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RIDE QUALITIES CRITERIA VALIDATION/PILOT PERFORMANCE STUDY — FLIGHT TEST RESULTS

Louis U. Nardi, Harry Y. Kawana,
and David C. Greek

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TABLE OF CONTENTS

	Page
SUMMARY	1
INTRODUCTION	3
SYMBOLS	4
Airframe	4
Display System	5
Miscellaneous	5
B-1 FLIGHT TEST PROGRAM	7
B-1 Aircraft Development	7
B-1 Flight Test Plans	8
Turbulence	8
Aircraft Systems	9
Terrain Route Selection	9
Flight Test Conditions	9
Test Subjects	10
DATA ANALYSIS	11
Identification of Performance Parameters	11
System and Environmental Conditions	12
Differences in Aircraft Response and Environmental Parameters Existing Between Flight Test and Earlier Simulator Tests	15
FLIGHT TEST PERFORMANCE RESULTS	16
Performance with SMCS On and Off	16
Performance During Long Duration Mission Runs	18
COMPARISON OF FLIGHT (PHASE II) WITH SIMULATOR (PHASE I) RESULTS	20
Test Condition Differences	20
Results where General Concurrence was Obtained	21
Results where Differences were Noted	21
Comments on Previously Identified Parameters	22
Comment on Display Steering Sensitivity	22

	Page
SUMMARY OF SIGNIFICANT FINDINGS	24
CONCLUSIONS	26
APPENDIX A PILOT RATING SCALES	27
APPENDIX B RIDE DISCOMFORT INDEX SCALE	30
REFERENCES	31

LIST OF ILLUSTRATIONS

Figure	Title	Page
1	MTF/pilot control loop block diagram.	41
2	Map of TR-368 and TR-391/360/385 routes	42
3	Terrain profiles over short- and long-duration routes	43
4	Measured accelerations at pilot seat versus estimated turbulence - SMCS on from run sets 2 and 3.	44
5	Measured accelerations at pilot seat versus estimated turbulence - SMCS off from run set 2.	45
6	PSD of vertical and lateral accelerations at pilot station - SMCS off, ocean	46
7	PSD of vertical and lateral accelerations at pilot station - SMCS on, ocean.	47
8	PSD of vertical and lateral accelerations at pilot station - SMCS off, terrain segment B1.	48
9	PSD of vertical and lateral accelerations at pilot station - SMCS on, terrain segment B1	49
10	Pilot seat vertical acceleration versus normal acceleration at CG.	50
11	Correlation of terrain and estimated turbulence level	51
12	TF performance comparison between MTF and ATF over TR-368 significant terrain peaks.	52
13	Pilot ratings versus $\sigma_{w_g \bar{H}_z}$ for SMCS on and off conditions . .	53
14	$n_{Z_{PS}}$ and X_θ time history traces and $\Phi_{n_{Z_{PS}}}$ plot-flight 3-71 MTF/SMCS on and off.	54
15	Pilot ratings versus $\sigma_{n_{Z_{PS}} f_1}$ for SMCS on and off conditions.	55
16	Standard deviation of Δh, horizontal bar and stick displacement versus terrain segment No.	56
17	TF performance comparison between MTF and ATF over TR-391/360/385 significant terrain peaks.	57
18	Pilot ratings versus exposure time for long duration - run set 3	58
19	Typical time history traces of horizontal bar and stick displacement.	59
20	TF performance versus maneuver load	60
21	Pilot tracking performance versus maneuver load	61
22	TF and pilot performance measures versus VSD gain sensitivities - run set 1	62

LIST OF TABLES

Table	Title	Page
I	Summary of Flight Test Conditions Analyzed	32
II	Flight Test Parameters Recorded and Reduced for Data Analysis	33
III	Ride Quality Index Comparisons	34
IV	Identification of Segment Number and Terrain Classification	36
V	Summary of Run Set 2 Data	37
VI	Summary of Run Set 3 Data - Flight 3-68, MTF/SMCS on Subject F	38
VII	Summary of Run Set 3 Data - Flight 3-74, MTF/SMCS on Subject G	39
VIII	Summary of Run Set 4 Data - Flight 3-76, ATF/SMCS on	40

RIDE QUALITIES CRITERIA VALIDATION/PILOT PERFORMANCE STUDY - FLIGHT TEST RESULTS

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SUMMARY

This report presents the results of a research contract to study pilot performance during terrain-following (TF) flight for ride quality criteria validation with the following specific study objectives:

(1) Develop improved ride qualities criteria for general use in the design of large, flexible aircraft with initial emphasis on low-altitude high-speed flight.

(2) Determine first-order interactions between ride, handling, and display qualities and their effects on pilot/vehicle performance during severe turbulence penetrations.

(3) Compare simulator test results with flight-test results to determine to what extent flight performance can be predicted from performance measured in current simulators.

The results from the B-1 flight test program and an earlier research contract (ref. 1) which used flight simulation data provided the data base for these investigations.

The ride quality design criteria for the B-1 includes requirements for both aircraft response to gusts and flexible mode response to control excitation as specified by the Air Force. The B-1 ride quality specification, formulated by J. Rustenburg, was derived from four documents (ref. 2, 3, 4, and 5). These documents specify the mathematical techniques for determining human response to vibration and subsequent aircraft response to gust. The B-1 with the structural mode control system (SMCS) on meets these requirements and with SMCS off does not meet the requirements. Data from manual and automatic TF operations conducted during low level penetrations for short durations (approximately 25 minutes) at four conditions with SMCS on and off and for long duration (approximately 65 minutes) with SMCS on were analyzed.

The performance measures considered included TF performance parameters, pilot/aircraft performance parameters, and subjective assessments by the pilot. The motion and vibration level, maneuver spectrum, display and control system dynamics, and task loading were monitored to define the environmental conditions and system parameters.

The results of the data analysis confirm earlier qualitative evaluations that the B-1 ride qualities with SMCS on are satisfactory for the long-duration low-level penetration in turbulence. The results indicate that satisfactory TF was accomplished for all of the conditions tested and no significant deterioration of TF performance was measured with SMCS off as compared to SMCS on for short durations. The subjective comments with SMCS off were less favorable as compared to SMCS on and were consistent with previous subjective comments in the B-1 program, to the effect that the SMCS is required for satisfactory crew effectiveness in the long-duration mission. The results highlight some of the first-order interactions between ride, handling, and display qualities and illustrate the importance of both gust response and excitation of bending modes by control motions in acceptable ride quality specification.

Accomplishment of automatic terrain-following (ATF) and manual terrain-following (MTF) during B-1 low-level penetration to date has provided partial validation of the B-1 ride quality criteria. The flight evaluations conducted have not included unsatisfactory conditions for determination of conditions in excess of the criteria. The turbulence encountered in flight has not been high enough to be representative of limiting conditions, and the structural excitation due to control motions of the B-1 aircraft, is not severe enough to permit assessment of the criteria as limits (an aircraft outside of the limits is unsatisfactory).

Additional test data in higher turbulence levels and TF evaluations for long-duration penetrations with SMCS off are necessary for more complete criteria validation.

INTRODUCTION

The low-altitude, high-speed (LAHS) flight environment poses potentially serious ride quality problems for accomplishment of long-duration missions. The persistent threat in flying LAHS demands intense concentration by the pilot. Associated cockpit duties compound the task loading. The aircraft is subjected to motions caused by turbulence and to maneuver loads imposed by TF. These motions can cause problems of inadvertent stick inputs, pilot-induced oscillations, difficulty in reading instruments, pilot fatigue, and body discomfort. These factors tend to reduce the pilot's ability to fly the mission with precision.

Aircraft handling and ride qualities in LAHS flight have been extensively studied and reported in the literature. However, very little data are available for prediction of acceptability or performance capability during exposure to multiaxis vibration conditions in the LAHS environment. Ride quality criteria have been developed based upon available data, and these criteria are being used for current aircraft, including the B-1. The development of these criteria is presented in ref. 4, but the criteria have not been validated in any current application.

The B-1 program provides a contemporary application of ride quality design for potential validation of the criteria. Both simulation and actual flight tests are being accomplished in the B-1 program to demonstrate performance capability in the low-altitude, high-speed environment.

This study covers the second and third phases of the three-phase B-1 Ride Quality Criteria Validation/Pilot Performance study by Rockwell International (Rockwell) and NASA. The second phase covers the analyses of pilot performance and ride qualities data obtained from B-1 flight tests, and the third phase covers the correlation of flight test data with simulation data. The phase 1 study effort was completed by Rockwell and NASA in March 1976 (ref. 1) and covered the analyses of the data obtained from the B-1 flight simulation tests.

SYMBOLS

Airframe

cg	Center of gravity
Fs	Pilot-applied stick force
g	Acceleration of gravity
Δh	Clearance altitude (aircraft minus terrain)
Δh_e	Clearance altitude minus desired set clearance
Mn	Mach number
$n_{y_{cg}}$, $n_{z_{cg}}$	Acceleration at aircraft cg along Y,Z body axes
$n_{y_{ps}}$, $n_{z_{ps}}$	Acceleration at pilot station along Y,Z body axes
$\left(\sigma_{\Delta n_{z_{ps}}}\right)_{f = f_1}$	Standard deviation of acceleration at pilot station evaluated at first fuselage mode specific frequency
w_g, v_g	Vertical and lateral gust velocity components
Y,Z	Vehicle body axes
X_θ, X_ϕ	Pitch and roll stick displacements
γ	Flight path angle
Λ	Wing leading edge sweep angle
ζ_{sp}	Longitudinal short-period damping ratio
ζ_d	Dutch roll damping ratio

ω_n	Undamped longitudinal short-period frequency
ω_d	Undamped Dutch roll natural frequency
σ_{turb}	Turbulence level in m/sec rms = $\sqrt{\sigma_{w_g}^2 + \sigma_{v_g}^2}$
δ_H	Horizontal tail control surface deflection
δ_{R_U}	Upper rudder control surface deflection
δ_{R_L}	Lower rudder control surface deflection
$\delta_{CV_{\theta_c}}$	Symmetric SMCS vane command
$\delta_{CV_{\phi_c}}$	Asymmetric SMCS vane command
	Display System
g_c	TF normal acceleration (g) command
$g_{feedback}$	Display feedback (g)
Horiz Bar	Pitch display error into VSD proportional to $(g_c - g_{feedback})$
Vert Bar	Roll display error into VSD proportional to $(\phi_c - \phi)$
ϕ_c	Roll angle command
	Miscellaneous
$\bar{A}_z$, $\bar{A}_y$	Vertical and lateral gust sensitivities
$\bar{H}_z$, $\bar{H}_y$	Vertical and lateral crew sensitivity indexes
rms	Root mean square
S	LaPlace variable
t	Time

T_D	Human frequency response function
K	System gain
Δ	Incremental value
f	Frequency
Φ	Power spectral density
Σ	Summation
σ	Standard deviation
$\sigma_{D_{\delta_H}}$	RMS discomfort index due to control surface excitation
$\sigma_{wg}\bar{H}_z$	Ride quality discomfort index
τ	Time constant

B-1 FLIGHT TEST PROGRAM

B-1 ride quality and terrain-following performance evaluation described herein was planned and conducted as part of the Air Force/Rockwell B-1 flight test program to demonstrate B-1 penetrativity, and to perform technology research in the areas of B-1 handling qualities, ride qualities, and TF performance for the low-altitude, high speed mission environment.

B-1 Aircraft Development

Of the first three B-1 aircraft, only aircraft 3 is equipped with TF capability and assigned the major TF demonstration objectives. The B-1 possesses a number of significant structural modes and unique dynamic response characteristics. These characteristics result in response to turbulence and control inputs which can provide an important data base in the study of ride quality criteria validation. The ride quality criteria or requirements were specified for the B-1 to provide satisfactory ride during the long-duration TF penetration condition.

The ride quality criteria include both a limit on the crew station response to turbulence, and a limit on the excitation of structural modes at the crew station due to TF control motions. The specific formulation of the requirement includes a human transfer function in addition to aircraft response.

The B-1 variable geometry configuration provides reduced vehicle gust response for the penetration condition. In addition, because of the flexible response of the aircraft, SMCS was provided in order to meet ride quality requirements. Use of the SMCS results in reduced response at the crew station, whether due to turbulence or control-induced motions primarily through the increase in damping of the significant fuselage bending modes. The manual and automatic flight control systems include a prefilter design feature which reduces adverse excitation of bending modes due to control motions, without serious reduction of TF maneuvering response capability.

TF has been a primary objective of the B-1 flight test program. The ATF system has been developed during the flight test program as part of low-level penetration demonstrations. ATF and combined ATF auto/navigation have been successfully demonstrated. The MTF system has been developed as a backup capability to ATF to enhance mission completion.

B-1 Flight-Test Plans

At the time of recent redirection of the B-1 research, development, test and evaluation (RDT&E) program, a series of selected MTF runs was incorporated into the B-1 flight test program to further evaluate ride quality and to further develop MTF control system requirements. The impact of the LAHS environment and mission duration on performance during TF flight was to be determined. This phase of the flight test program included ATF/MTF flights over a standard route (TR 368) with SMCS on and off at flight conditions representative of the B-1 TF envelope, and ATF/MTF flights over a long-duration composite route (TR 391/360/385) at a penetration condition. Air Force and Rockwell pilots flew these missions. With this test program accomplished, a data base for criteria evaluation was available. Validation of criteria and determination of pilot performance based upon analysis of the data from this phase of the test program was the primary objective of phase 2 of this contract effort.

These MTF and ATF runs for both short- and long-time periods provide data for measurement of system performance in this environment.

The control tasks defined for the pilots in MTF flight were as follows: perform the blind letdown to the set clearance altitude (122 meters above ground), trim the aircraft, and perform maneuvers as directed by pitch channel TF and roll channel navigation commands displayed on the vertical situation display (VSD) steering cross while maintaining the desired mach number. In addition, the pilot was required to monitor the system response and performance with information from the radar altimeter, the E-scope display, audio climb/dive tones, and other flight instrumentations. High fidelity onboard recording instruments along with crew comments provided the data base for this study.

Turbulence

The atmospheric turbulence encountered in the TF runs conducted to date was rated as being "light" to "moderate" with maximum turbulence intensity estimated at approximately 1.4 meters per second rms. For a more in-depth evaluation of ride quality criteria limits, a larger number of TF runs would have been desirable under more intense turbulence conditions.

Aircraft Systems

A description of the B-1 control systems (e.g., automatic flight control system (AFCS), stability control augmentation system (SCAS), SMCS, and the terrain-following radar (TFR) system) are presented in ref. 1 which covers the results of the previous flight simulation tests. The MTF/pilot control loop block diagram, which shows the control/display parameters used in the simulation and flight test program, is shown in figure 1.

Terrain Route Selection

The B-1 test program was defined to evaluate ride qualities during B-1 penetrations over a wide range of conditions. Two types of test runs from those accomplished in the current B-1 flight test program were selected for data analyses: (1) short runs of approximately 490 km length of continuous TF flight, and (2) relatively long-duration runs of approximately 1,100 km of continuous TF flight. The short-run route, known as TR-368, is representative of mild to moderate terrain, which starts north of Lake Arrowhead and concludes before the Salton Sea of Southern California. The long route, known as TR-391/360/385, is composed of ocean, flat, mild, moderate, and rugged terrain segments. The long route starts over the Pacific Ocean, flies over the eastern edge of Sierra Nevada and ends approximately 46 km east of Edwards AFB. Figure 2 shows the route map of TR-368 and TR-391/360/385. Figure 3 shows the in-route terrain features and altitude profile, along with route segment designations and significant terrain peaks referred to in later data analysis measurements. Each terrain segment designated is 2 minutes in actual flying time. The instrumentation recorded data over these segments were processed into statistical format for data analysis correlations. These segments were selected to provide various terrain composition and pitch/roll maneuver combinations.

Flight Test Conditions

The test conditions selected for this analysis are shown in table I. Run sets 1 and 2 are short-duration runs over TR-368, and run sets 3 and 4 are long-duration over TR-391/360/385. Run set 1 provides MTF flight evaluation variations in the tracking task with three different VSD gain sensitivities (see figure 1) with SMCS on. Run set 2 provides data for MTF evaluation at various aircraft weight/flight conditions with the SMCS both on and off. Run set 3 provides additional data to evaluate the pilot's ability to conduct MTF operations for longer duration (approximately 60 minutes of time) at the penetration condition with SMCS on. Run set 4 is an ATF baseline data, with the

SMCS on and off over TR-368 and with the SMCS on over TR-391/360/385, to provide a comparison with MTF runs. The instrumented parameters used in data analysis are listed in table II.

Test Subjects

All of the test pilots who participated in this flight test evaluation were current B-1 flight test pilots. Five test pilots (listed as A, B, C, D, E in table I) flew the short-duration runs, and two additional pilots (F and G) flew the B-1 for the long-duration runs. The pilots' B-1 experience ranged from 1 to 14 previous terrain following flights.

DATA ANALYSIS

The performance measures used in the data analysis included TF performance parameters, pilot/aircraft performance parameters, and qualitative assessments by the flight crew. The environmental parameters included the aircraft g motions, system characteristics, and task loading associated with MTF mission. Data reduction to provide quantitative measures of the pilot performance, system performance, and aircraft "g" motions were obtained from a frequency analysis program (ref. 6) which provides: (1) mean, (2) standard deviation, (3) power spectral density, and (4) frequency response (gain and phase estimates of a pair of time-related parameters) from digitized data tapes.

Identification of Performance Parameters

TF Performance. - The primary measures of the TF performance are the standard deviation, mean, and power spectral density of the clearance altitude of the aircraft above terrain, Δh. In addition, the aircraft altitude deviation from the set clearance altitude, Δh_e, and flight path angle over the prominent peaks (see figure 3) were measured from recorded strip chart data to further evaluate TF performance.

Pilot-Tracking Performance and Workload. - The mean, standard deviation and PSD of the following pilot tracking performance and workload measures were also determined:

(1) Horizontal bar* $(g_c - g_{feedback})$

(2) Vertical bar* $(\phi_c - \phi)$

(3) Mach number (Mn)

(4) Pitch and roll control stick displacements (X_θ and X_ϕ)

(5) Throttle positions (PLA)

*The horizontal and vertical bars refer to the horizontal and vertical elements of the VSD steering cross displacement.

Qualitative Evaluation of Handling Quality and Ride Quality. - Pilot comments included assessment in the form of Cooper-Harper handling quality ratings, turbulence effects ratings, ride quality comfort ratings, and workload ratings (appendix A).

System and Environmental Conditions

The following system response characteristic parameters were computed from previously available analytical models and compared with flight test data where possible.

(1) Crew sensitivity index ($\overline{H}_z$ and $\overline{H}_y$)

(2) Gust sensitivities at the crew station ($\overline{A}_z$ and $\overline{A}_y$)

(3) Discomfort index due to control excitation ($\sigma_{D_{\delta_H}}$)

Statistical values (mean, standard deviation, and PSD) of the following environmental parameters and ride-quality indicators were obtained from measured data.

(1) Pilot seat accelerations ($n_{z_{ps}}$ and $n_{y_{ps}}$)

(2) Vertical and lateral gusts (w_g and v_g)

The gust values were estimated from the control vane measurements using the sensitivity of vane motion due to turbulence from the analytical model.

Crew Sensitivity Index ($\overline{H}$). - The ride quality specifications for the B-1 are defined in terms of the crew sensitivity index for crew tolerance to vertical and lateral motions, $\overline{H}_z$ and $\overline{H}_y$. Table III presents the B-1 design requirement values and the analytical values of $\overline{H}$ for the aircraft configuration tested with SMCS on and off. The B-1 meets the vertical requirement of 0.0919 and the lateral requirement of 0.023 with SMCS on but not with SMCS off. The $\overline{H}$ requirement for the B-1 is a single-point design requirement addressing the crew tolerance to long-duration penetration in turbulence. The development of the $\overline{H}$ requirement for the B-1 is based upon providing a ride discomfort index, $\sigma_{wg}\,\overline{H}_z$, less than 0.11 with the gust intensity expected during TF at a probability of 0.20. The ride discomfort index scales ($\sigma_{wg}\,\overline{H}_z$) are presented in appendix B with a brief description of some physiological effects as derived from both simulator and flight test data. A more detailed discussion of the development of the $\overline{H}$ criteria can be found in ref. 1, 2, 3, and 4.

Since the initiation of the B-1 program, a similar ride smoothing requirement has been published in the flight control system specification MIL-F-9490D, ref. 8 covering both short- and long-duration missions.

RMS discomfort due to Control Excitation ($\sigma_{D_{\delta H}}$). - In addition to the crew sensitivity index for gust response, another parameter used in the B-1 ride quality criteria is the discomfort index, $\sigma_{D_{\delta H}}$. This discomfort index is a measure of pilot discomfort caused by the horizontal tail control surface induced excitation of the flexible aircraft structure. The $\sigma_{D_{\delta H}}$ expression is defined in table III. The parameter contains structural mode motions only (a more detailed explanation can be found in ref. 5). The $\sigma_{D_{\delta H}}$ values for SMCS on and off are shown in table III. These values were determined from the analytical structural response model using the transfer function of structural mode motion due to control surface deflection, and test data of the PSD of control surface motion required for terrain following from simulator test. The values of $\sigma_{D_{\delta H}}$ meet the B-1 requirement of 0.021 with SMCS on and off. The SMCS on and off values are well below the B-1 requirement value.

Motion Levels and Turbulence Encountered During Flight. - The standard deviations of the measured accelerations at the pilot seat and the estimated turbulence levels are shown in figures 4 and 5 for SMCS on and off. Analytically computed crew station accelerations versus turbulences (solid lines) obtained from ATF simulation runs are also plotted in the figures to show the expected trends. The value of $\sigma_{n_{z_{ps}}}$ for no turbulence is the maneuver load required to follow the terrain profile for that level of terrain difficulty. The $\sigma_{n_{z_{ps}}}$ versus σ_{w_g} over the ocean would have a linear relationship (equal to $\bar{A}_z$) since no maneuver load is required over water. The non-linear curves over various types of terrain result from the approximation of

$$\sigma_{n_{z_{ps}}} = \left\{ \left(\sigma_{n_{z_{ps}}}\right)^2_{\text{due to maneuver}} + \left(\frac{\partial \sigma_{n_{z_{ps}}}}{\partial \sigma_{w_g}} \Delta\sigma_{wg}\right)^2 \right\}^{1/2}$$

Typical power spectral densities of the pilot seat accelerations are shown in figures 6 through 9. Figures 6 and 7 are the $\Phi_{n_{z_{ps}}}$ and $\Phi_{n_{y_{ps}}}$ which were obtained over the ocean with SMCS on and off; and figures 8 and 9 were obtained from data over terrain segment B 1, route TR-368, with SMCS on and off.

At very low frequency, below 0.5 Hz, the primary content of the pilot station acceleration PSD is due to the aircraft maneuvering required to conduct terrain following. In the aircraft response range of 0.5 to 1.0 Hz, the

short-period mode, and at frequencies above 1.0 Hz due to structural motions primarily due to turbulence and to a smaller degree due to control surface motions.

Figure 10 shows the dynamic relationship of the $\sigma_{n_{z_{ps}}}$ and $\sigma_{n_{z_{cg}}}$ of the B-1 aircraft under various terrain and turbulence conditions during TF flight. The higher acceleration at the cg location versus the pilot seat is attributed to the aircraft center of rotation due to both gusts and control motions being forward of the cg at low frequencies. The flight test data show more additional motions in the short-period frequency range due to small amplitude residual oscillation tendencies than does the analytical model.

The turbulence levels estimated during these flights are plotted against the terrain classification types in figure 11 to show the probability of encountering a given turbulence level over several types of terrain. The data shows that low turbulence levels exist for milder terrain, and higher turbulence levels exist over rougher terrain. These results are in general concurrence with the gust intensity distributions report in ref. 9.

Classification of Terrain Roughness. - Two terrain routes frequently used in the current B-1 flight test program were selected for the TF performance analyses. Although these terrain routes were not previously simulated, an evaluation of terrain roughness is possible. The two terrain routes have segments of terrain features such as ocean, flat, mild, moderate, and rugged terrains. The maneuver load factor required for automatic terrain following over these segments was used to define a terrain roughness factor. This terrain classification was used in the previous simulation study (ref. 1) and is convenient for comparison of results obtained over different terrain routes.

Terrain type	Maneuver load factor ($\sigma_{n_{z_{cg}}} \sim g$) measured during ATF flight
Ocean	0 to 0.1
Flat	0.1 to 0.2
Mild	0.2 to 0.3
Moderate	0.3 to 0.4
Rugged	> 0.4

Table IV identifies the terrain classification for each terrain segment tested.

Differences in Aircraft Response and Environmental Parameters Existing Between Flight Test and Earlier Simulator Tests

The analytical values of $\overline{A}$, $\overline{H}$, and $\sigma_{D_{\delta_H}}$ which represent the flight/simulated aircraft are shown in table III. The $\overline{H}$ values with SMCS on meet the allowable requirement level. With SMCS on, the $\overline{H}z$ values of the flight test aircraft and simulated aircraft are similar. The corresponding $\overline{H}y$ values are also similar. However, with SMCS off, the $\overline{H}z$ and $\overline{H}y$ values differ significantly primarily due to the difference in the first fuselage mode frequencies of the present flight test aircraft and that previously simulated. With the flight test aircraft, the human frequency response function of $\overline{H}z$ is larger at 2.7 Hz than at 2.0 Hz while the function of $\overline{H}y$ is lower at 4.8 Hz than at 2.6 Hz as shown in table III. This difference is not noticed with SMCS on because of the increased damping (reduced response of the first fuselage mode) in both flight test and simulated aircraft. The $\sigma_{D_{\delta H}}$ values meet the required levels with SMCS on and off. The flight test aircraft values are lower than those of simulated aircraft. The lower flight test values are also a result of the difference in the structural mode frequency. However in this case, the power spectral density, $\Phi_{\delta H}(\omega)$ at 2.7 Hz is much lower than at 2.0 Hz resulting in a lower $\sigma_{D_{\delta H}}$, as shown in table III. The acceleration environment measured at the pilot's seat during flight test (figures 4 and 5) and during earlier simulated tests (figures 10 and 11 of ref. 1) are substantially different primarily due to the low-frequency region where the terrain-following maneuver loads cannot be simulated in a limited amplitude simulator motion system.

In the simulator program, a wider range of turbulence levels were evaluated. The maximum σ_{w_g} encountered in flight test was approximately 1.4 m/sec versus 2.13 m/sec evaluated in the simulator study.

The VSD presentation associated with the MTF tracking tasks was essentially identical between flight test and simulator. The flight test tasks included TF monitoring on the E-scope, which was not included in the simulation. The E-scope provides both a performance confidence factor and terrain anticipation to the pilot; however, this display was not available in the simulator program.

In flight test, the TF system has an inherent fly-high bias of approximately 6 meters throughout the TF flight test program. This will cause some difference in the average TF clearance altitude comparison data between flight and simulator results.

FLIGHT TEST PERFORMANCE RESULTS

Performance with SMCS On and Off

The results from run set 2 are summarized in table V for four different conditions with SMCS on and off. The aircraft longitudinal and lateral-directional short-period characteristics for these conditions are as follows:

Parameters	Flight 3-71	3-72	3-73	3-77
ω_n, rad/sec	4.6	4.8	4.3	2.8
ζ_{sp}	0.423	0.415	0.456	0.420
F_s/g, newton/g	49.8	49.4	52.1	86.0
ω_d	2.4	2.4	2.1	1.8
ζ_d	0.33	0.33	0.40	0.42

Terrain following at these conditions on flights 3-71, 3-72, 3-73, 3-77 was flown by four different subjects, B, C, D, and E (see table I). Each TF run was conducted first with the SMCS on, followed by the SMCS off, over TF-368 using the same subject for both runs.

The altitude performance ($\sigma_{\Delta h_e}$) from table V shows a small but consistent improvement on all three flights with SMCS on as compared to SMCS off. The TF performance measurements of Δh_e and γ over the TR-368 terrain peaks (see figure 3) are shown in figure 12. In the figure, three MTF flights plus one ATF run are compared with SMCS on and off. These specific TF performance measurements show a wide variation in performance over the entire run with approximately the same performance level with SMCS on and off. The ATF runs show a smaller deviation over the terrain peaks than the MTF runs.

The other pilot tracking performance parameters, $\sigma_{\text{horiz bar}}$ and σ_{χ_a}, from table V show a smaller display g error and stick displacement, with SMCS on during flight 3-72 and 3-73. However, flight 3-71 appears to contradict the performance improvement measured with SMCS on compared with SMCS off.

The effects of SMCS and turbulence on pilot ratings can be seen by comparing the Cooper-Harper, turbulence effect, and ride quality discomfort ratings against the acceleration at the crew station, and ride discomfort index values, as shown in table V and figures 13 through 15.

The turbulence effect ratings and the ride quality comfort ratings do not appear to be influenced by the magnitude of the total pilot seat acceleration, $\sigma_{n_{z_{ps}}}$, but do exhibit a reasonable correlation with the accelerations due to structural motions as represented by the estimated ride discomfort index, $\sigma_{w_g}\ \overline{H}z$, or the power spectral density of the acceleration due to first fuselage bending mode motions $(\sigma_{n_{z_{ps}}})\ f=f_1$.

The pilot ratings obtained from these tests are shown as a function of the estimated ride discomfort index, $\sigma_{w_g}\ \overline{H}z$, in figure 13. The ride quality rating data with SMCS off shows a generally poorer rating than the data with SMCS on even though the maximum value of $\sigma_{w_g}\ \overline{H}z$ is 0.118, which is well within the satisfactory range as given in appendix B. Extrapolation of the data would indicate that if evaluated in higher turbulence levels, the ride quality would not be satisfactory with SMCS off even for the short duration runs. The estimated value of RMS discomfort due to control excitation is small with SMCS on or off and therefore not significant in the pilot ratings.

The handling quality comments indicate no rating changes with $\sigma_{w_g}\overline{H}_g$ for flights 3-72, 3-73, and 3-77, but on flight 3-71, a significantly poorer Cooper-Harper rating is shown in both the SMCS on and off runs with a larger deterioration in rating shown in the SMCS off case. Review of the pilot comments indicate that PIO tendencies were experienced by the pilot during flight 3-71, and this was the primary reason for poor Cooper-Harper rating. The evidence of this PIO caused by inadvertent inputs due to structural excitation is seen on the time history traces shown in figure 14. This data includes a portion of the crew station acceleration $(n_{z_{ps}})$ and pitch stick (X_θ) traces taken over terrain segments B 1 (SMCS off) and B 2 (SMCS on) of route TR 368 during flight 3-71. The data show a continuous crew station acceleration of 3 Hz motions accompanied by either an occasional burst of 3 Hz or step type of stick movements. These oscillations appear to be due to both the turbulence-induced and control stick-induced effects. Similar time history traces for other tests on flights 3-72, 3-73 and 3-77 were examined but indicated no apparent stick-induced motions. The PSD of the $n_{z_{ps}}$ over the terrain segments B 1 and B 2 flight 3-71 is also shown in figure 14. The figure also shows the rms measurement of the 3-H_z vertical acceleration at the pilot seat. This parameter was computed for run set 2 data and also tabulated in table V. Figure 15 shows the Cooper-Harper and ride-quality discomfort ratings plotted against this potential indication of PIO or adverse structural exciation. The ride quality discomfort rating deterioration showed an overall trend with this

measurement, but the handling quality ratings did not. Further separation of the gust-induced and control-induced motions appears to be needed to develop a PIO or adverse structural excitation predictor from the data.

Performance During Long-Duration Mission Runs

The data from run sets 3 and 4 were processed into statistical form (σ and mean) for each previously defined segment. The significant parameters are tabulated in tables VI, VII, and VIII. Other TF performance measures including the average of the deviation from set clearance, $|\Delta h_e|$, and flight path angle, γ, over the selected peaks, taken for each 10 minutes of elapsed time, were measured for comparison purpose. The relationships between terrain segments, selected peaks, and range (or time) are shown for run sets 3 and 4 in figure 3.

Figure 16 is the plot of σ values of Δh, horizontal bar, and χ_θ measures obtained for each segment number for two MTF (subjects F and G) runs. The σ value of Δh is also provided for the ATF run for comparison. Figure 17 is the TF performance over the terrain peaks plotted versus mission times (10-minute time slice). Figure 18 shows the workload, turbulence effect, and ride quality comfort ratings against flight phase duration time. These data were representative of SMCS on conditions. It should be emphasized that since the data represent only two MTF and one ATF runs, any conclusions reached will be tentative. The trends observed from these data are as follows:

(1) Satisfactory MTF performance was accomplished during these low-level penetrations in turbulence. The level of MTF altitude clearance was similar to ATF performance during this evaluation.

(2) For the conditions tested, there was no significant change of performance ($\sigma_{\Delta h}$ and $\sigma_{\text{horiz bar}}$) toward the end of these runs as compared with the beginning of the runs.

(3) The work load and ride quality ratings showed a trend (deterioration) with mission time. The accompanying comments included the effect of pilot fatigue. The turbulence effect rating showed no change for the one-hour mission.

(4) There was some evidence of a gradual increase in tracking error ($\sigma_{\text{horiz bar}}$) and an associated reduction in stick control activity (σ_{χ_θ}) with time.

(5) Subject G had very little prior B-1 MTF flying experience (one flight) before accomplishing the long-duration run. Observation of his performance data indicates that the $\sigma_{\Delta h}$ and $\sigma_{\text{horiz bar}}$ data during the middle of the run (see figure 16) was improved relative to performance at the beginning for similar terrain (segments 1, 2, 6, and 8). Subject G consistently ballooned over the peaks (figure 17), but the amount of ballooning decreased throughout the

mission. Toward the end of the route, a slight degradation in TF performance is evidenced with altitude deviation below the set clearance at the peaks. This was caused by degraded operation of the left TF channel and not deterioration in subject G performance.

(6) Subject F performed best at TF tracking at the beginning of the run versus the end of the run (i.e., segments 1, 2, 6 and 3, 5, 10). Subject F commented that the workload varied significantly with terrain features and his right wrist became very tired in approximately 10 minutes over rugged terrain. Observations of the flight test data indicate that the mean stick position for subject F was offcentered by 0.4 cm or 20 newtons of steady force applied onto the stick for the first half of the mission.

This stick displacement force (due to A/C out-of-trim condition) was not reflected in pilot tracking performance (figure 16). However, it could explain the pilot's comment concerning his tired right wrist.

(7) Subject F's comments in the postflight questionnaire sheet in response to the question "What aspects of your assigned task requires the most effort" was "Most effort was concentration on the tasks and resisting desire to relax a bit. Pilot must stay alert to steering cross commands, mach number, etc, at all times." Boredom or relaxation as a possible source of performance deviation as reported in previous simulation studies (ref. 10, 11, and 12) must be ruled out in the actual TF mission.

(8) Performance during turns (segment 4, 5, 8, and 11) as compared with those segments without turns over the similar terrain types showed very little indication of pitch-tracking degradation associated with combined pitch-roll tasks during turn maneuvers.

(9) The MTF (run set 3) and ATF (run set 4) TF performance comparisons are plotted in figures 16 and 17. ATF data were measured to provide a base level of performance. In general, the ATF provides more consistent performance. The MTF flights resulted in ballooning over the terrain peaks as opposed to near level for ATF runs (refer to γ values in figure 17). Variability in γ over selected peaks was also significantly greater during the MTF runs versus the ATF runs.

(10) The mean value of the MTF tracking error (horizontal bar) was consistently negative (approximately -0.05 g in dive command) during the long duration runs for both subjects.

(11) Satisfactory aircraft speed control (within 0.05 ΔMn) was maintained by the pilot using manual thrust control during the long duration TF tracking task. The speed was maintained closer to the reference speed during ATF than during MTF.

COMPARISON OF FLIGHT TEST (PHASE II) WITH SIMULATOR (PHASE I) RESULTS

Test Condition Differences

Several differences in the condition which existed for these tests are listed below:

(1) The analytical model available at the time of and simulated in the analysis of data in phase 1, was substantially different than the present B-1 analytical model. The vertical gust response component due to first fuselage bending motion was near 2.0 Hz (figure 13 in ref. 1) instead of the present 2.7 Hz. (See figure 8.)

(2) The analytical values of the ride quality index from flight are compared against the index values used in the simulator study in table III. The crew sensitivity indexes, $\bar{H}_Z$ and $\bar{H}_Y$, and the analytical value of $\bar{A}$ were in close agreement for the SMCS on case. The aircraft gust sensitivities, $\bar{A}_Z$ and $\bar{A}_Y$, measured in flight test were higher than those measured from the simulator motion system. The simulation reproduced that part of the LAHS environment contributed by structural mode motions due to gusts and control inputs. The primary motion factors not included in the flight simulation are the lower frequency terrain-following and aircraft damping motions.

(3) The characteristics of the TF tracking task were different than previously simulated (figure 1). The parameters of the MTF system were modified during the early flight test development to provide good flight test performance. Because of these differences, correlation of the detailed results in some cases was not possible.

(4) The flight simulation does not include the many actual mission stress factors (ref. 13) which are important in low-level flying, and the limited data available in this study showed differences in piloting technique with a much tighter control in flight test.

Results where General Concurrence was Obtained

Some of the results which showed general concurrence are as follows:

(1) The ride quality ratings with SMCS on were satisfactory for both short- and long-duration runs in both flight test and simulation. The ratings with SMCS off were somewhat degraded but were satisfactory for the levels of turbulence encountered in flight.

(2) The handling qualities ratings with SMCS on and off from flight test were consistent with the data obtained from the simulation study. At low levels of turbulence, the handling qualities are satisfactory. At higher levels of turbulence, a PIO tendency can result in degraded flying qualities ratings.

(3) General concurrence on the acceptability of the B-1 ride for accomplishment of the mission was achieved.

(4) General agreement was achieved in the need for limitation on the coupling of the bending modes and control inputs.

Results where Differences were Noted

Several differences in the qualitative and quantitative results were as follows:

(1) In flight test, the pilots suggested that the upper time limit for uninterrupted LAHS MTF (SMCS on) by a pilot without relief from the copilot is from 10 (subject F) to 30 minutes (subject G) for rugged terrain and 30 minutes (subject F) to 2 hours (subject G) for flat terrain. In the flight simulation programs of phase I, long-duration runs (up to 4 hours) were accomplished by single pilots although the pilots reported onset of fatigue effects after about 2 hours.

(2) In flight test, the continuous control motions with large pitch control forces resulted in extreme forearm fatigue during long-duration MTF runs. Typical time histories of tracking error signal (horiz bar) and pilot's stick deflection obtained during flight and simulator tests are shown in figure 19. These traces show the pilot's stick response to the tracking error signal. In the simulator test, the pilot's stick movement shows a very low-frequency behavior with relatively smooth changes in response to horizontal bar movement. In flight test, the control stick movement appears continuously active. Also a steady offcentered stick as seen in the flight test data (figure 19) partly explained a reason for increased fatigue as compared to the simulator.

(3) The standard deviation of Δh and horizontal bar from flight and simulator tests are compared in figures 20 and 21. Larger variations of $\sigma_{\Delta h}$ and $\sigma_{horiz\ bar}$ are seen in the flight test data for a given value of $\sigma_{n_{z_{cg}}}$. This may be attributed to several factors including fly-high bias in TFR computer, pilot fatigue and stress, and different flying techniques. The ATF data points from flight test correlate closely with the simulator results when the fly-high bias is taken into account.

Comments on Previously Identified Parameters

In the phase 1 flight simulator study, two new parameters were identified which could be useful in prediction of aircraft ride and handling qualities. These parameters were postulated from the results of parameter variations which were evaluated in the simulation program. The results of the simulation program showed that deterioration of pilot rating could be related to the magnitude of the phase lag in the TF feedback system for several variations of feedback (figure 24 of ref. 1), and that the pilot ratings were sensitive to a crew discomfort related parameter (figure 25 of ref. 1), which is similar to the B-1 $\sigma_{D_{\delta H}}$ requirement. These values during flight test were measured and compared against simulator results. The phase shift of the MTF feedback system developed for flight test was measured to be -63 degrees. The increased phase shift is due to the increased lag in the stick feedback from 0.5 to 1 second and modification of the stick to g feedback gain ratio. (See figure 1.) The Cooper-Harper rating predicted for this amount of TF feedback phase shift based on simulator results was 4.5 (figure 24 of ref. 1) which agrees with the flight test generated pilot rating. A "slight" PIO comment would also be predicted for this level of phase shift. (See table V of ref. 1.)

In flight test, Cooper-Harper ratings for the system evaluated vary from 2.0 for conditions where no PIO tendency is present to 4.5 for a case where the pilot had experienced the PIO. The second parameter which is related to the B-1 $\sigma_{D_{\delta H}}$ requirement also appears to be validated by the flight test results in that improvement in ride and handling quality are provided with SMCS on versus SMCS off. Amplitude of the $n_{z_{ps}}$ to X_θ transfer function measured at 3 Hz from the flight results indicate approximately 0.36 g per cm with SMCS on, and 0.68 g/cm with SMCS off.

Comment on Display Steering Sensitivity

Although not reported in the previous flight simulation studies, the display steering sensitivity was found to be an important parameter for satisfactory handling qualities during manual terrain following. Variations of

this parameter were accomplished in flight test to select the optimum for further terrain-following evaluation. Flight test data are available and are reported here in figure 22 for tests with three levels (A, B, C) of VSD gain sensitivity with SMCS on (run set 1). The following significant results were obtained:

(1) The TF performance data obtained from flight showed the "B" setting was the optimum, based upon both pilot ratings and performance. The "A" setting tends to cause ballooning, and the "C" setting tends to result in clipping over the terrain peak. (See γ values in figure 22.) These results verified the results of the simulation studies which also showed the "B" setting to be optimum.

(2) The pilot workload (σ_{X_θ}) and g error ($\sigma_{horiz\ bar}$) showed an increasing amount of $\sigma_{horizontal\ bar}$, and an increasing amount of stick movement for sensitivity higher or lower than optimum.

(3) The pilot's gain (K_{pilot}) shows pilot compensation for the change in VSD gain. The pilot loop control gain ($K_{VSD}\ K_{pilot}$) remained approximately constant (= 4.4 cm/g_c).

SUMMARY OF SIGNIFICANT FINDINGS

Satisfactory manual and automatic terrain following were accomplished in the B-1 aircraft at low-altitude, high-speed flight conditions in turbulence during B-1 penetration mission evaluation. The terrain routes included a range of terrain roughness representative of future penetrator requirements. The data obtained indicated satisfactory levels of terrain clearance and display tracking error for the B-1 terrain-following conditions, including the long-duration run.

The B-1 analytical models show that the B-1 with SMCS on meets the ride-quality requirement of $\overline{H}_z < 0.0919$ and $\overline{H}_y < 0.023$ and $\sigma_{D\delta H} < 0.021$. These requirements are not met with SMCS off. Qualitative evaluation of the B-1 with SMCS on indicates that the ride qualities are satisfactory for the long duration mission. The B-1 characteristics with the SMCS off or failed are not considered satisfactory for B-1 penetration.

The development of this ride quality criteria, as given in the literature, is based upon early research on tolerance to sinusoidal vibration. The structural response characteristics of the B-1 at the crew station, as seen in the flight data, show a strong 2.7 Hz component in the vertical axis and a strong 5 Hz component in the lateral axis due to bending in the first fuselage modes in the vertical and lateral axes. The SMCS is very effective in reducing the response on these modes. Because of this single-mode response characteristic, the flight evaluation concurrence with previous ride quality criteria development work and tolerance to sinusoidal motion studies appears to be reasonable.

The data analyzed from the flight evaluations of this study provide "limited" validation of the gust-response criteria. For the levels of turbulence which existed during these flight evaluations, no significant deterioration in TF performance was measured with SMCS on or off. The ratings indicated degraded condition with SMCS off and, when extrapolated to higher turbulence levels and long duration, would indicate unsatisfactory characteristics with SMCS off. Additional evaluations in higher levels of turbulence are necessary for more complete criteria validation.

Satisfactory TF performance and crew comments during automatic terrain following and manual terrain following including the long-duration runs provide limited validation of the bending mode excitation requirement. However, the data showed a strong ride quality-handling quality interaction related to excitation of the first fuselage bending mode near 2.7 Hz. Pilot comments on PIO were received under certain conditions. Degraded flying quality ratings and degraded ride comfort ratings accompanied these comments.

The analytical model of the B-1 has been upgraded during the B-1 program as additional test data have become available. Recent flight test data have been obtained for this specific purpose in order to provide an analytical model for B-1 ride quality requirement compliance. Therefore, at this date, the analytical model shows excellent correlation with system dynamics (damping, frequency) and response to control inputs. A direct measurement of gust intensity has not been accomplished in the B-1 program and, therefore, the gust response has not been officially validated based upon flight test data. Although not validated by test data, the comparison of the shape of the power spectral density data, flight test versus analytical model, is very good, and a high confidence exists in the gust response level correlation. This quasi validated model provides a technique for estimation of the turbulence level and was used in this study.

Analysis of the flight test data shows the expected MTF and ATF performance variation with terrain roughness with SMCS on or off. The estimate of gust levels encountered showed gust intensity as a function of the terrain as expected (low levels for over the ocean and higher levels for rugged terrain).

Deterioration of performance due to boredom has been reported during simulated flights in ref. 10, 11, and 12. Inflight boredom was not a factor in the B-1 flight test results.

Flight test results concur in general with the results obtained from the B-1 terrain-following simulation study. General concurrence on the acceptability of the B-1 ride for accomplishment of the mission was achieved. Although there were some differences in conditions evaluated, the results of the simulation did not result in performance conclusions conflicting with those derived from the flight test data.

CONCLUSIONS

Analysis of data from selected flights during the B-1 flight test program provided the basis for evaluation of quantitative and qualitative performance under realistic low-level penetration conditions. This evaluation led to the following conclusions:

(1) The B-1 ride quality criteria provided a satisfactory design for long-duration, low-level penetration. Satisfactory terrain-following performance in flight test and flight simulation provide limited validation of the criteria.

(2) The results of this study, when extrapolated to higher turbulence levels and longer durations with SMCS off, indicate possible validation of the criteria as an upper limit value. Additional evaluation in higher turbulence is necessary for this more complete validation.

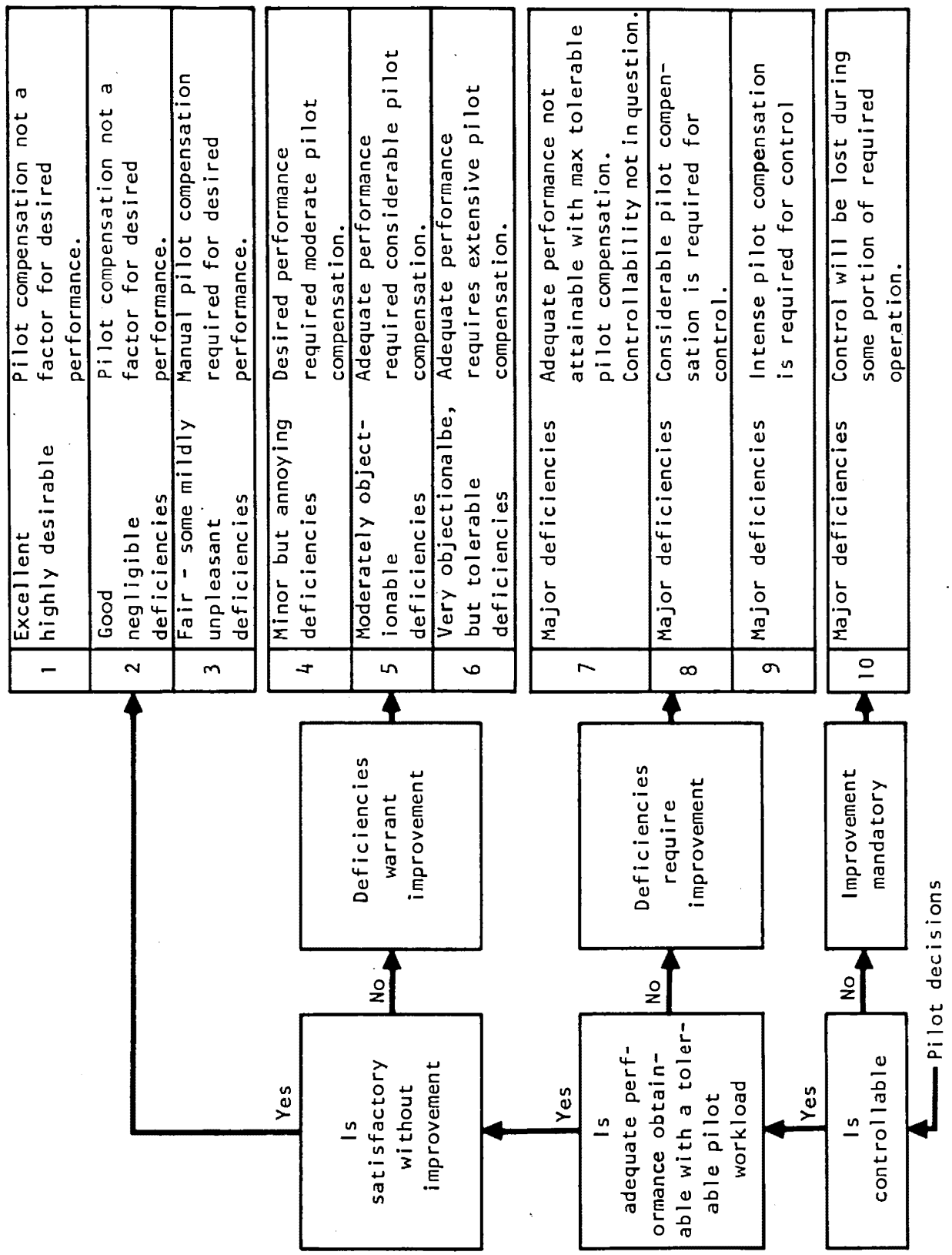
(3) Fatigue is a very important factor in long-duration manual terrain following, in particular with relatively high pitch control forces. Continuous long duration MTF would require a copilot to time share the MTF tracking task. Consideration should be given modification of handling qualities requirements for control forces to reduce pilot fatigue during MTF.

(4) A handling/ride quality coupling exists in the B-1 low-level penetration potentially not addressed via existing criteria. This coupling with the first fuselage bending mode in the B-1 appears to be related to both pilot technique and aircraft response. Parameters which quantify this coupling were identified.

(5) The dynamic characteristics of the TF tracking control tasks are significant in handling/ride quality evaluation. A parameter to quantify these dynamics was identified but not validated.

APPENDIX A - PILOT RATING SCALES

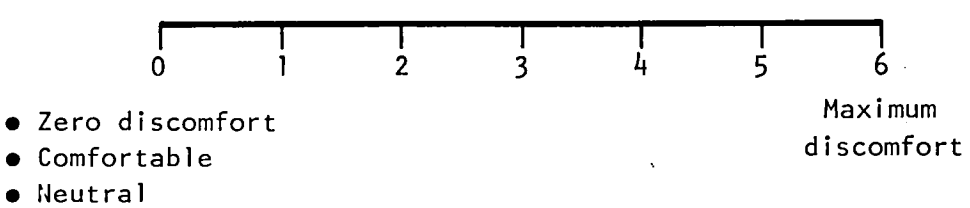
a. Cooper-Harper rating scale



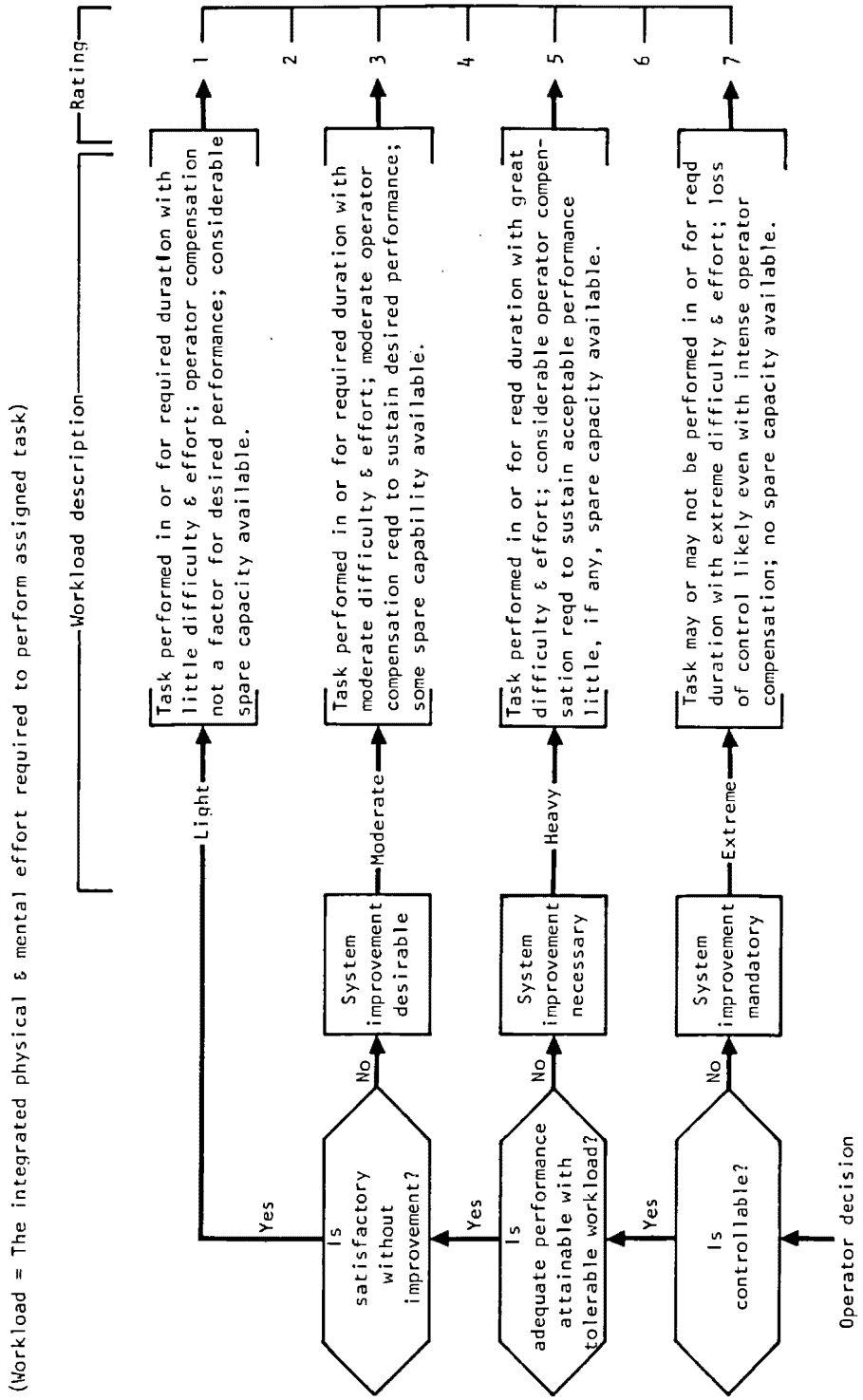
b. Turbulence effects rating scale

Increase of pilot effort with turbulence	Deterioration of task performance with turbulence	Rating
No significant increase	No significant deterioration	A
More effort required	No significant deterioration	B
	Minor	C
	Moderate	D
Best effort required	Moderate	E
	Major (but evaluation tasks can still be accomplished)	F
	Large (some tasks cannot be performed)	G
Unable to perform tasks		H

c. Ride quality comfort rating scale (ref. 7)



d. Workload rating scale



APPENDIX B - RIDE DISCOMFORT INDEX SCALE - REF. 4

$\sigma_{w_g}\bar{H}_z$	Aircraft Acceptability	Mission performance & crew effort	Physiological effects
0.07	Acceptable for unlimited exposure	Mission performance not affected	No effort on normal tasks.
.14	Acceptable normal operation	Mission performance adequate	No effect on normal tasks, writing becomes difficult, small dials become difficult to read.
.21	Acceptable normal operation not exceeding allowable exposure time	Adequate for mission success, reasonable performance requires considerable crew concentration	Normal tasks still possible. Manual control demands considerable attention and psychometer coordination is reduced. Time to read instruments and displays and adjust controls increases. Small dials unreadable, eventual setting-in of fatigue.
.28	Unsatisfactory for normal operations, unacceptable when exceeding allowable exposure times	Adequate for mission success, but requires max available pilot/ crew concentration to achieve acceptable performance	Limits of effective tracking - Manipulation of controls and other psychometer tasks requires bracing of arms and legs and movements become deliberate. Pilot looks forward with only brief glances at instruments which cannot be read accurately. Cross checks are slowed down and tolerances widened. Rapid increase in fatigue.
.35	Unacceptable except for emergency conditions	Inadequate performance for mission success, aircraft controllable with minimum cockpit duties	Beginning of unworkable level - Control of aircraft requires full pilot attention. other than stick and throttle control almost impossible. Pilot will establish hierarchy of tasks. Attention cannot be diverted from tracking task without immediate deterioration.
.42	Unacceptable dangerous	Aircraft just controllable requiring max pilot skill, mission success	Performance levels low and all tasks impossible except for gross adjustments. Displays difficult if not impossible to read, concern for structural integrity.

REFERENCES

1. Nardi, L. U., Kawana, H. Y., Borland, C. J., and Lefritz, N. M., "Ride Qualities Criteria Validation/Pilot Performance Study – Flight Simulator Results," NASA CR-143838, March 1975

2. Grande, D. L., "Some Effects of Random Turbulence on Weapon System Performance," Aerospace Engineering, pp 35-43, October 1962

3. Rustenburg, J. W., "A Technique for the Evaluation of Aircraft Ride Quality," ASD-TR-68-18

4. Rustenburg, J. W., "Development of Ride Quality Analysis Methods and Criteria for Low-Altitude, High-Speed Aircraft," paper presented to AIAA

5. Rustenburg, J. W., "Development of Tracking Error Frequency Response Function and Aircraft Ride Quality Design Criteria for Vertical and Lateral Vibration," ASD-TR-70-18, January 1971

6. Bunn, D. B., and Stidham, L. H., "Data Processing and Frequency Analysis Program, Program XQ0034," Rockwell International, May 1969

7. Dempsey, T. K.; Coates, G. D., and Leatherwood, J. D., "An Investigation of Ride Quality Rating Scales," NASA Tech Paper 1064, November 1977

8. Military Specification, "Flight Control System – Design, Installation and Test of, Piloted Aircraft," General Specification for MIL-F-9490D (USAF), 6 June 1974

9. Saunders, K. D., "B-6613 Low Level Gust Study, Vol. I, Technical Analysis," WADD TR60-305, Vol 5, March 1961

10. Holland, C. L., "Performance and Phychological Effects of Long Term Vibration," AMR-TR-66-143, October 1966

11. Dudek, R. A., Ayoub, N. M., and El-Nawawi, M. A., "Optimal Work-Rest Schedules Under Prolonged Vibration," Ergonomics, 1973, 16, pp 469-479

12. Soliday, S. M., and Schohan, B., "A Simulator Investigation of Pilot Performance During Extended Periods of Low-Altitude, High-Speed Flight," NASA CR-63, June 1964

13. Sadoff, M., and Wempe, T. E., "Pilot-Vehicle System Simulation for Low-Altitude, High-Speed Flight," NASA TN D-2793, June 1965

TABLE I. - SUMMARY OF FLIGHT TEST CONDITIONS ANALYZED

Run set	Flight	Subjects (pilot/ copilot)	Terrain	Control axes			Display MTF system	SMCS	Duration (minutes)	Purpose
				Pitch	Roll	Speed				
1	3-65	A	TR-368	MTF	Manual Nav	Manual	VSD[1] sensitivity variations	On	20	Display variations
2[2]	3-71 3-72 3-73 3-77	B C/D D/E B/C	TR-368	MTF	Manual Nav	Manual	B-1 baseline	Off On	20	Nominal B-1 MTF evaluation
3	3-68 3-74	F G	TR-391/ -360/ -385	MTF	Manual Nav	Manual	B-1 baseline	On	60	Nominal B-1 long-duration evaluation
4	3-64 3-76	C C	TR-368 TR-391/ -360/ -385	ATF	Auto Nav	Manual	B-1 baseline	On Off On	60	ATF/MTF comparison

[1] VSD gain sensitivities:

	Pitch axis	Roll axes
"A"	2.87 cm/g	3.05 cm/30 deg roll
"B"	1.78 cm/g	1.14 cm/30 deg roll
"C"	0.97 cm/g	1.02 cm/30 deg roll

[2] Four different flight conditions:

3-71, A/C weight = 127 Kg, 3-72, A/C weight = 120 Kg } Mn=0.85, Λ=65°
3-73, A/C weight = 149 Kg
3-77, A/C weight = 118 Kg, Mn=0.65, Λ=55°

TABLE II. - FLIGHT TEST PARAMETERS RECORDED AND REDUCED FOR DATA ANALYSIS

Parameter identification	Instrumentation no.	Instrumentation parameters	Form of data reduction		
			Time history	Mean and standard deviation	PSD
TF performance	M1010	Radar altimeter, Δh	✓	✓	✓
	{M1005, M1010}	Altitude deviation from set clearance altitude measured at terrain peak, Δh_e	✓		
	M1415	Flight path angle, γ	✓		
Pilot/aircraft performance	M1218	Pitch tracking error, horiz bar	✓	✓	✓
	A2009	Normal load factor at cg, $n_{z_{cg}}$	✓	✓	✓
	X3002	Pitch stick position, x_θ	✓	✓	✓
Environmental	A2006 A2007	Normal and lateral load factors at pilot's seat, $n_{z_{ps}}$, $n_{y_{ps}}$	✓	✓	✓
Control surfaces	C0918 C9019	Horizontal and rolling tail deflections, δ_H and δ_H'	✓	✓	✓
	M1031 M1032	Vertical and lateral control vane command deflections, $\delta_{CV_{\phi_c}}$ and $\delta_{CV_{\phi_c}}$	✓	✓	✓

TABLE III. - RIDE QUALITY INDEX COMPARISONS

	B-1 Design Requirement	Flight Test (Estimated)		Simulator Test (Ref. 1)	
		SMCS Off	SMCS On	SMCS Off	SMCS On
$\bar{H}z$ (per m/sec)	$\leq$ 0.0919	0.1296	0.0853	0.1006	0.0869
$\bar{H}y$ (per m/sec)	$\leq$ 0.0230	0.0282	0.0210	0.0404	0.0207
$\sigma_{D_{\delta_H}}$	$\leq$0.0210	0.0110	0.0037	0.0171	0.0056
$\bar{A}z$ (g/m/sec)	Analytical Measured	0.1560	0.1024	0.1740 0.0400	0.0984 0.0276
Vertical frequency f_1 (hertz)		2.7		2.0	
$\bar{A}y$ (g/m/sec)	Analytical Measured	.0509	.0420	0.0804 0.0184	0.0505 0.0118
Lateral frequency f_1 (hertz)		4.8		2.6	

Effects of mode frequency change resulting in a different ride quality index between flight test and simulator - SMCS off:

$$\frac{\bar{H}z(flt)}{\bar{H}z(sim)} \cong \left\{ \frac{\left[T_D(\omega)^2 \, \phi_{gust}(\omega) \quad f_1 = 2.7 \right]}{\left[T_D(\omega)^2 \, \phi_{gust}(\omega) \quad f_1 = 2.0 \right]} \right\}^{1/2} = 1.2$$

$$\frac{\bar{H}y(flt)}{\bar{H}y(sim)} \cong \left\{ \frac{\left[T_D(\omega)^2 \, \phi_{gust}(\omega) \quad f_1 = 4.8 \right]}{\left[T_D(\omega)^2 \, \phi_{gust}(\omega) \quad f_1 = 2.6 \right]} \right\}^{1/2} = 0.4$$

TABLE III. - RIDE QUALITY INDEX COMPARISONS - Concluded

$$\frac{\sigma_{D_{\delta H(flt)}}}{\sigma_{D_{\delta H(sim)}}} \cong \left\{ \frac{\left[T_D(\omega)^2 \, \Phi_{\delta_H}(\omega) \quad f_1 = 2.7 \right]}{\left[T_D(\omega)^2 \, \Phi_{\delta_H}(\omega) \quad f_1 = 2.0 \right]} \right\}^{1/2} = 0.85$$

Definitions:

Gust sensitivity

$$\bar{A} = \frac{1}{\sigma_{gust}} \left[\int_0^\infty |T_{A/P}(\omega)|^2 \; \Phi_{gust}(\omega) \; d\omega \right]^{1/2}$$

Crew sensitivity

$$\bar{H} = \frac{1}{\sigma_{gust}} \left[\int_0^\infty |T_D(\omega)|^2 \; |T_{A/P}(\omega)|^2 \; \Phi_{gust}(\omega) \; d\omega \right]^{1/2}$$

RMS discomfort due to δ_H

$$\sigma_{D_{\delta_H}} = \left[\int_0^\infty |T_D(\omega)|^2 \; |T_{A/P}'(\omega)|^2 \; \Phi_{\delta H}(\omega) \; d\omega \right]^{1/2}$$

σ_{gust} = rms gust velocity

$|T_D(\omega)|$ = human frequency response function

$|T_{A/P}(\omega)|$ = crew compartment acceleration frequency response function

$|T_{A/P}'(\omega)|$ = crew compartment acceleration frequency response function due to control surface excitation (acceleration due to structural mode motion only)

$\Phi_{gust}(\omega)$ = turbulence spectrum of unit rms gust velocity

$\Phi_{\delta_H}(\omega)$ = power spectral density of surface deflection during ATF over rough terrain

TABLE IV. - IDENTIFICATION OF SEGMENT NUMBER AND TERRAIN CLASSIFICATION

Training route	Segment (a)	(b) Maneuver Load $\sigma_{\Delta n_{z_{cg}}}$	Terrain Classification
TR-391	0	0.072	Ocean
	1	.451	Rugged
	2	.455	Rugged
	3	.382	Moderate
TR-360	4	.114	Flat
	5	.365	Moderate
	6	.431	Rugged
TR-385	7	.209	Mild
	8	.418	Rugged
	9	.224	Mild
	10	.324	Moderate
	11	.137	Flat

Training route	Segment (a)	(b) Maneuver Load $\sigma_{\Delta n_{z_{cg}}}$	Terrain Classification
TR-368	A	0.331	Moderate
	B1	.319	Moderate
	B2	.206	Mild
	C	.312	Moderate

(a) Each segment selected has 2-minute interval for data analysis.

(b) $\sigma_{n_{z_{cg}}}$ is the standard deviation obtained from the ATF flights.

*The following segment numbers have 30 deg turning maneuvers:
4, 5, 8, and 11 on TR-360/385, and
B1 on TR-368.

TABLE V. - SUMMARY OF RUN SET 2 DATA

Flight	SMCS	TF/pilot performance			Pilot seat accel		Turbulence			Pilot ratings			$\sigma_{n_{z_p}}$ $f = f_1$ (g)**	$\sigma_{w_g} \bar{H}_z$**
		$\sigma_{\Delta h_e}$ (m)	$\sigma_{horiz\ bar}$ (g)	σ_{x_θ} (cm)	$\sigma_{n_{z_{ps}}}$ (g)*	$\sigma_{n_{y_{ps}}}$ (g)	σ_{w_g} (m/s)	σ_{v_g} (m/sec)	σ_{turb} (m/sec)	Cooper-Harper	Ride Quality Comfort	Turbulence Effect		
3-71	ON	54.7	0.180	1.30	0.263	0.058	1.006	0.942	1.378	4	2	C	0.051	0.086
	OFF	66.6	.163	1.19	.262	.080	.914	.823	1.230	5	4	C/D	.103	.118
3-72	ON	61.7	.194	1.13	.250	.058	.753	.747	1.061	2.5	0.5	A/B	.036	.064
	OFF	75.8	.202	1.15	.268	.066	.649	.954	1.155	2.5	1.5	B	.070	.084
3-73	ON	69.3	.207	1.12	.237	.036	.549	.600	0.813	2	1.0	B/C	.017	.047
	OFF	72.3	.271	1.29	.287	.066	.680	.850	1.088	2	1.5	C/D	.077	.088
3-77	ON	79.8	.198	0.82	.180	.044	.483	.628	0.792	2	1.1	B	.022	.041
	OFF	81.2	.218	0.80	.184	.051	.423	.896	.991	2.3	2.1	B	.062	.055

* These accelerations are primarily very low-frequency terrain-following motions.

** These accelerations are representative of aircraft bending mode motions.

TABLE VI. - SUMMARY OF RUN SET 3 DATA - FLIGHT 3-68, MTF/SMCS ON SUBJECT F

	Parameters	Terrain segment number and terrain types											
		Ocean	1 Rugged	2 Rugged	3 Moderate	4 Flat	5 Moderate	6 Rugged	7 Mild	8* Rugged	9 Mild	10 Moderate	11 Flat
TF performance	$\sigma_{\Delta h_e}$ - m		73.2	103.3	123.4	10.1	55.8	91.1	25.0	192.9	101.8	91.7	9.1
	$\Delta h_{e_{mean}}$ - m		212.1	280.7	258.2	133.5	192.0	244.8	146.6	390.4	173.1	229.2	130.1
Pilot performance	$\sigma_{horiz\ bar}$ - g		0.126	0.158	0.146	0.119	0.251	0.130	0.135	0.192	0.245	0.140	0.175
	$\sigma_{vert\ bar}$ - deg		1.936	2.242	2.489	6.657	5.297	2.690	2.429	6.562	2.833	2.001	6.074
	$\sigma_{\Delta MN}$		.010	.014	.016	.009	.015	.015	.013	.019	.014	.015	.010
	σ_{x_θ} - cm		1.79	1.83	1.50	.55	1.53	1.58	.83	1.33	.75	1.36	.87
	σ_{x_ϕ} - cm		.55	.54	.61	.79	.78	.44	.35	.79	.38	.48	.74
	$\sigma_{\Delta PLA}$ - deg		4.0	19.2	17.6	.3	11.8	19.0	7.5	19.2	17.3	13.3	2.1
Environmental conditions	$\sigma_{n_{z_p}}$ - g	0.021	.353	.371	.322	.113	.326	.347	.183	.311	.162	.305	.213
	$\sigma_{n_{y_p}}$ - g	.020	.041	.051	.048	.039	.055	.057	.048	.046	.040	.044	.042
	$\sigma_{n_{z_{cg}}}$ - g	.020	.402	.416	.364	.134	.372	.394	.217	.363	.195	.353	.247
	σ_{w_g} - m/s	.128	.579	.671	.731	.549	.732	.671	.671	.549	.671	.823	.792
	σ_{v_g} - m/s	.372	.808	.856	1.122	.777	.975	1.180	.877	.594	.585	.817	.665

Ride discomfort index $\sigma_{W_g} \bar{H}_z$ 0.011 0.049 0.054

Subjective ratings:

Workload	1.5	2.5	2.5
Ride quality comfort		0.5	0.8
Turbulence effect		B	B

*Fly-ups had occurred during segments 5 and 8.

Filled out after completion of TR-360

Filled out at the end of route

TABLE VII.- SUMMARY OF RUN SET 3 DATA - FLIGHT 3-74, MTF/SMCS ON SUBJECT G

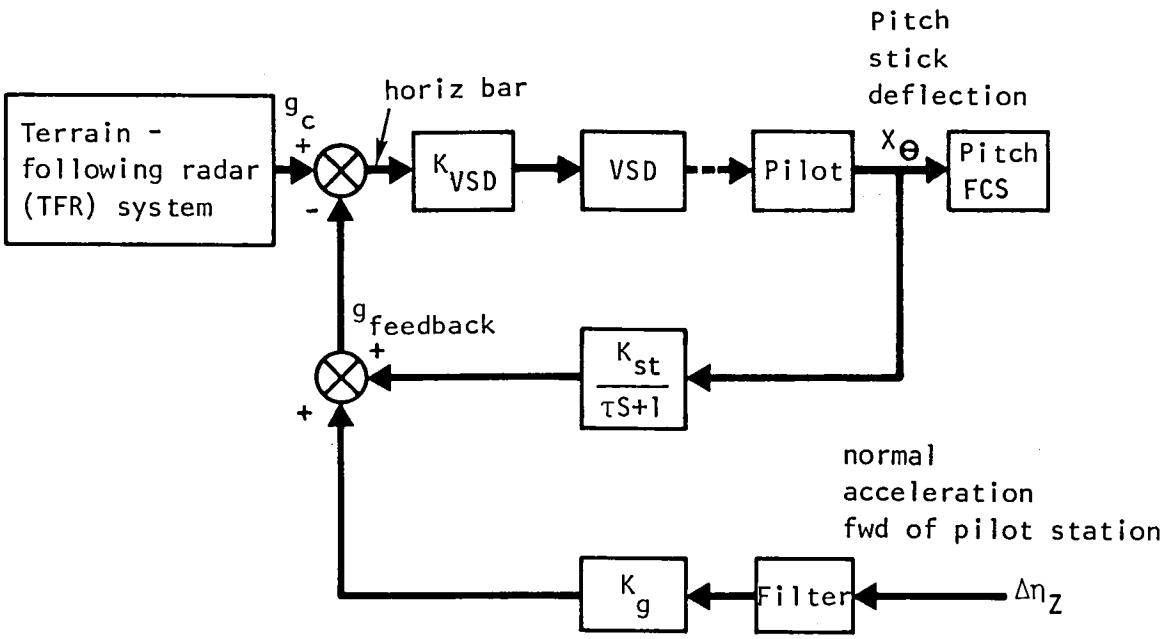
	Parameters	Terrain segment number and terrain types											
		Ocean	1 Rugged	2 Rugged	3 Moderate	4 Flat	5 Moderate	6 Rugged	7 Mild	8 Rugged	9 Mild	10 Moderate	11 Flat
TF performance	$\sigma_{\Delta h_e}$ - m		124.7	123.4	108.8	5.8	47.5	97.2	22.9	79.6	53.0	64.9	11.4
	$\Delta h_{e_{mean}}$ - m		236.0	317.6	232.4	127.7	167.7	237.1	140.1	181.0	168.8	211.1	128.9
Pilot performance	$\sigma_{horiz\ bar}$ - g		0.289	0.216	0.159	0.134	0.210	0.202	0.156	0.278	0.231	0.171	0.128
	$\sigma_{vert\ bar}$ - deg		3.350	4.900	2.720	7.950	4.890	5.13	2.431	5.114	2.990	3.578	4.875
	$\sigma_{\Delta MN}$		.011	.019	.014	.005	.009	.0133	.011	.035	.017	.019	.010
	σ_{x_θ} - cm		1.275	1.547	1.175	.547	1.250	1.712	.906	1.084	.910	.661	.518
	σ_{x_ϕ} - cm		.404	1.417	.508	.719	.683	1.803	.490	.622	.369	.548	.723
	$\sigma_{\Delta PLA}$ - deg		7.7	15.1	14.0	3.8	10.1	13.9	9.4	8.2	11.2	19.9	6.0
Environmental conditions	$\sigma_{n_{z_p}}$ - g	0.032	.262	.344	.275	.082	.369	.439	.312	.209	.182	.130	.101
	$\sigma_{n_{y_p}}$ - g	0.004	.030	.040	.031	.034	.046	.030	.052	.035	.035	.046	.038
	$\sigma_{n_{z_{cg}}}$ - g		.293	.392	.308	.108	.305	.406	.211	.240	.208	.164	.130
	σ_{w_g} - m/s	0.152	.732	.808	.488	.549	.671	.732	.914	.777	.975	1.006	.777
	σ_{v_g} - m/s	0.061	.485	.899	.591	.604	.829	.472	.951	.652	.594	.695	.573
Ride discomfort index	$\sigma_{W_g} \bar{H}_z$	0.013						0.050					0.061
Subjective Ratings:	Workload	1.0						3					3.5
	Ride-quality comfort							2					3.25
	Turbulence effect							D					D
								Filled out after completion of TR-360					Filled out at the end of route

TABLE VIII - SUMMARY OF RUN SET 4 DATA - FLIGHT 3-76, ATF/SMCS ON

	Parameters	Terrain segment number and terrain types											
		Ocean	1 Rugged	2 Rugged	3 Moderate	4 Flat	5* Moderate	6 Rugged	7 Mild	8 Rugged	9 Mild	10 Moderate	11 Flat
TF performance	$\sigma_{\Delta he}$ - m		88.5	107.1	123.2		136.5	75.2	14.7	94.9	31.1	68.4	7.4
	$\Delta_{he_{mean}}$ - m		205.6	266.6	253.8		278.6	221.1	146.2	250.2	151.7	192.8	71.5
Pilot performance	$\sigma_{vert\ bar}$ - deg		1.038	2.801	1.186	Data not available	5.197	1.172	1.083	8.280	8.579	1.266	4.359
	$\sigma_{\Delta MN}$		0.010	0.013	0.027		0.019	0.028	0.009	0.026	0.012	0.021	0.008
	$\sigma_{\Delta PLA}$ - deg		6.7	8.7	11.3		5.5	4.5	6.7	5.9	5.3	3.3	9.1
Environmental conditions	$\sigma_{n_{zp}}$ - g	0.051	.378	.399	.325		.381	.375	.170	.360	.208	.271	.102
	$\sigma_{n_{yp}}$ - g	.016	.034	.031	.030		.032	NA	.037	.032	.039	.037	.037
	$\sigma_{n_{z_{cg}}}$ - g		.451	.455	.382		.399	.431	.209	.419	.225	.324	.137
	σ_{w_g} - m/s	.076	.488	.640	.274		.335	.366	.305	.244	.305	.305	.213
	σ_{v_g} - m/s	.189	.705	.680	.616		.442	.610	.777	.649	.768	.777	.741

*Fly-up had occurred during this segment.

No subjective data available.



MTF feedback gains and lag:

	Kst (g/cm)	Kg (g/g)	τ (second)
Flight test	0.142	0.4	1.0
Simulator test (reference 1)	0.197	0.5	0.5

VSD gain sensitivity settings:

Position switch	K_{VSD} (cm/g)
A	2.87
B	1.78
C	0.97

Figure 1.- MTF/pilot control loop block diagram.

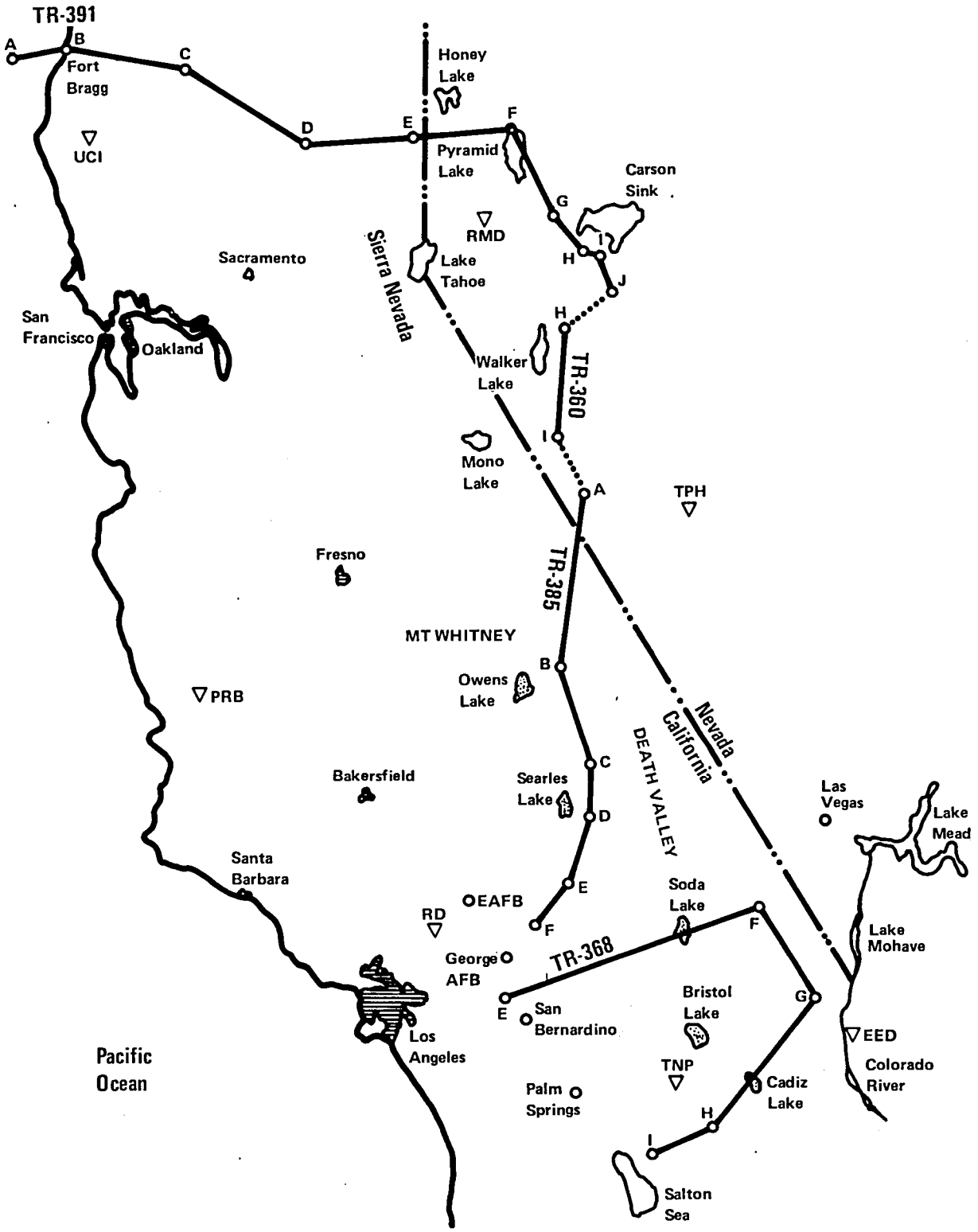


Figure 2. - Map of TR-368 and TR-391/360/385 routes.

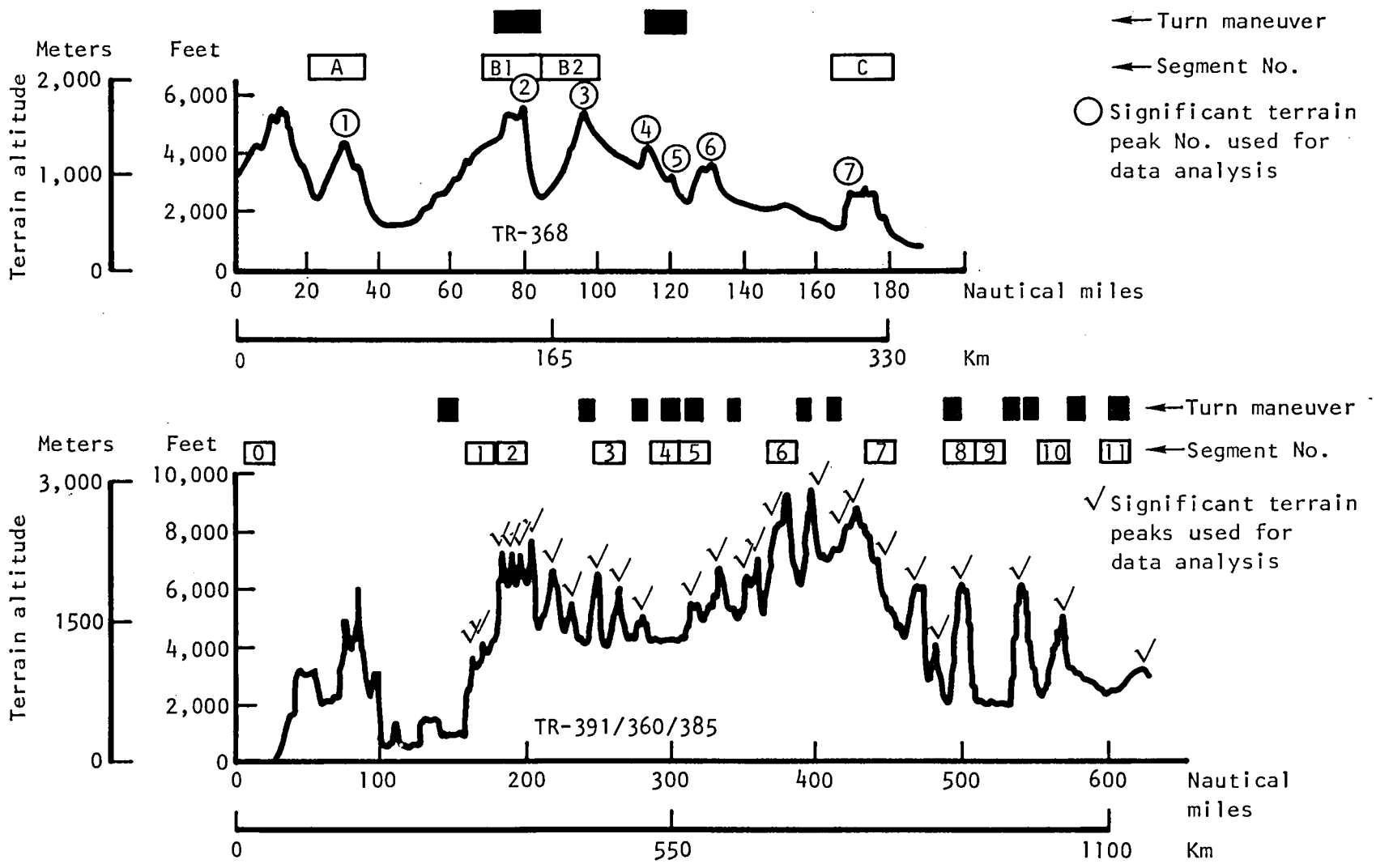


Figure 3.- Terrain profiles over short- and long-duration routes.

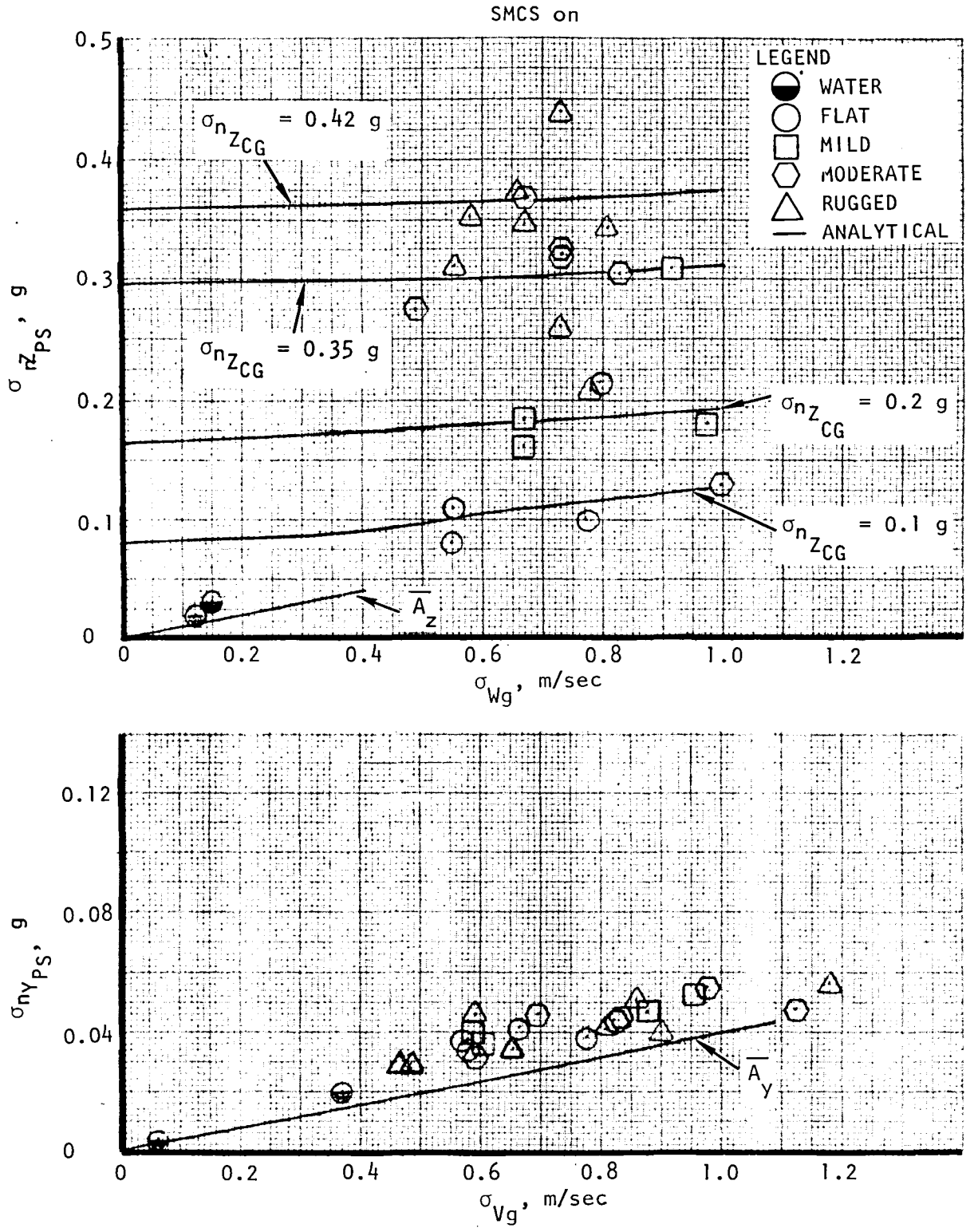


Figure 4.- Measured accelerations at pilot seat versus estimated turbulence - SMCS on from run sets 2 and 3.

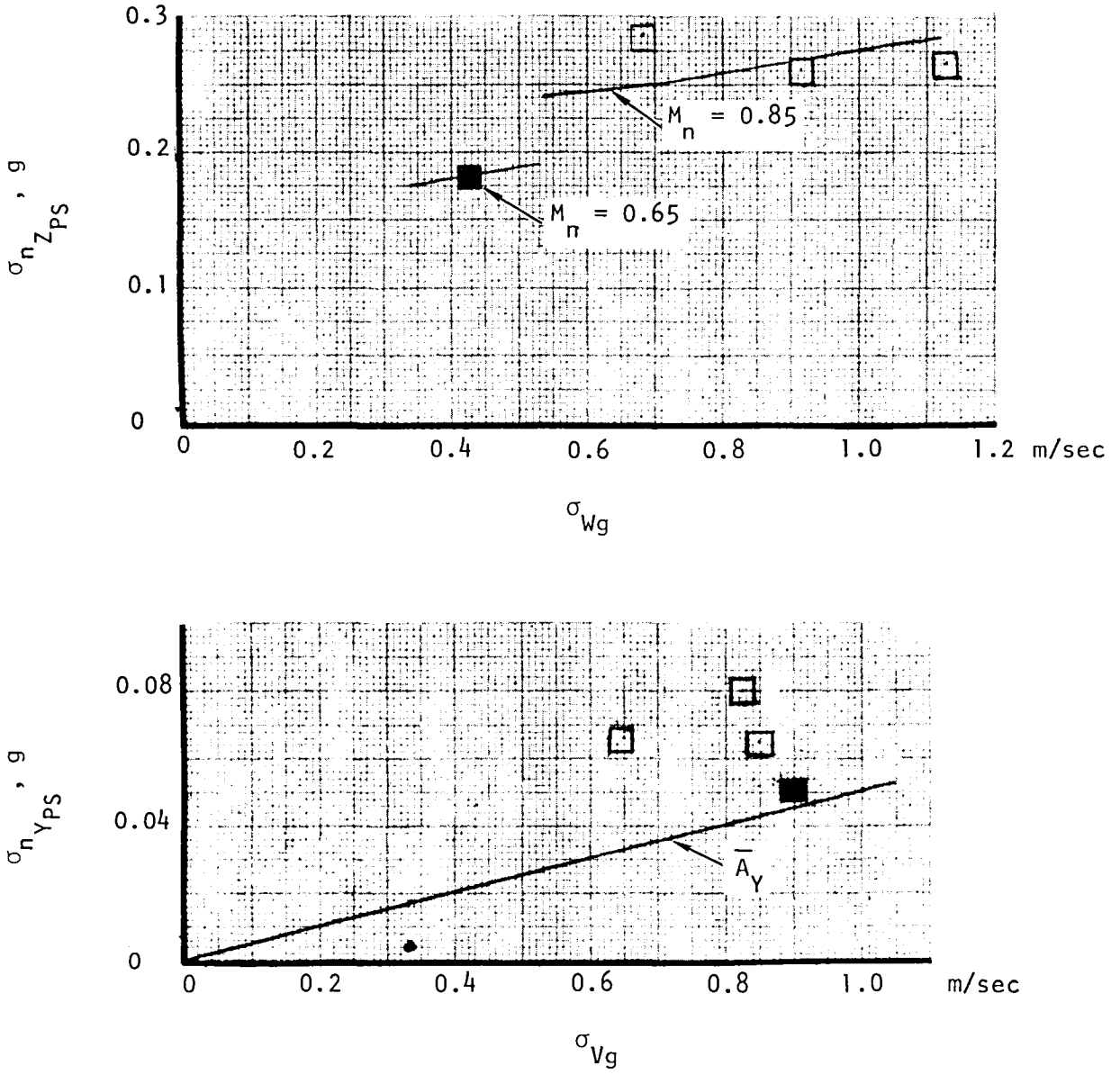


Figure 5.- Measured accelerations at pilot seat versus estimated turbulence - SMCS off from run set 2.

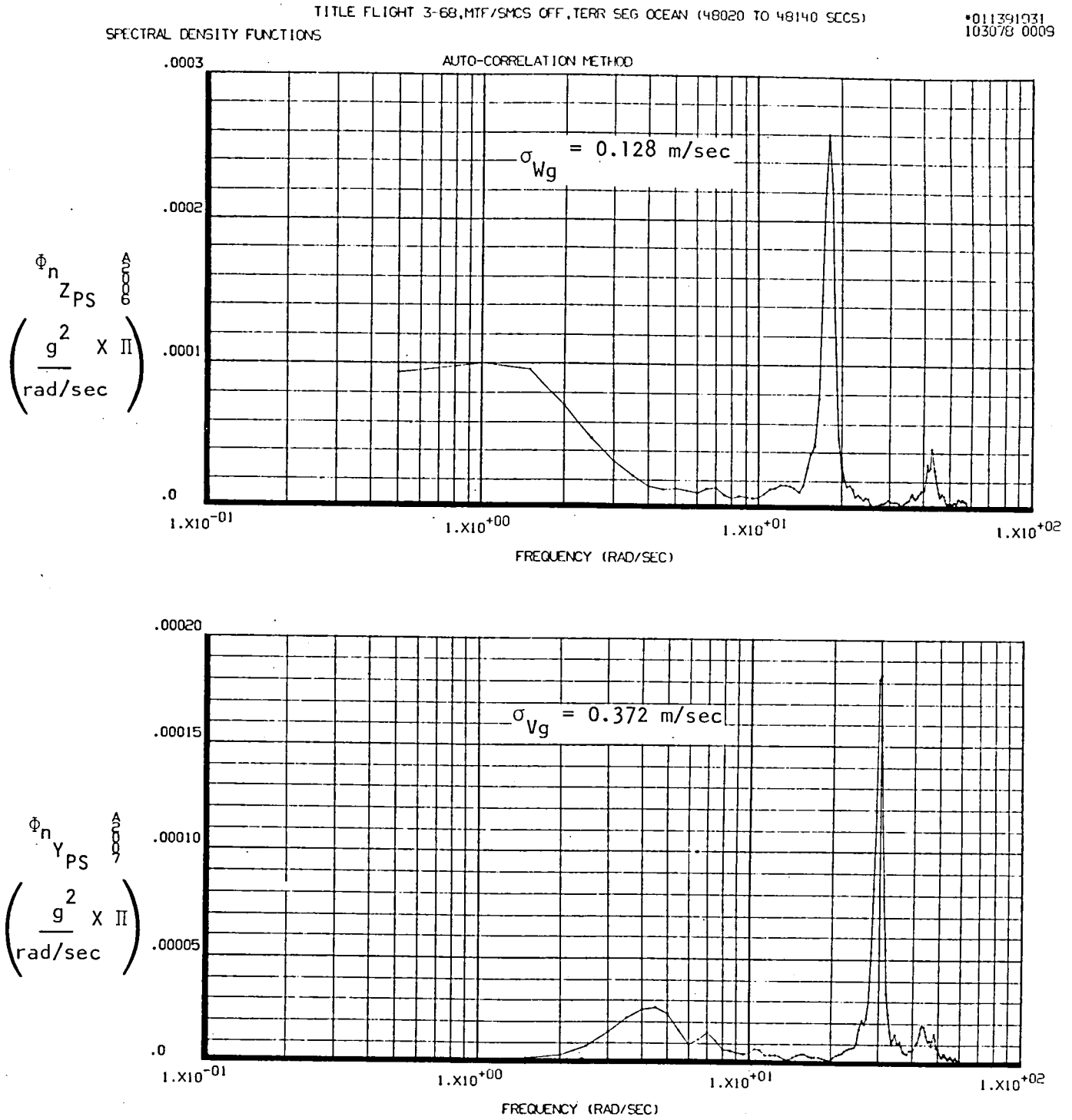


Figure 6.- PSD of vertical and lateral accelerations at pilot station - SMCS off, ocean.

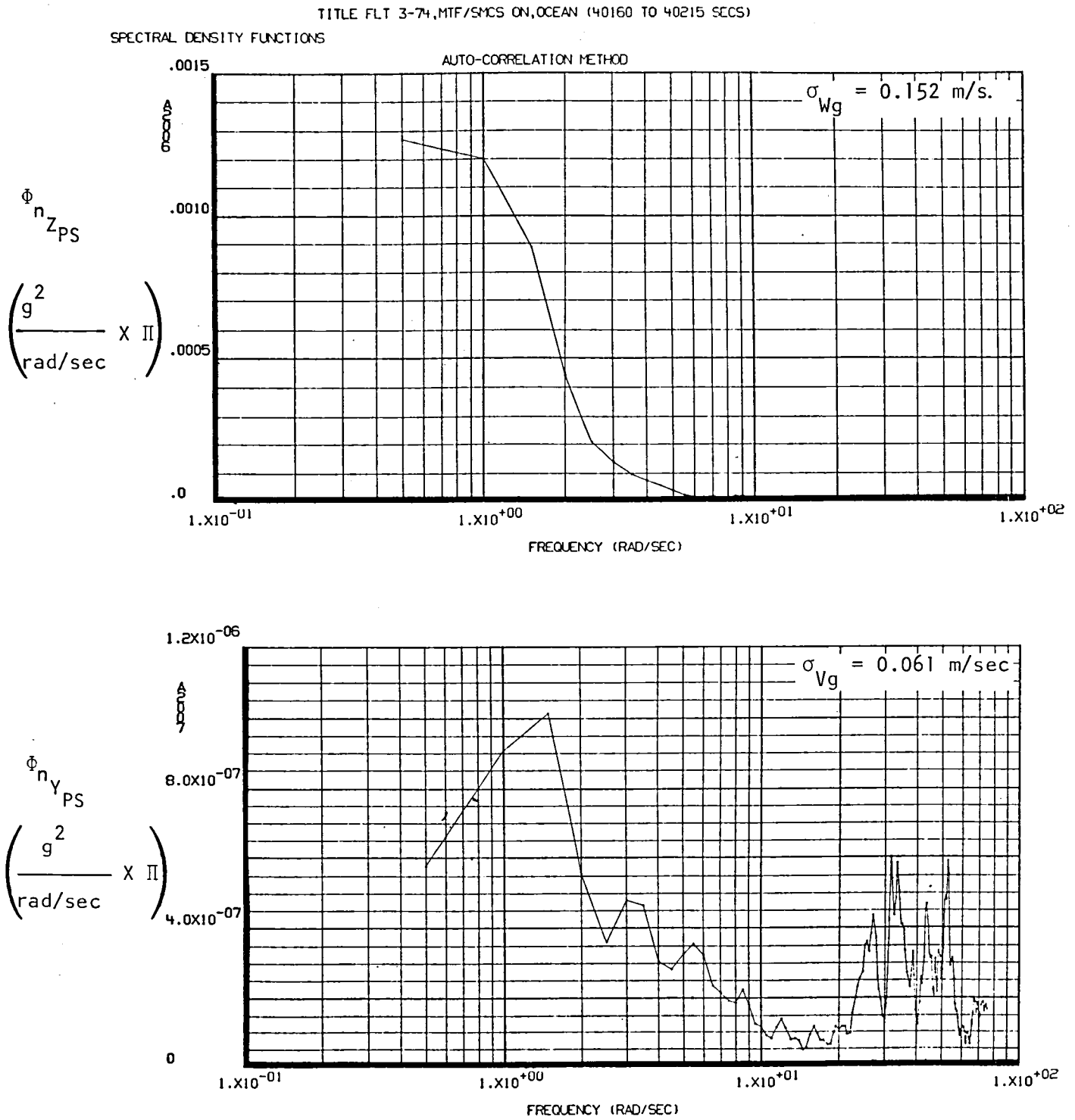


Figure 7.- PSD of vertical and lateral accelerations at pilot station - SMCS on, ocean.

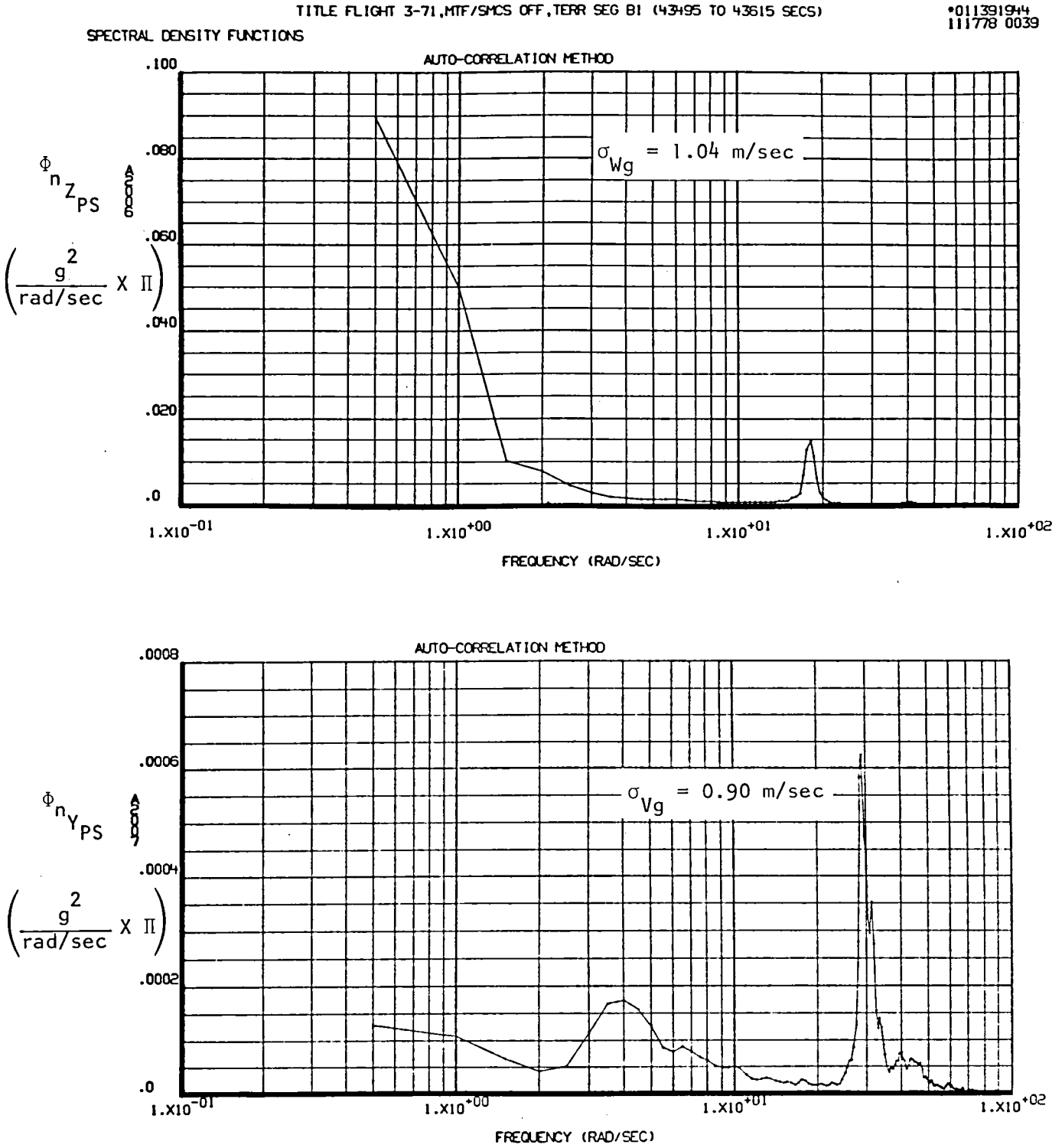


Figure 8.- PSD of vertical and lateral accelerations at pilot station - SMCS off, terrain segment B1.

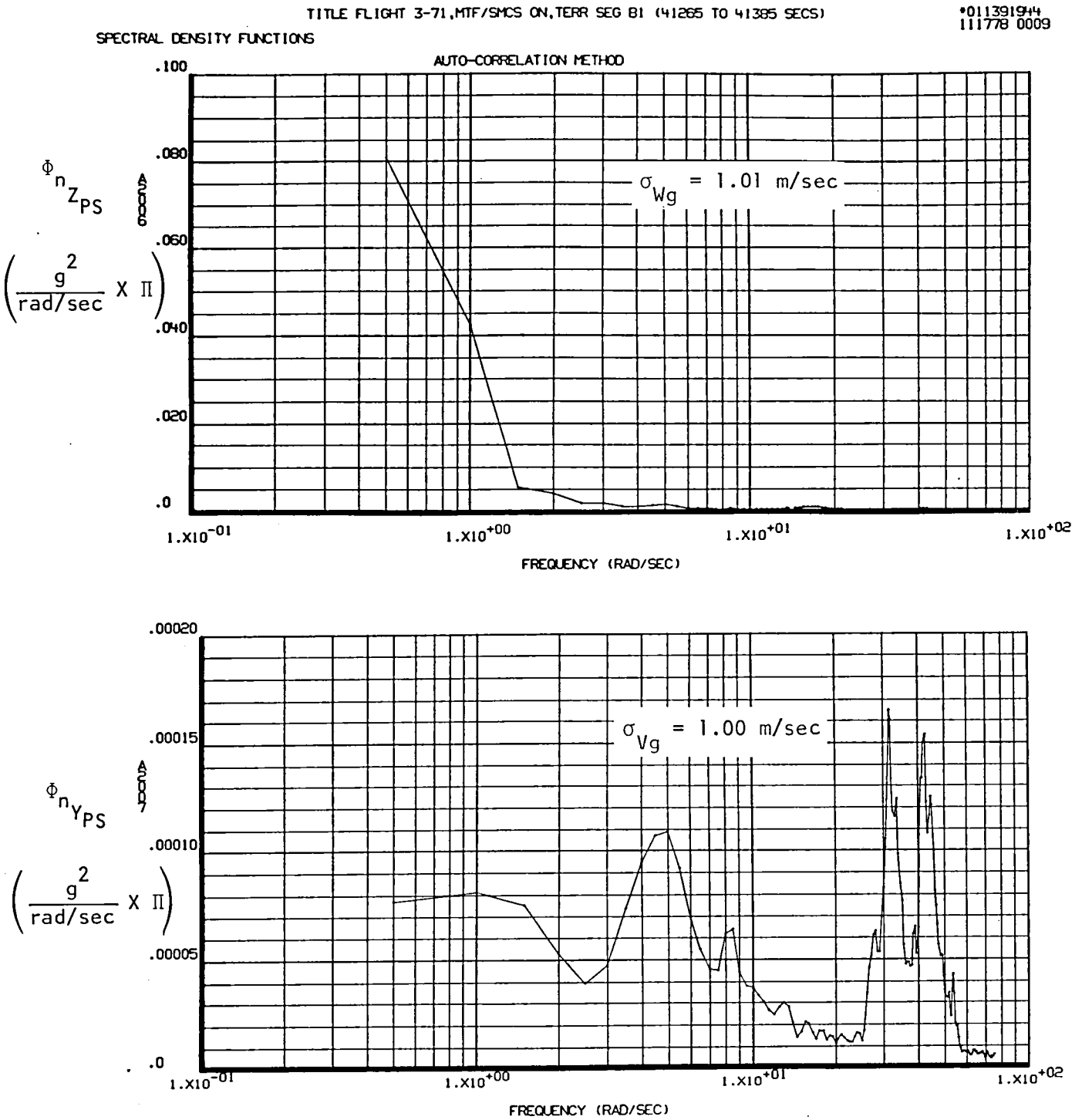


Figure 9.- PSD of vertical and lateral accelerations at pilot station - SMCS on, terrain segment B1.

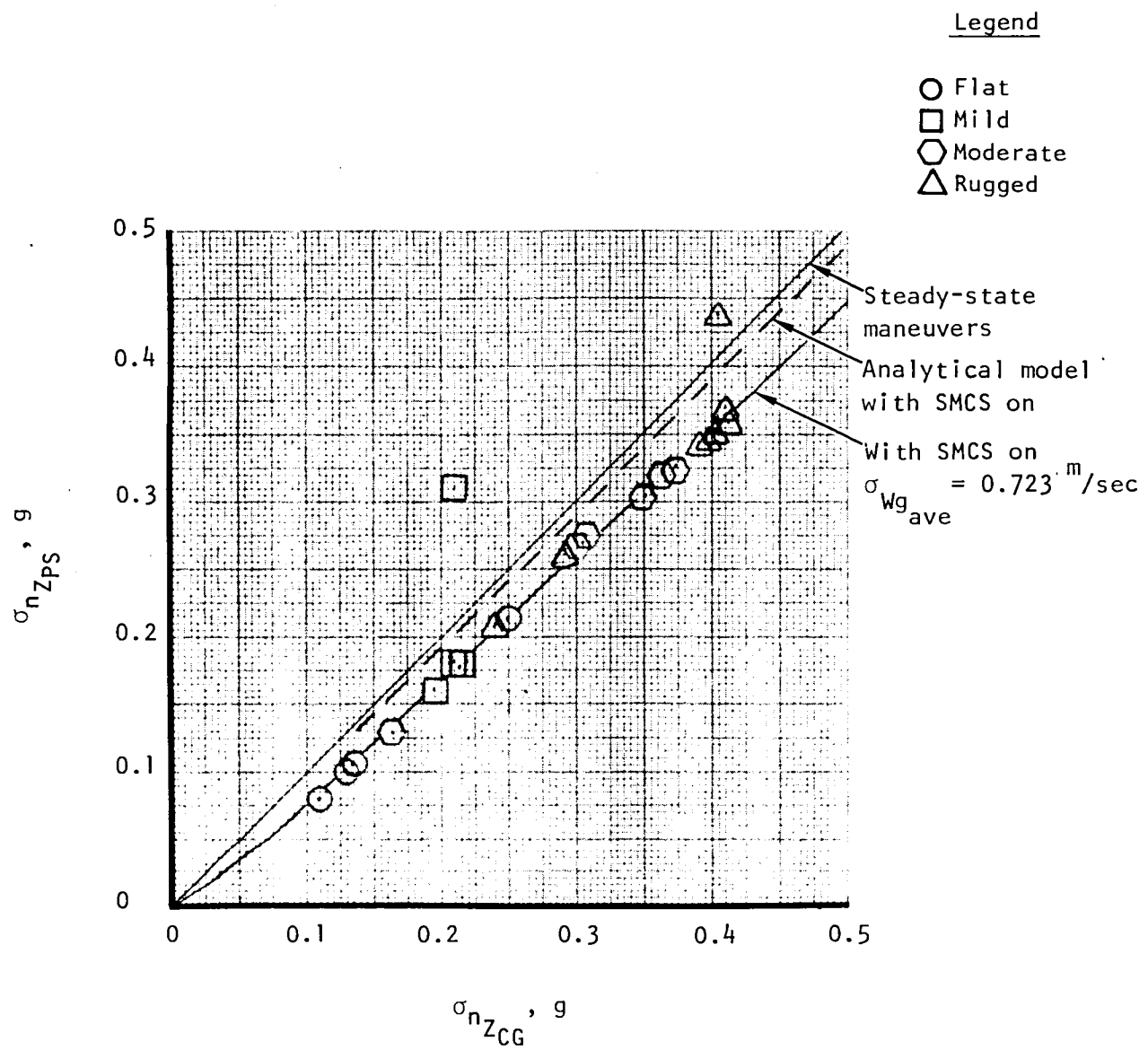


Figure 10.- Pilot seat vertical acceleration versus normal acceleration at CG.

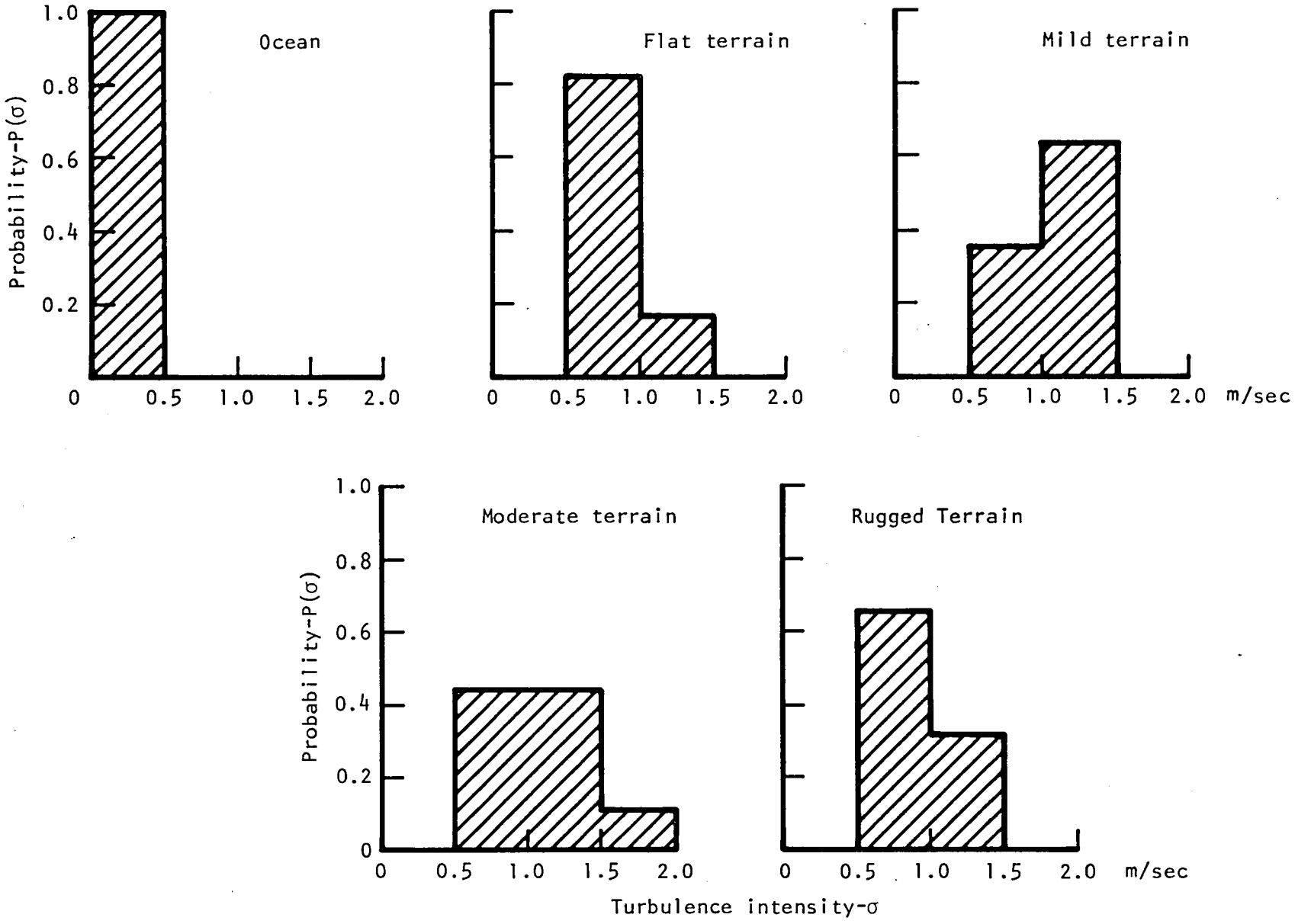


Figure 11.- Correlation of terrain and estimated turbulence level.

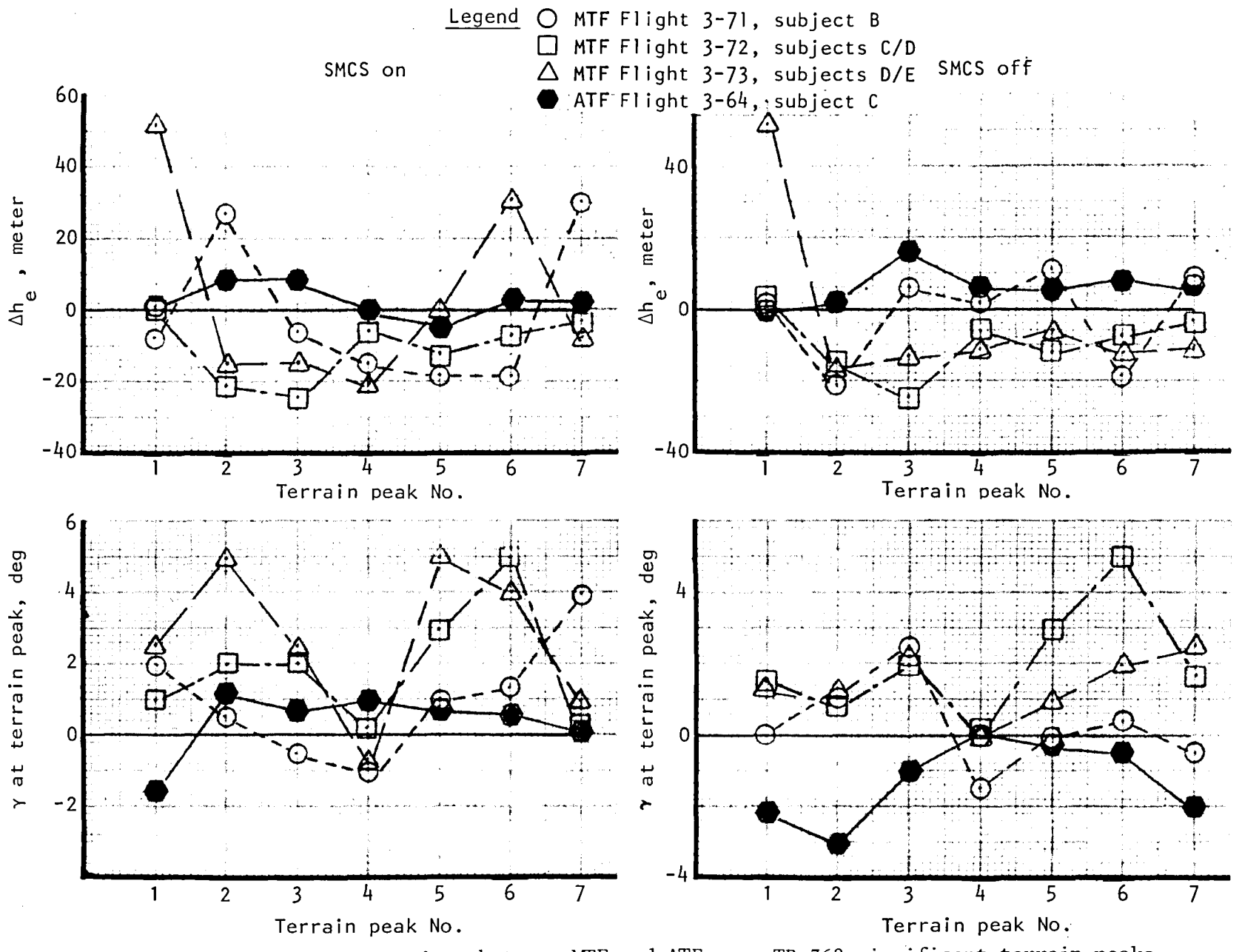


Figure 12.- TF performance comparison between MTF and ATF over TR-368 significant terrain peaks.

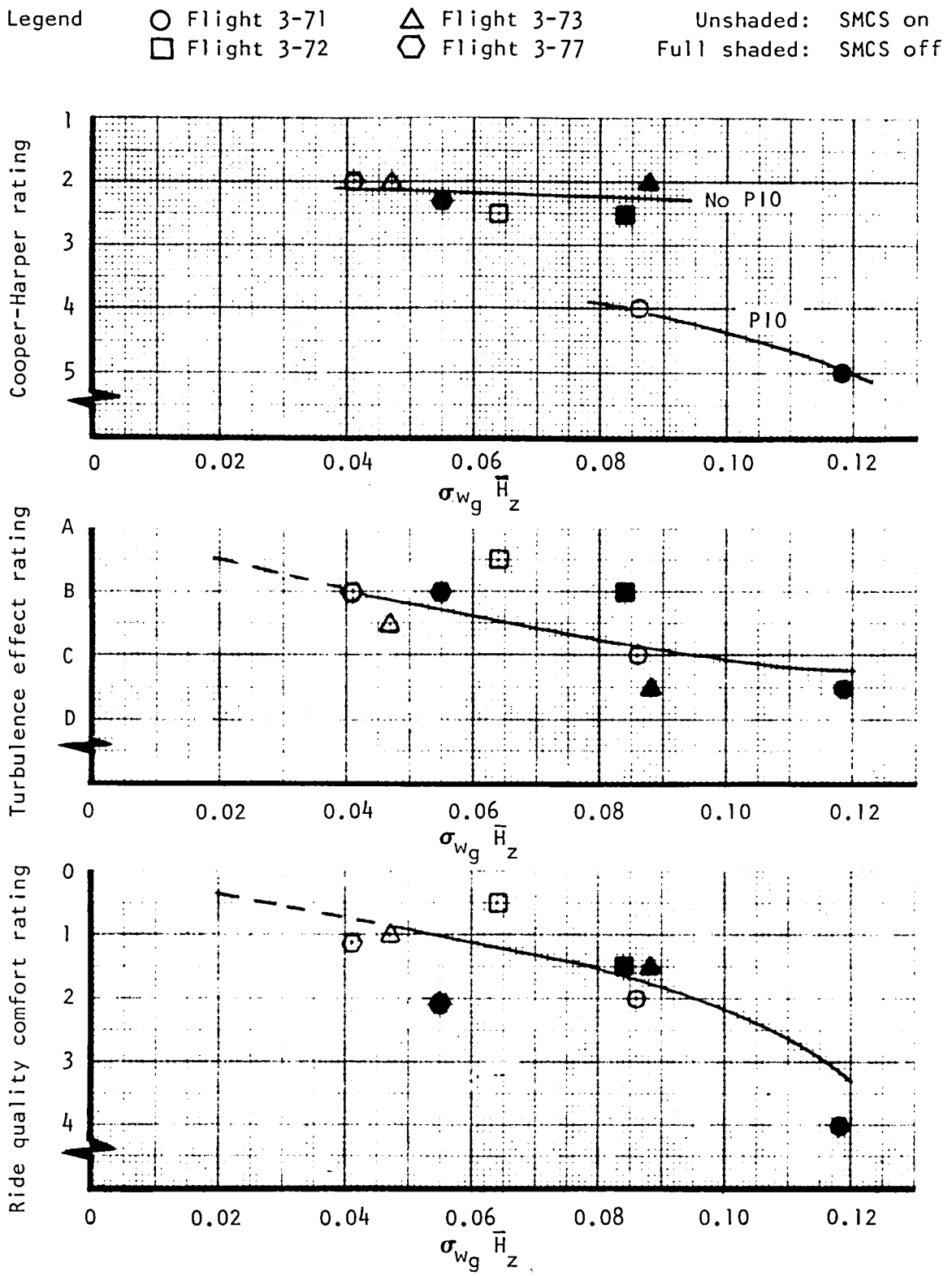


Figure 13. - Pilot ratings versus $\sigma_{w_g} \bar{H}_z$ for SMCS on and off conditions.

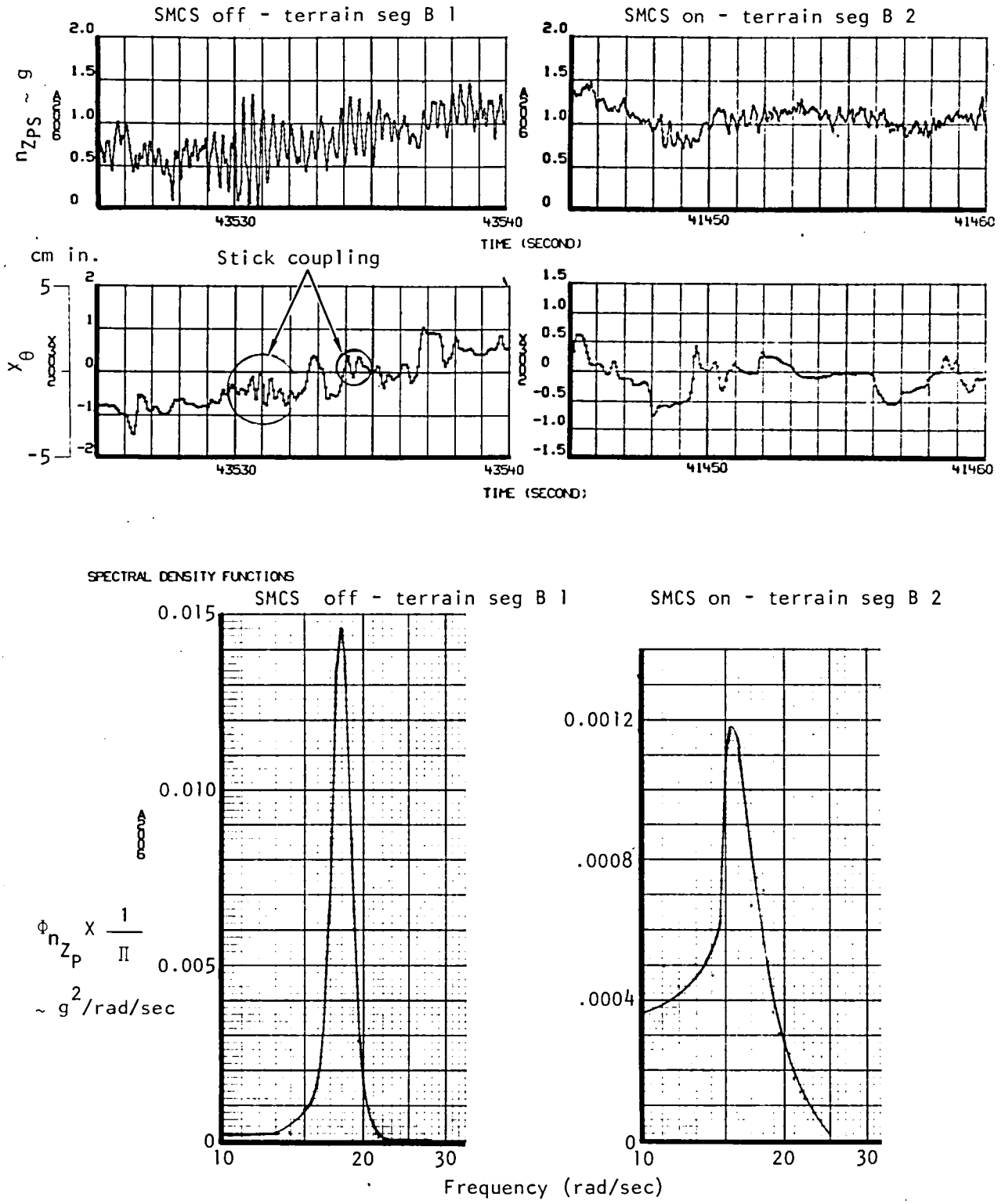


Figure 14. - $n_{Z_{PS}}$ and X_θ time history traces and $\Phi n_{Z_{PS}}$ plot-flight 3-71.

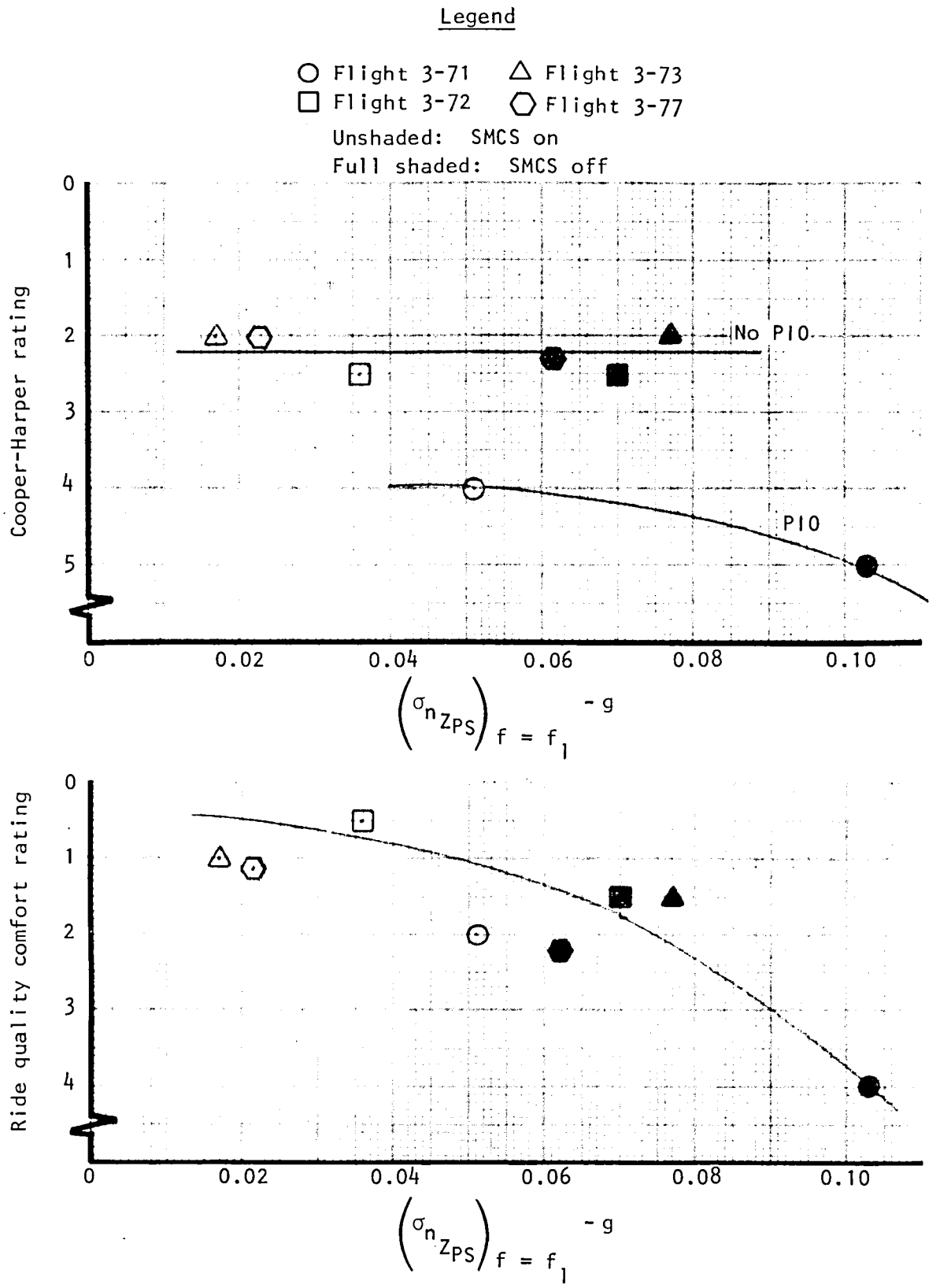


Figure 15. - Pilot ratings versus $\left(\sigma_{n_{Z_{PS}}}\right)_{f = f_1}$ for SMCS on and off conditions.

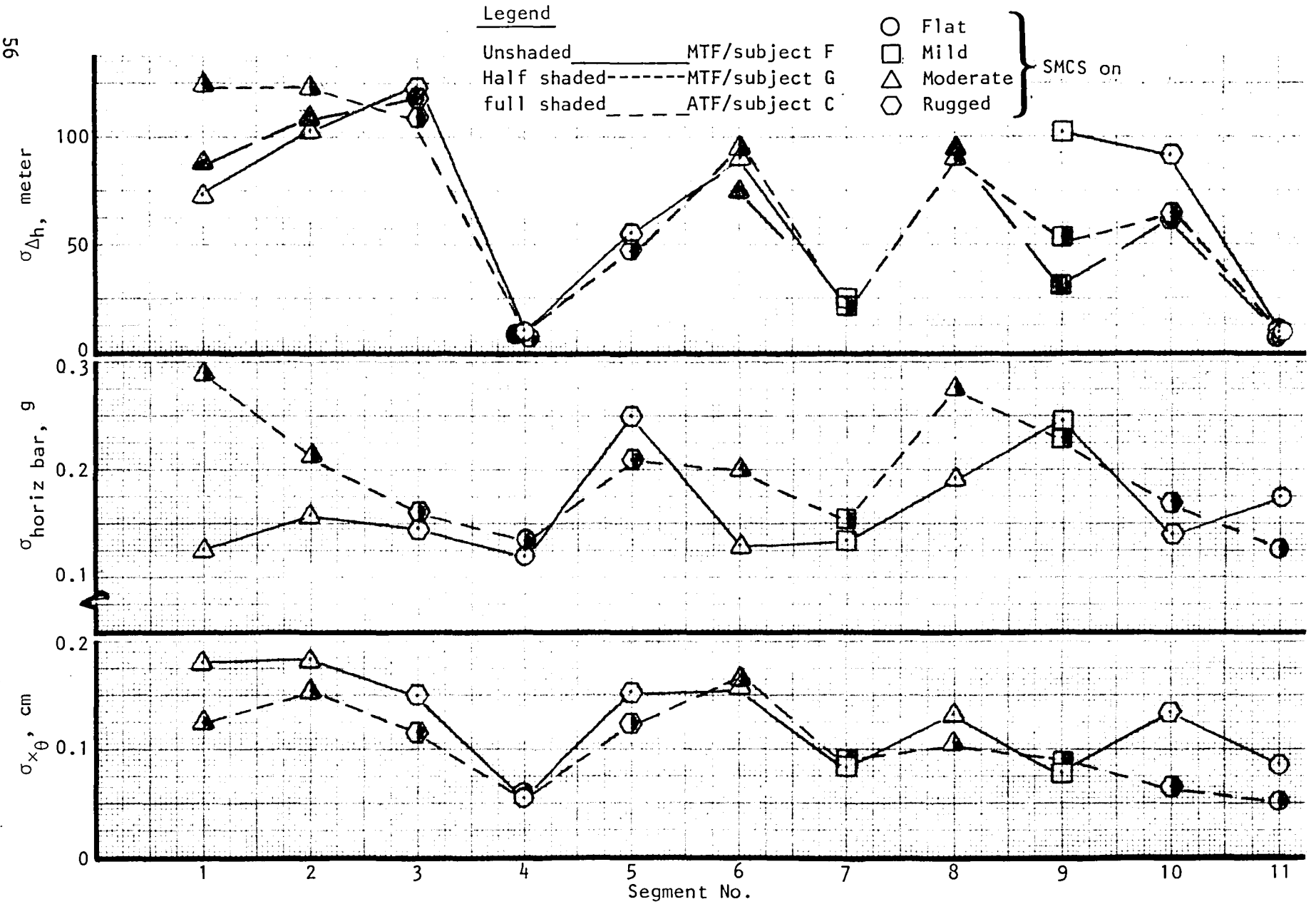


Figure 16.- Standard deviation of Δh, horizontal bar and stick displacement versus terrain segment No.

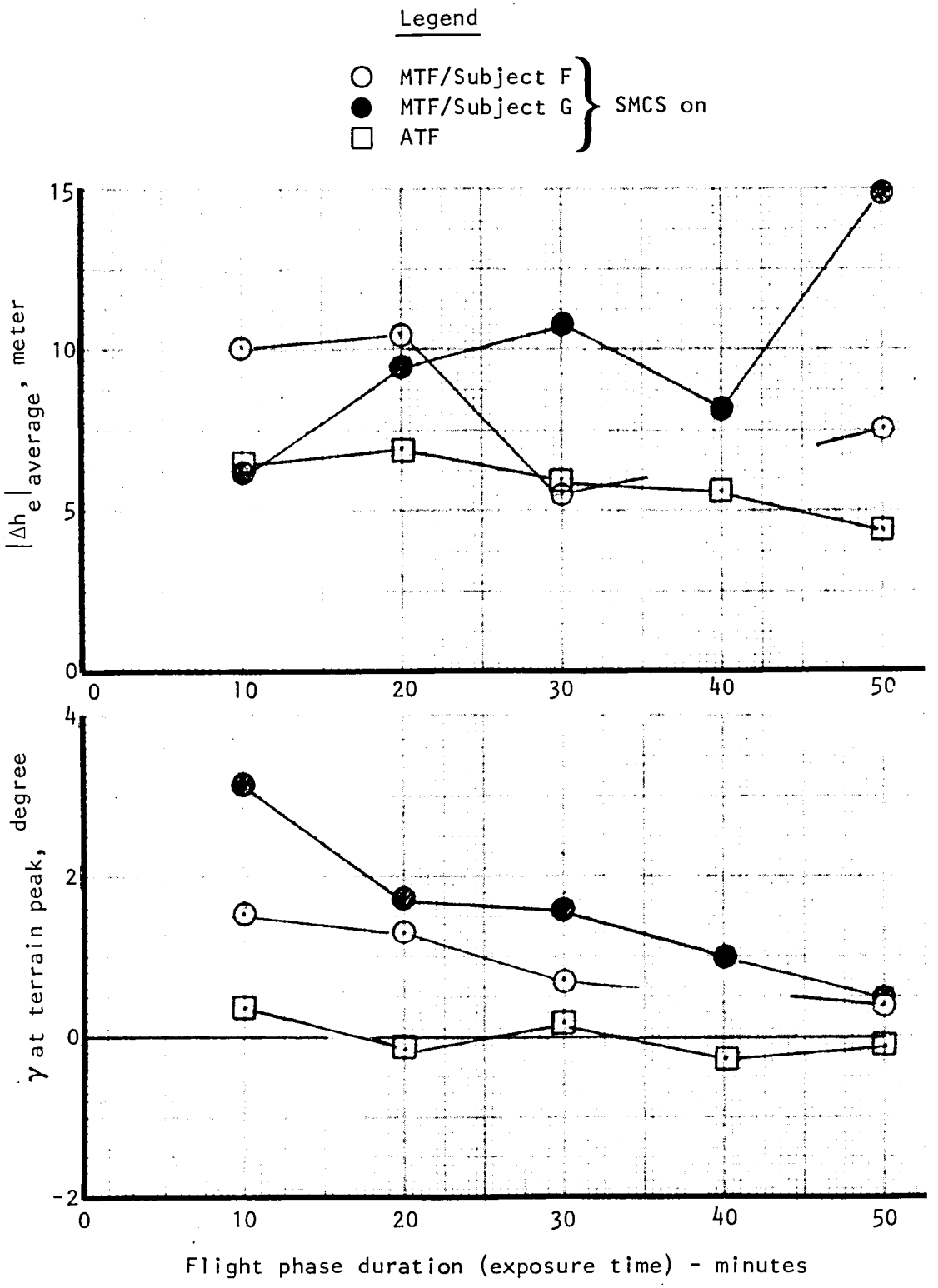


Figure 17.- TF performance comparison between MTF and ATF over TR-391/360/385 significant terrain peaks.

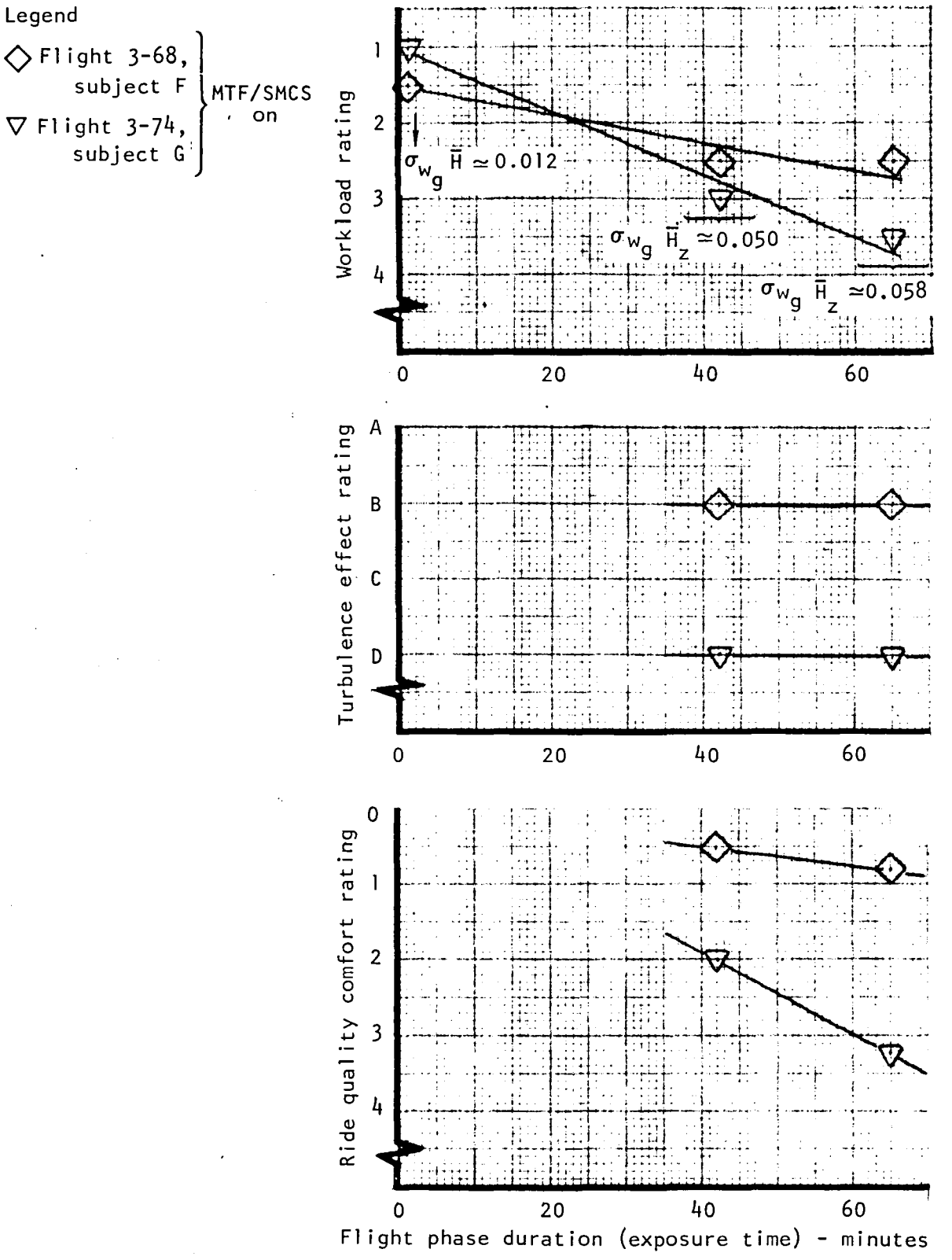


Figure 18. -Pilot ratings versus exposure time for long -duration runs - run set 3.

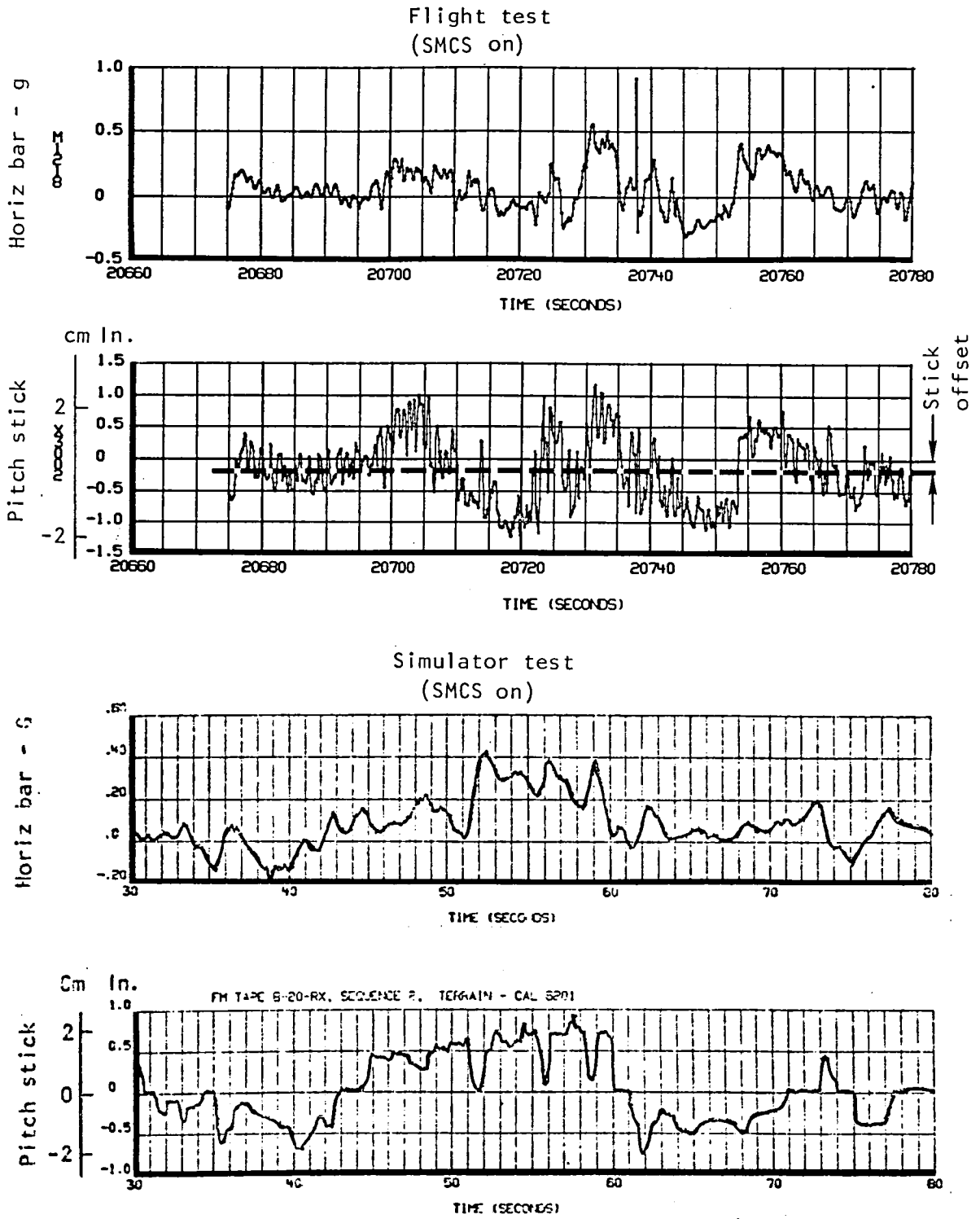


Figure 19.- Typical time history traces of horizontal bar and stick displacement.

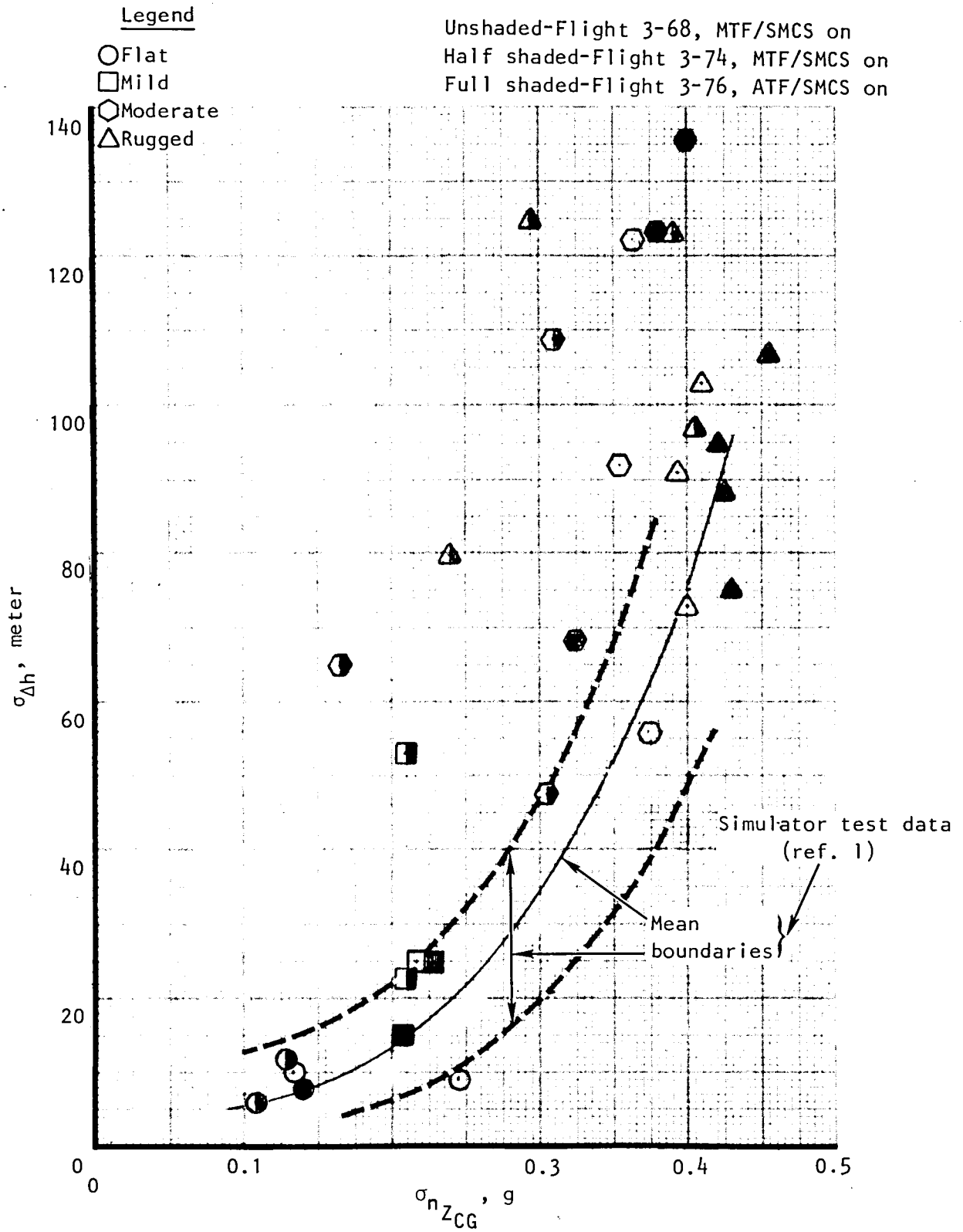


Figure 20.- TF performance versus maneuver load.

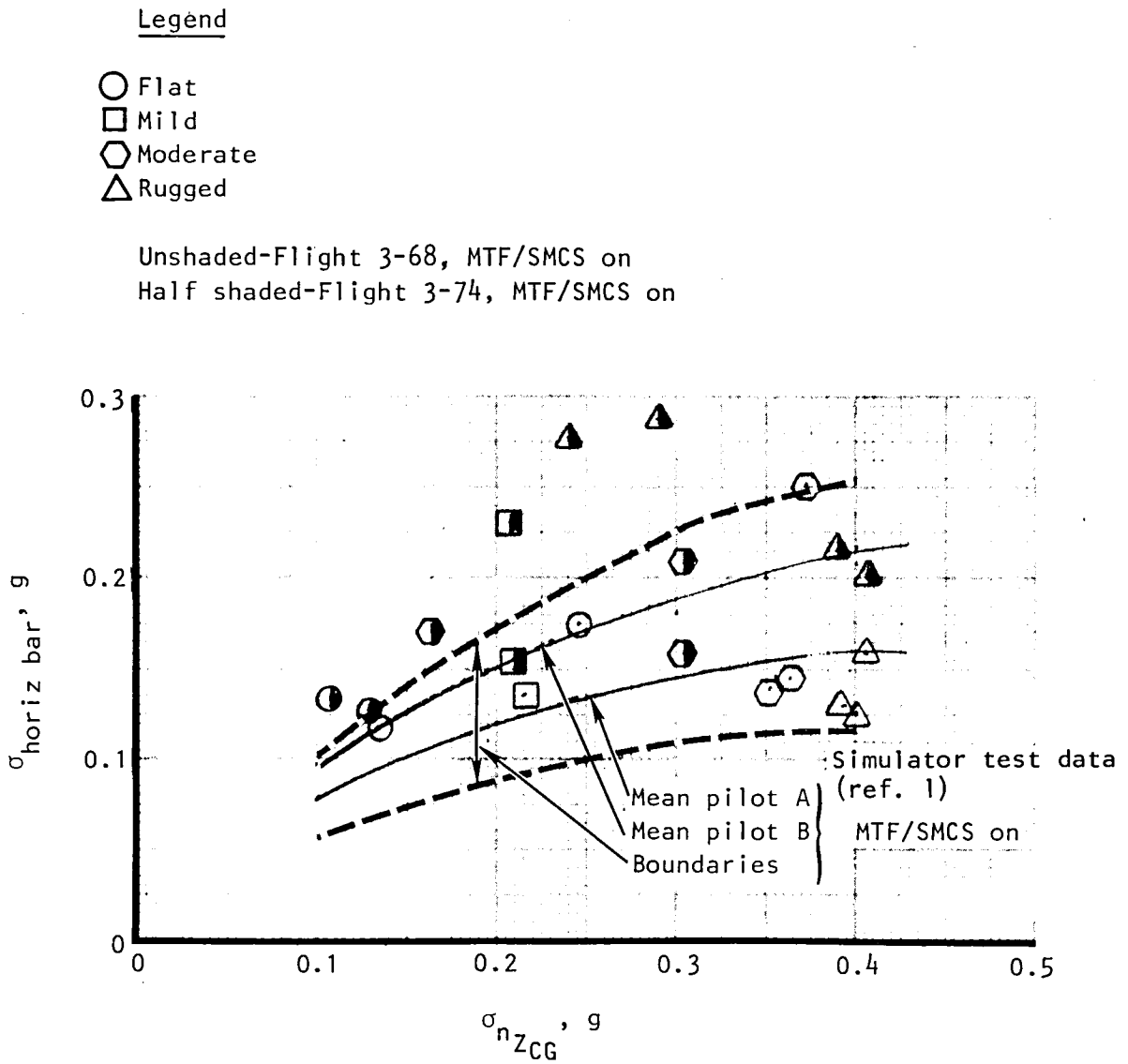


Figure 21.- Pilot tracking performance versus maneuver load.

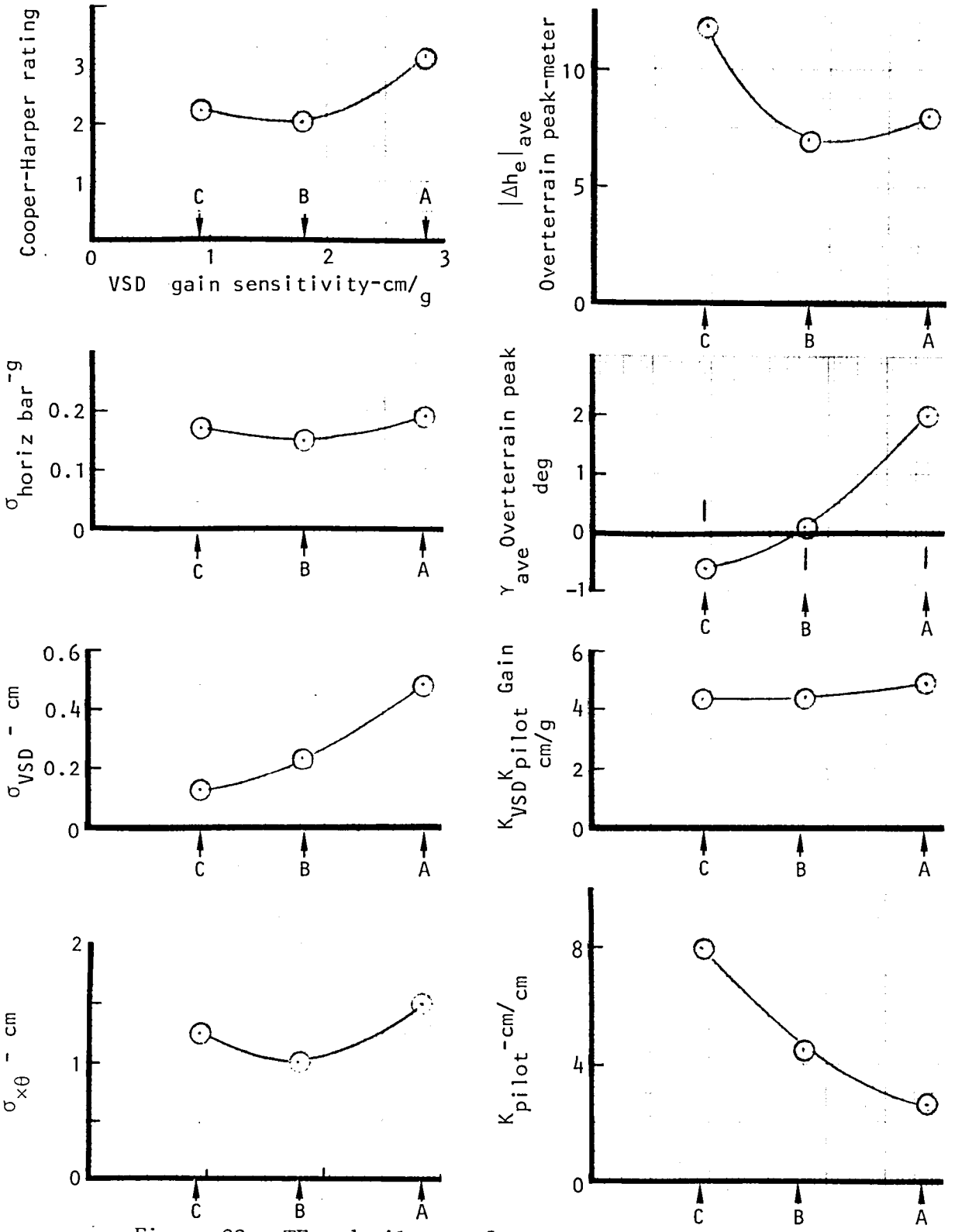


Figure 22.- TF and pilot performance measures versus VSD gain sensitivities - run set 1.

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15. Supplementary Notes

NASA Technical Monitor: Melvin Sadoff, Ames Research Center
NASA Program Manager: Jack Nugent, Dryden Flight Research Center

16. Abstract

A research program was conducted to study pilot performance during terrain following flight for ride quality criteria validation. The B-1 flight test program conducted by the Air Force/Rockwell provided data for these investigations.

Data from manual and automatic terrain following operations conducted during low level penetrations were analyzed to determine the effect of ride qualities on crew performance. The conditions analyzed included varying levels of turbulence, terrain roughness, and mission duration with a ride smoothing system on and off.

The results of this study highlight some of the first-order interactions between ride qualities and pilot/vehicle performance and provide limited validation of the B-1 ride quality criteria. Results obtained in an earlier B-1 flight simulation program correlated well with the flight test results.

17. Key Words (Suggested by Author(s))	18. Distribution Statement
Ride qualities criteria Manual terrain following Ride smoothing system Structural mode control system Correlation of flight test and flight simulation results	Unclassified - Unlimited STAR category: 05

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