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ATLAS/CENTAUR AC-5

ANALOG/DIGITAL

LOAD REDUCTION AUTOPILOT STUDY

Prepared under Contract
NAS3-3232

PREPARED BY R Harris
R. Harris
Senior Dynamics Engineer

CHECKED BY M J Hurley
M. J. Hurley
Design Specialist

APPROVED BY M J Hurley
for D. R. Lukens
Sr. Dynamics Group Engineer

APPROVED BY R. E. Martin
R. E. Martin
Chief of Dynamics

REVISIONS

NO.	DATE	BY	CHANGE	PAGES AFFECTED

FOREWARD

This report contains the results of an investigation performed using a hybrid analog digital system to evaluate the merits of a load relief autopilot on the Atlas/Centaur AC-5 vehicle. During this study new techniques for analysis of vehicle inflight bending moments and launch availabilities were used and are herein documented. This study was conducted under contract NAS3-3232.

SUMMARY

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Based on the magnitude of inflight bending moments, the number of days suitable for launch (launch availability) of Atlas/Centaur AC-5 is much lower than is desired. An appreciable portion of these bending moments is caused by the wind profile through which the vehicle flies. An increase of the launch availability can be realized by two basic methods, increasing structural integrity and/or use of a load reduction autopilot.

The load reduction autopilot is a standard autopilot with the addition of a differential pressure (angle of attack) sensor on the vehicle's nose which sends a signal to the autopilot. This signal results in a reduction of the vehicle angle of attack and hence a reduction in loads, but introduces trajectory dispersions. The primary purpose of this investigation is to study the effect of the load relief autopilot on the vehicle's launch availability.

A hybrid analog/digital system has been developed to determine inflight bending moments and launch availabilities. This system also provides information for stability, control, and trajectory analyses. The basic advantages of the hybrid system method over a previously used all digital method are increased flexibility for engineering analysis, greater speed in performing the study, and significantly lower cost.

The prime purpose of issuing this report is to document the method of analysis used and illustrate the form of the results which can be obtained. This report predicts much lower launch probability than Reference 1, primarily due to use of a less optimum pitch program for winter winds. Although Ref. 1 should be considered the more accurate estimate of AC-5 launch availability, the results of this report show dramatically that a vehicle with low launch availability is very sensitive to relatively minor trajectory changes (45% per Ref. 1 vs. 8.77% per this report for standard autopilot). These results indicate a launch availability of 63% with the load relief autopilot and 8.77% for the standard autopilot based on a sample size of approximately 200 Avidyne winter winds. Also discussed are: the effect of structural integrity on the launch availability, critical flight times and vehicle stations, and trajectory dispersions.

author

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SECTION 1

INTRODUCTION

The analysis and design of a load relief autopilot for the Atlas/Centaur (AC-5) vehicle is a complex engineering task. To properly perform this task, the analyst must utilize the techniques of many technical disciplines including stability and control, structural loads, trajectory (performance) analysis and aeroheating analysis. Design ground rules in each area must be adhered to, resulting in design compromises for the optimum over-all design. For example, a change in booster pitch program effects not only performance, but also structural loading and aeroheating.

Stability requirements restrict autopilot gain settings and filter values. These restrictions are determined through an analysis of rigid body control, liquid propellant sloshing, and elastic missile bending modes. A complete stability analysis of the AC-5 configuration in which all of the modes are considered simultaneously, is not practical. Such an analysis would make the synthesis of an autopilot control system very difficult because the pertinent physical phenomena would be obscured. However, the various degrees of freedom are to a large extent, dynamically uncoupled. Thus, the stability of the rigid body control and propellant sloshing modes can be analyzed independently of the higher frequency elastic bending modes. This procedure greatly reduces the complexity of the task.

Trajectory analysis becomes more complex with a load relief autopilot in that the relief of loads (i.e. reduction of the launch vehicle angle of attack) creates trajectory dispersions of a greater magnitude than those encountered with the conventional autopilot. The guidance system design must allow for these larger dispersions and be able to correct for them. If there were no restrictions on the maneuvers which the launch vehicle might make during the powered flight, the guidance would be relatively simple and the only major obstacle would be that of precision in guidance. However, the structural limitations, due to loading and heating, and flight performance requirements, will combine to restrict the trajectory such that only limited correction maneuvers may be employed.

The vehicle structure determines the limit allowable loads and hence the limit allowable bending moments. The bending moments on the vehicle during flight are imposed by axial acceleration, aerodynamic loading, propellant sloshing, and rigid body control response. To get a true indication of actual flight conditions, the vehicle must be subjected to the effects of winds aloft. An Avidyne wind study consisting of 200 days of actual wind soundings at Montgomery, Alabama, was used to determine bending moments both with and without a load relief autopilot (LRAP) feedback loop. A statistical comparison was then made to show the effect of the LRAP on the launch availability based upon structural limitations.

The aeroheating analysis is dependent upon the vehicle trajectory. The Atlas/Centaur trajectory studied in this report is a heat limited performance trajectory which means that a depressed trajectory will exceed the aeroheating allowables for critical areas of the vehicle. A lofted trajectory will be a cooler trajectory but both will result in a loss of performance. Aeroheating input changes when vehicle trajectory is altered by the wind response of the load relief autopilot and also when these trajectory dispersions are corrected by guidance commands. Aeroheating therefore must be analyzed in the same manner as the structural loading, i.e. using a statistical wind analysis.

To undertake a load relief autopilot study of this complexity required the development of a large analog/digital (hybrid) system capable of solving the many degree of freedom equations necessary for full vehicle description. The system allowed digital input of wind data to an analog simulation of the Atlas/Centaur AC-5 launch vehicle stability and trajectory. Outputs of this simulation, both continuous and digitally recorded, are used in analyses of stability, trajectory, structural loads, and aeroheating. This system therefore allows the analyst an over-all perspective of the effects of load relief parameter variations.

No attempt has been made tooptimize the load relief autopilot or the trajectory shaping. The primary purpose of this report is to indicate the effect of load relief on launch probability using a wind sample to describe some of the optimization techniques and constraints, and to outline the available analytical, digital and analog methods for such analyses. Ref. 1, which is compared with this report in Section 4.4, should currently be used as the more accurate estimate of launch availability.

SECTION 2

LOAD RELIEF AUTOPILOT PHILOSOPHY AND STABILITY

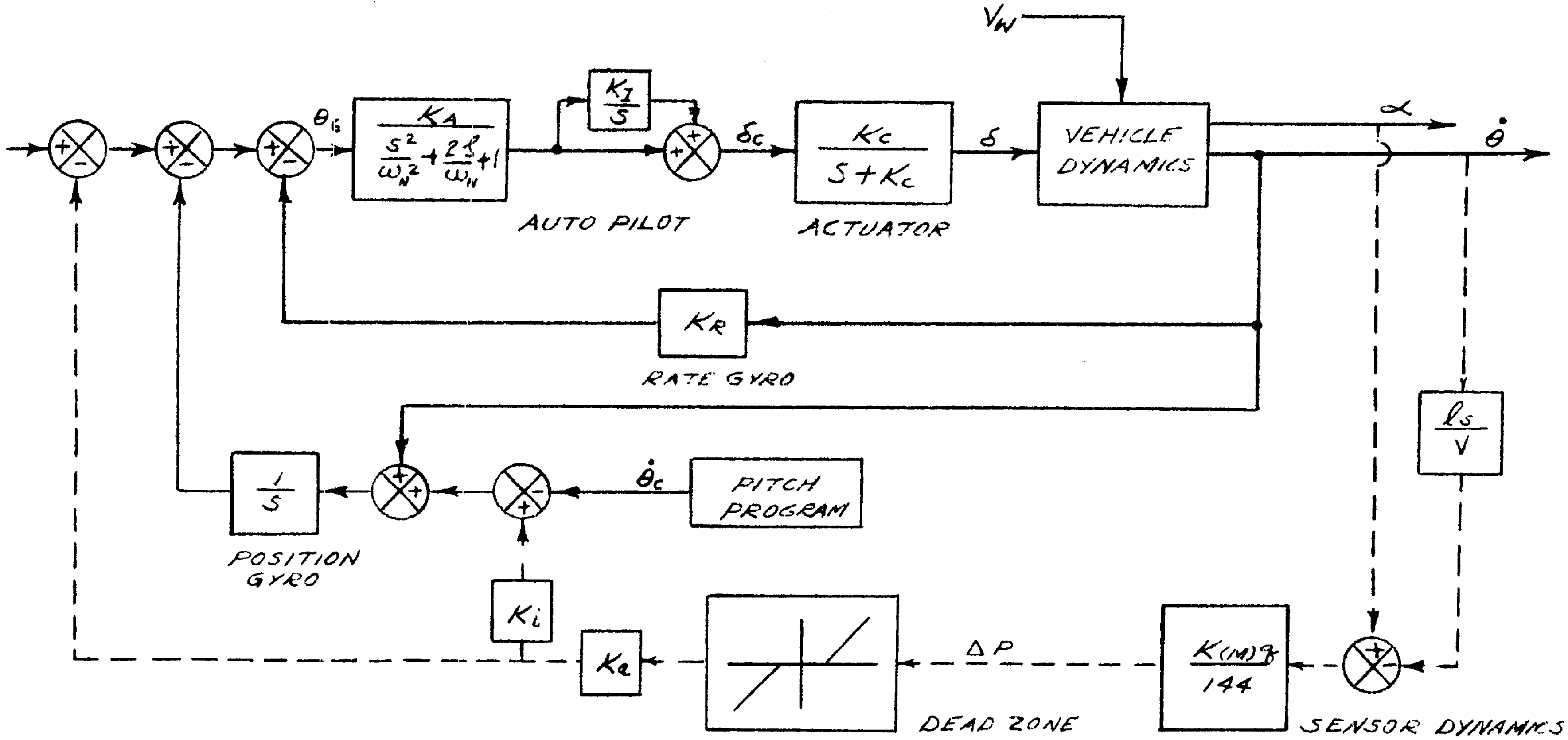
The primary purpose for the addition of a load relief feedback loop to the conventional AC-5 autopilot is, as the name implies, to relieve loads caused by excessive angles of attack. By relieving loads, this autopilot can increase the vehicle launch availability which is based upon the probability that the allowable bending moment will not be exceeded during the severe winds of the winter months. However, the load relief loop alters vehicle stability when added to the conventional autopilot. Root locus techniques in combination with an analog simulation are necessary to analyze the stability of both conventional and load relief autopilots for the rigid body control mode, propellant sloshing modes, and elastic missile modes.

2.1 LOAD RELIEF AUTOPILOT DESCRIPTION

The load relief autopilot is basically a conventional autopilot with an additional feedback signal to the error input channel, and an additional feedback to the position gyro torquer. A simplified block diagram of the autopilot is shown on Figure 1. The dotted lines indicate the load relief loop. This autopilot is only valid for flight times up to 110 seconds as the guidance platform which replaces the position gyro at this time is not shown. Circuitry modeling of this autopilot was used in the analog simulation with the gain and filter configuration shown in Figure 2. The load relief signal is initially produced by a differential pressure (angle of attack) sensor located in the nose of the AC-5 vehicle. The nose surface contains pressure ports which enable measurement of the differential pressure in the pitch and yaw planes by diaphrams. The diaphram movement is converted into an electric signal with an electronic dead zone provided to eliminate sensor output below 0.05 psi. This is necessary to prevent electrical null errors from providing a biased output signal. The output signal represents the total angle of attack times dynamic pressure with an approximate gain variation (shown in Figure 3) due to Mach number.

Activation of the load relief loop takes place at 40 seconds of flight, preceding entry of the vehicle into the high dynamic pressure region. De-activation takes place at 110 seconds when the dynamic pressure has dropped to less than one-half its maximum value for the nominal trajectory. The signal from the pressure sensor electronic package is sent to the position gyro torquer with a gain of $K_a K_i$ and directly to the error channel of the autopilot with a gain K_a. The signal to the position gyro torquer provides an integral signal to the error channel proportional to the $K_a K_i$. This signal causes the vehicle to turn in a direction so as to reduce the angle of attack resulting in an approximate zero lift trajectory for the encountered wind profile. As the pitch program is designed to fly the nominal zero lift trajectory for no wind and no load relief, a trajectory dispersion will occur. An increase of $K_a K_i$ produces a more rapid reduction of angle of attack and an increase in trajectory dispersion.

AC-5 AUTOPILOT BLOCK DIAGRAM



α = Vehicle angle of attack, Deg
δ_c = Engine Command, Deg
δ = Engine Angle, Deg
$\dot{\theta}_c$ = Pitch Program Command, Deg/Sec
$\dot{\theta}$ = Vehicle Turning Rate, Deg/Sec
θ_ϵ = Autopilot Error Signal, Deg
ΔP = Differential Pressure, PSI
ℓ_S = ΔP Sensor Moment Arm, Ft
ω_N = Filter Natural Frequency, RAD/Sec
ζ = Filter Damping Ratio , N.D.
q = Dynamic Pressure, PSF

M = Mach. Number, N.D.
K_A = Autopilot position gain, N.D.
K_c = Actuator Gain Factor, Sec
K_I = Autopilot Integral Gain, 1/Sec
$K_{(M)}$ = Differential Pressure Sensor Gain, 1/Deg
K_R = Autopilot Rate Gain, Sec
K_a = Load Relief Position Gain, Deg/PSI
K_i = Load Relief Integral Gain, 1/Sec
S = LaPlace Operator
V = Vehicle Velocity, Ft/Sec
V_W = Wind Velocity, Ft/Sec

FIGURE 1

AC-5 AUTOPILOT SPECIFICATIONS

Gains and Filters Used   Analog/Digital System Analysis

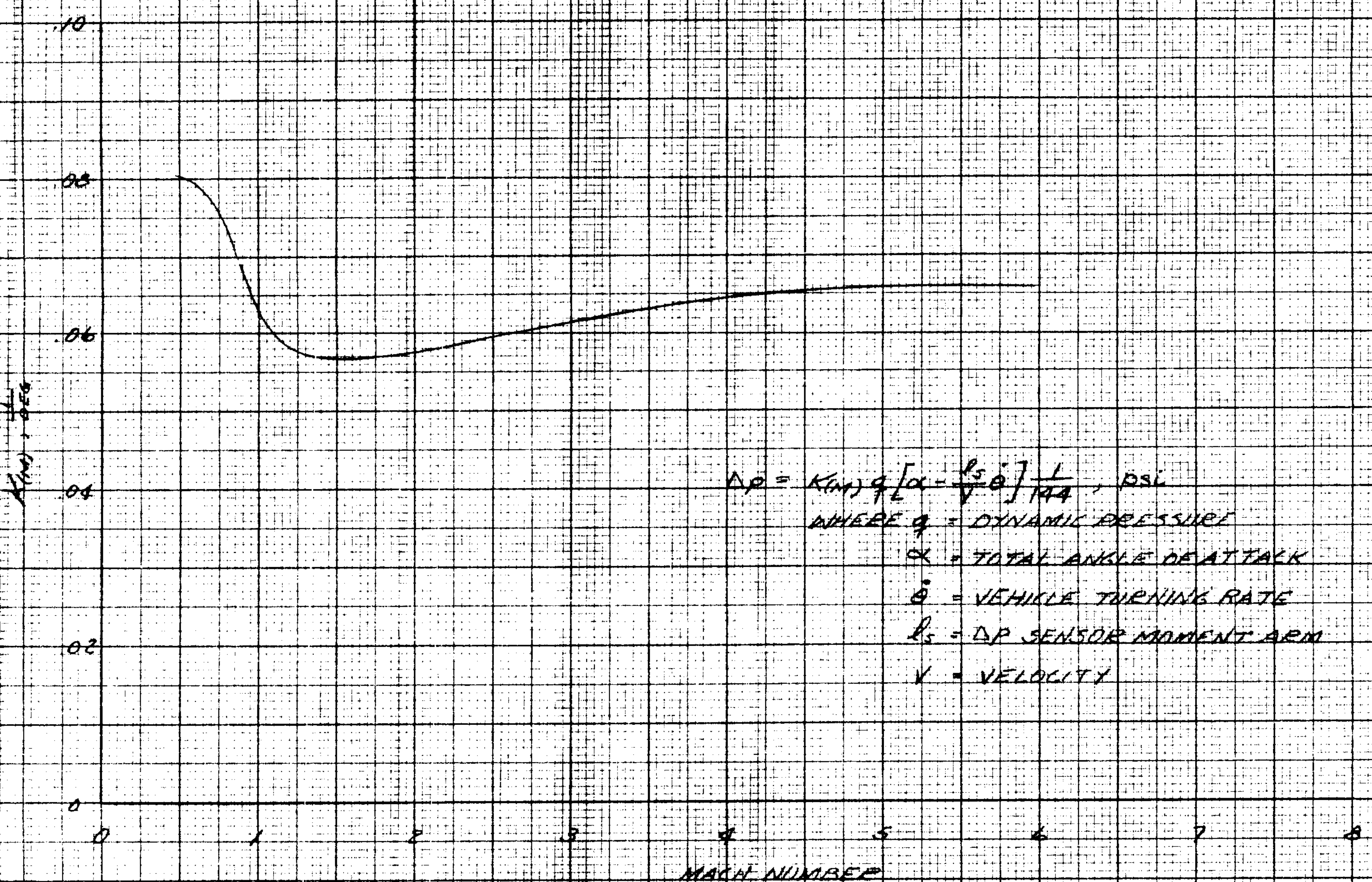
Autopilot Channel	Pitch and Yaw				Roll	
Engines Controlled	Booster				Booster	Vernier
Time, Seconds	0-40	40-70	70-110	110-152.6	0-152.6	0-152.6
End to End Position Gain, K_A, N.D.	2.0			1.0	.083	7.5
End to End Rate Gain, $K_A K_R$, Sec (K_R)	0.8 (0.4)			0.485 (0.485)	.032 (.385)	3.0 (0.4)
End to End Integral Gain, $K_A K_I$, 1/Sec (K_I)	0 (0)			.2 (.2)	.083 (1.0)	0 (0)
Filter	$\dfrac{1}{\dfrac{S^2}{(13.0)^2}+\dfrac{2(0.5)S}{13.0}+1}$		$\dfrac{1}{\dfrac{S^2}{(17.5)^2}+\dfrac{2(0.5)S}{17.5}+1}$		0	
Load Relief Integral Gain, K_i, 1/Sec	0	2.0		0		
Load Relief Position Gain, K_a, Deg/psi	0	1.25		0		

FIGURE 2

A single $K_a K_i$ gain setting to produce both minimum trajectory dispersions and maximum load reduction is therefore impossible and a compromise is necessary. The signal input to the error channel through the gain K_a has the effect of increasing stability and improving vehicle gust response.

2.2 STABILITY ANALYSIS

A complete stability analysis of the AC-5 flexible bodied vehicle for both standard and load relief autopilot is contained in Reference 1. The referenced report also presents the rigid body and propellant sloshing stability results obtained during the analog study and will not be repeated here.



DIFFERENTIAL PRESSURE SENSOR GAIN

FIGURE 3

SECTION 3

ANALOG/DIGITAL SYSTEM AND SIMULATION DESCRIPTION

The entire analog/digital system has the capability to provide a complete dynamic analysis of the Atlas/Centaur booster and sustainer phases including the areas of trajectory and guidance, stability, structural loads, launch availability and aeroheating. The basic advantages in using a combined analog/digital system for the design of the AC-5 load relief autopilot are 1) increased flexibility for engineering analysis, 2) greater speed in performing the study, and 3) significantly lower cost when compared to all digital studies. Speed of solution of the analog simulation, in combination with the input/output data handling and reduction (using digital methods) provides a very efficient design analysis tool. The following sections provide a functional description of the analog/digital system, its programmed analog simulation, and monitoring techniques. The additional details necessary for operation of the system are located in Reference 2.

3.1 ANALOG SIMULATION

Although preliminary design work may be accomplished with planar studies, realistic vehicle response requires a three dimensional trajectory analysis. The analog simulation provides a continuous solution of the stability and trajectory equations in six rigid body degrees of freedom. The complete analog simulation can be broken into three major sets of equations; trajectory, vehicle and autopilot.

The trajectory equations, referenced to a rotating spherical earth, describe the path of the launch vehicle. Gravitational acceleration, velocity of sound and atmospheric density are represented as a function of the vehicle altitude, an output parameter of the simulation. In addition to altitude, trajectory calculations include flight path angle, down range position, cross range position and other parameters necessary for a complete trajectory description of the Atlas launch vehicle flight to sustainer engine cutoff.

The equations describing the launch vehicle motion are based on the fact that the liquid propellants comprise a major portion of the vehicle's mass during powered flight. A mechanical analogy is used to duplicate the forces and moments of the liquid propellant sloshing consisting of a pendulum series plus a rigid mass. The rigid mass is constrained to move with the container (thus simulating the portion of fluid that does not participate in the sloshing motion) while a series of pendulums (one for each fluid mode) of specific length and mass are pivoted so that the sloshing forces and moments are duplicated. Only the first propellant mode for each of the four tanks is included in both the pitch and yaw planes, as the higher propellant sloshing modes produce negligible contributions. The anti-slosh baffles in the Atlas and Centaur liquid oxygen tanks and the shear membrane in the Atlas fuel tank introduce damping to the fluid modes and therefore have been included. This baffle damping is a function of both propellant height above a baffle and slosh amplitude. In addition to propellant sloshing forces acting on the rigid body vehicle, aerodynamic forces are present and create an inherently unstable vehicle. The necessary input data for the above is located in Reference 3 and is the June 1963 design configuration using 154,000 lb thrust booster engines.

Control of the vehicle is provided by pitch, yaw and roll autopilot circuitry which duplicate autopilot gain and filter specifications throughout Atlas launch vehicle flight. Prior to 110 seconds, signals produced by vehicle motion (e.g. from rate gyros, position gyros, the differential pressure sensor, and the pitch programmer) combine to provide the autopilot error signal. Following 110 seconds a simplified guidance platform and computer simulation replaces the simulated position gyro. The differential pressure sensor is also switched out at this time. The simplified* guidance simulation can also make trajectory modifications during sustainer phase. The autopilot outputs are fed into simulated nonlinear electro-hydraulic actuators which convert the signal into engine deflections. The nonlinearities reflect the effects of oil compressibility, orifice flows, and viscous and coulomb friction and are closely approximated in the simulation. The autopilots, both conventional and load relief are described in Section 2.

The analog output is continuously recorded on two twelve channel wet pen recorders and includes gyro outputs, engine deflections, angle of attack, side slip angle, and magnitude of propellant sloshing for all four propellant tanks. These recordings provide an excellent method of comparison between the stability characteristics of the AC-5 autopilot with and without load relief.

A detailed development of the simulation's equations of motion may be found in Reference 4.

3.2 ANALOG/DIGITAL INTERFACE EQUIPMENT

The purpose of this equipment is to provide analog simulation input of the digitalized wind data stored on magnetic tape and to process analog data into the CDC 160A digital computer.

Altitude from the analog simulation is sent via a control board to the CDC 160A digital computer where it is used to position the digital magnetic tape. The tape's digital output (wind speed and direction) is sent through a Packard Bell Computer Linkage System, converted into an analog signal and fed into the analog simulation. A typical wind profile is shown in Figure 4. Because the actual wind soundings end before 60,000 feet, the wind speed was linearly extrapolated to zero at 100,000 ft. with the direction remaining constant. This allows a more comprehensive analysis of the autopilot with and without load relief capabilities.

*Additional sophistication of the guidance platform and computer simulation can be readily implemented because of the flexibility of the simulation.

AVIDYNE WIND PROFILE
MONTGOMERY, ALABAMA
MARCH 10, 1955

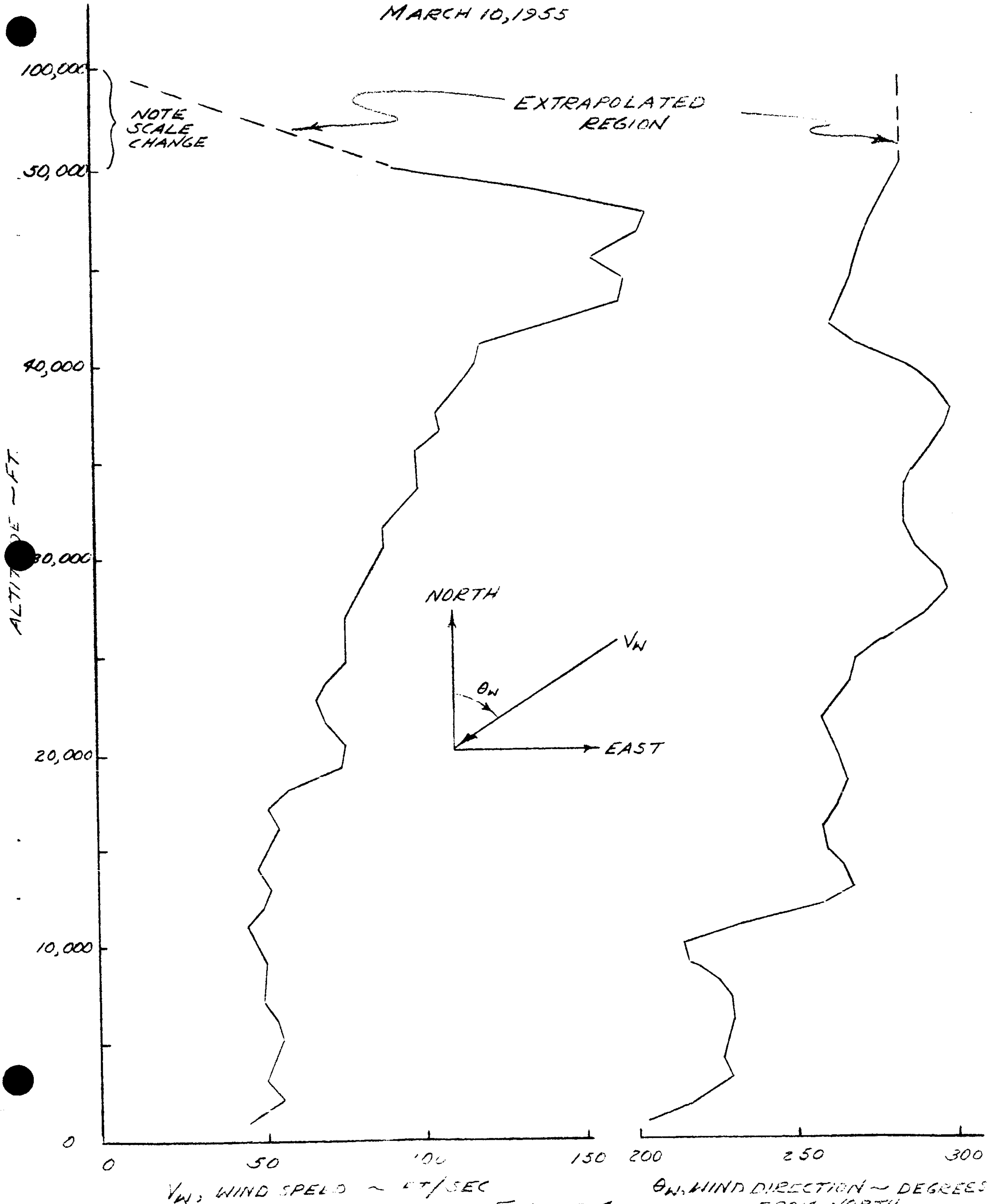


FIGURE 4

The control board provides semi-automatic control of the entire system and sychronizes the converter equipment, analog simulation and the CDC 160A digital computer. In addition the control board is used to calibrate the CDC 160A.

3.3 DIGITAL RECORDING EQUIPMENT

Use of the CDC 160A and related analog digital conversion equipment extends the capabilities of the analog simulation beyond the stability and trajectory areas. Fifteen channels of data were digitally recorded on magnetic tape and then used as input to an IBM 7094 digital program (MADCAP) which calculates the inflight bending moments as a function of vehicle station and flight time. A detailed discussion of this digital program will follow in Section 4. In addition, the tape is printed to provide additional data for trajectory analysis, and also to check repeatability and accuracy.

3.4 REPEATABILITY AND ACCURACY

Because of the complex nature of the system, methods of assuring valid solutions were utilized. A complete series of static and dynamic system checks was run to assure accuracy of solution. In the final dynamic check, analog simulation outputs are compared to the same set of equations solved on a digital computer.

In order to assure repeatability during operation, a check case (identical wind input) was run as every tenth run. Critical parameters were recorded on large x-y plotters and inspected for matching of amplitude and frequency. This method allowed monitoring of the system while operating. Following the system operation, the CDC 160A digital trajectory check cases were statistically analyzed for repeatability. The mean value and standard deviation of velocity, flight path angle, and altitude were calculated. These results along with the percentage deviation are presented in Figure 5 and indicate the excellent repeatability (considering the complexity of the system) using the AC-5 autopilot with and without load relief. A higher degree of repeatability is experienced without load relief because of the removal of the additional feedback loops in the pitch and yaw planes.

AC-5 ANALOG TRAJECTORY REPEATABILITY

CHECK CASES

CONVENTIONAL AC-5 AUTOPILOT

Parameter	Mean Value At 102 Seconds	Standard Deviation	Percentage Deviation
Flight Path Angle	28.23	.488	1.73
Velocity	3041	19.86	0.65
Altitude	68,850	348.8	0.51

LOAD RELIEF AC-5 AUTOPILOT

Parameter	Mean Value At 102 Seconds	Standard Deviation	Percentage Deviation
Flight Path Angle	40.13	1.347	3.36
Velocity	2877	13.16	0.46
Altitude	77,160	980.4	1.27

FIGURE 5

Section 4

LAUNCH AVAILABILITY STUDY

Determination of bending moments during vehicle flight with and without the load relief autopilot is necessary, as structural launch availability is based upon the allowable bending moments. Launch availability is defined as the percentage ratio of flights which do not exceed the allowable bending moments at any station and time to the total number of flights sampled. In this study, the launch availability was based on a sample of approximately 200 flights and for both the standard and load reduction autopilot using actual wind soundings and the latest available allowable limit bending moments.

4.1 LIMIT ALLOWABLE BENDING MOMENTS

The limit allowable bending moments used in this study are shown in Figure 6 for the four vehicle stations investigated (viz station 214, 415, 570 and 812). These results represent the best available curves at the time of writing of this report. The output of the 7094 digital program MADCAP (i.e. calculated bending moments) is given as the maximum bending moment encountered at each station during a given time interval. The allowable bending moments are therefore presented as functions of these time intervals. Limit allowables for Stations 214 and 415 are based upon the preliminary AC-3 pressure schedule which keeps the low range LH_2 tank vent valve locked until T = +70 seconds. The SN 219 interface was assumed to be a two latch separation system and the SN 408 interface was assumed to be bolted with a shaped charge type of separation system. The allowables for these stations take into account not only failure at the latch points but also such phenomena as buckling of the pressurized tanks adjacent to the structural rings. The investigations to determine these allowables showed that, in the vicinity of SN219, the latch system is the critical area. A design change to a shaped charge separation scheme would probably result in increased allowables.

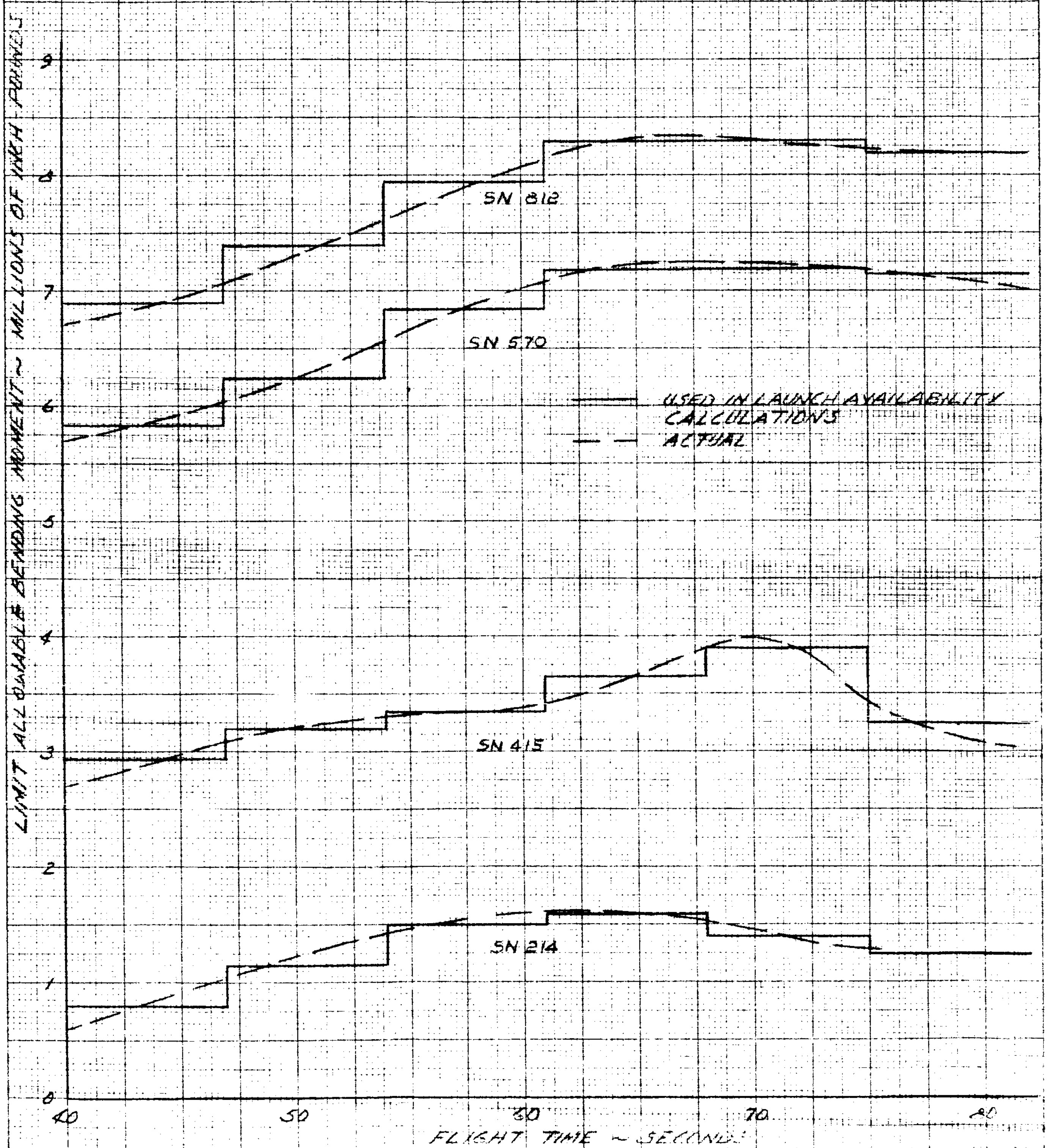
SN 570 and 812 limit allowable bending moments are based upon design limit bending moments and conversion of +3 sigma standard deviation axial load values to bending moments.

4.2 INFLIGHT BENDING MOMENTS

The calculated bending moment includes the bending moment due to axial loading, gusts and wind response. Since the structure is designed as a beam column, the axial load due to vehicle acceleration decreases the bending capability and is accounted for by converting it to an equivalent bending moment. The vehicle acceleration increases throughout booster phase as propellants are depleted, and therefore the equivalent bending moment increases.

FIGURE 6

AC-5 LIMIT ALLOWABLE BENDING MOMENTS



To determine bending moment due to gusts, a gust was assumed to envelope the entire length of the missile instantaneously and to act in both the pitch and yaw planes perpendicular to the vehicle axis. The gust loading takes into account rigid body and aeroelastic response. Data for several time slice analyses is input to a digital program, to calculate bending moments with a (1-cos kt) shape gust. By varying k, the maximum missile bending moment as a function of time for each station was determined.

The magnitudes of the bending moments due to wind are functions of the time history of the vehicle wind combination. It is therefore possible to predict those flight loads on the basis of a statistical wind analysis. Real wind velocity and direction profiles should be used because:

1. The velocity and shear rates of a synthetic series of flight wind profiles produce erroneous bending moments.

2. Inertia reactions vary widely between real winds and synthetic winds.

3. The lofting of a load reduction autopilot can only be analyzed by using the long wave length wind profiles.

Data from Cape Kennedy is preferred providing:

1. It is consistently recorded by personnel with standard training.
2. It is observed on a regular time interval for statistical significance.
3. The data is available over a long time interval preferably at least for 5 years.
4. The measured data points average 1000 feet or less.

The data from Montgomery, Alabama (Avidyne Corporation Tape III) meets the 4 preceeding requirements but was taken about 350 miles NW of Cape Kennedy. Considering the flat terrain between the two locations, the latitudes of Cape Kennedy and Montgomery, and the prevailing westerly winds during the winter months, it is felt that, until data from Cape Kennedy meets the four requirements mentioned above, the Montgomery data must be used for design purposes. The wind velocity and direction are recorded as a function of altitude with the individual wind soundings arranged in chronological order every third day for the months of December through February over a six year period.

The vehicle response is measured in terms of lateral and rotational accelerations and contributes to the encountered bending moments. In addition, the liquid propellant sloshing and aerodynamics create bending moments which must be accounted for. The hybrid system supplies this input data to MADCAP for bending moment calculations in both the pitch and yaw planes. In addition to the analog/digital system magnetic tape, MADCAP input data in card form are necessary and include aerodynamic bending moment coefficients as a function of Mach number and angle of attack, propellant sloshing bending moment coefficients as a function of liquid level in the tanks, structural bending moment coefficients, and bending moment experienced due to gusts. The resultant bending moment at each vehicle station analyzed was taken as the root-sum-square of the pitch and yaw bending moments.

4.3 COMPARISON OF STANDARD AND LOAD RELIEF AUTOPILOT RESULTS

The overall effectiveness of the load relief autopilot in reducing loads can easily be illustrated by histograms, Figure 7, of the maximum bending moment encountered during flight (at each station) with the standard autopilot and the load relief autopilot. Six flights for the standard autopilot were discarded as invalid runs during the data post processing. A large lowering of the mean value of bending moment and a reduction of skewness to the right is indicated when using the load relief autopilot. In most cases the upper limit encountered with the load relief autopilot is about the same as the mean value encountered with the standard autopilot. The maximum bending moment encountered with the load relief autopilot therefore is significantly less than the maximum encountered with the standard autopilot.

The launch availability was calculated by assuming that any flight that contains a calculated bending moment (at any station and time) which exceeded the limit allowable bending moment is not a successful flight. Figures 8 and 9 show the launch availability calculations for the load relief and the standard autopilots respectively. The overall launch availability using winter winds for the load relief autopilot is 63%; for the standard autopilot is 8.77%.

The critical stations are clearly shown on Figure 10 which in addition shows launch availability "sensitivity" to increase and decrease of limit allowable bending moments. The load relief autopilot launch availability ranges from 19.5% at 90% of limit allowable bending moment to 79% at 110%. This means that the desirable overall launch probability of 80% could be met with an increase of structural integrity to approximately 110% of nominal at SN 812 combined with the LRAP. The standard autopilot has a launch availability of 0.0 at 90% of limit allowable bending moment and increases to only 14.5% at 110%. The critical station for either autopilot is SN 812 and has approximately the same launch availability as the overall vehicle.

Figure 11 gives histograms of failure times for both the standard and load relief autopilot. These plots indicate the first time of failure at each station. The plot titled overall vehicle indicates first time of failure for any station for each flight.

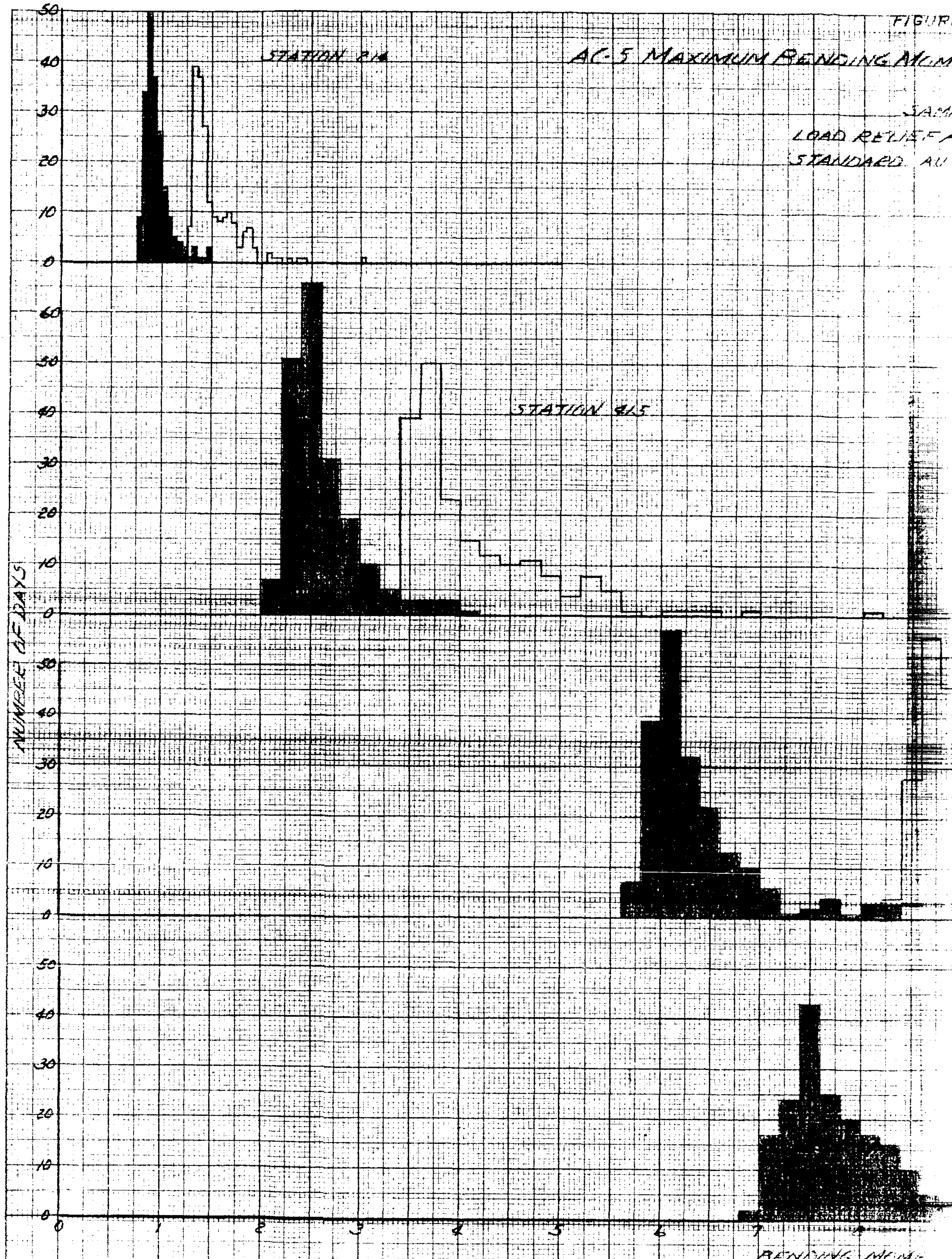
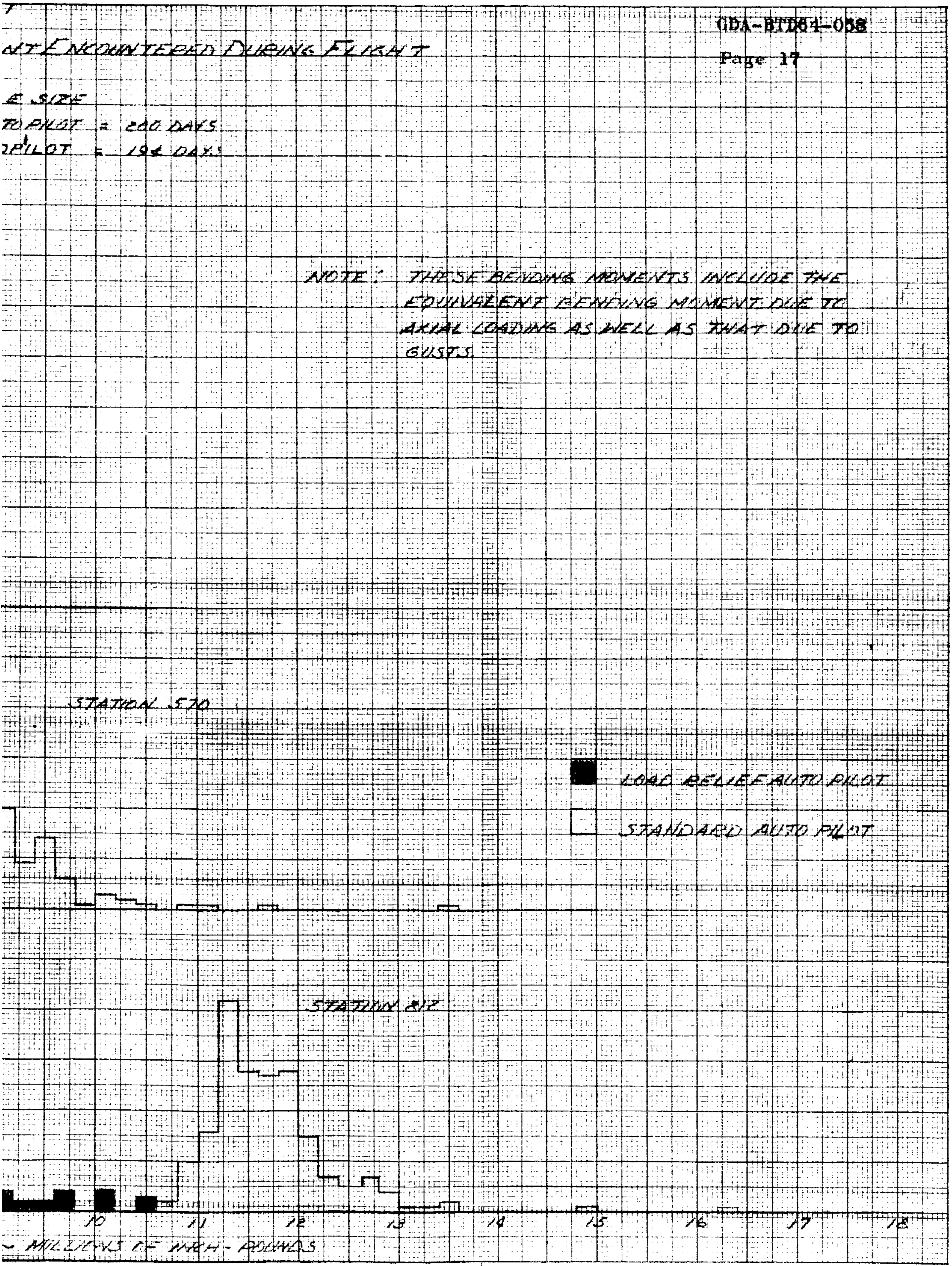


FIGURE
AC-5 MAXIMUM BENDING MOM
SAM
LOAD RELIEF A
STANDARD AUT
STATION 214
STATION 415
NUMBER OF DAYS
BENDING MOM
0
1
2
3
4
5
6
7
8
10
20
30
40
50
60


NT ENCOUNTERED DURING FLIGHT
E SIZE
TO PILOT = 200 DAYS
OPILOT = 194 DAYS
NOTE: THESE BENDING MOMENTS INCLUDE THE EQUIVALENT BENDING MOMENT DUE TO AXIAL LOADING AS WELL AS THAT DUE TO GUSTS.
STATION 570
LOAD RELIEF AUTO PILOT
STANDARD AUTO PILOT
STATION 812
10
11
12
13
14
15
16
17
18
– MILLIONS OF INCH - POUNDS

AC-5 LAUNCH AVAILABILITY - LOAD RELIEF AUTOPILOT

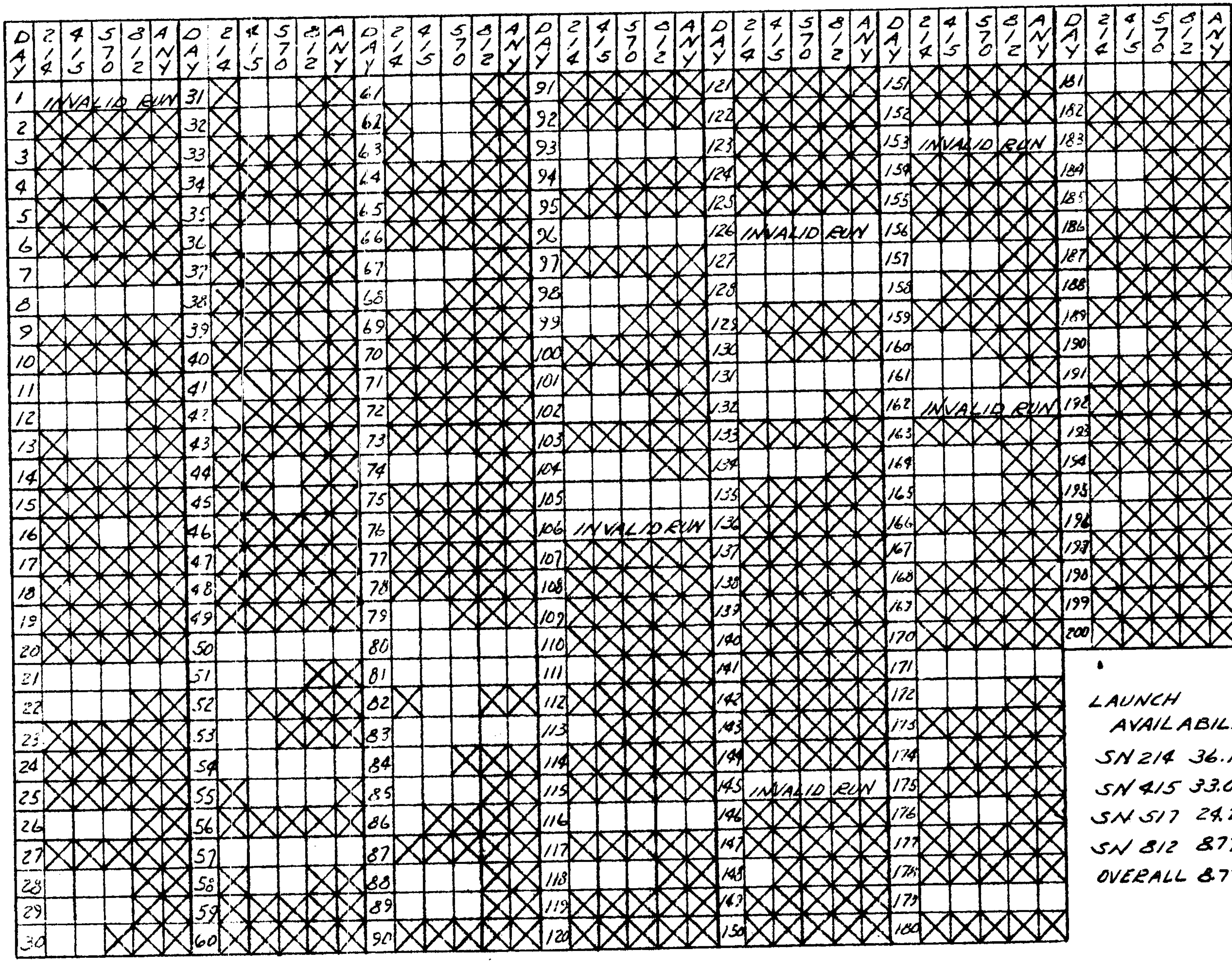
DAY	214	415	570	812	ANY
1					
2	X			X	X
3				X	X
4	X			X	X
5	X			X	X
6				X	X
7					
8					
9					
10					
11	X			X	X
12					
13					
14					
15	X			X	X
16	X			X	X
17	X			X	X
18					
19			X	X	X
20		X	X	X	X
21	X			X	X
22					
23					
24				X	X
25	X			X	X
26					
27				X	X
28					
29	X			X	X
30					
31				X	X
32					
33				X	X
34					
35					
36				X	X
37				X	X
38	X	X	X	X	X
39					
40					
41					
42					
43					
44					
45					
46				X	X
47					
48					
49					
50					
51				X	X
52	X				X
53					
54					
55					
56					
57					
58					
59					
60					
61					
62	X			X	X
63	X			X	X
64					
65				X	X
66	X			X	X
67					
68	X			X	X
69	X			X	X
70					
71	X			X	X
72				X	X
73				X	X
74					
75					
76					
77	X			X	X
78	X			X	X
79					
80				X	X
81					
82					
83				X	X
84				X	X
85					
86					
87					
88					
89					
90	X			X	X
91					
92	X			X	X
93					
94					
95					
96				X	X
97					
98					
99					
100					
101	X			X	X
102					
103	X			X	X
104					
105					
106					
107	X			X	X
108					
109					
110					
111					
112					
113					
114					
115				X	X
116					
117					
118					
119					
120					
121	X	X	X	X	X
122					
123				X	X
124		X	X	X	X
125	X			X	X
126	X			X	X
127	X			X	X
128					
129					
130					
131					
132					
133					
134					
135	X		X	X	X
136					
137	X			X	X
138					
139		X		X	X
140				X	X
141	X			X	X
142	X	X	X	X	X
143	X			X	X
144					
145	X			X	X
146					
147	X			X	X
148					
149				X	X
150	X	X	X	X	X
151				X	
152					
153					
154					
155				X	
156					
157					
158				X	
159				X	X
160					
161	X			X	X
162					
163			X	X	X
164					
165					
166					
167					
168					
169					
170	X	X	X	X	X
171					
172					
173					
174					
175					
176					
177					
178					
179					
180				X	X
181					
182	X		X	X	X
183					
184					
185					
186				X	X
187					
188					
189					
190					
191					
192		X	X	X	X
193	X			X	X
194					
195					
196					
197					
198	X	X	X	X	X
199				X	X
200					

LAUNCH AVAILABILITY

SN 214	79%
SN 415	95%
SN 570	92.5%
SN 812	63%
OVERALL	63%

FIGURE 8

AC-5 LAUNCH AVAILABILITY - STANDARD AUTOPILOT



LAUNCH AVAILABILITY

SN 214 36.1%

SN 415 33.0%

SN 517 24.2%

SN 812 8.77%

OVERALL 8.77%

FIGURE 9

AC-5 LAUNCH AVAILABILITY SENSITIVITY

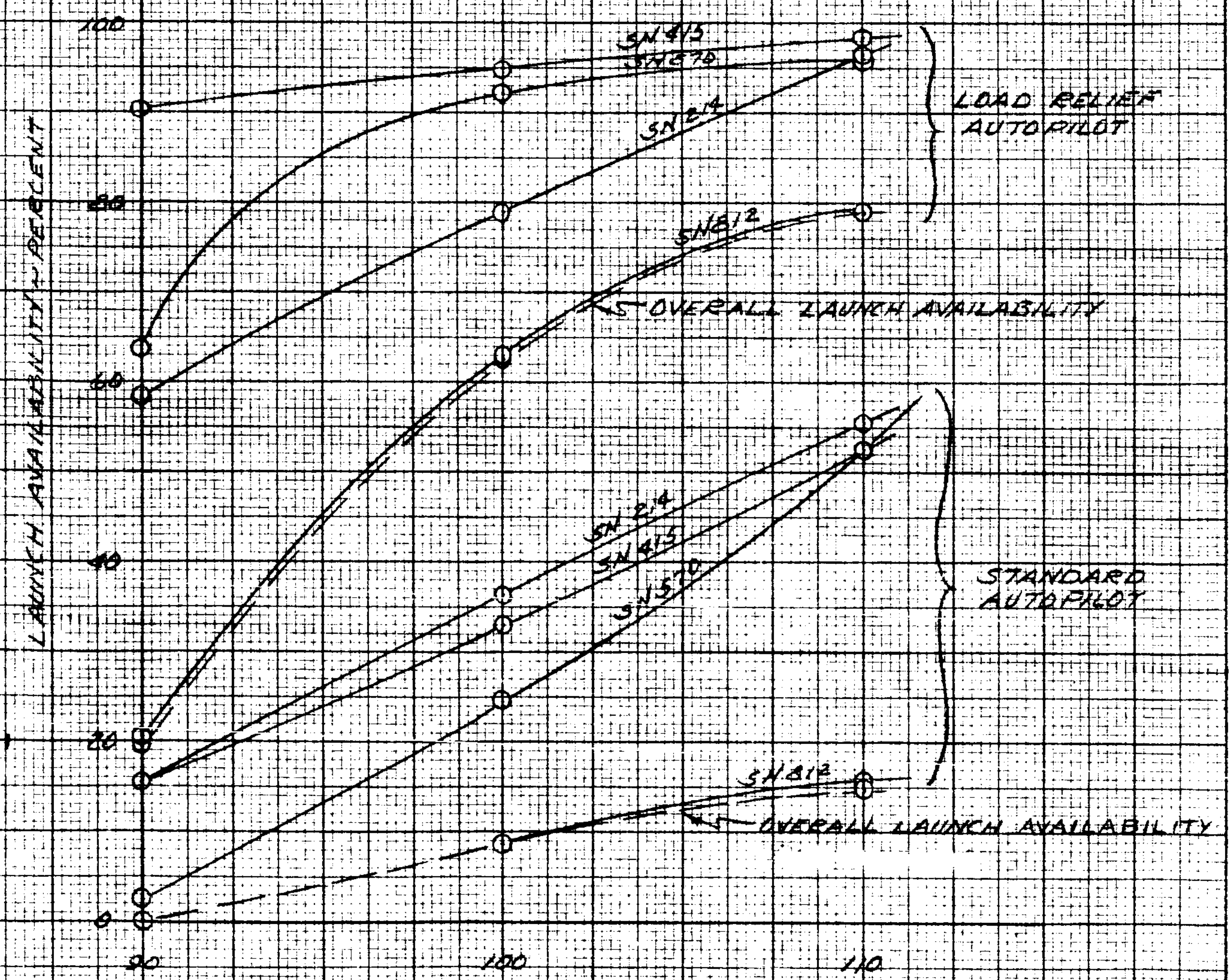


FIGURE 10

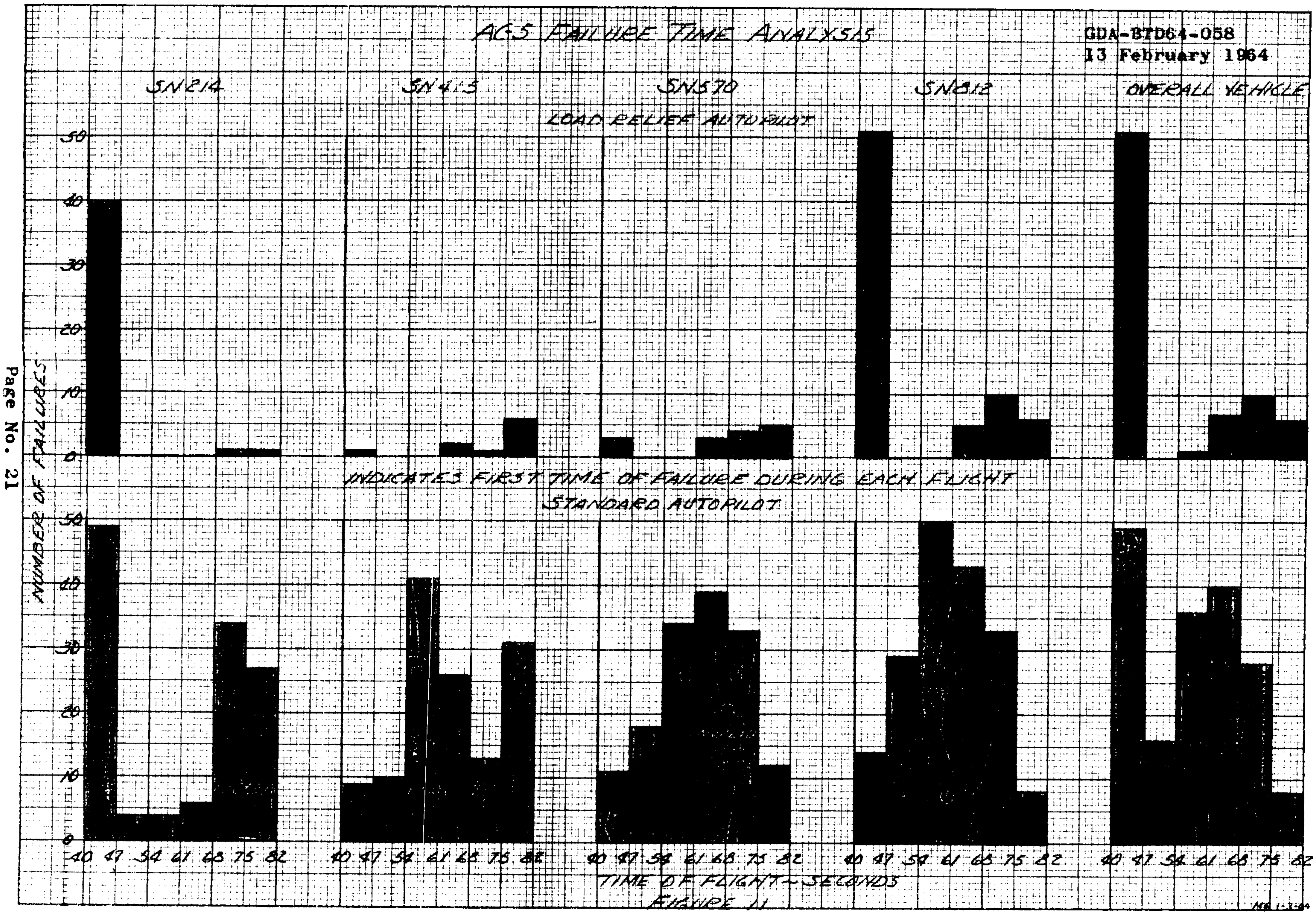

ACS FAILURE TIME ANALYSIS
SN214
SN415
SN570
SN812
OVERALL VEHICLE
LOAD RELIEF AUTOPILOT
INDICATES FIRST TIME OF FAILURE DURING EACH FLIGHT
STANDARD AUTOPILOT
NUMBER OF FAILURES
0
10
20
30
40
50
40 47 54 61 68 75 82
TIME OF FLIGHT – SECONDS

FIGURE 11

The standard autopilot overall vehicle plot on Figure 11 indicates that the two critical times are the maximum dynamic pressure region (as expected) and also the 40 to 47 second flight time segment. Looking at station 812 (the critical station) we see that the critical time is the maximum dynamic pressure region. Station 214 however is shown to be weak during the 40 to 47 second flight time regime.

The effectiveness of the load relief autopilot system is demonstrated by the reduction of failures during the maximum dynamic pressure region. The time segment from 40 to 47 seconds for stations 214 and 812 does not show this substantial decrease in failures and is therefore the critical time for the load relief autopilot. In addition, station 214 is critical with the standard autopilot for this same time segment.

A review of the mission sequence indicates that a step in the pitch program and the activation of the load relief autopilot occur simultaneously at 40 seconds. These events result in vehicle maneuvers that can increase angle of attack and hence can increase bending moments. For example, if the vehicle has negative angle of attack at 40 seconds, the load relief autopilot command in the form of a step adds to the pitch program step command.

Station 812, not critical at this early time for the standard autopilot, exhibits a majority of its failures for LRAP between 40 and 47 seconds. This indicates that in addition to increases in structural strength for increased launch availability, a possible benefit would be the activation of the load relief autopilot pressure sensor loop at a slightly earlier time in flight. An earlier initiation of the load relief loop would reduce the vehicle transients as they are a function of dynamic pressure times angle of attack.

4.4 COMPARISON OF THE ANALOG/DIGITAL METHOD (MADCAP) TO THE ALL DIGITAL METHOD (BEMO)

The analog/digital method of computation of bending moments and resulting launch availabilities produces noticeably different values when compared to the all digital method. The all digital method launch availabilities for the winter months were 45% for the standard autopilot and 80% for the load relief autopilot as shown in Reference 1. These results are higher in each case than those shown herein and the reasons for this difference are easily shown in the following discussion.

The major difference is the pitch program, both in philosophy and in method of application. The pitch program used in Reference 1 (all digital study) was an unbiased pitch program based on the Atlas/Centaur F-1 pitch program. This pitch program therefore provided a nominal aerodynamic load in a zero wind which would not exceed 1000 pounds up to 95 seconds of flight. This means the program was optimized to give an increase in the launch availability at the cost of performance. In addition, this pitch program was used as a continuous function as shown in Figure 12. The pitch program used in the analog/digital study can also be seen and is in the normal form as used in the actual flight article. This AC-5 pitch program represents the best available data at the time of the study and is primarily a heat limited performance trajectory with a positive angle of attack bias resulting in large vehicle bending moments for a no wind flight. The difference between these two trajectories can be seen by integrating the two curves. The result is that the AC-5 performance pitch program pitches the missile over further during the early phases of booster flight resulting in a lower, faster, (and higher performance) trajectory. This trajectory, while providing the necessary performance, allows the dynamic pressure to build up more rapidly and reach a higher maximum value resulting in larger bending moments.

A second difference is the number of samples run. The all digital study used 100 winds for the standard autopilot launch availability and 60 winds for the load relief autopilot launch availability. These numbers were determined by a statistical analysis of Atlas ranked winds. The high cost of digital computation precluded the use of the total sample of 200 Avidyne winter winds. The analog/digital method however used all 200 winds for the study due to the large saving of digital computer time through use of the multidegree analog simulation to provide the necessary trajectory and vehicle parameters.

An additional minor difference is the mathematical model used for each method. The vehicle dynamic quantities necessary for the determination of bending moments are discretely calculated in the digital method and do not include effects of such items as center of gravity offset and propellant sloshing. The analog method provides a continuous calculation of the dynamic quantities and therefore allows proper handling of non-linear effects caused by hydraulic actuators for engine positioning and liquid propellant anti-slosh baffles. Even more important is the proper coupling of the propellant sloshing modes with the rigid body control modes in both pitch and yaw. This coupling, found only in the analog method, allows the vehicle to oscillate with its proper angular acceleration which directly influences calculated bending moments.

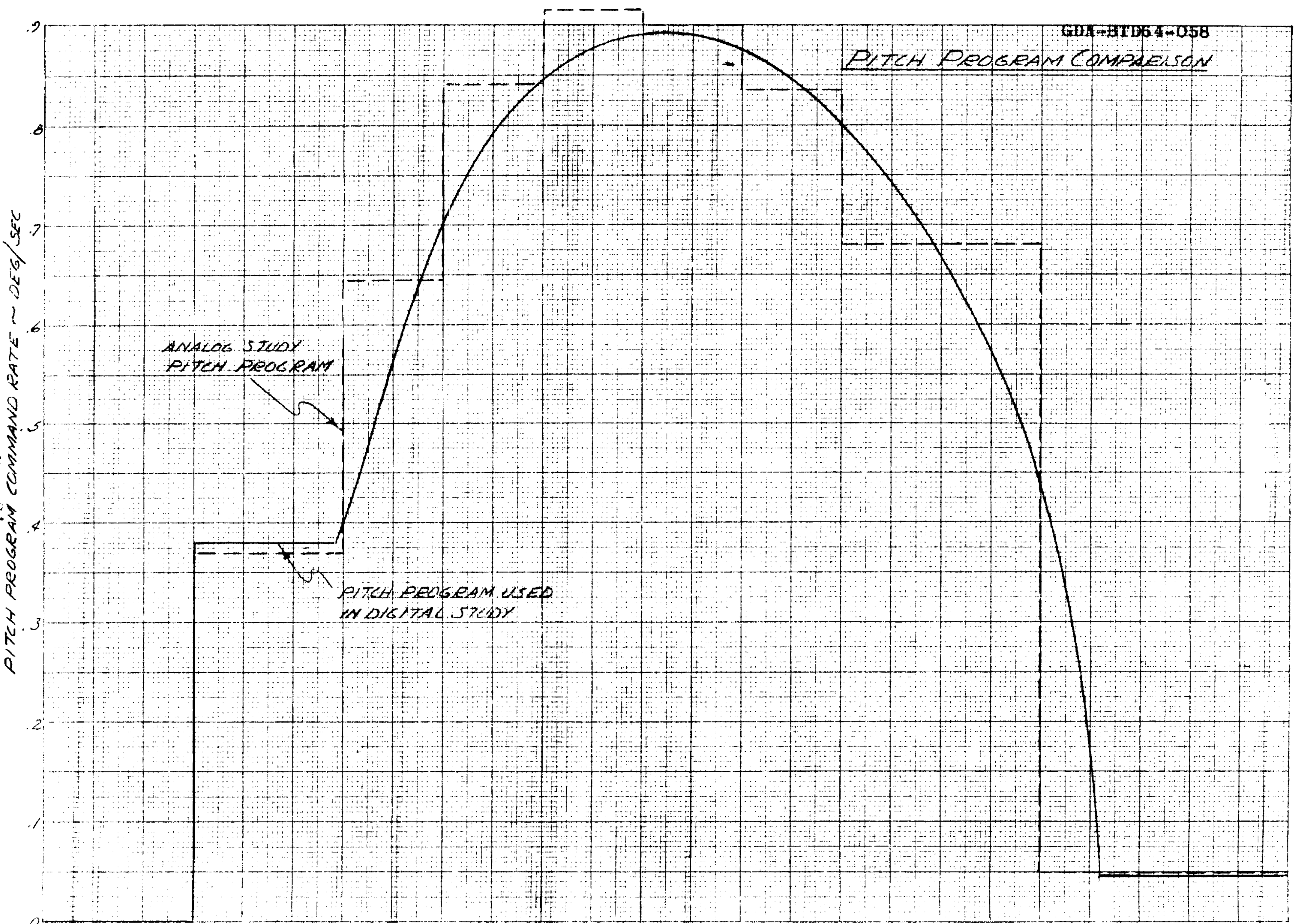

PITCH PROGRAM COMPARISON
ANALOG STUDY PITCH PROGRAM
PITCH PROGRAM USED IN DIGITAL STUDY
PITCH PROGRAM COMMAND RATE ~ DEG/SEC
FLIGHT TIME ~ SEC
0
.1
.2
.3
.4
.5
.6
.7
.8
.9
10
20
30
40
50
60
70
80
90
100
110
120

FIGURE 12

Section 5

TRAJECTORY ANALYSIS

The AC-5 trajectory used in this study is a direct ascent lunar mission with the basic philosophy of injecting the vehicle into a trans-lunar ellipse with a given energy, such that the position and velocity at injection result in achieving the desired target vector. The launch availability analysis is concerned with the trajectory during booster phase.

Booster phase of the trajectory consists of an unguided boost for approximately 110 seconds using predetermined pitch rates. At 110 seconds the guidance input is switched into the autopilot error channel replacing the position gyro signal. This allows any dispersions from the nominal trajectory to be minimized. If there were no restrictions on the maneuvers which the missile can make during the powered flight, the guidance and control would be relatively simple and the major problem would be that of precision in guidance. However, the structural limitations due to loading and heating, and flight performance requirements will combine to restrict the trajectory such that only limited correction maneuvers may be employed.

The performance philosophy utilized during booster phase is based upon providing a lofted trajectory while meeting vehicle dynamic and aeroheating constraints. The method used for the trajectory studied was to approximate a zero lift flight path (slight positive angle of attack) until 100 seconds at which time a large positive angle of attack is commanded. This angle of attack causes vehicle lift but is unacceptable at booster staging. Therefore at booster engine cut-off minus 10 seconds the guidance commands a zero angle of attack which minimizes aerodynamic disturbances to the control system during staging. Details of guidance and trajectory philosophy are located in Reference 1.

The pitch program used in this study for the nominal no wind trajectory during booster phase was shown in Figure 12. This provides a preliminary performance trajectory which does not satisfy dynamic constraints. The pitch program must therefore be changed but will be based on the same philosophy. As it now stands, the pitch program does provide a nominal trajectory to use for autopilot performance comparison.

Dispersions from the nominal trajectory can be seen in Figures 13, 14 and 15. These histograms show velocity, altitude and flight path angle with and without the load relief loop. A comparison of the altitude histograms shows a much wider dispersion from the mean due to the load relief loop. This is to be expected as the load relief autopilot tends to follow a new zero lift trajectory dependent upon the particular wind. Also, the load relief autopilot distribution has a mean to the right or towards higher altitude when compared to the conventional autopilot. This is due to the predominance of tail winds in the set of Avidyne winter winds and also the lofted load relief autopilot trajectory due to the slight positive angle of attack of the nominal no wind trajectory (as provided by the pitch program).

Similar increased dispersions with the load relief autopilot exist for velocity and flight path angle. The mean value of the flight path angle is also greater with the load relief autopilot but the velocity is reduced because of this higher trajectory.

These dispersions would be reduced starting at 110 seconds when guidance commands would revise the nominal trajectory to meet the mission requirements. Guidance equipment could handle the dispersions around the mean value but structural and aero heating limitations would have to be observed. A pitch program for use with the load relief autopilot could be used to shift the mean values of the trajectory parameters closer to those of the nominal conventional autopilot trajectory. Use of a pitch program tailored to the load relief autopilot and guidance beginning at 110 seconds will allow reduction of dispersions and result in more efficient vehicle from the performance viewpoint.

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15 February 1964

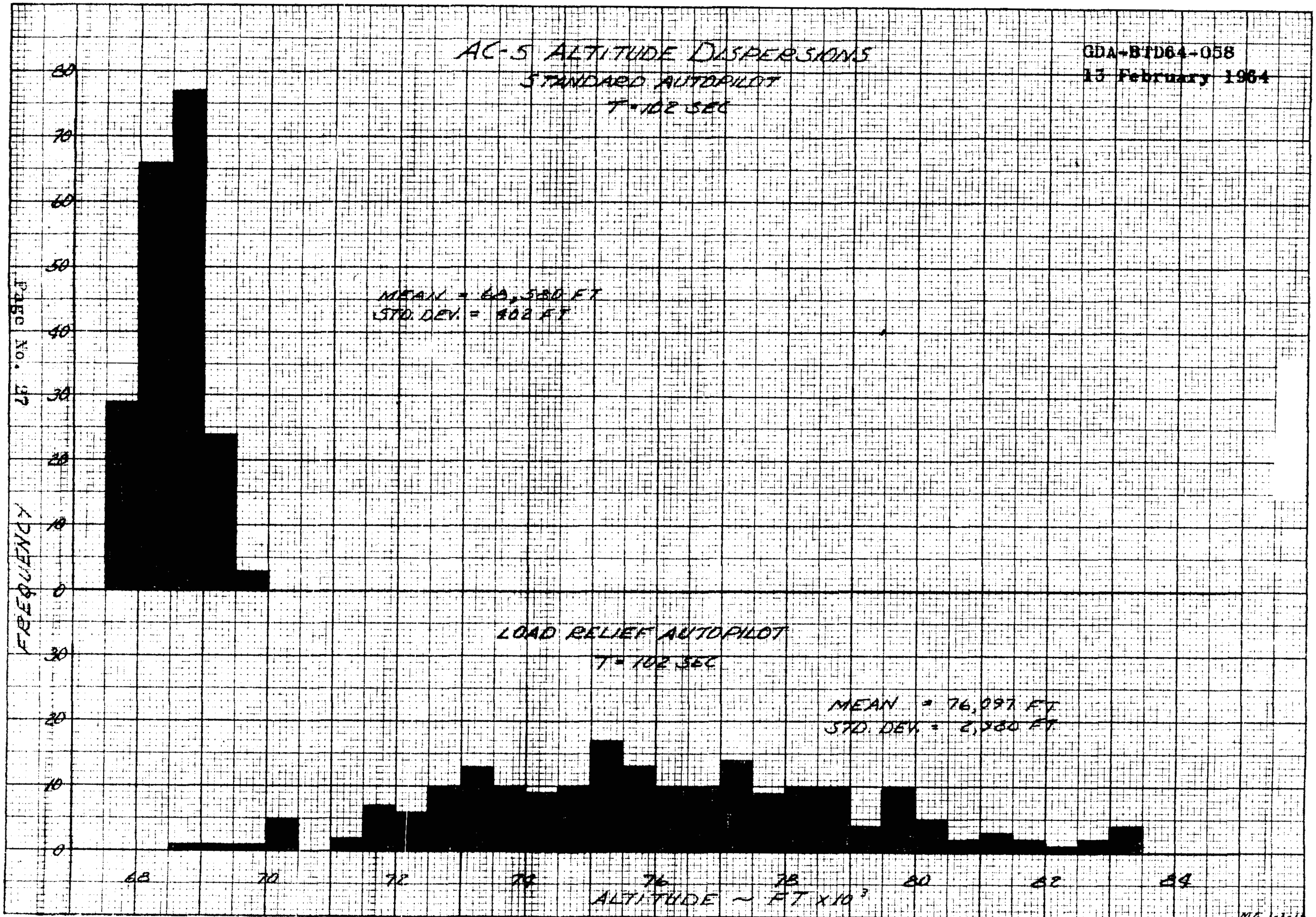

FIGURE 13

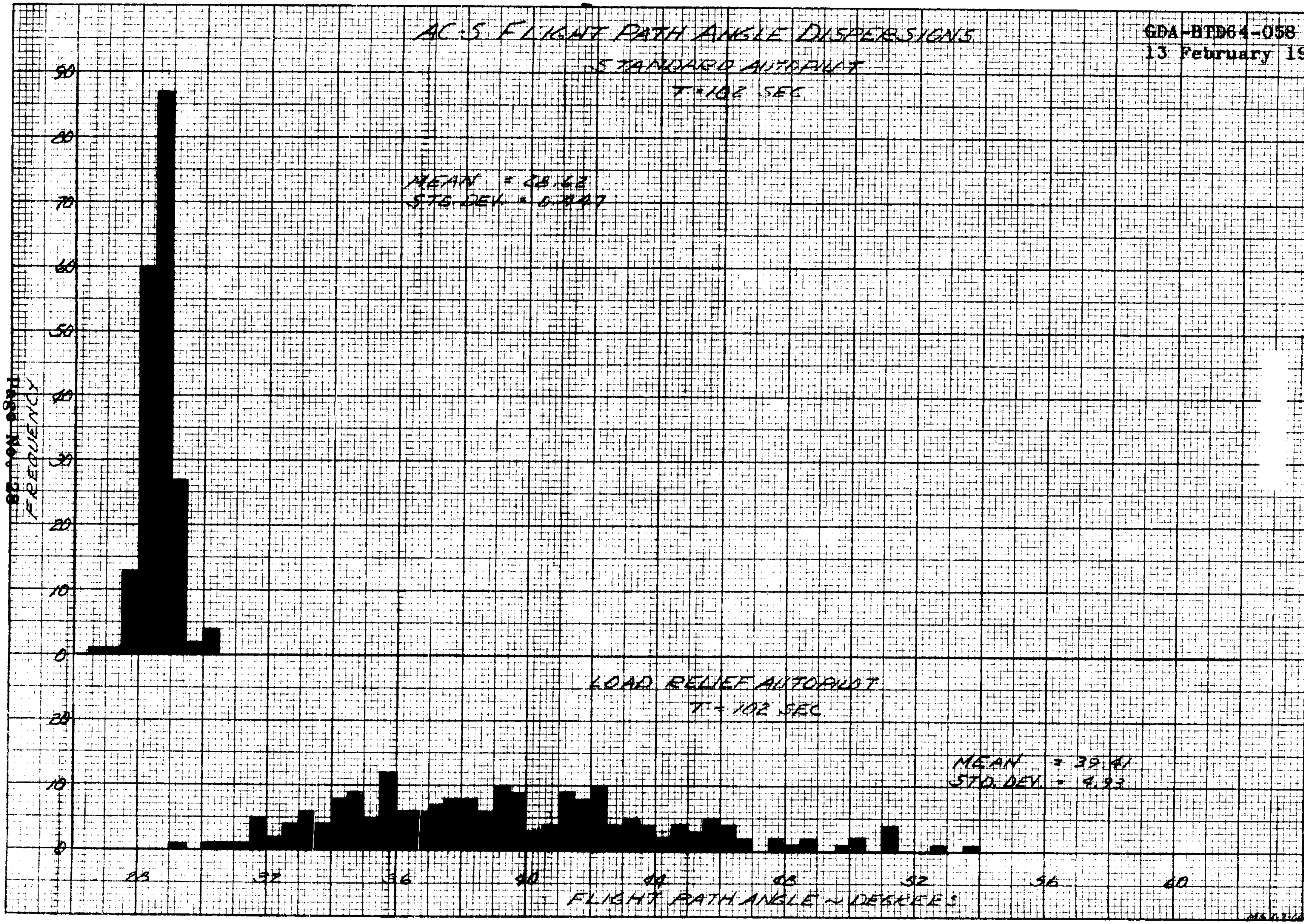
AC-5 FLIGHT PATH ANGLE DISPERSIONS
STANDARD AUTOPILOT
T = 102 SEC
MEAN = 28.62
STD. DEV.
LOAD RELIEF AUTOPILOT
T = 102 SEC
MEAN = 39.41
STD. DEV. = 4.93
FREQUENCY
0
10
20
30
40
50
60
70
80
90
28
32
36
40
44
48
52
56
60
FLIGHT PATH ANGLE ~ DEGREES

FIGURE 14

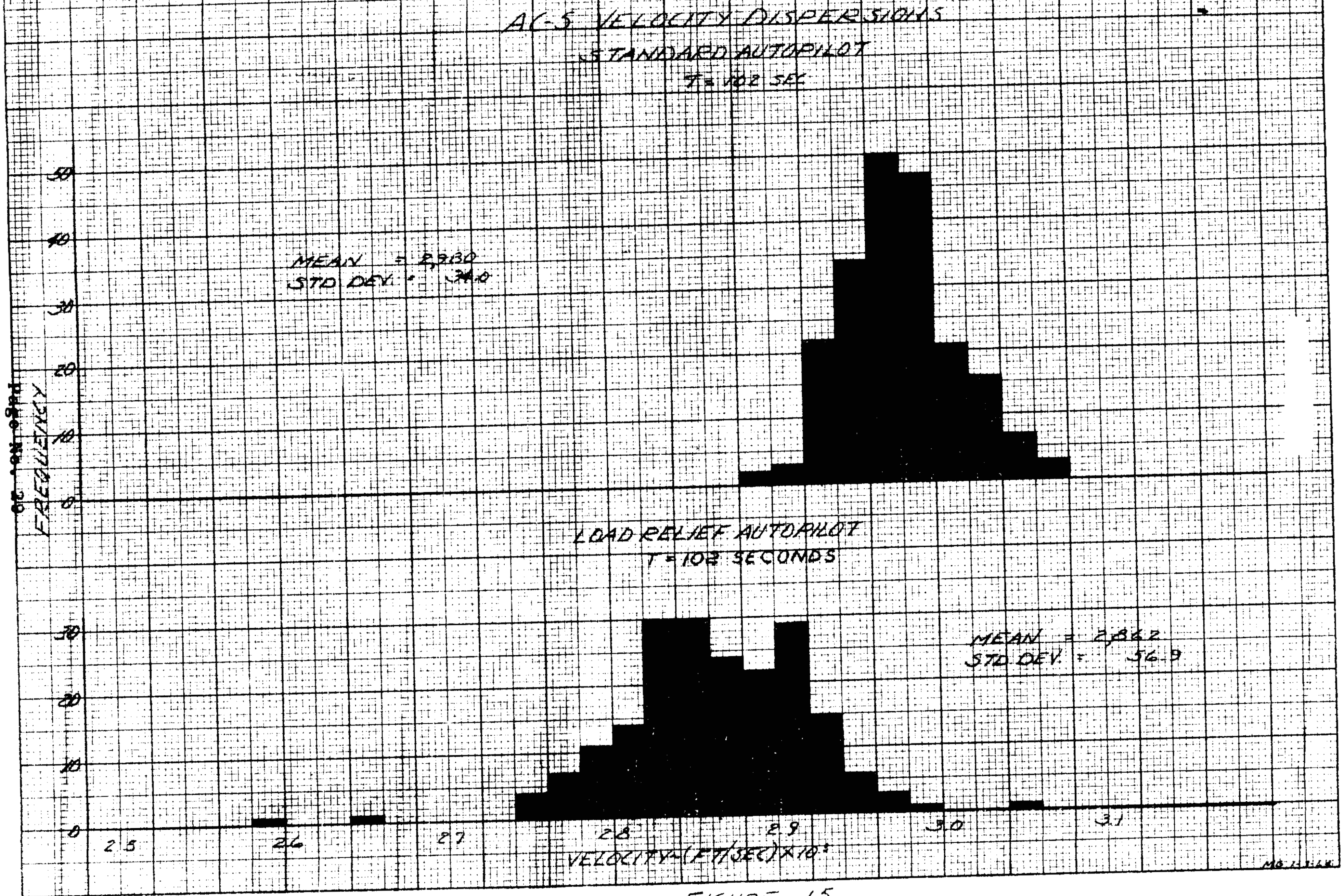
AC-5 VELOCITY DISPERSIONS
STANDARD AUTOPILOT
T = 102 SEC
MEAN = 2,930
STD DEV = 34.0
LOAD RELIEF AUTOPILOT
T = 102 SECONDS
MEAN = 2,862
STD DEV = 56.9
FREQUENCY
0
10
20
30
40
50
2.5
2.6
2.7
2.8
2.9
3.0
3.1
VELOCITY-(FT/SEC)X10³

FIGURE 15

Section 6

CONCLUSIONS:

1. The load relief autopilot provides adequate stability and control throughout the launch vehicle phase of the Atlas/Centaur AC-5 powered flight (see Reference 1).

2. The analog/digital system provides the necessary repeatability and accuracy at less cost than the equivalent study using all digital techniques.

3. The load relief autopilot provides a large reduction of the maximum encountered bending moment at all stations when compared to the standard autopilot.

4. The launch availability based on a sample of 200 Avidyne winter winds for the load relief autopilot is 63%, and based on a sample of 194 winter winds for the standard autopilot is 8.77%.

5. A 10% increase in allowable bending moment at station 812, the critical station, would raise the launch availability to 79% for the load relief autopilot and 14.3% for the standard autopilot.

6. The critical times for the standard autopilot are the 40 to 47 second region and the maximum dynamic pressure region. The load relief autopilot is most effective during the maximum dynamic pressure region and hence only the 40 to 47 second region remains critical.

7. The differences in the results of this study and the one contained in Reference 1 can be mainly attributed to the difference in both the philosophy and method of application of the pitch programs used. Also effecting the results were the differences in the wind sample size, and the different vehicle mathematical models used.

8. The trajectory dispersions associated with the load relief autopilot are much greater than those associated with the standard autopilot and result in a loss of performance.

9. Further studies in the area should include determination of an optimized sequence of events (pitch program, load relief loop activation, guidance activation) and also launch availability, aeroheating, and performance trade off studies between the load relief autopilot and pure increases in structural integrity.

Section 7

REFERENCES

1. "Atlas/Centaur Load Reduction Autopilot System Study", R. L. Holt, R. F. Ringland, L. G. Wilson, GD/A63-0554, 12 August 1963 (Confidential), Addendum to be published.

2. "Multidegree Analog Simulation Operation Handbook", K. Nelson, GDA63-0573, 13 September 1963, (Review copy).

3. Atlas/Centaur AC-5 Green Door, GD/A 7094 Digital Program #2520, 25 June 1963.

4. "Analog Simulation of a Multidegree-of-freedom Space Boost Vehicle", K. Nelson, GD/A-DDE64-001, 31 January 1964, (Review copy).