N87-22735

A TREETOPS SIMULATION OF THE HUBBLE SPACE TELESCOPE-HIGH GAIN ANTENNA INTERACTION

JOHN P. SHARKEY
NASA/MARSHALL SPACE FLIGHT CENTER
HUNTSVILLE, AL

WORKSHOP ON STRUCTURAL
DYNAMICS AND CONTROL INTERACTION
OF FLEXIBLE STRUCTURES
APRIL 22-24, 1986
MARSHALL SPACE FLIGHT CENTER, AL

C-3

A TREETOPS SIMULATION OF THE HUBBLE SPACE TELESCOPE - HIGH GAIN ANTENNA INTERACTION

Virtually any project dealing with the control of a Large Space Structure (LSS) will involve some level of verification by digital computer simulation. While the Hubble Space Telescope might not normally be included in a discussion of LSS, it is presented at this workshop to highlight a recently developed simulation and analysis program named TREETOPS. This program was developed by Honeywell, Inc. under sponsorship of a Marshall Space Flight Center research and development program called Augmented Flexible Body Dynamics Analysis Program (AFBDAP). TREETOPS, the second program to be developed under AFBDAP, provides digital simulation, linearization and control system interaction of flexible, multibody spacecraft which admit to a point-connected tree topology. The HST application of TREETOPS is intended here to familiarize the LSS community with TREETOPS by presenting a user's perspective of its key features.

Figure 1 outlines some of the outstanding features of TREETOPS. The program is intended as a tool for evaluating the interaction of a LSS and its associative control system. The program

ORGANIZATION	MARSHALL SPACE FLIGHT CENTER	NAME
SYSTEMS DYNAMICS LAB	OAST RTOP REVIEW	J. SHARKEY
CHART NO	CONTROL TECHNOLOGY/GUIDANCE CONCEPTS	DATE
		OCTOBER 1985

NONLINEAR DYNAMICS

SIMULATION OF NONLINEAR DYNAMICS AND CONTROL

OBJECTIVE: PROVIDE AN EFFICIENT MEANS FOR FLEXIBLE BODY CONTROL SYSTEM ANALYSIS OF COMPLEX SPACECRAFT.

APPROACH: HONEYWELL'S AUGMENTED FLEXIBLE BODY DYNAMIC ANALYSIS PROGRAM.

FEATURES:
- NONLINEAR TIME DOMAIN SOLUTION ENCOMPASSING LARGE ANGLES AND LARGE ANGULAR RATES.
- DYNAMICS FORMULATED VIA KANE's METHOD OF GENERALIZED SPEEDS.
- ELIMINATES CONSTRAINED DEGREES OF FREEDOM (D.O.F.).
- ADMITS ARBITRARY, POINT-CONNECTED TOPOLOGIES (CHAIN, TREE, RING).
- STRUCTURE CONNECTED BY ARTICULATED JOINTS WITH ZERO TO SIX D.O.F.
- COMPONENT MODES OF EACH FLEXIBLE BODY ARE UTILIZED.
- LINEARIZED, STATE VARIABLE SYSTEM MATRICES PROVIDED.
- INTERACTIVE PREPROCESSOR PROGRAM GENERATES INPUT DATA BASE.

FIGURE 1

alleviates the control system analyst of the burden of generating the equation of motion (EOM) for flexible, multibody spacecraft. This is accomplished with the Singh-Likins formulation of Kane's method of generalized speeds. This formulation is amenable to the automatic generation of minimal order EOM which eliminate constrained degrees of freedom. The structure is modeled with articulated joints allowing zero to six degrees of freedom. Component modes are used to model flexible substructures, thereby permitting large relative angles and relative rates. Since the system equations are in general nonlinear, a linearization subprogram is provided which generates the linear system matrices suitable for control law development. An interactive preprocessor program is also provided which generates and edits the input data base in an easy to use, menu driven fashion.

The development history of AFBDAP is presented in figure 2. The first simulation program, simply named AFBDAP, was released in 1982. This was a proof of concept program applicable to structures with a chain topology. In 1984, TREETOPS was released featuring the linearization subprogram, an improved interactive preprocessor, an interactive postprocessor for plotting, and the ability to model structures with a tree topology. A limited, closed tree topology modeling capability

NIZATION SYSTEMS DYNAMICS LAB	MARSHALL SPACE FLIGHT CENTER OAST RTOP REVIEW	NAME J. SHARKEY
CHART NO.	CONTROL TECHNOLOGY/GUIDANCE CONCEPTS	DATE OCTOBER 1985

NONLINEAR DYNAMICS

DEVELOPMENT HISTORY

1982 AUGMENTED FLEXIBLE BODY DYNAMICS ANALYSIS PROGRAM (AFBDAP)

- PROOF OF CONCEPT
- CHAIN TOPOLOGIES

1984 TREETOPS

- IMPROVED COMPUTATIONAL EFFICIENCY
- TREE TOPOLOGIES
- LOOP CLOSURE SPRINGS

1986 CONTOPS

- CLOSED TOPOLOGIES
- EQUALITY AND/OR INEQUALITY CONSTRAINTS

FIGURE 2

was provided through the use of "loop closure spring," whereby spring force constraints were accommodated, but not kinematic constraints. The CONTOPS program was released in early 1986 as the final product of AFBDAP. CONTOPS admits structures with constrained topologies; both holonomic constraints, such as loop closures or prescribed velocities, and nonholonomic constraints such as Coulomb damping, gimbal stops, etc. Since CONTOPS is still in the verification phase, this presentation will concentrate on TREETOPS.

The basic TREETOPS program structure is shown in figure 3. Working from left to right, HITIP is the interactive preprocessor used to create, edit and error-check the problem specific input data base, which is subsequently read into the basic simulation/linearization program, TREETOPS. HITIP creates and edits two other files, a machine dependent job control file and a parameter dimension file used in compiling the ANSI FORTRAN TREETOP program. The simulation/linearization program, which is usually run in a batch mode, generates three output files: a time-history output file, a linear system matrix file, and a restart file. The restart file can later be used to continue the simulation, perhaps to perform parameter variation studies about a nominal operating point. The output and linear matrice files can be examined with the postprocessor program TREEPLOT.

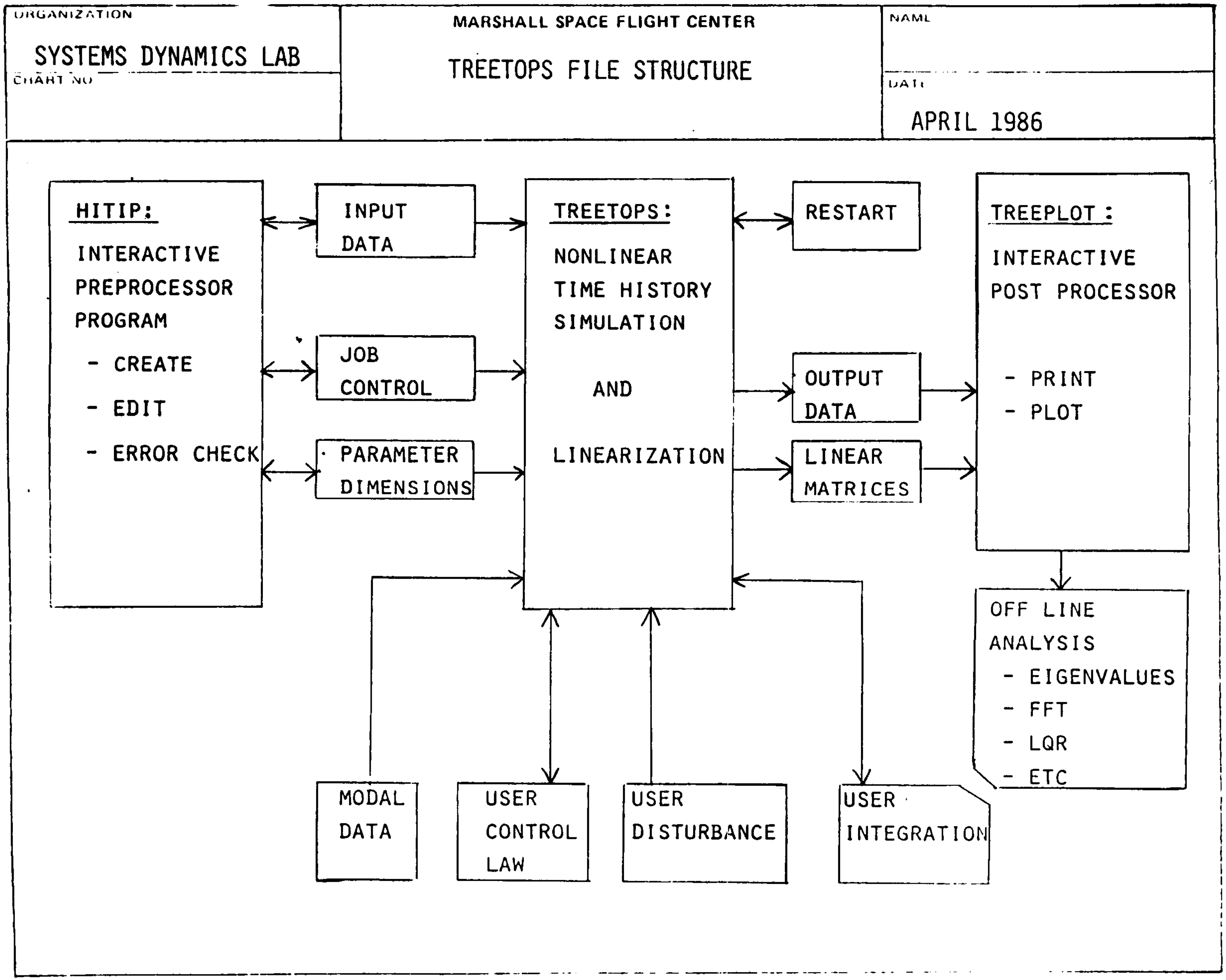

ORGANIZATION
SYSTEMS DYNAMICS LAB
CHART NO
MARSHALL SPACE FLIGHT CENTER
TREETOPS FILE STRUCTURE
NAME
DATE
APRIL 1986
HITIP:
INTERACTIVE
PREPROCESSOR
PROGRAM
- CREATE
- EDIT
- ERROR CHECK
INPUT
DATA
JOB
CONTROL
PARAMETER
DIMENSIONS
TREETOPS:
NONLINEAR
TIME HISTORY
SIMULATION
AND
LINEARIZATION
RESTART
OUTPUT
DATA
LINEAR
MATRICES
TREEPLOT :
INTERACTIVE
POST PROCESSOR
- PRINT
- PLOT
OFF LINE
ANALYSIS
- EIGENVALUES
- FFT
- LQR
- ETC
MODAL
DATA
USER
CONTROL
LAW
USER
DISTURBANCE
USER
INTEGRATION

FIGURE 3

Alternatively, these files can be analyzed off-line to determine eigenvalues, FFT's, LQR's, etc.

The simulation program can also interface with up to four user supplied files: (1) a model data input file, (2) a user supplied control law, (3) a disturbance algorithm, and (4) alternate integration programs as an option to the standard Runga-Kutta four pass.

Figure 4 depicts the conceptual components of a TREETOPS model. The HITIP program allows the user to interactively select the components listed in figure 4 and assemble them into a multibody structure with control laws, sensors and actuators. Function generators can be treated as controller inputs or system disturbances. The control law can be any combination of continuous, discrete or user defined segments. The continuous and discrete controllers are composed of transfer functions (in S or Z), summing junctions and gain blocks. The controllers can be arbitrarily interconnected or tied to any of the ideal actuators listed. The structure is composed of flexible and/or rigid bodies, rotation and translational hinges, and loop closure springs. The bodies are defined on an independent basis, with user defined local coordinate frame locations and orientations. The hinges are used to define Euler angles for

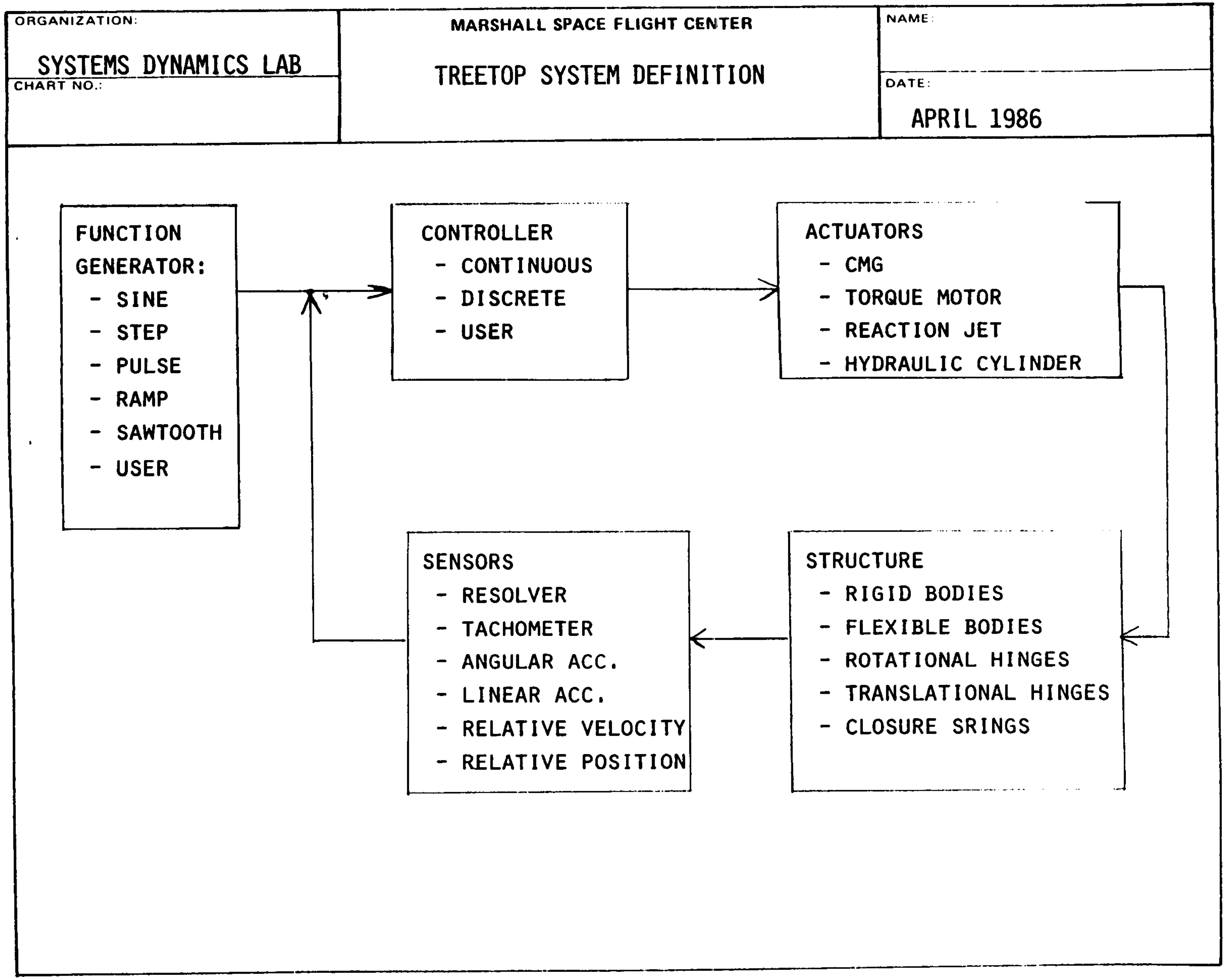

ORGANIZATION:
SYSTEMS DYNAMICS LAB
CHART NO.:
MARSHALL SPACE FLIGHT CENTER
TREETOP SYSTEM DEFINITION
NAME:
DATE:
APRIL 1986
FUNCTION GENERATOR:
- SINE
- STEP
- PULSE
- RAMP
- SAWTOOTH
- USER
CONTROLLER
- CONTINUOUS
- DISCRETE
- USER
ACTUATORS
- CMG
- TORQUE MOTOR
- REACTION JET
- HYDRAULIC CYLINDER
SENSORS
- RESOLVER
- TACHOMETER
- ANGULAR ACC.
- LINEAR ACC.
- RELATIVE VELOCITY
- RELATIVE POSITION
STRUCTURE
- RIGID BODIES
- FLEXIBLE BODIES
- ROTATIONAL HINGES
- TRANSLATIONAL HINGES
- CLOSURE SRINGS

FIGURE 4

coordinate transformations. Like the actuators, the sensors also represent ideal devices while the sensor and actuator dynamics can be built into the control law definitions.

Figure 5 presents a segment of the input data base generated by HITIP for the HST TREETOP simulation. Body 1 data is identified as a flexible body which has seven node points and six modes. Hinge 1 is a "fictitious hinge" which connects the base body of a model (always labeled at 1) to the inertial frame, herewith six degree of freedom. Hinge 2 is a single degree of freedom hinge which connects body 2 to body 1. All of the input data appears in a similar format, wherein the user merely fills in the blank of the menu driven preprocessor. Table 1 describes the set of modal data required for each flexible body.

Figure 6 depicts the TREETOPS model of the HST with two High Gain Antennas (HGA's) mounted on flexible masts. Body 1 represents the core of the HST along with the two solar array panels. Bodies 2 and 5 represent 3.27 meter, deployable masts which also serve as waveguides for the antenna RF signals. Each antenna is connected to the mast through a pair of orthogonal, single axis gimbals with dc torque motors. The table on the lower right identifies the vibration frequencies of each

ORIGINAL PAGE IS
OF POOR QUALITY

EXAMPLE OF INPUT DATA FOR HST/HGA TREETOPS MODEL

```
331.000 BODY   $ 1 Type of body (R=rigid, F=flexible),ID$               = F              1.0000
332.000 BODY   $ 1 Mass of body (kg)                                    =    10881.
333.000 BODY   $ 1 Inertia (kg-m2) Ixx,Iyy,Izz                          =    32160.       80772.      83771.
334.000 BODY   $ 1 Inertia (kg-m2) Ixy,Ixz,Iyz                          =   -28.000      -1263.0     -5.0000
335.000 BODY   $ 1 modal data option (T=tape,D=disc),fname and tape$    = D              HGATWO:TAPE
336.000 BODY   $ 1 Modal inertia opt (N=none,I=inertia M,N,P dyadics)=  = N
337.000 BODY   $ 1 Modal coupling opt (N=none,C=coupling PHIXPHI vec)=  = N
338.000 BODY   $ 1 Number of flexible modes                             =    8.0000
339.000 BODY   $ 1 Attach point coordinates (m) x,y,z                   =    .00000       .00000      .00000
340.000 BODY   $ 1 NODE    1 mass center coordinates (m) x,y,z          =    .00000       .00000      .00000
341.000 BODY   $ 1 NODE    2 coordinates (m) x,y,z                      =    1.7617       .00000      1.9736
342.000 BODY   $ 1 NODE    3 coordinates (m) x,y,z                      =    1.7617       .00000     -1.9736
343.000 BODY   $ 1 NODE    4 coordinates (m) x,y,z                      =    .53432       1.3048      1.3048
344.000 BODY   $ 1 >>>>>zzzzz END OF DATA zzzzz<<<<<                    =
345.000 BODY   $ 1 >>>>>zzzzz END OF DATA zzzzz<<<<<                    =
106.000 HINGE  $ 1 ID$ of hinge, ID$ of inbd body, ID$ of outbd body    =    1.0000       .00000      1.0000
107.000 HINGE  $ 1 Node index of inboard body attach point              =
108.000 HINGE  $ 1 Rotation degrees of freedom                          =    3.0000
109.000 HINGE  $ 1 Base body(ID$ 1)rotation option(F=free,G=gimbaled)=  = G
110.000 HINGE  $ 1 Rotation axis unit vector L1 inboard body  X,Y,Z     =    1.0000       .00000      .00000
111.000 HINGE  $ 1 Rotation axis unit vector L1 outboard body X,Y,Z     =    1.0000       .00000      .00000
112.000 HINGE  $ 1 Rotation axis unit vector L3 inboard body  X,Y,Z     =    .00000       .00000      1.0000
113.000 HINGE  $ 1 Rotation axis unit vector L3 outboard body X,Y,Z     =    .00000       .00000      1.0000
114.000 HINGE  $ 1 Rotation spring stiffness (N/R)    k1,k2,k3          =    .00000       .00000      .00000
115.000 HINGE  $ 1 Rotation spring damping (N/R/S)    b1,b2,b3          =    .00000       .00000      .00000
116.000 HINGE  $ 1 Initial rotation angle (DEG) theta1,theta2,theta3    =    .00000       .00000      .00000
117.000 HINGE  $ 1 Null torque angle (DEG)      theta1,theta2,theta3    =    .00000       .00000      .00000
118.000 HINGE  $ 1 Translation degrees of freedom                       =    3.0000
119.000 HINGE  $ 1 Translation axis unit vector of 1ST DOF  X,Y,Z       =    1.0000       .00000      .00000
120.000 HINGE  $ 1 Translation axis unit vector of 2ND DOF  X,Y,Z       =    .00000       1.0000      .00000
121.000 HINGE  $ 1 Translation axis unit vector of 3RD DOF  X,Y,Z       =    .00000       .00000      1.0000
122.000 HINGE  $ 1 Translation spring stiffnes (N/M)  k1,k2,k3          =    .00000       .00000      .00000
123.000 HINGE  $ 1 Translation spring damping (N/M/S) b1,b2,b3          =    .00000       .00000      .00000
124.000 HINGE  $ 1 Initial translation displacement (M)   y1,y2,y3      =    .00000       .00000      .00000
125.000 HINGE  $ 1 Null force position (M)                y1,y2,y3      =    .00000       .00000      .00000
126.000 HINGE  $ 1 >>>>>zzzzz END OF DATA zzzzz<<<<<                    =
127.000 HINGE  $ 2 ID$ of hinge, ID$ of inbd body, ID$ of outbd body    =    2.0000       1.0000      2.0000
128.000 HINGE  $ 2 Node index of inboard body attach point              =    2.0000
129.000 HINGE  $ 2 Rotation degrees of freedom                          =    1.0000
130.000 HINGE  $ 2 Base body(ID$ 1)rotation option(F=free,G=gimbaled)=  =
131.000 HINGE  $ 2 Rotation axis unit vector L1 inboard body  X,Y,Z     =    .00000       1.0000      .00000
132.000 HINGE  $ 2 Rotation axis unit vector L1 outboard body X,Y,Z     =    .00000       1.0000      .00000
133.000 HINGE  $ 2 Rotation axis unit vector L3 inboard body  X,Y,Z     =    .00000       .00000      1.0000
134.000 HINGE  $ 2 Rotation axis unit vector L3 outboard body X,Y,Z     =    .00000       .00000      1.0000
135.000 HINGE  $ 2 Rotation spring stiffness (N/R)    k1,k2,k3          =    4457.3
136.000 HINGE  $ 2 Rotation spring damping (N/R/S)    b1,b2,b3          =    13.385
137.000 HINGE  $ 2 Initial rotation angle (DEG) theta1,theta2,theta3    =    .00000
138.000 HINGE  $ 2 Null torque angle (DEG)      theta1,theta2,theta3    =    .00000
139.000 HINGE  $ 2 Translation degrees of freedom                       =    .00000
140.000 HINGE  $ 2 Translation axis unit vector of 1ST DOF  X,Y,Z       =
141.000 HINGE  $ 2 Translation axis unit vector of 2ND DOF  X,Y,Z       =
142.000 HINGE  $ 2 Translation axis unit vector of 3RD DOF  X,Y,Z       =
143.000 HINGE  $ 2 Translation spring stiffnes (N/M)  k1,k2,k3          =
144.000 HINGE  $ 2 Translation spring damping (N/M/S) b1,b2,b3          =
145.000 HINGE  $ 2 Initial translation displacement (M)   y1,y2,y3      =
146.000 HINGE  $ 2 Null force position (M)                y1,y2,y3      =
147.000 HINGE  $ 2 >>>>>zzzzz END OF DATA zzzzz<<<<<                    =
```

FIGURE 5

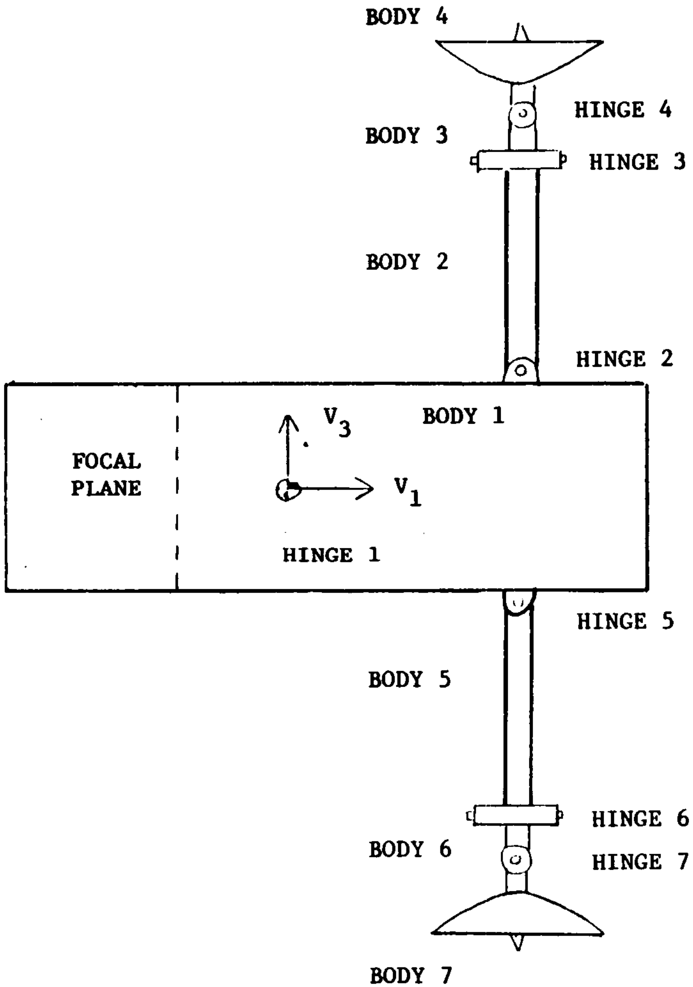
Table 1. Modal Data for the j^{th} Body

Symbol	Mnemonic	Dimension	Description
j	IDBODY		Body ID number (j^{th} body)
NM	NMODE		Number of modes for j^{th} body
NN	NNODE		Number of nodes for j^{th} body
$\phi^T M \phi$	MMASS (k, k)	(NM, NM)	Augmented modal mass (kg)
$\phi^T D \phi$	MDAMP (k, k)	(NM, NM)	Augmented modal damping (nt/msec)
$\phi^T K \phi$	MSTIFF (k, k)	(NM, NM)	Augmented modal stiffness (nt/m)
$\underline{\alpha}^j{}_k$	ALPHABJ (i, k)	(3, NM)	Mass center mode shape of k^{th} mode
$\underline{\phi}^j{}_k\ (\underline{r}\ell)$	PHIDNLBJ (i, k, ℓ)	(3, NM, NN)	Mode shape of k^{th} mode at the ℓ^{th} node
$\underline{\phi}'^j{}_k\ (\underline{r}\ell)$	PHIPNLBJ (i, k, ℓ)	(3, NM, NN)	Mode slope of k^{th} mode at the ℓ^{th} node (rad/m)
$\underline{h}^j{}_k$	RJXPHIBJ (i, k)	(3, NM)	h-Parameter due to the k^{th} mode (kg-m)
$\underline{\underline{M}}^j{}_k{}^*$	DINERTM (ICOL, IROW, k)	(3, 3, NM)	Change in inertia of j^{th} body due to the k^{th} mode (kg-m)
$\underline{\underline{P}}^j{}_{qk}{}^*$	PDYADIC (ICOL, IROW, q, k)	(3, 3, NM, NM)	Change in inertia of the k^{th} mode due to the q^{th} mode (kg)
$\underline{Y}^j{}_{qk}{}^{**}$	PHIXPHIJ (i, q, k)	(3, NM, NM)	Coupling influence of the q^{th} mode into the k^{th} modal equation (kg)

NOTES

1. Index Definition - k = Mode, i = Axis, ℓ = Node, q = Mode, IROW, ICOL = Dyadic matrix elements
2. * indicates optional data is deleted when "time varying inertial option = no."
3. ** indicates optional data is deleted when "PHIXPHI modal term option = no."

HST/HGA TREETOPS MODEL



	HGA		HST & SA	
MODE	FREQ (HZ)	DAMPING	FREQ (HZ)	DAMP
1	0.531	0.005	0.086	0.005
2	1.247	0.005	0.087	0.005
3	8.985	0.005	0.515	0.005
4	21.32	0.005	0.891	0.003
5	24.67	0.005	1.031	0.003
6			2.937	0.003

FIGURE 6

HGA and the core HST. The basic problem to be addressed is the interaction of the fundamental antenna mast modes at 0.531 with the 0.515 HST mode. The stringent 0.007 arc-second pointing stability requirement of the HST budgets only 0.003 arc-second disturbances of the Line of Sight (LOS) to be caused by the HGA's. Analysis showed the possibility of Dahl friction in the HGA gimbal bearings to excite the fundament mast modes during slow HGA tracking maneuvers. TREETOPS was employed to verify the predictions made by the HST prime contractor.

Figure 7 shows the detailed components of the HST TREETOPS model, consisting of seven bodies three of which are flexible, seven hinges with a total of three translational and nine rotational degrees of freedom; eleven sensors, seven actuators, a discrete and a user controller. The discrete controller models the HST fine guidance control system. The user controller models the HGA discrete P-I-D controllers along with bearing friction and roughness, cogging torques and quantization nonlinearities. The model thus contains 22 degrees of freedom plus 14 controller states.

Figures 8, 9, and 10 show results obtained by TREETOPS. In figure 8, a TREETOPS HGA step response compares favorably with simulation results obtained by the HST contractor. This plot

HST/HGA TREETOPS SIMULATION

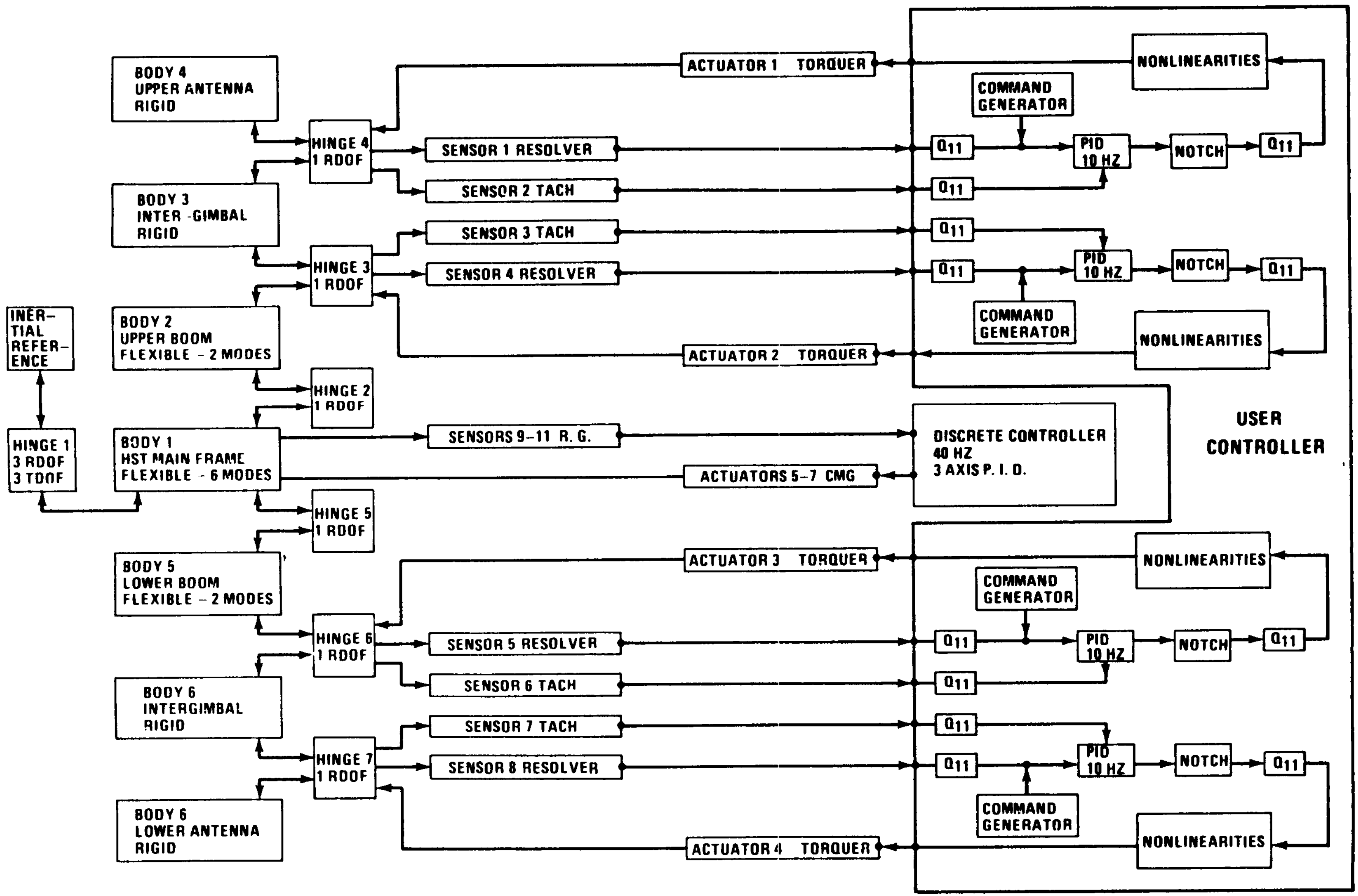


FIGURE 7

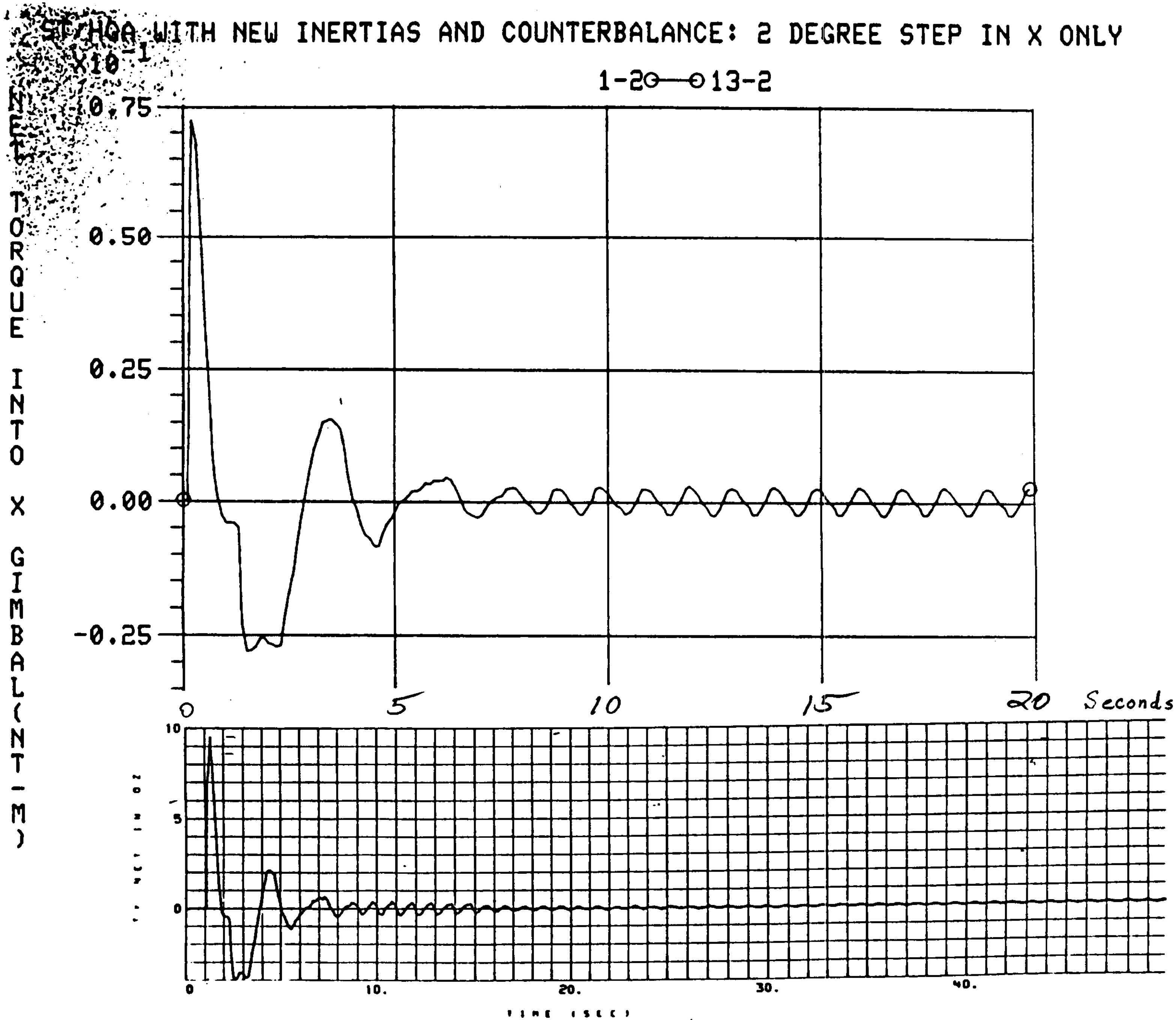

ST/HGA WITH NEW INERTIAS AND COUNTERBALANCE: 2 DEGREE STEP IN X ONLY
1-20—013-2
X10^-1
NET TORQUE INTO X GIMBAL(NT-M)
0.75
0.50
0.25
0.00
-0.25
0
5
10
15
20
Seconds
10
5
0
0
10.
20.
30.
40.
TIME (SEC)

FIGURE 8

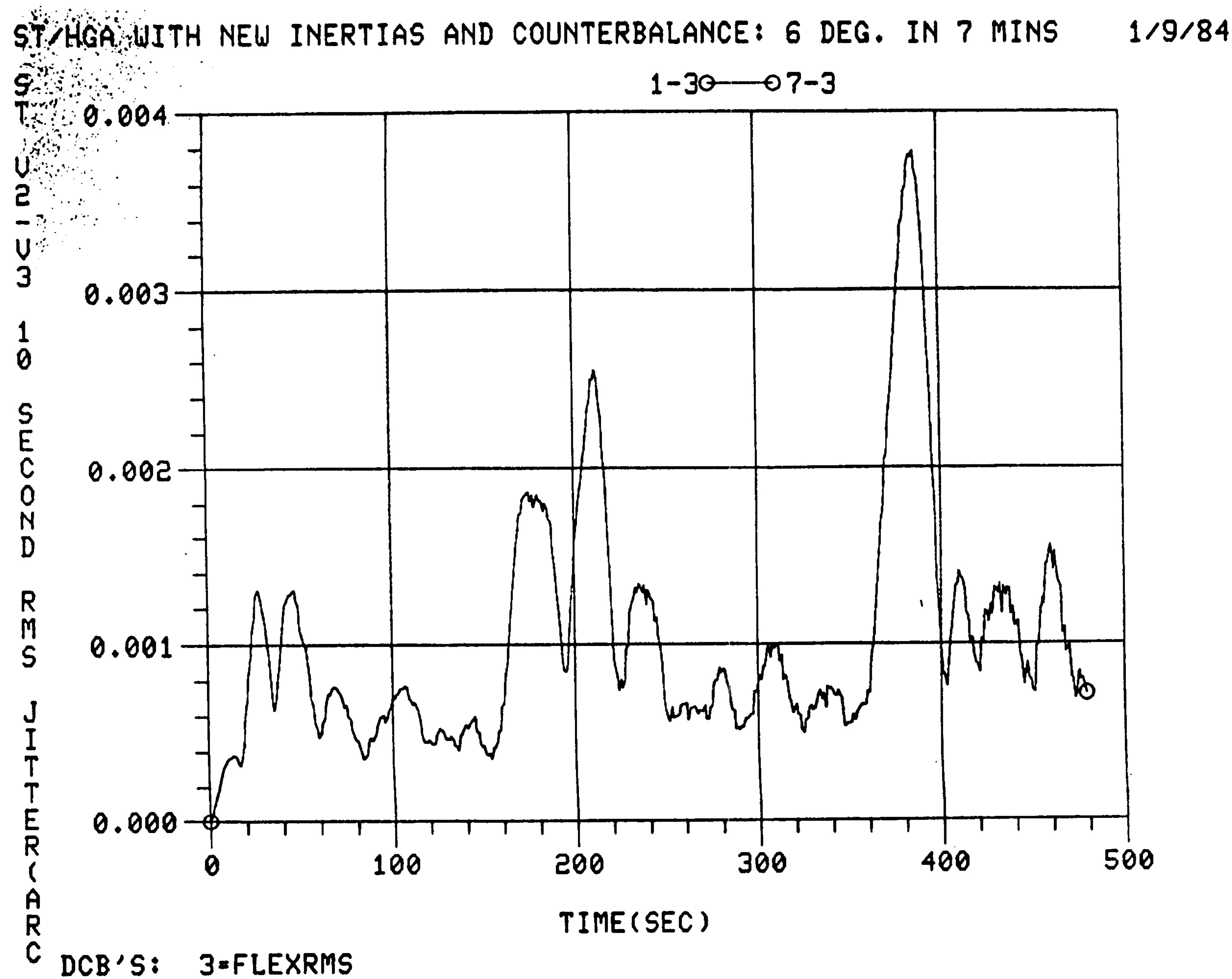

ST/HGA WITH NEW INERTIAS AND COUNTERBALANCE: 6 DEG. IN 7 MINS
1/9/84
1-3
7-3
ST V2-V3 10 SECOND RMS JITTER(ARC
0.004
0.003
0.002
0.001
0.000
0
100
200
300
400
500
TIME(SEC)
DCB'S: 3=FLEXRMS

FIGURE 9

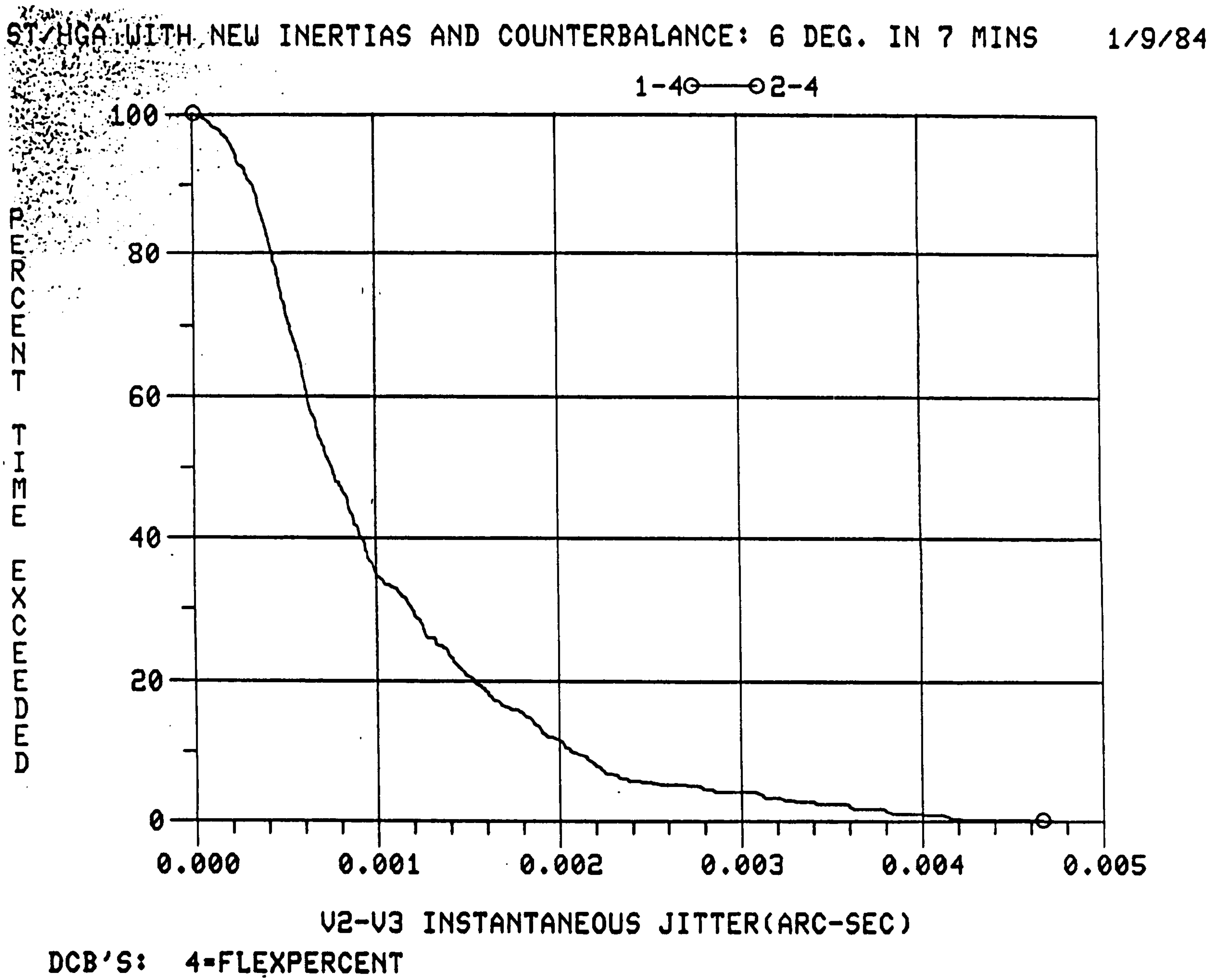

ST/HGA WITH NEW INERTIAS AND COUNTERBALANCE: 6 DEG. IN 7 MINS
1/9/84
1-4
2-4
PERCENT TIME EXCEEDED
100
80
60
40
20
0
0.000
0.001
0.002
0.003
0.004
0.005
V2-V3 INSTANTANEOUS JITTER(ARC-SEC)
DCB'S: 4=FLEXPERCENT

FIGURE 10

shows the net torque applied between bodies 2 and 3 of figure 6 in response to a two degree step command (note the difference in torque units). Figure 9 shows the time history of the HST LOS during a typical HGA tracking maneuver of the Tracking and Data Relay Satellite. Notice that the 0.003 arc-second error budget is exceeded at the end of the maneuver as the HGA pointing control system overcomes the Dahl friction forces at very slow speeds. The 480 seconds of simulation time required approximately 56 minutes of CPU time on a Sigma V computer. Figure 10 summarizes the LOS disturbance caused by the HGA's over the same maneuver. The interaction of the HGA mast modes with the HST is again demonstrated as the error budget is exceeded. Note also that the data plotted in figure 8 is standard TREETOPS output data while the information in figures 9 and 10 were generated during run time in the user controller subroutine, which increased CPU time somewhat.

The proceeding discussion indicates some of the potential applications of the TREETOPS program. Typically, programs of the magnitude receive a rather cool response until a sufficient number of users and check cases have been used to eliminate the unavoidable software bugs and idiosyncrasies. At MSFC, TREETOPS has been employed on the six programs listed in figure 11. In each case alternate simulation results were available

ORGANIZATION	MARSHALL SPACE FLIGHT CENTER	NAME
SYSTEMS DYNAMICS LAB	OAST RTOP REVIEW	J. SHARKEY
CHART NO.	CONTROL TECHNOLOGY/GUIDANCE CONCEPTS	DATE OCTOBER 1985

NONLINEAR DYNAMICS

FUTURE ENHANCEMENTS

- ORBITAL DYNAMICS (GRAVITY GRADIENT, AERODYNAMIC, AND MAGNETIC FIELD MODELS).
- CMG DYNAMICS.
- NASTRAN INTERFACE PROGRAM.
- MODE SELECTION CRITERIA BASED ON COMPONENT MODE SYNTHESIS.
- SUBMIT TO COSMIC FOR MAINTENANCE SUPPORT.

MSFC PROJECTS UTILIZING TREETOPS

- SPACE TELESCOPE (HIGH GAIN ANTENNA/SOLAR ARRAY INTERACTION STUDIES).
- SPACELAB II INSTRUMENT POINTING SYSTEM.
- SPACELAB II INFRARED TELESCOPE.
- PINHOLE/OCCULTER FACILITY.
- SPACE STATION (REBOOST, POINTING MOUNTS).
- GROUND FACILITY FOR LARGE SPACE STRUCTURES.

FIGURE 11

for verification. Honeywell also has an extensive list of check cases and projects used to verify TREETOPS. Over twenty other companies, universities, or other Government agencies have received a copy of TREETOPS and are currently evaluating its potential applications. Most responses indicate close agreement with other such programs while acknowledging TREETOPS' easy to use format and versatility. Soon CONTOPS will be released to the public domain through NASA's COSMIC network whereby maintenance provision should become available. Figure 11 also list some future enhancement considered for TREETOPS and CONTOPS.