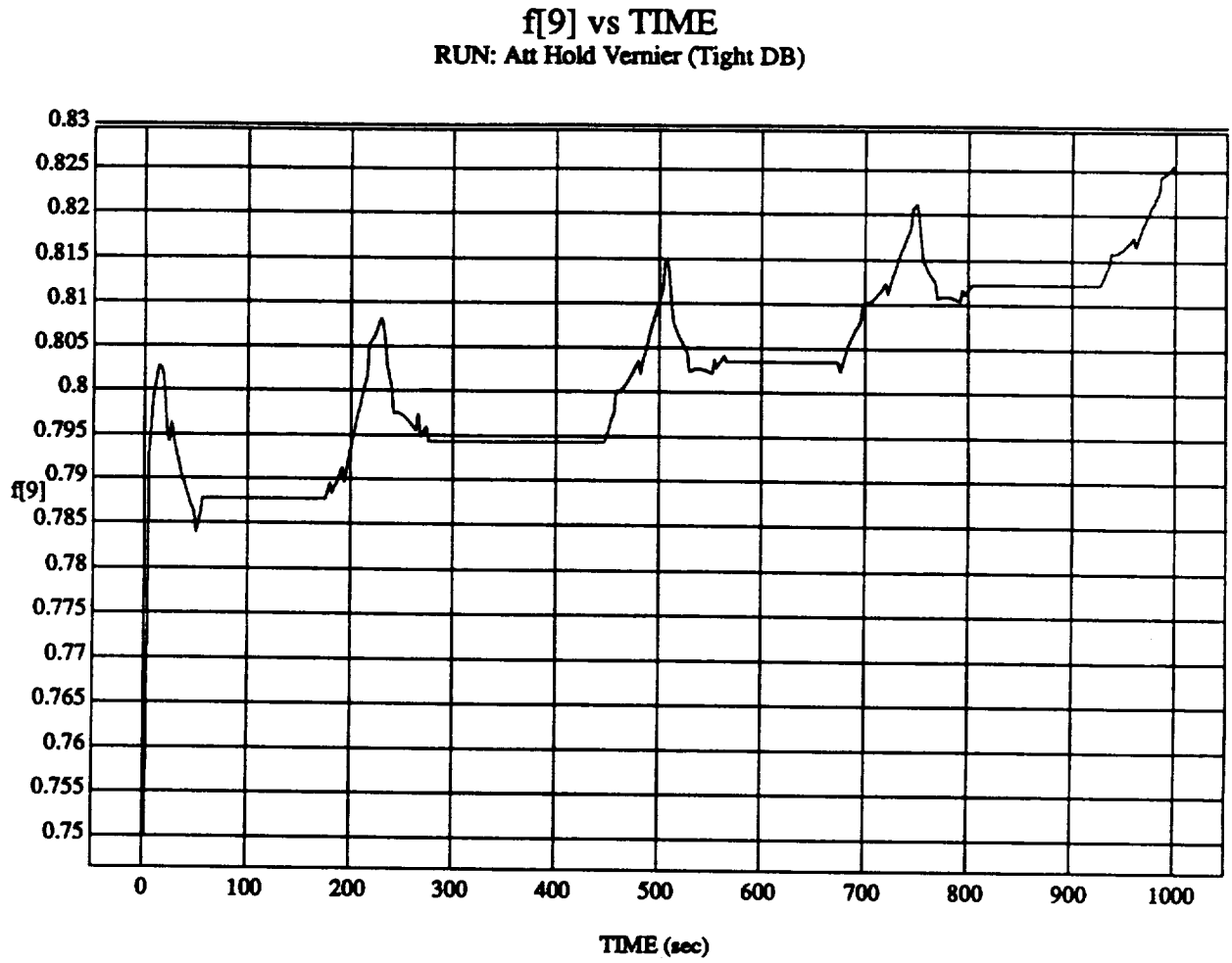
f[8] vs TIME

RUN: Att Hold Vernier (Tight DB)



MODULE: ORB_FUZZ_BATCH.learn2

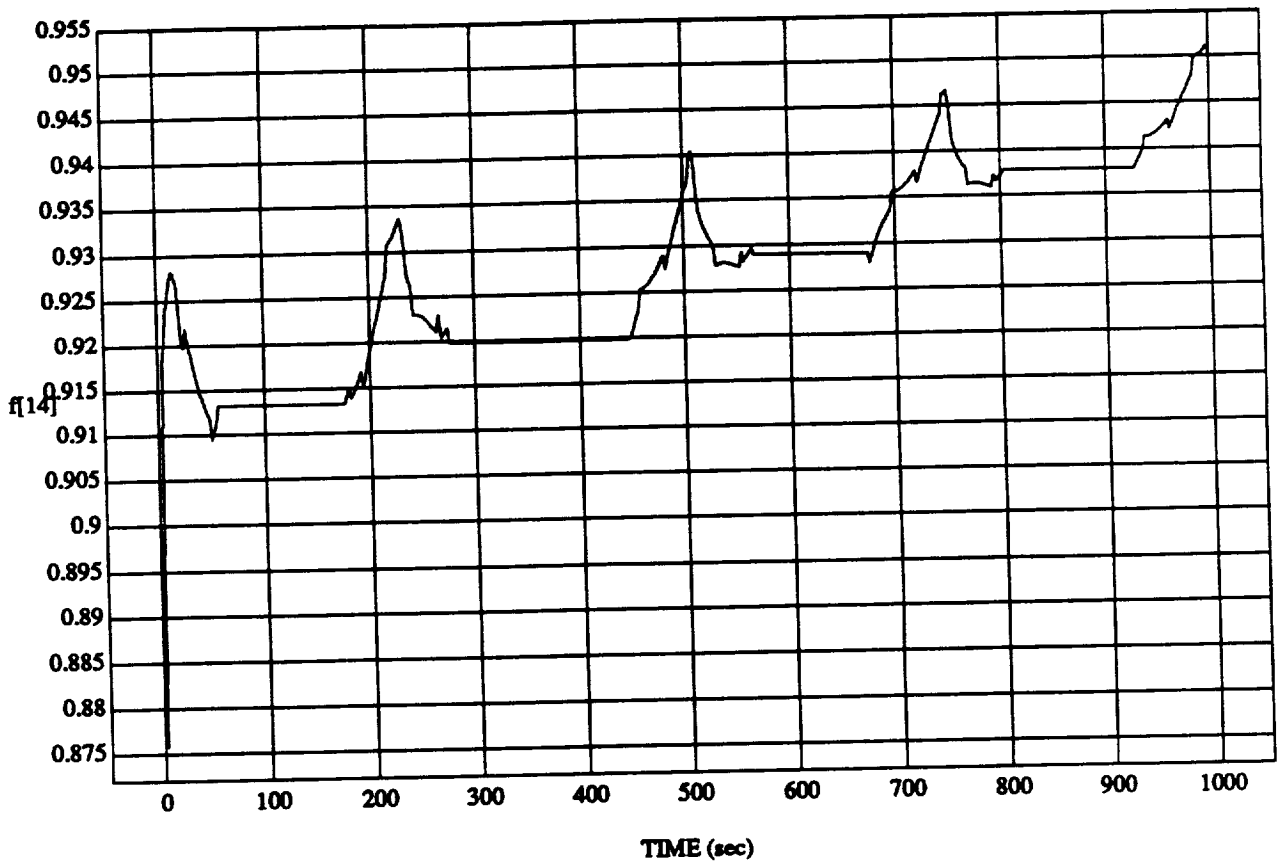
DATA SAMPLING FREQUENCY: 0.500 Hz



MODULE: ORB_FUZZ_BATCH.learn2
DATA SAMPLING FREQUENCY: 0.500 Hz

f[14] vs TIME

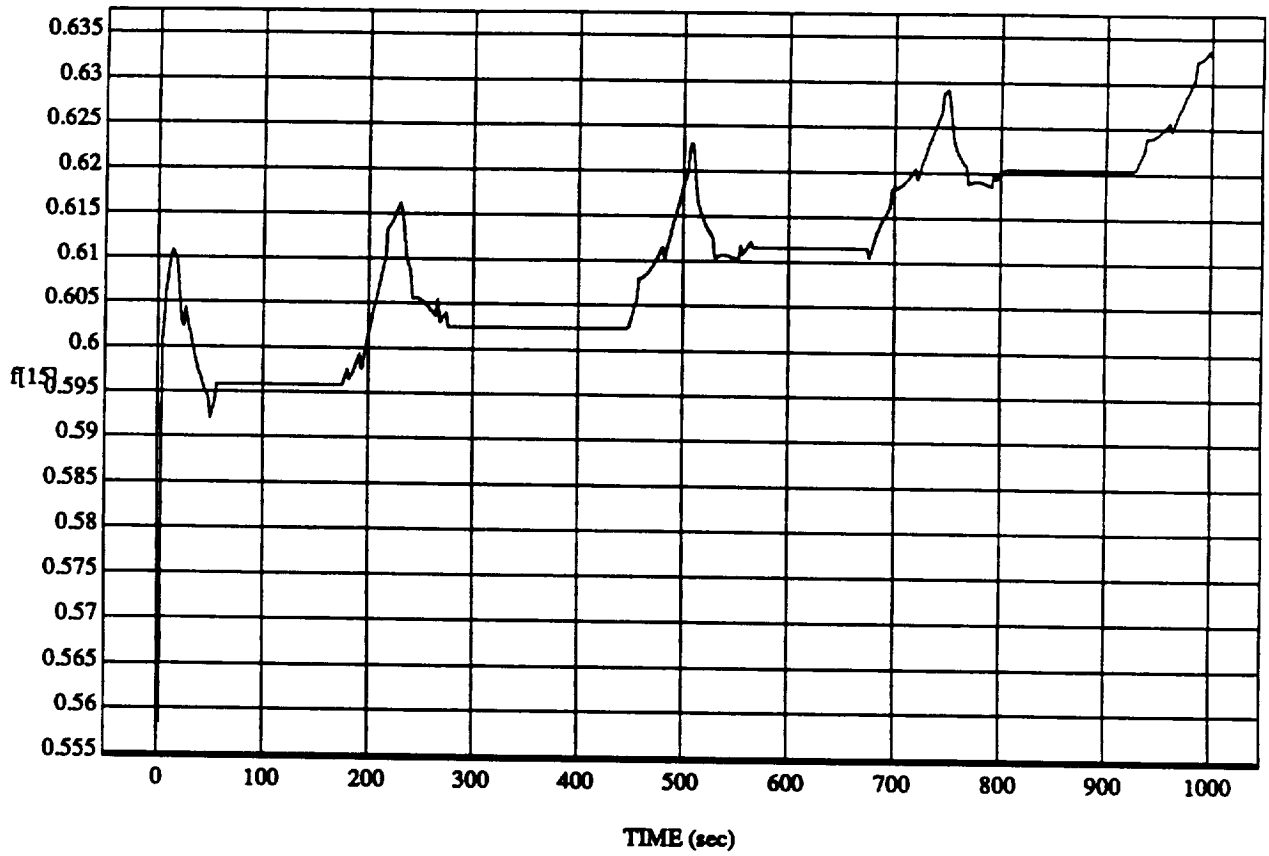
RUN: Att Hold Vernier (Tight DB)



MODULE: ORB_FUZZ_BATCH.learn2
DATA SAMPLING FREQUENCY: 0.500 Hz

f[15] vs TIME

RUN: Att Hold Vernier (Tight DB)

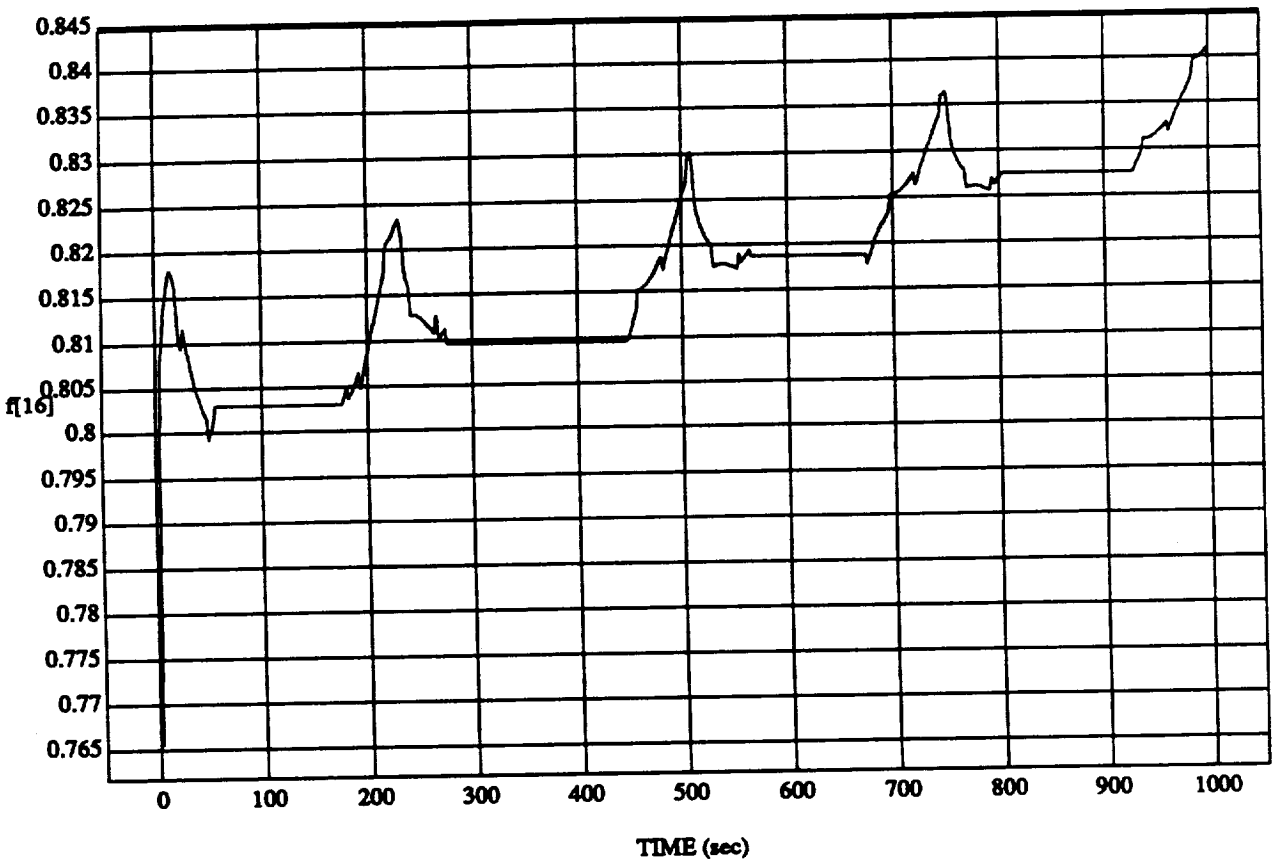


MODULE: ORB_FUZZ_BATCH.learn2

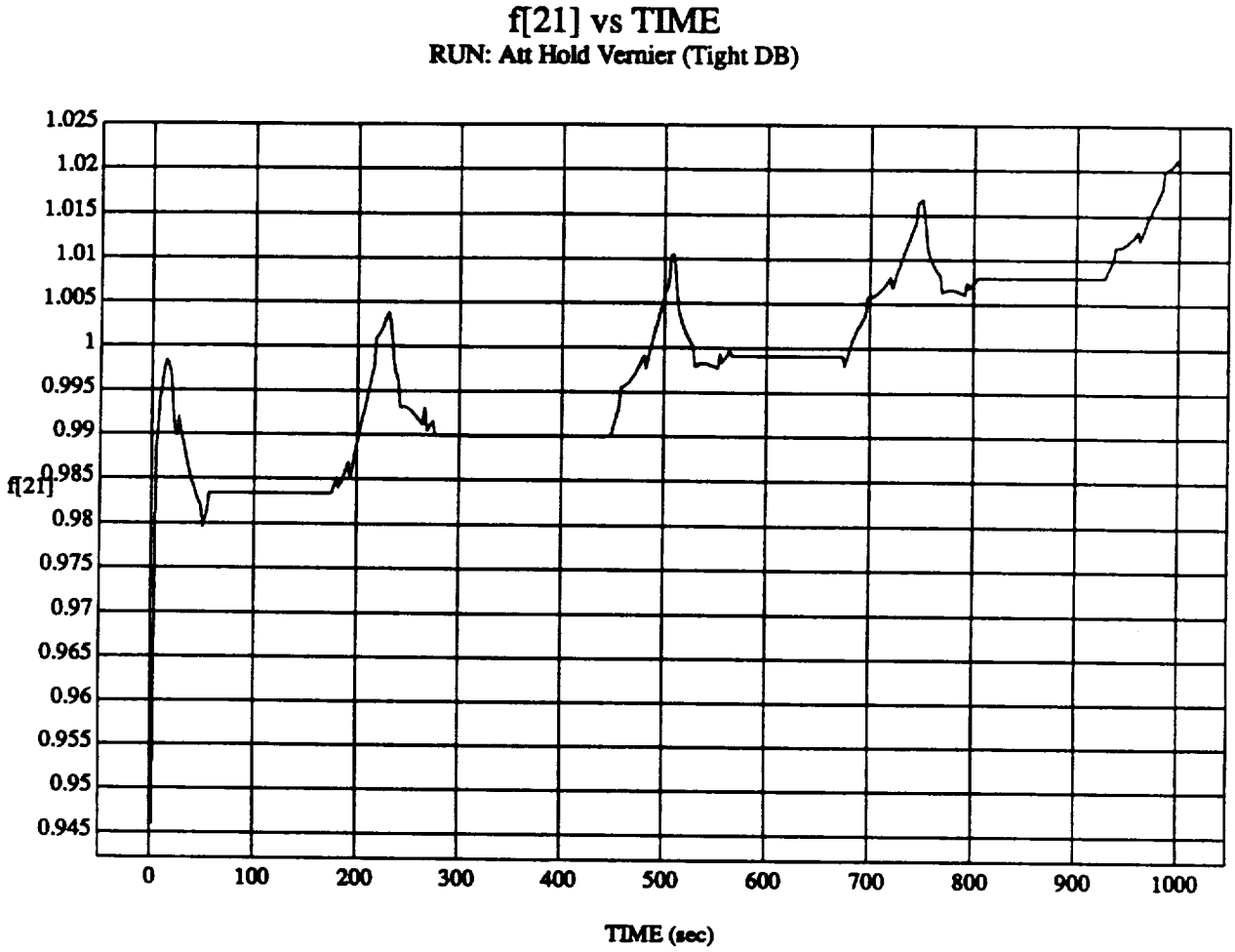
DATA SAMPLING FREQUENCY: 0.500 Hz

f[16] vs TIME

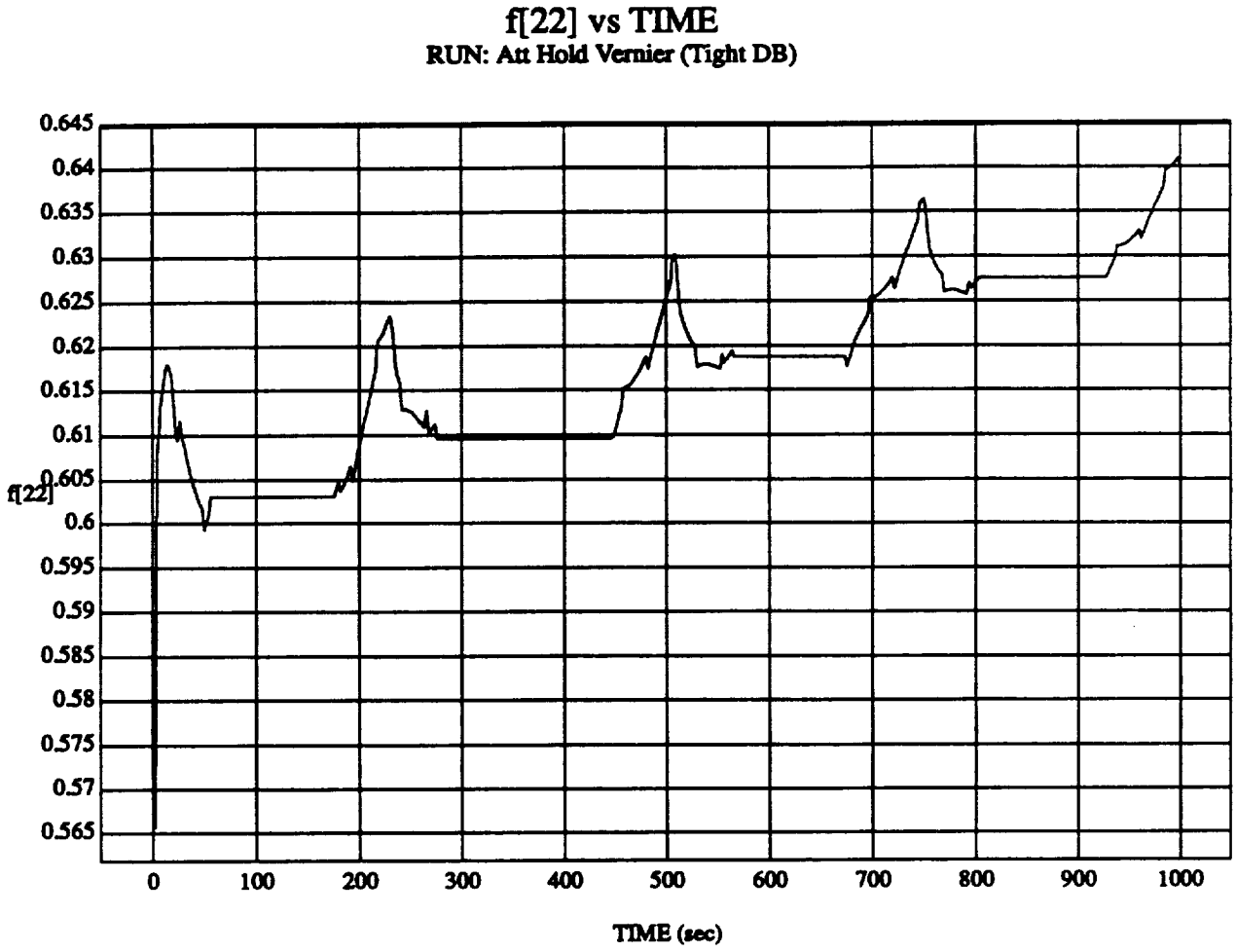
RUN: Att Hold Vernier (Tight DB)



MODULE: ORB_FUZZ_BATCH.learn2
DATA SAMPLING FREQUENCY: 0.500 Hz



MODULE: ORB_FUZZ_BATCH.learn2
DATA SAMPLING FREQUENCY: 0.500 Hz



MODULE: ORB_FUZZ_BATCH.learn2
DATA SAMPLING FREQUENCY: 0.500 Hz