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CARRIER LANDING PERFORMANCE; AN ANALYSIS OF FLIGHT TESTS UNDER SIMULATED PITCHING DECK CONDITIONS

(Final Report)

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FOREWORD

This report covers one phase of an overall program aimed at improved carrier landing methods and systems. This phase deals with determination of pilot/aircraft characteristics during carrier landings with pitching deck conditions.

This program was directed by the Aeronautics Division of the Office of Naval Research and cosponsored by the Naval Air Systems Command and the Naval Air Test Center under Contract Nonr 4156(00). The work was performed by Systems Technology, Inc., Hawthorne, California. Mr. G. Flohil, ONR Code 461, was the Navy's project officer and Mr. Irving Ashkenas was STI's Technical Director. The STI project engineers were Tulvio Durand, who carried out the initial portion of the program, and Gary Teper, who completed the program after Mr. Durand's resignation to form his own company. The authors gratefully acknowledge the assistance of Messrs. John McDonnell and John Best during the actual flight test program; and of Messrs. Duane McRuer, Robert Stapleford, and David Weir during the data reduction and interpretation process. Mr. Joseph Durand was responsible for the design and construction of the specialized test-gear utilized; and also assisted Mr. Anthony Campbell in obtaining the FLOLS servo response data. Special appreciation is due the pilots and ground personnel of the Carrier Suitability Branch of NATC who, in many instances, worked after hours to gather the data reported here.

ABSTRACT

A shore-based flight test program was conducted at the Naval Air Test Center, Patuxent River, Maryland. Its objective was the determination of pilot/aircraft characteristics during simulated carrier landings with pitching deck conditions using the Fresnel Lens Optical Landing System (FLOLS). The results indicate that a pilot can and will track a moving FLOLS "meatball." Significant performance variations were found which were a function primarily of airplane type. Reductions of as much as 50 percent in the altitude dispersions of some airplane types were indicated for Compensated Meatball Stabilization (CMS) of FLOLS. Limited data also indicate that FLOLS error perception is far better than expected. At one mile range the pilots were able to resolve altitude errors as small as 6 ft during the day and 12 ft at night; it had previously been assumed that the minimum detectable altitude error at one mile was 54 ft.

CONTENTS

FIGURES

TABLES

SYMBOLS

C	Normalized crosscovariance function
C_{xx}	Autocovariance of function x
C_{xy}	Crosscovariance of functions x and y
$E[\ ]$	Expected value
$G(s)$	Transfer function
h_a	Aircraft altitude from nominal path
h_c	Commanded aircraft altitude from nominal path
h_d	Desired altitude
h_e	Altitude error
j	$\sqrt{-1}$
N	Number of samples
R	Range
R	Normalized autocorrelation function
R_{xx}	Autocorrelation of function x
R_{xy}	Crosscorrelation of functions x and y
s	Laplace transform variable
t	Time
T	Time-to-go, a particular time
Z_e	Cell displacement of Fresnel Lens meatball from datum
α	Beam angle
ϵ	Visual angle
σ	Root mean squared value
τ	Time delay or advance
φ_c	Commanded Fresnel Lens roll angle
φ_L	Fresnel Lens roll angle
Φ	Phase angle
ω	Frequency
$\lvert\ \rvert$	Magnitude of
$\measuredangle$	Phase angle of

SECTION I

INTRODUCTION

A. BACKGROUND

The Navy continues to strive to reduce the number of carrier landing accidents and to extend aircraft recovery to more severe conditions. For the last few years we have studied (Refs. 1, 2, and 3) that facet of carrier landing which we believe is a major cause of accidents and the key to extended recovery operations — vertical flight path control. Our analytical studies and fixed-base simulation led to a number of concepts which appeared to have the potential of significantly improving landing performance. These concepts centered on modified stabilization and operational use of the Navy's current primary visual landing aid, the Fresnel Lens Optical Landing System (FLOLS).

Initial steps were taken towards implementing Compensated Meatball Stabilization (CMS), the modified FLOLS control logic recommended in Ref. 1. It was found that an improved overall carrier landing aid stabilization system (CLASS) was needed before advanced control logic could be used. (CLASS is currently being developed under Contract N00156-69-C-0710.) We also found the need for additional operational data and, to this end, various tests were conducted. The work reported herein covers these tests.

B. OBJECTIVES OF CURRENT PROGRAM

Knowledge of the characteristics of the pilot/aircraft during landing approach are a prerequisite for successful implementation of CMS. The main portion of the current program was concerned with a shore-based flight test program aimed at determining these characteristics and proving the feasibility of CMS by observing the piloted airplane's response to commanded "meatball" motions. It was also hoped that the flight test would provide background data for considering possible changes to current recovery doctrine, or for specific testing needed to update present recovery practice.

A second part of our program was determining whether the performance of the current FLOLS servos would meet the requirements of improved stabilization concepts.

Finally, existing carrier motion data on the USS INDEPENDENCE (CVA-62) in sea state 6 conditions was analyzed to obtain a quantitative description of that portion of the severe "pitching deck" aircraft recovery environment. The results of this latter work are separately reported (Ref. 4).

C. MAJOR CONCLUSIONS

1. The flight test program was designed to simulate carrier landings with FLOLS "meatball" motions that a pilot would see under pitching deck conditions. The results indicate that the pilot can and will track a moving meatball. Under these conditions significant performance variations were found to exist which were a function primarily of aircraft type (see p. 36).

2. The flight test results indicate that Compensated Meatball Stabilization (CMS) is capable of decreasing the altitude dispersions of some airplane types as much as 50 percent with little or no effect on the performance of others. Because the effect is either neutral or favorable, regardless of aircraft type, CMS can provide a net overall performance improvement for carrier recoveries in high sea states (see p. 39). For good tracking aircraft, optimum CMS can theoretically reduce landing accidents by roughly a factor of 5 (see p. 41).

3. The form of the ideal CMS "law" that emerges from these data is that of a simple time (or phase) shift as a function of airplane type; this "law" is consistent with the theoretical considerations of Ref. 1 (see p. 39).

4. The reduced data currently available are considered insufficient to define a tenable variation of optimum CMS lead with airplane type. However the available data do support the notion that even a fixed lead (i.e., not variable with airplane type) would offer significant albeit nonoptimum improvement (see p. 39).

5. Performance variations between pilots in a given airplane type are noticeable but not overriding as regards the efficacy of CMS for that type (see p. 36).

6a. Previously it had been assumed (e.g., Refs. 1-3) that the pilot's perception of FLOLS was measured by the visual angle (the angle between the meatball and the datum bar with apex at the pilot's eyeball). The relation between the FLOLS visual angle and the aircraft altitude error varies inversely proportional to range squared. The flight test results indicate that the cue used from FLOLS is the beam angle (the angle between the meatball and the datum bar with apex at the virtual image) or its equivalent, meatball displacement (see Fig. 10). The relation between beam angle and the aircraft altitude error varies inversely proportional to only range.

b. The flight tests show that the pilot's ability to discriminate meatball displacement (i.e., beam angle) errors is independent of range, for ranges as large as 10,000 ft. Furthermore, this error detection acuity is twice as good in daylight as at night. At one mile range the pilot is able to resolve height errors as small as 6 ft during the day and 12 ft at night. It had previously been assumed that the minimum detectable error at one mile was 54 ft (see p. 48).

c. It was also expected that in the absence of (simulated) air wake disturbances the pilot, using the visual angle from FLOLS, would largely compensate for the range-varying nature of the display and effectively operate on aircraft altitude error <u>independent of range</u>. However, it was found, as noted above, that the pilot uses meatball displacement as a cue; and that he apparently operates on this information so that for a given aircraft altitude error signal his output <u>is</u> a function of range. That is, a given aircraft altitude error results in different pilot control inputs at close range than at far range. This range-dependent (simulated) behavior <u>is</u> consistent with (qualitative) operational experience (e.g., Refs. 13, 14) and, in this respect, the "simulation" is realistic.

7a. Describing function analysis techniques can be and were, with appropriate input-frequency tailoring, successfully applied to short-run-length measurements during range-fixed, time-invariant flight situations such as with a hovering helicopter (see p. 10). The technique can readily and economically be applied to the flight test identification of airplane/flight control system dynamic properties at a given (time-invariant) flight condition.

b. On actual approaches significant time-varying changes occurred in the pilot's, and pilot/vehicle/FLOLS closed-loop characteristics (as noted in 6c). When describing function analyses were applied to these time-varying data the results showed significant power at noninput frequencies. One consequence was to increase the apparent noise at shelf frequencies (Fig. 3a) sufficiently to make these usually marginal points unreliable (see p. 13). In spite of these difficulties, data derived from single run describing function calculations are qualitatively useful, particularly at the two lowest input frequencies where signal-to-noise is greatest.

c. To obtain improved definition, particularly in phase (which is critical regarding CMS), an alternate form of correlation was applied. In this technique ensemble averages replace time averages and the correlation functions are used directly rather than a frequency domain equivalent. For ergodic situations the results of the time domain analysis using an ensemble of runs and the describing function analysis using a single run would be identical. In time-varying situations, this equivalence no longer applies and the ensemble averaging technique gives results which can describe more of the output in a quasi-linear (albeit time-varying) model rather than casting such effects into remnant "noise." Although this technique requires more test data and more extensive data reduction effort than describing function techniques, it does enable the identification of system characteristics during the actual time-varying approach conditions (see p. 15).

8. The moving (shore based) meatball system developed for the flight test program can be used effectively as a training aid to improve pilot proficiency and acceptance of meatball tracking, thereby possibly reducing the pilot variations noted in item 5. Furthermore it also appears to provide a sensitive check on desirable versus marginal aircraft and subsystem characteristics (see p. 42).

9. The performance of the current FLOLS servo is good, but needs improvement to avoid dynamic beam errors discernible by the pilot, on the basis of the above results (see p. 67).

D. RECOMMENDATIONS

1. The basic notion of using CMS to reduce landing dispersions in high sea states is supported by the flight test data reported herein. It had been hoped that sufficient data would be taken and reduced during the current program to finalize CMS "laws" for a number of aircraft types and also to consider possible changes to current recovery doctrine. The flight test program was essentially "piggybacked" onto existing operations at the Naval Air Test Center and although data were obtained for a larger number of passes than originally anticipated, the mix of aircraft types, pilots, etc., represented is far from that corresponding to a good experimental design.

It had also been anticipated that previously developed describing function techniques would be directly applicable and that, therefore, the data requirements (i.e., the number of passes by a given pilot in a given aircraft type, etc.) and the data reduction efforts would be moderate. To identify system characteristics during actual approach situations, the development of an alternative data reduction technique was required. This correlation technique is less economic than describing function techniques insofar as data requirements and computation effort. The amount of reduced and analyzed data was accordingly limited to about 30 percent of the recorded and usable passes. Recovery of the information residing in the remaining raw data would provide added information on the required "optimum" variation of CMS lead with airplane type (item 4 above) and yield additional data on pilot variability in both performance and visual acuity.

Data were taken on two fully instrumented airplanes (F-4G and F-111B); reduction of these data would permit more detailed comparison with theory and holds great potential for furthering our understanding of the pilot/aircraft/FLOLS system.

In view of the above, it is recommended that serious consideration be given to implementing additional data reduction and analysis efforts. In this connection the available fully instrumented airplane data present a real opportunity to distinguish "good" and "bad" airplanes (independently of pilot's actions).

2. The Navy is currently interested in various "improved" Visual Landing Aids (VLA). To be seriously considered a new system should be an improvement over the current FLOLS. The fairly limited data obtained as a fallout of our tests indicate that long-range usefulness of FLOLS is greater than anticipated, but more definitive tests should be performed to determine the actual limits of FLOLS.

3. The Naval Air Test Center (NATC) should be provided with a good moving meatball system along with reliable data measurement, reduction, and analysis capabilities. This would give them a powerful additional tool for aircraft and subsystem evaluation. A similar moving meatball system should be of great use at all Naval Training Centers for pilot training and evaluation.

I. ORGANIZATION OF REPORT

Section II describes the flight test program and analysis of the data on in-flight pilot/aircraft characteristics. It is supported also by an Appendix which describes the physical test setup, the airplanes flown, etc.

Section I covers the data and conclusions pertaining to the pilot's perception of FLOLS.

Section IV describes tests of the current FLOLS servos.

Section V considers the possible impact of the studies on operational procedures.

Each of the above sections contains a summary of the pertinent detailed conclusions. The major conclusions and recommendations have been given above.

SECTION II

MEASUREMENT OF IN-FLIGHT PILOT/AIRCRAFT CHARACTERISTICS DURING LANDING APPROACH

A. BASIC PURPOSE OF TESTS

The flight test program investigated the pilot's ability and willingness to track a moving meatball in full-scale simulated carrier approaches. We hoped to obtain data on the effects of airplane model, configuration, and day/night on meatball tracking performance. There was no express provision for obtaining data on the airplane characteristics themselves (i.e., model, configuration, etc., effects).* This was beyond the scope of the program, which was essentially piggybacked onto existing or contemplated flight test activities at the Naval Air Test Center, Patuxent River, Maryland.

The foregoing was derived from our desire to:

1. Prove the feasibility of improved recovery operations through FLOLS stabilization laws reflecting pilot/airframe beam-following capabilities.

2. Provide background data for considering changes to current recovery doctrine, or for specific testing needed to update present recovery practice.

B. TEST PROCEDURE

A modified Mark 8 FCLP FLOLS unit which included an STI-designed lens roll servo drive was used to simulate the meatball motions that a pilot would see under heaving deck conditions. The servo was driven by a programmed altitude command stored on magnetic tape. During each pass the following measurements were recorded:

1. Altitude command, i.e., lens roll angle
2. Aircraft altitude, range, and lateral displacements as determined by SPN-42 radar
3. Pilot's meatball calls (high, low, center, etc.)

The details of the test setup are more fully described in Appendix A.

*However, such basic data were obtained, but are as yet unprocessed, for the F-4G and F-111B which were "fully-instrumented" aircraft.

About 375 passes were made by 14 pilots in 8 fixed-wing aircraft (A-7, F-4, A-3, A-4, F-8, RA5-C, F-6, F-111) in day and night landings and with and without APC; also fixed-range meatball tracking was performed in an H-34 helicopter. Of these passes, approximately 25 percent were calibration (fixed-beam) passes, radar lock-on was lost or radar data was too noisy to be useful on another 10 percent, and about 15 percent of the passes were used for pilot practice with the moving meatball. Runs representative of actual pilot performance under pitching deck conditions number about 180.

The data sought were those indicative of normal carrier landing technique. Therefore, the desired practices of holding angle of attack, lineup, and meatball, and flying the meatball versus spotting the deck, etc., were stressed in pilot/LSO-briefing/debriefing sessions. Pilots were asked to duplicate their usual control technique in the vicinity of the ramp throughout the 25 sec duration of the approach in order to reduce the effects of time variations. Two sets of inputs were used corresponding to 15 sec and 25 sec run lengths.

C. DESCRIBING FUNCTION DATA ANALYSES — RESULTS AND PROBLEMS

1. Describing Function Techniques

Best-fit linear describing functions have proven very powerful in analyzing data taken from other in-flight pilot/airframe tests (Refs. 5, 6, 7). Nevertheless, we were aware of possible problems that might beset their application in the present instance, viz.:

a. The possibility that the situation might be sufficiently time-varying to negate the successful use of the techniques.

b. The fact that the time on the beam — the run length — would only be of the order of 25 sec.

Accordingly, we took steps in designing the input, i.e., the programmed command tape, to circumvent, or at least expose, these potential problems.

The input was the sum of 5 sine waves of frequency and amplitude shown in Fig. 3a. The frequencies were picked to reveal possible time-varying (nonstationary) or nonlinear system behavior, to obtain an indication of the noise level in the data, and to get as much usable data in the short run length as possible. The frequencies correspond to 2, 3, 4, 5, and 7 cycles in the 25 sec run length used in analyzing the data. The 1 and 6 cycle per run length frequencies were deliberately omitted from the input. In a stationary and linear situation no significant power in the system output would be expected at these two frequencies. Power in the system output at these two noninput frequencies would be evidence of nonstationary and/or nonlinear system behavior or of the presence of additional input (e.g., gusts). For runs in smooth air, power at the lowest noninput frequency would indicate time variations over the 25 sec run length. The amount of power at the 6 cycle per run length frequency, when compared to that of 5 and 7 cycles per run length, would be an indication of total noise level from all sources. Power at the 6 cycle per run length frequency would infer that the adjacent frequencies were likely to be contaminated and therefore unreliable as measurements of system characteristics. Power at the 6 cycle per run length frequency would also be a clue to possibly nonlinear system behavior generating harmonics of the 2 and 3 cycle per run length input frequencies. It was also desirable that the input frequencies be chosen such that the possible harmonics generated by nonlinearities would not coincide with other input frequencies. Although this was difficult, because of the extremely short run lengths, only one such possibility exists. The use of both the 2 and 4 cycle per run length frequencies was found to be necessary.

The amplitudes of the command input, also shown in Fig. 3a, indicate that the main input power occurs at the two lowest frequencies, 0.5 and 0.75 rad/sec. These were selected to provide an effective input bandwidth consistent with normally expected ship-motion frequencies (Ref. 4). The lower-amplitude, higher frequency components were added to supply additional data beyond this bandwidth. Such procedures are necessary and common when dealing with closed-loop piloted situations because the pilot "regresses" (Ref. 8) if the effective input bandwidth is greater than his, and the airplane's capability to follow (i.e., he "averages" the meatball). Thus the lower-amplitude, "shelf", inputs were constructed to be largely subliminal. Because of the lower input amplitude, the shelf frequencies inherently have a low signal:noise ratio; however, they would be expected to provide usable data for stationary conditions.

2. Results of Describing Function Analysis

As a check to determine if the tailoring of the input command had obviated the short run length problem, the known stationary (nontime-varying) FLOLS servo drive system was tested. The servo output position response to the sum-of-sine-wave input was recorded for run lengths of 100 sec. Describing functions were computed using the total 100 sec of data and using 25 sec segments of the data. For a linear, time-invariant system these are equivalent to the system transfer function (i.e., the "remnant," measuring the not linearly correlated output, is negligible). The results are shown in Fig. 1. There is very little variability between the describing functions based on different 25 sec segments and that based on the total 100 sec run length. The output power measured at noninput frequencies was not significant. This indicates that, with the input used and a stationary system, short run lengths are not a barrier to obtaining reliable describing functions.

A second test of short run lengths was made. A pilot hovering at fixed range in a helicopter (an H-34) tracked the FLOLS meatball when driven by the programmed input. In this case (very similar to that of Ref. 7) the normal time variations due to having a human pilot in the loop were present but possible excess time variations due to the display geometry during a landing approach were removed. Again, 100 sec runs were made and describing functions based on 25 sec segments and the total 100 sec run computed. The results are shown in Fig. 2. The output power at noninput frequencies, although higher than in the above case, was not significant.

The scatter for the hovering helicopter is greater than that for the servo. Past experience (Ref. 8) suggests training as a possible cause. That is, when first subjected to a given task, pilot characteristics are quite variable. They become more repeatable as the task is fully learned. (The pilot had a large number of flying hours in the H-34 but tracking the

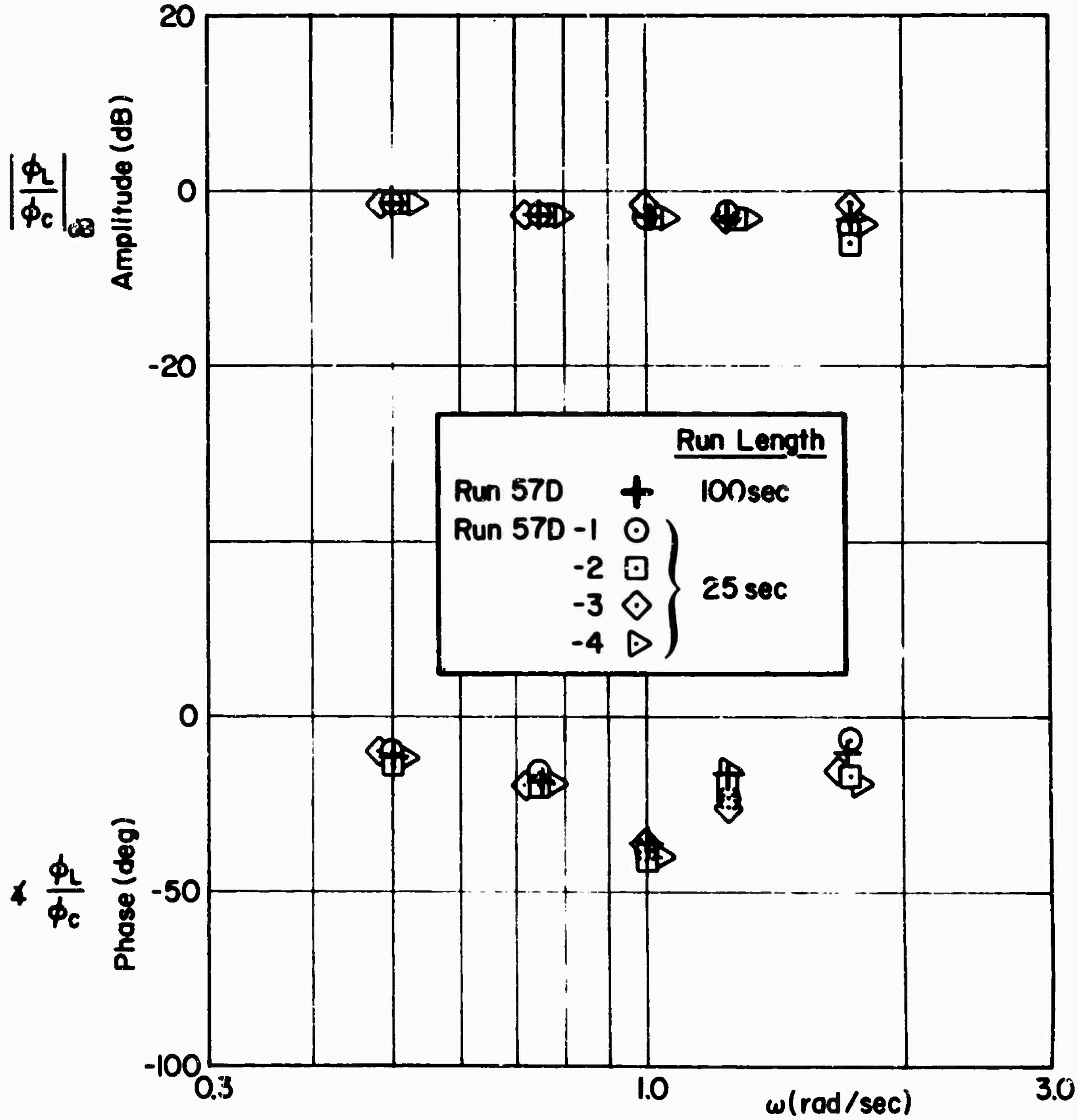


Figure 1. Describing Function Measurements for the Closed-Loop Lens Servo-Drive; Comparison Between Different 25 Sec Segments and Total 100 Sec Run Length

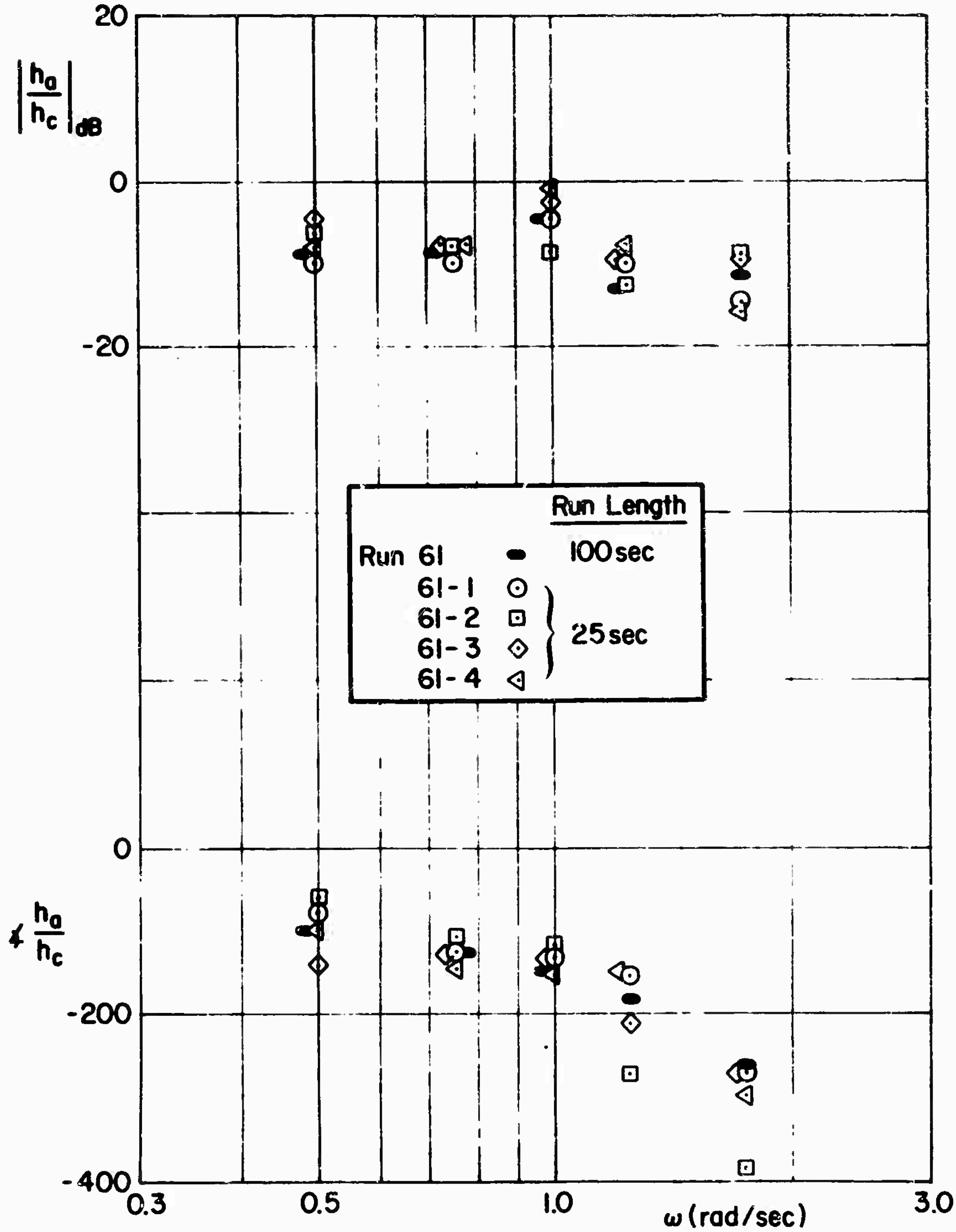


Figure 2. Describing Function Measurements for the Hovering Helicopter Based on 25 Sec Run Length Segments

FLOLS meatball was novel.) The data shown in Fig. 2 represents the fourth 100 sec run made by this pilot during the program. Describing functions based on the earlier runs (not shown) do indicate greater scatter and the trend appears to support our conclusion that a major cause of the variability is the training effect. We should also note, however, that the increased variability shown for the three highest frequency points may be additionally influenced by the low signal to noise inherent at these frequencies (see above).

Describing functions of the helicopter making low speed (≈ 30 knots) approaches and, to an even greater extent, those of fixed-wing aircraft making normal landing approaches show significant effects due to time variations. Significant power was found at both critical noninput frequencies (1 and 6 cycles per run length). Nevertheless, certain important conclusions can be drawn from these describing functions. For example, the large amounts of power in the aircraft's response spectrum at the main (the two lowest) input frequencies indicate that the pilot was attempting to track the meatball, as evident, too, from the recorded time histories. Also, consistent variations between aircraft can be seen in the describing functions. Both effects are shown in Fig. 3 which presents the results for the same pilot for a number of passes in both the A-4F and F-8 airplanes. The possibility of harmonics due to system nonlinearities as the third highest frequency and signal to noise at all three highest frequencies (as indicated by the power at noninput frequencies) dictate that these points should be discounted in Fig. 3. Confining our attention, therefore, to the two lowest input frequencies we see that for the A-4F both frequencies are being tracked with sufficient gain to yield airplane excursions in altitude (h_a) equal to those commanded (h_c). For the F-8, the drop in amplitude at 0.75 rad/sec is interpreted as far "looser" tracking than for the A-4F.

3. Summary

Describing function analysis techniques can be successfully applied to the short run-length measurement of fixed properties such as exist for

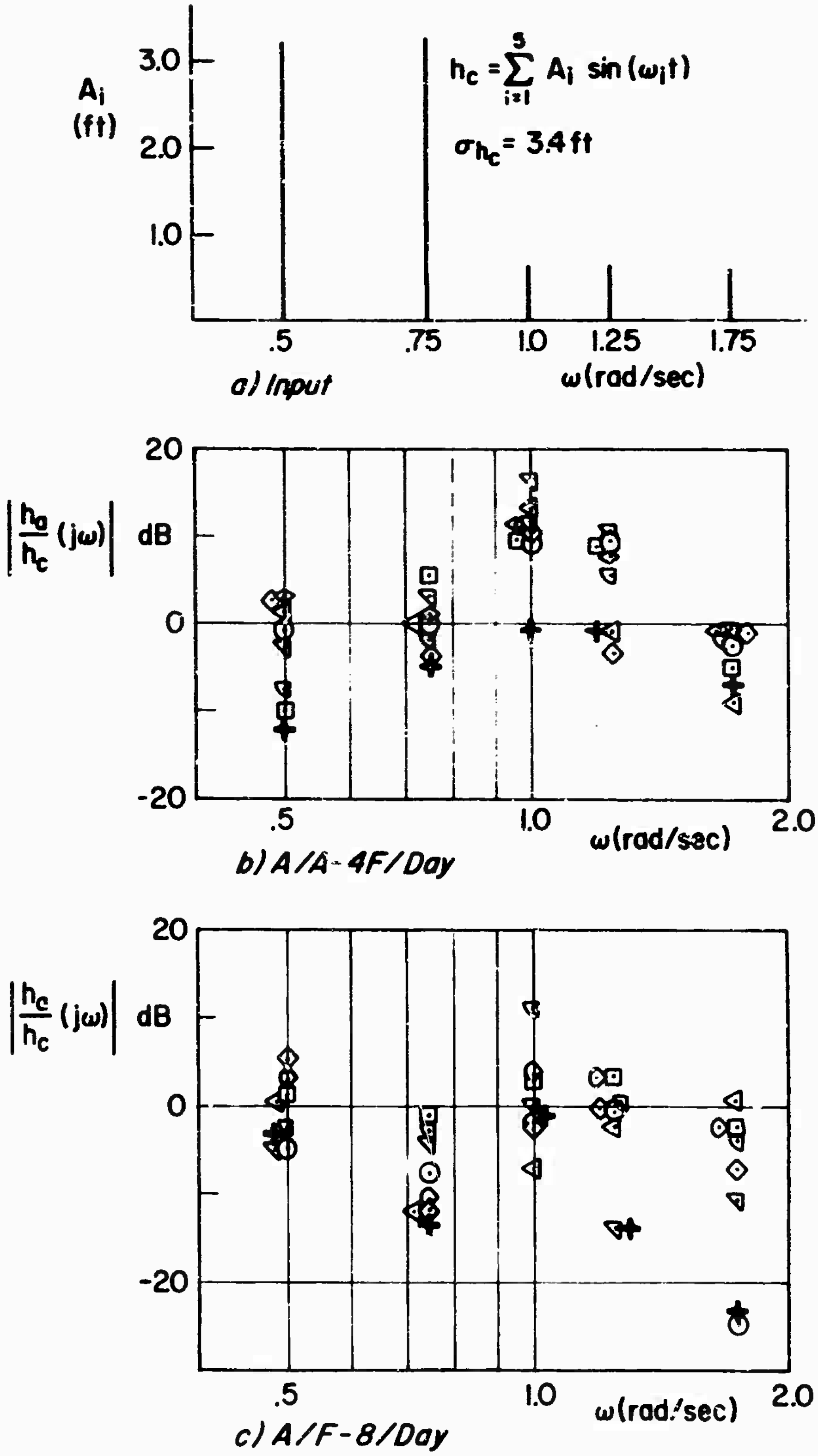


Figure 3. Describing Function Amplitude Comparisons for A-4, F-8 Airplanes
(Symbols denoted individual passes)

a given airplane, airplane/autopilot, or airplane/pilot combination for a fixed-flight situation. This experience is consistent with other recent aircraft/system identification flight tests (Refs. 5 and 7). In the present instance, however, the time-varying nature of the data obtained in actual approaches, and the input limits imposed by the short run-lengths, combined to restrict the utility of the describing function technique to the rather gross indications apparent in Fig. 3, despite progressive "refinements" involving some 150 reanalyses. Such activities, and the final selection and substitution of alternative analysis techniques, constituted a serious drain on the project funds. Because of such limits only about 30 percent of the usable data were subjected to the more applicable time-domain analyses now to be described.

D. TIME-DOMAIN ANALYSIS PROCEDURES

1. Correlation Functions

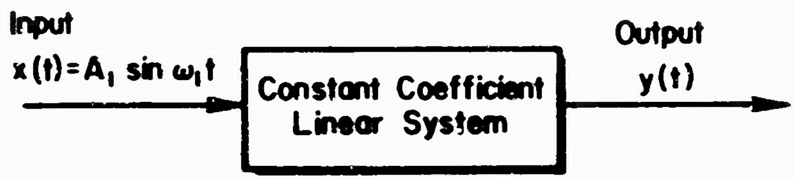
a. Ideal Cases. Because of the nonstationary (time-varying) nature of the approach, correlation functions were used to further analyze the data. Before discussing the results obtained, a description of the technique will be given.*

In Fig. 4a we show an ideal case of a constant-coefficient, linear system excited by a single sine wave input after system transients have settled out.

The autocorrelation, $R_{xx}(\tau)$, of a time function is the expected value of the product of the time function and the time function delayed:

$$R_{xx}(\tau) = E[x(t)x(t+\tau)] \quad (1)$$

*A more complete discussion can be found in various texts such as Refs. 9 and 10.

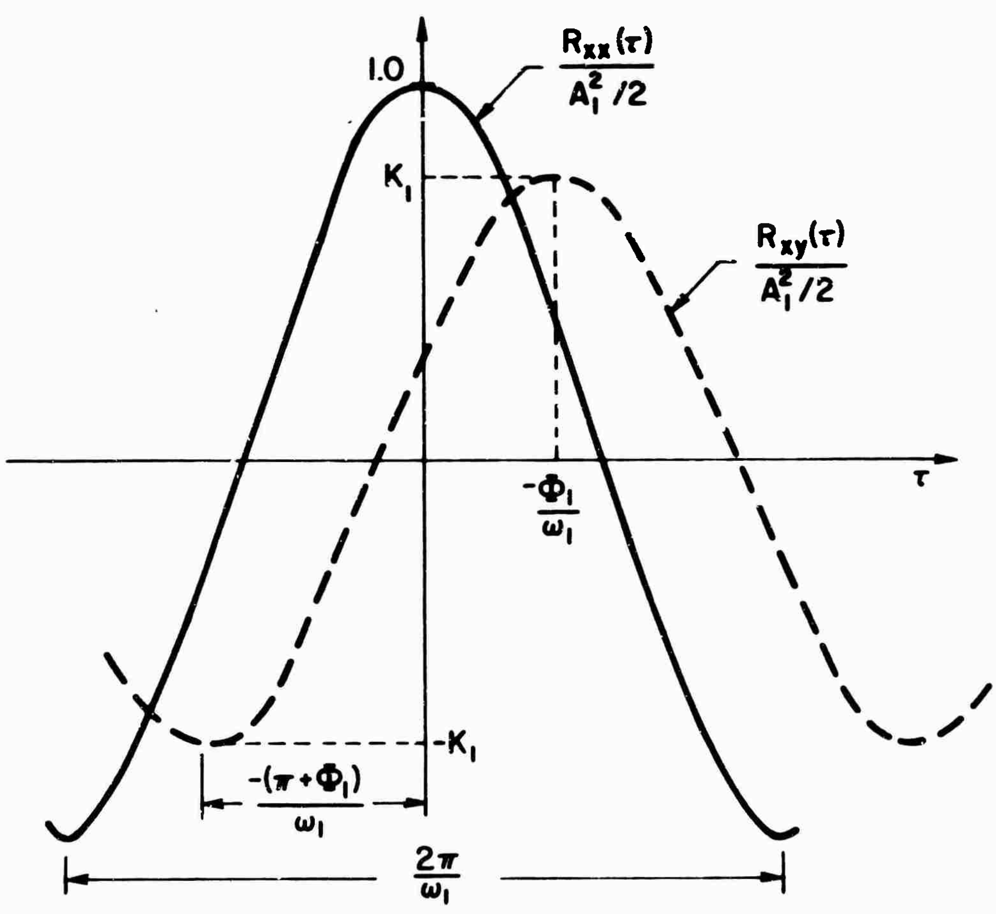


Assumptions 1) System Transfer Function is G(s)
2) Times of interest are such that transients have settled out

$$y(t) = A_1 K_1 \sin(\omega_1 t + \Phi_1)$$

where
$$K_1 = |G(s)|_{s=j\omega_1}$$
$$\Phi_1 = [\measuredangle G(s)]_{s=j\omega_1}$$

a) System Description



b) Autocorrelation, $R_{xx}(\tau)$, and Crosscorrelation, $R_{xy}(\tau)$, Functions

Figure 4. Correlation Functions for an Ideal Case

As indicated, the autocorrelation is a function of the time delay τ. When the time function is a single sine wave, $A_1 \sin \omega_1 t$, as in the ideal case, the autocorrelation function is given by:

$$R_{xx}(\tau) = \frac{A_1^2}{2} \cos \omega_1 \tau \qquad (2)$$

The crosscorrelation, $R_{xy}(\tau)$, of two time functions x(t) and y(t) is the expected value of the product of the first and the delayed second:

$$R_{xy}(\tau) = E[x(t)y(t+\tau)] \qquad (3)$$

For the ideal case this becomes:

$$R_{xy}(\tau) = \frac{A_1^2}{2} K_1 \cos(\omega_1 \tau + \Phi_1) \qquad (4)$$

Normalized plots (i.e., based on the mean-squared input $A_1^2/2$) of these functions are shown in Fig. 4b. It can be seen that the system characteristics, K_1 and Φ_1, at the input frequency, ω_1, can be read directly from the crosscorrelation function.

Expanding the above to the case of summed sine wave inputs, $x(t) = \sum_i A_i \sin \omega_i t$, to a constant-coefficient linear system, G(s), the correlation functions are:

$$R_{xx}(\tau) = \sum_i \frac{A_i^2}{2} \cos \omega_i \tau \qquad (5)$$

$$R_{xy}(\tau) = \sum_i \frac{A_i^2}{2} K_i \cos(\omega_i \tau + \Phi_i)$$

where: $K_i = |G(s)|_{s=j\omega_i}$

$\Phi_i = [\measuredangle G(s)]_{s=j\omega_i}$

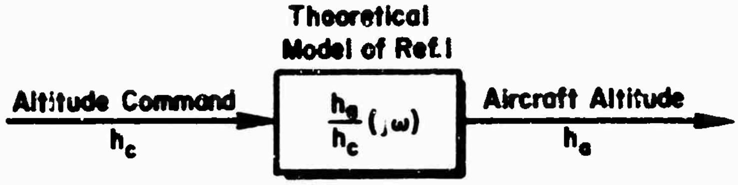
These functions were computed using the actual flight test input (see Fig. 3a) and the theoretical closed-loop, pilot/aircraft, carrier landing model developed in Ref. 1 (for the F-6 airplane). The system block diagram is shown in Fig. 5a; the correlation functions, normalized by the variance of the input, are shown in Fig. 5b.

The difficulty in interpreting this plot, and the general disadvantage of using correlation functions, is their inability to separate the system characteristics as a function of frequency. However, the shift in the crosscorrelation-function peak indicates an amplitude of 0.77 and an effective delay of about 3.25 sec; so, grossly speaking, the pilot/aircraft system is representable by $G(j\omega) \doteq 0.77e^{-3.25j\omega}$. It is known that the input is dominated by frequencies of 0.5 and 0.75 rad/sec; and it would be expected that the system characteristics indicated by the crosscorrelation function would be appropriate for this frequency region. In Fig. 5c, the amplitude and phase characteristics of the crosscorrelation-derived system function are compared with the exact transfer function characteristics of the theoretical system (from Ref. 1). It can be seen that effective time delay and gain measurements taken from the crosscorrelation function do provide an adequate system description in the frequency region of the input.

b. **Nonstationary cases.** For nonstationary cases where time variations* are present, e.g., due to time varying or nonlinear system behavior, time-variations in the input, or interest in the response while significant transients still exist, the definitions of the correlation functions need to be expanded. The autocorrelation then becomes the expected value of the product of the time function at a particular time T, and the same time function delayed:

$$R_{xx}(T,\tau) = E[x(T)x(T+\tau)] \tag{6}$$

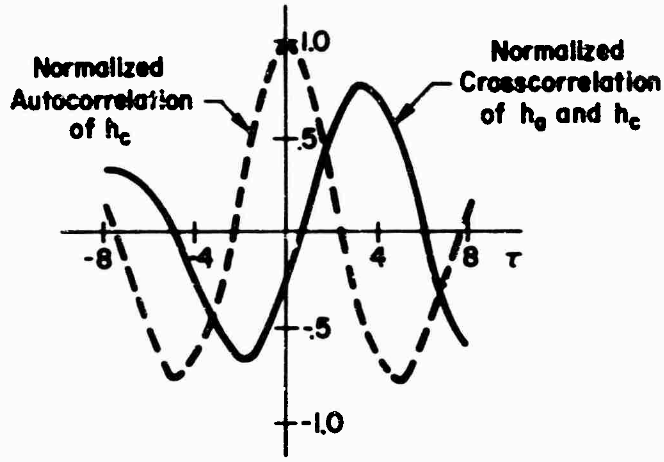
*"Time variation" is used in the sense that the average properties of the signal vary with time. A single sine wave is time-varying for times less than its period, but stationary if considered over integral periods or times greater than many periods.



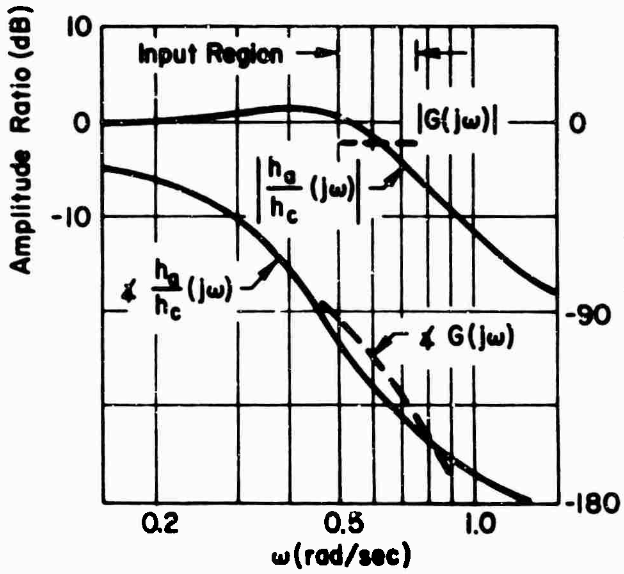
$$h_c = \sum_{i=1}^{5} A_i \sin(\omega_i t)$$

where amplitudes and frequencies
as used in flight test program (see Fig 3)

a) System Block Diagram



b) Normalized Correlation Functions



c) Frequency Response Comparison of System Function, $G(j\omega)$, Derived from Crosscorrelation and Theoretical (Ref. I) System Function, $h_a/h_c\,(j\omega)$

Figure 5. Correlation Functions and Frequency Response for Pilot/Aircraft Model of Ref. 1

It is thus a function of two variables, the particular time T and the delay τ. The expected value cannot be obtained by time averaging but must be obtained by averaging over a number of samples of the process, i.e.,

$$R_{xx}(T,\tau) = \frac{1}{N}\sum_{j=1}^{N} x_j(T)x_j(T+\tau)$$

where $x_j(T)$ is the j^{th} sample at time T and the ensemble average is taken over N samples. Similarly, the crosscorrelation becomes

$$R_{xy}(T,\tau) = E[x(T)y(T+\tau)] \tag{7}$$

$$= \frac{1}{N}\sum_{j=1}^{N} x_j(T)y_j(T+\tau)$$

A simple extension to autocovariance, $C_{xx}(T,\tau)$, is required to take account of signals with a time-varying ensemble mean such as exhibited by the aircraft attitude time histories from the flight tests. The ensemble mean is defined by:

$$\bar{x}(t) = \frac{1}{N}\sum_{j=1}^{N} x_j(t) \tag{8}$$

Then the autocovariance is:

$$C_{xx}(T,\tau) = E\left\{[x(T) - \bar{x}(T)][x(T+\tau) - \bar{x}(T+\tau)]\right\} \tag{9}$$

$$= \frac{1}{N}\sum_{j=1}^{N} [x_j(T) - \bar{x}(T)][x_j(T+\tau) - \bar{x}(T+\tau)],$$

and the crosscovariance is:

$$C_{xy}(T,\tau) = E\left\{[x(T) - \overline{x}(T)][y(T+\tau) - \overline{y}(T+\tau)]\right\} \tag{10}$$

$$= \frac{1}{N}\sum_{j=1}^{N} [x_j(T) - \overline{x}(T)][y_j(T+\tau) - \overline{y}(T+\tau)]$$

It should be noted that for signals with zero means the covariance functions are identical to the correlation functions.

To ease the interpretation of plots of these functions, they are normalized, as before (e.g., Fig. 4) by dividing them by an appropriate mean-squared input,

$$\sigma_x^2(T) = C_{xx}(T,0) = \frac{1}{N}\sum_{j=1}^{N} [x_j(T) - \overline{x}(T)]^2 \tag{11}$$

Then: $$R(T,\tau) = \frac{R_{xx}(T,\tau)}{\sigma_x^2(T)} \tag{12}$$

$$C(T,\tau) = \frac{C_{xy}(T,\tau)}{\sigma_x^2(T)} \tag{13}$$

The above defined crosscovariance of the input altitude command and output aircraft altitude will be used to analyze the data. The input is a stationary signal with zero mean. Therefore, its autocorrelation and autocovariance should be identical and independent of the particular time along the approach. Deviations of the autocorrelation functions computed from the flight test results from the analytically computed autocorrelation shown in Fig. 5b are indications of measurement and data processing errors. The reliability of the results using these techniques is also a strong function of the number of samples on which the averages are based. The autocorrelation function is a stronger test of a sufficient number of passes than the autocovariance function. The autocorrelation of the input will be shown for each of the cases analyzed.

As in the simple cases shown in Figs. 4 and 5, primary attention will be focused on the sinusoidal nature of the plots and their relative peak locations.

2. Application to Flight Test Data

Table I summarizes the conditions for which the above described correlation functions were computed. The limiting factor in these computations was the number of passes over which the ensemble average is taken. To separate the effects of pilot, airplane, time of day, and APC, it was necessary, of course, to average over passes for which these conditions were the same. Attempts to use less than 7 passes led to results which were considered erratic. To reduce the effects of training, discussed in the previous section, obviously bad passes were dropped. As indicated in the table, we had to mix APC on and off conditions in several cases in order to obtain a sufficient number of passes. Also we mixed pilots (the last three sets of conditions) in an attempt to evaluate the effects of APC.

About 20 sec of flight test data was available for each pass. Loss of radar lock-on, approximately corresponding to the intended touchdown point, was taken as zero time to go (T = 0). The data from T = 0 to T = 2 sec to go was erratic. As we are mostly concerned with performance in close, the analysis was limited to T = 2 to T = 10 sec to go.

The normalized autocorrelation and crosscovariance functions for the 10 sets of conditions given in Table I are shown in Fig. 6. An interpretation of selected cases is as follows:

Figure 6a (T = 8): A/A-4F/day

> A good job of tracking (one of our best examples), he's lagging the input by about 2 sec and the amplitude ratio is slightly greater than one.

Figure 6b (T = 9): B/A-4F/day

> Fairly good job, the amplitude ratio is down, but the lag is only about 2-1/2 sec (compare with Fig. 6a).

TABLE I

CONDITIONS FOR WHICH COVARIANCE FUNCTIONS WERE COMPUTED

PILOT	AIRFRAME	TIME OF DAY	APC	NO. OF PASSES
a) A	A-4F	Day	None	10
b) B	A-4F	Day	None (?)	10
c) B	F-4G	Night	At least 2 on	11
d) C	A-3B	Night	5 on/2 off	7
e) C	F-4B	Day	None	8
f) D	F-8	Day	4 on/4 off/1?	9
g) A	F-8	Day	3 on/4 off	7
h) D and A	F-8	Day	7 on/8 off/1?	16
i) D and A	F-8	Day	On	7
j) D and A	F-8	Day	Off	8

Figure 6c (T = 3): B/F-4G/night

About 2-1/2 sec of lag, aircraft motion mostly made up of only lowest frequency component of input. The longer "period" of the crosscovariance plot (compare this with Fig. 6a) is indicative of this.

Figure 6d: C/A-3B/night

With the exception of the T = 10 and T = 9 sec-to-go data the erratic nature of the autocorrelation function of the command for this series of passes raises serious questions as to their validity. At T = 9 there appears to be about a 4 sec lag.

Figure 6e (T = 3): C/F-4B/day

Reasonable evidence of correlation, but about 180 deg out of phase.

Figure 6f (T = 7): D/F-8/day

More evidence of correlation than A in same aircraft (Fig. 6g) but still close to 180 deg out of phase (the C curve inverted approximates the R curve).

Figure 6g (T = 6): A/F-8/day

Though some evidence of tracking, the amplitude ratio of the aircraft motion to the command is small and he's more than 180 deg out of phase (the latter is not particularly evident at T = 6, but is at T = 2 and 3).

These interpretations can be expanded to cover comparisons between pilots, airplanes, day and night operations, as follows:

a. Comparison with Ideal (Model) Pilot/Airframe. A/A-4F/day, B/A-4F/day, B/F-4G/night show evidence of as good or better tracking, in terms of amount of correlated output and effective τ, as the theoretical pilot/airframe of Ref. 1. This comparison is shown in Fig. 7.* Other cases in Fig. 6 show considerably worse performance or very little tracking going on.

*The slight differences between the same plots shown in Fig. 6 and Fig. 7 are due to the resolution limitations of the automatic plotting routine used for Fig. 6. Figure 7 was plotted from the actual numerical data.

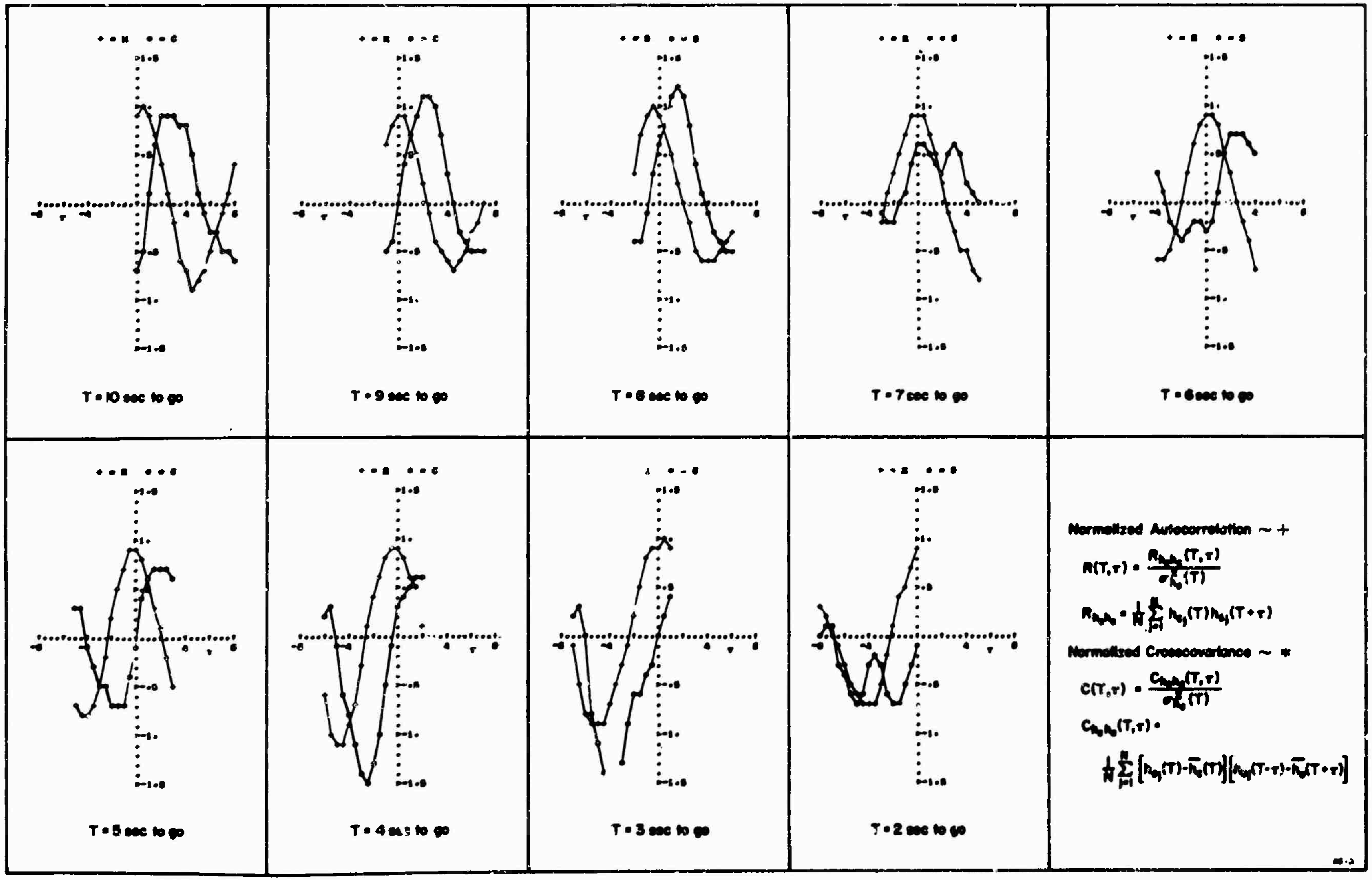


Figure 6. Plots of Correlation and Covariance Functions (a) A/A-4F/Day

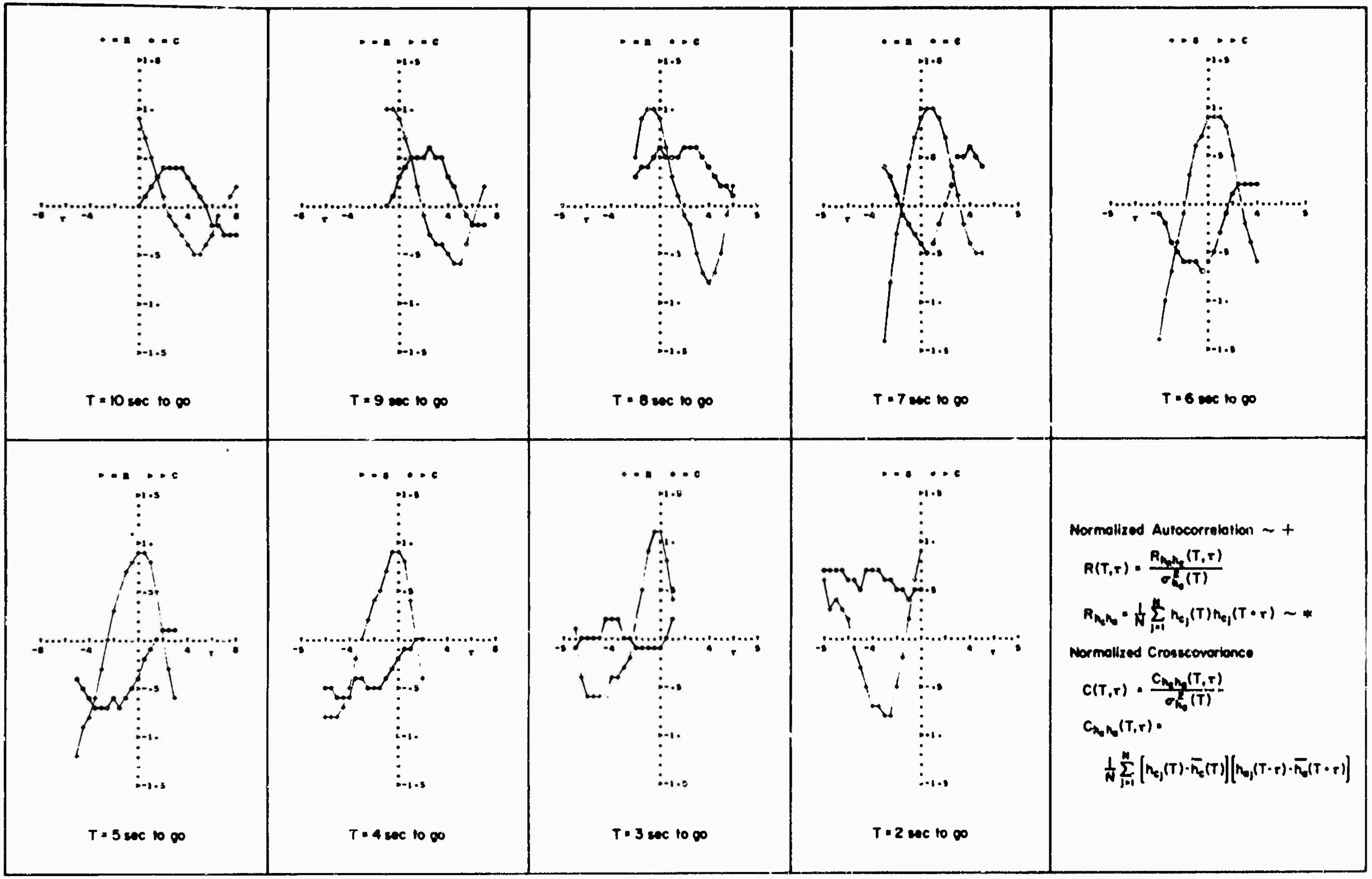


Figure 6 (Continued) (b) B/A-4F/Day

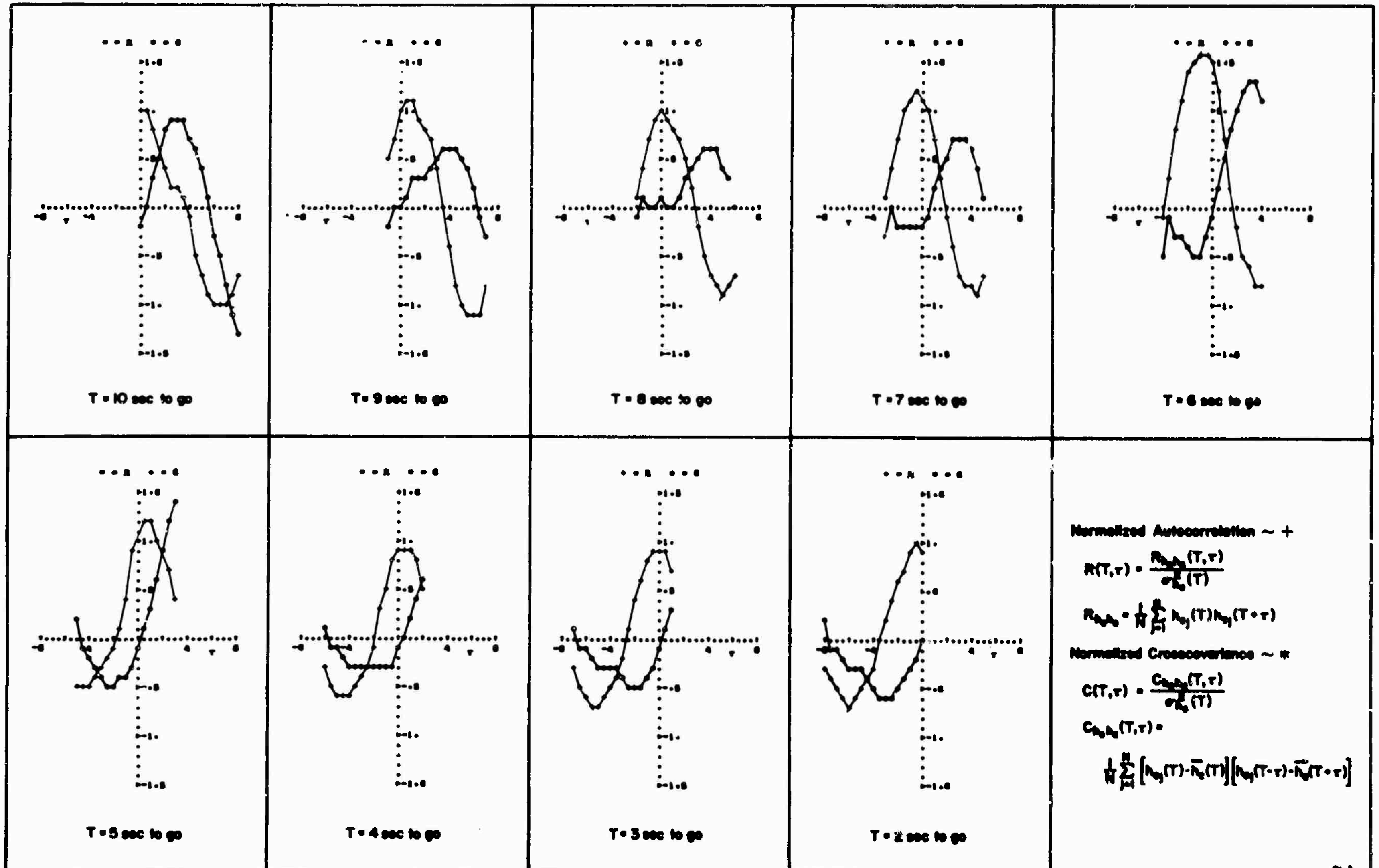


Figure 6 (Continued) (c) B/F-4G/Night

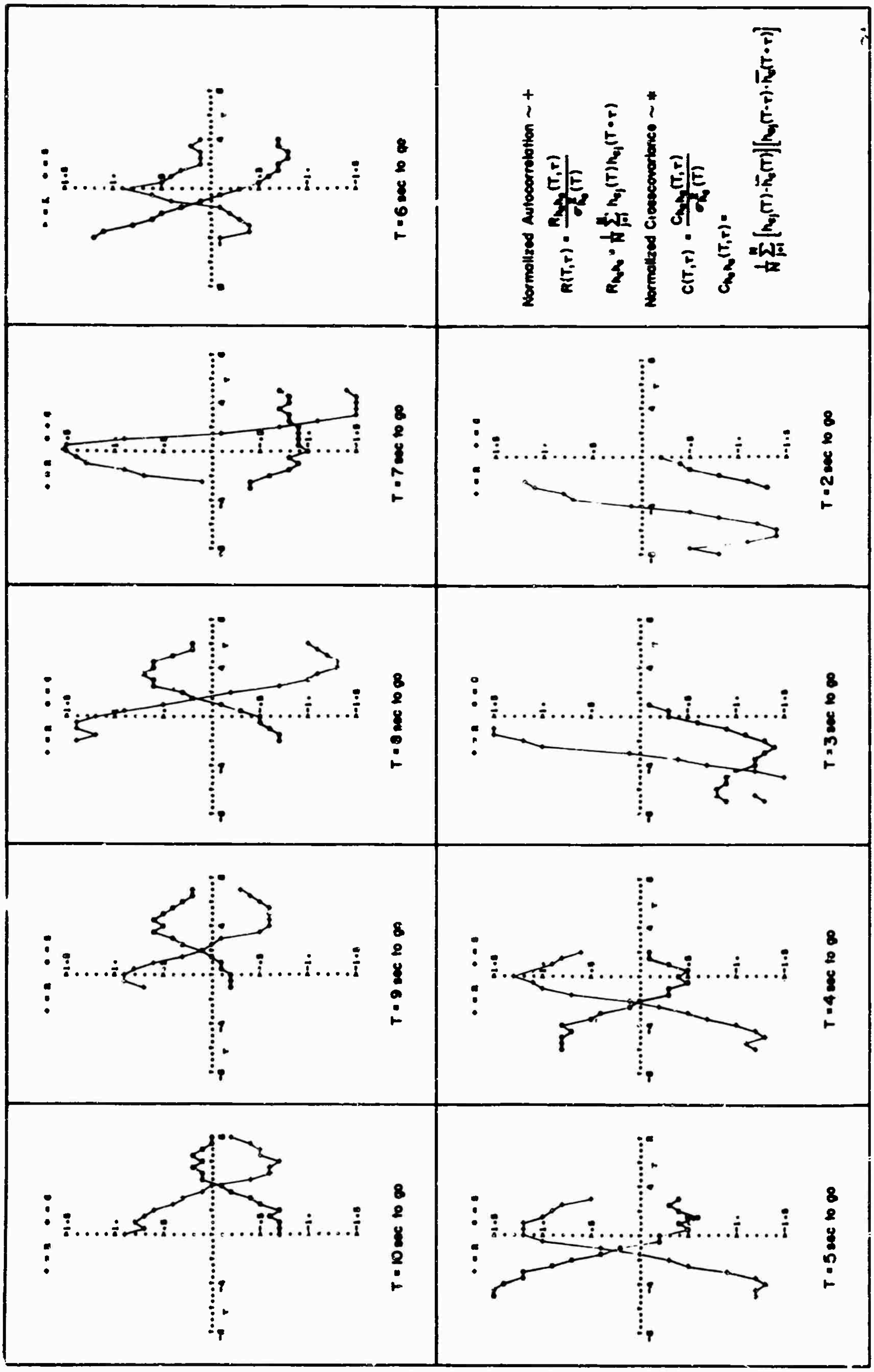
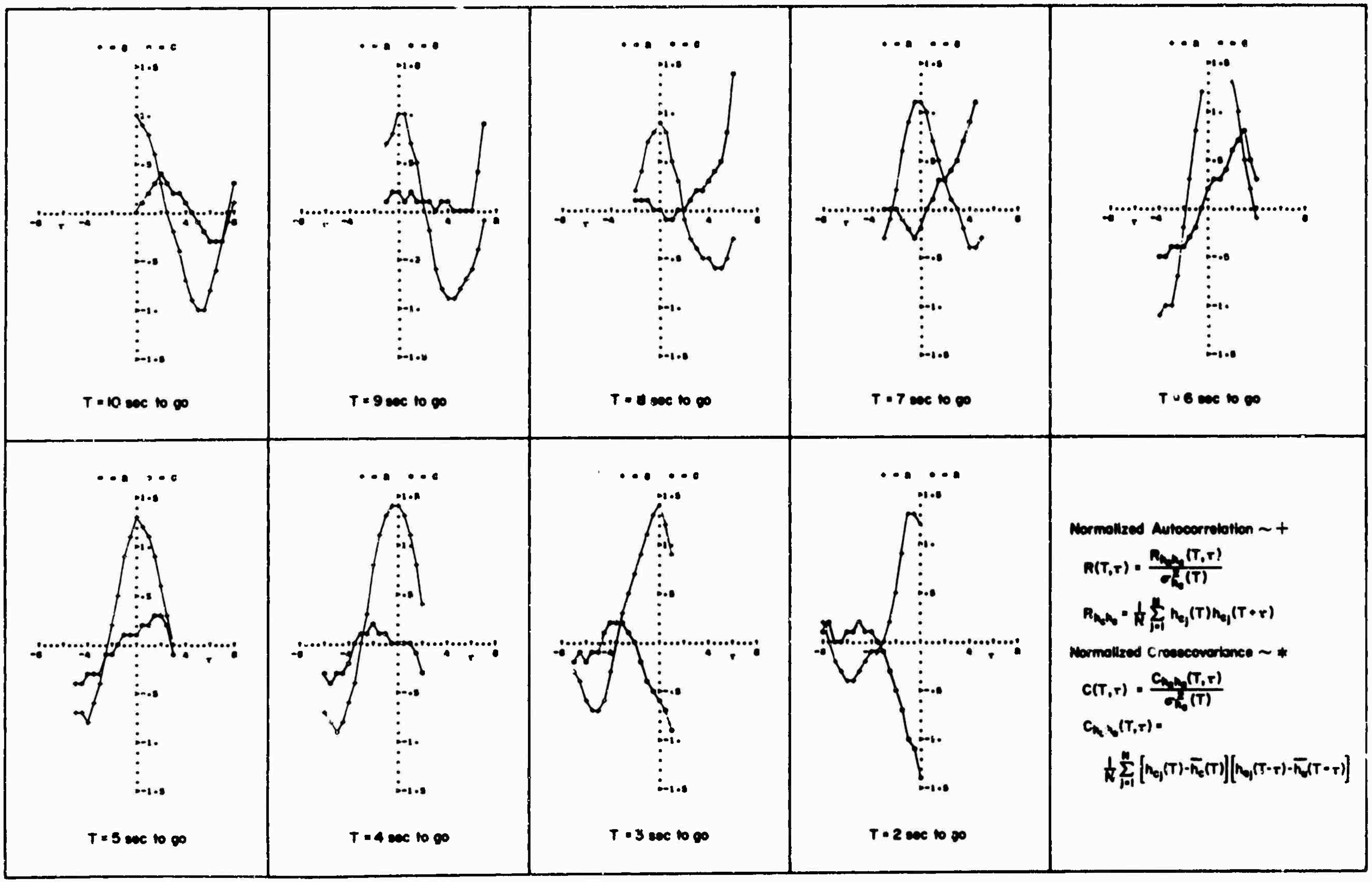


Figure 6 (Continued) (d) C/A-3B/Night



$$R(T,\tau) = \frac{R_{h_e h_e}(T,\tau)}{\sigma^2_{h_e}(T)}$$

$$R_{h_e h_e} = \frac{1}{N}\sum_{j=1}^{N} h_{e_j}(T)\,h_{e_j}(T+\tau)$$

$$C(T,\tau) = \frac{C_{h_e h_e}(T,\tau)}{\sigma^2_{h_e}(T)}$$

$$C_{h_e h_e}(T,\tau) = \frac{1}{N}\sum_{j=1}^{N}\left[h_{e_j}(T)-\bar{h}_e(T)\right]\left[h_{e_j}(T-\tau)-\bar{h}_e(T-\tau)\right]$$

Figure 6 (Continued) (e) C/F-4B/Day

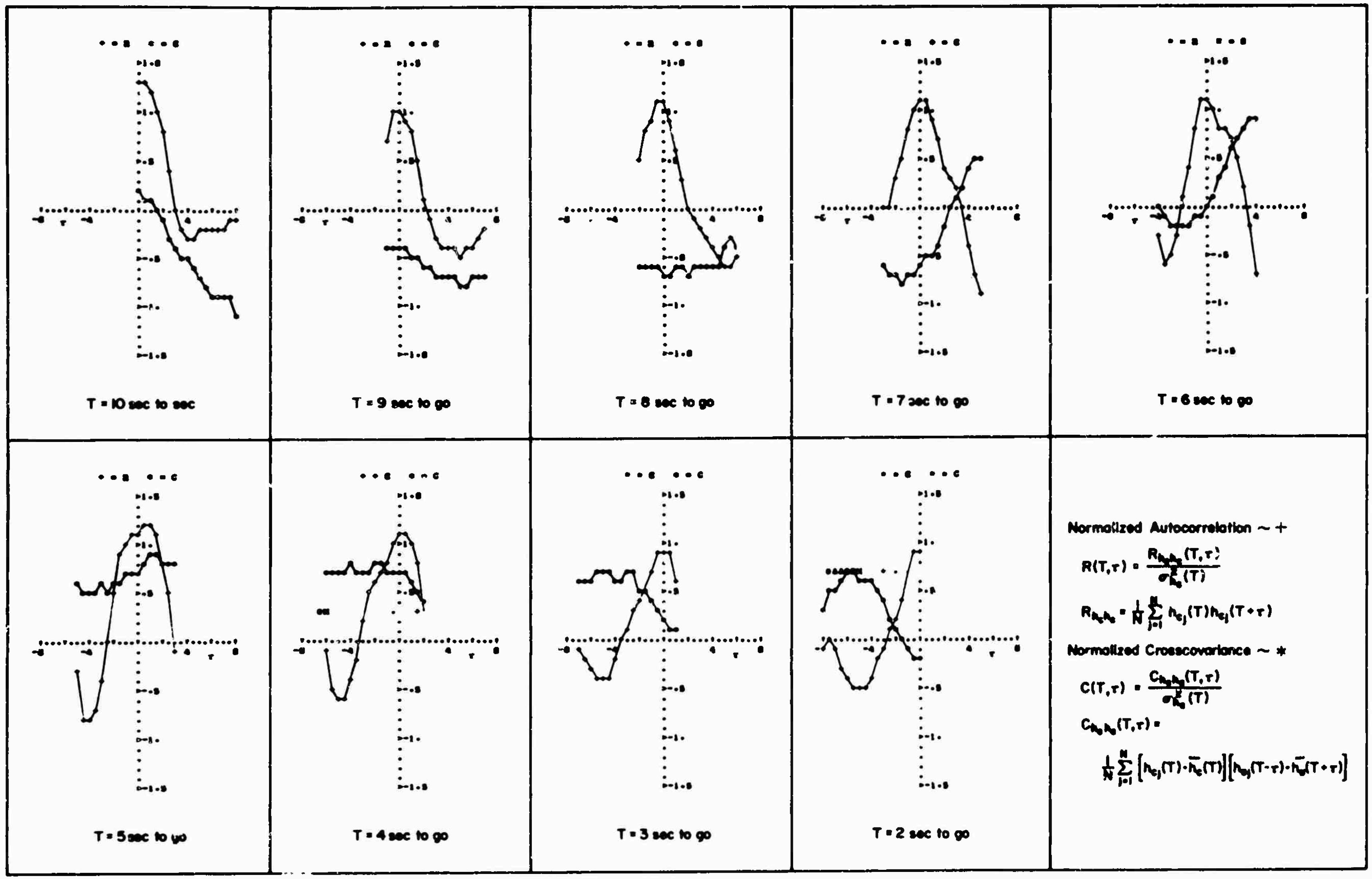


Figure 6 (Continued) (f) D/F-8/Day

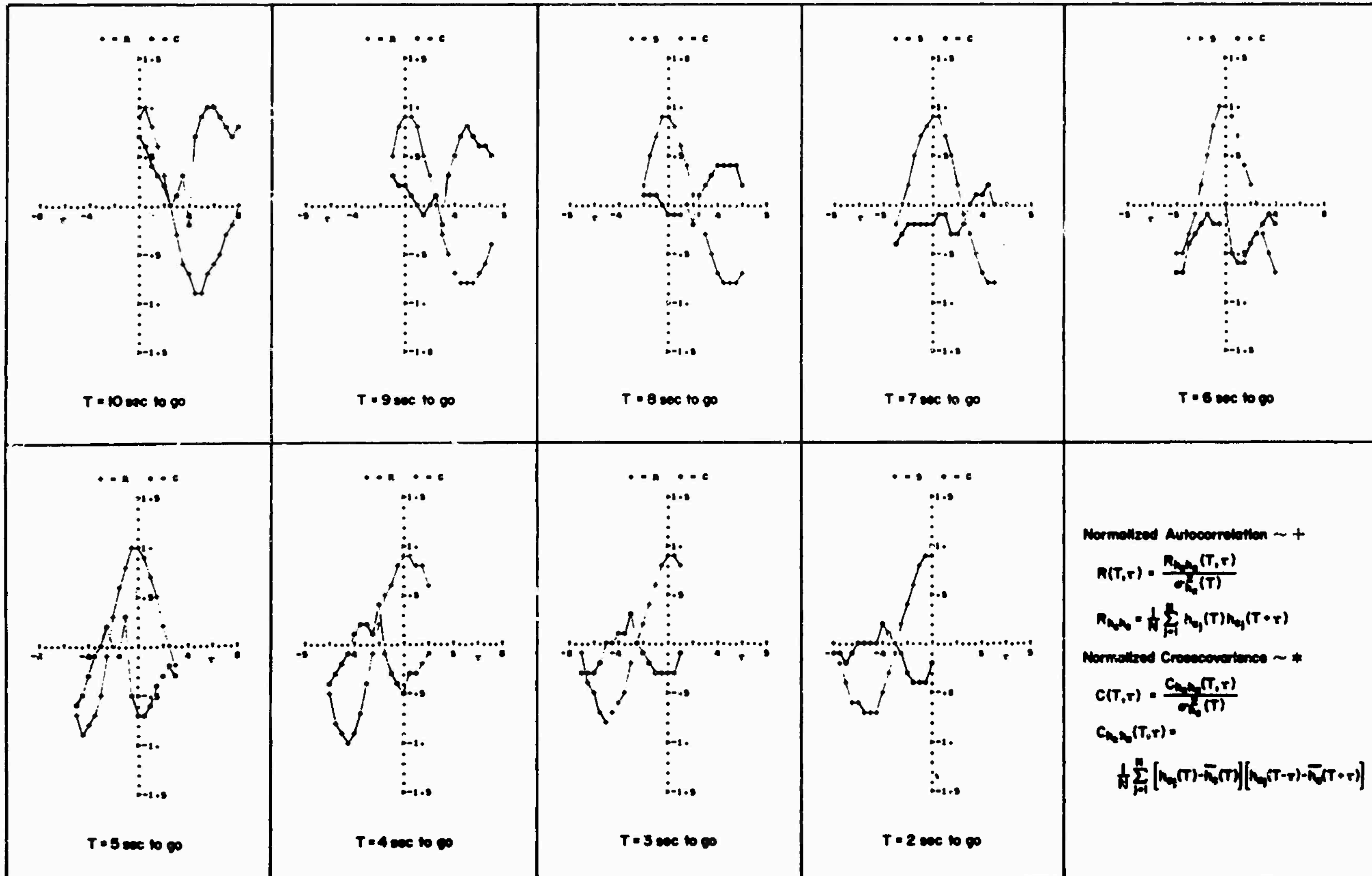
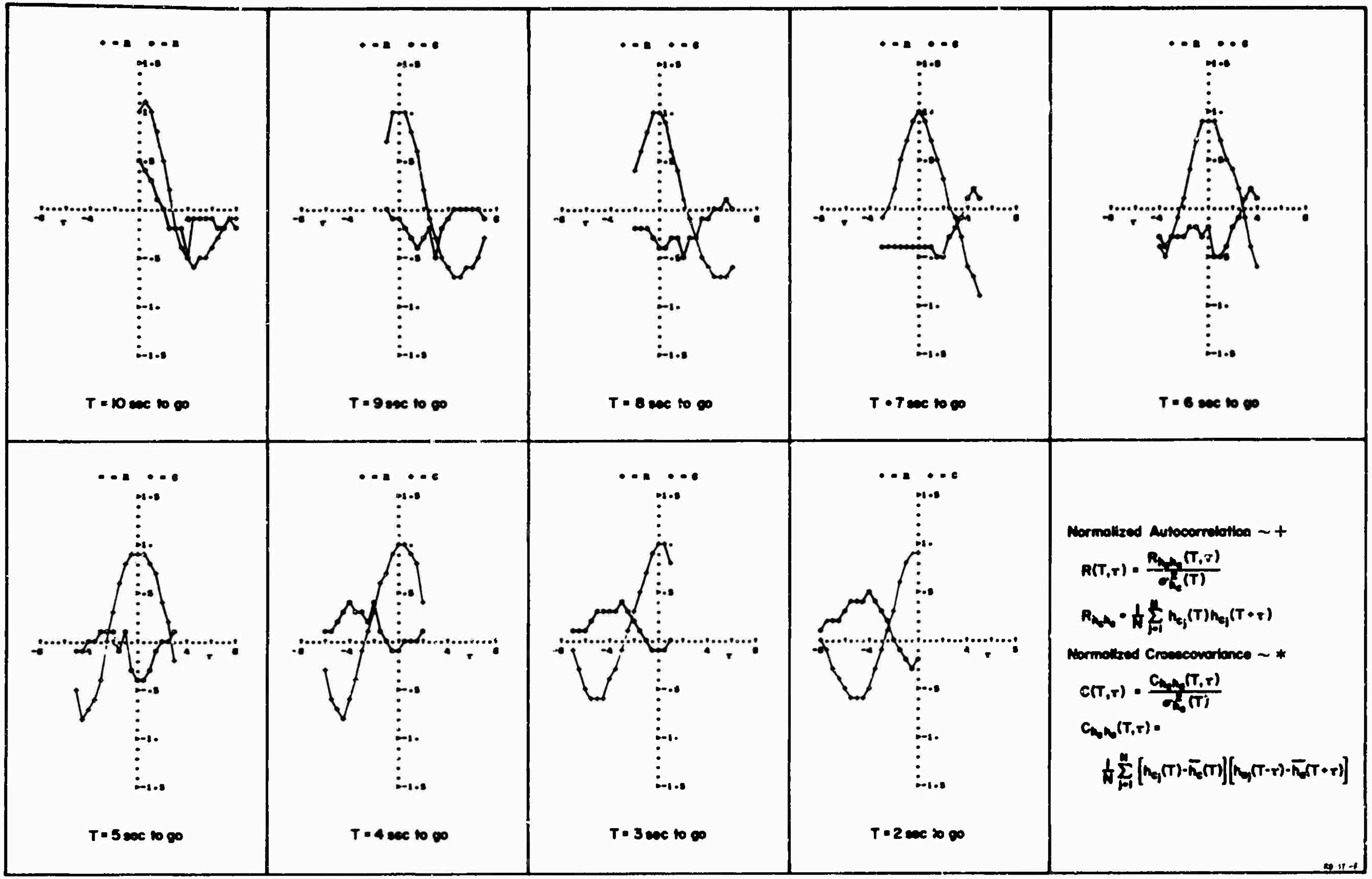


Figure 6 (Continued) (g) A/F-8/Day



$$R(T,\tau) = \frac{R_{h_e h_e}(T,\tau)}{\sigma^2_{h_e}(T)}$$

$$R_{h_e h_e} = \frac{1}{N}\sum_{j=1}^{N} h_{e_j}(T)\,h_{e_j}(T+\tau)$$

$$C(T,\tau) = \frac{C_{h_e h_e}(T,\tau)}{\sigma^2_{h_e}(T)}$$

$$C_{h_e h_e}(T,\tau) = \frac{1}{N}\sum_{j=1}^{N}\left[h_{e_j}(T)-\bar{h}_e(T)\right]\left[h_{e_j}(T-\tau)-\bar{h}_e(T+\tau)\right]$$

Figure 6 (Continued) (h) D and A/F-8/Day

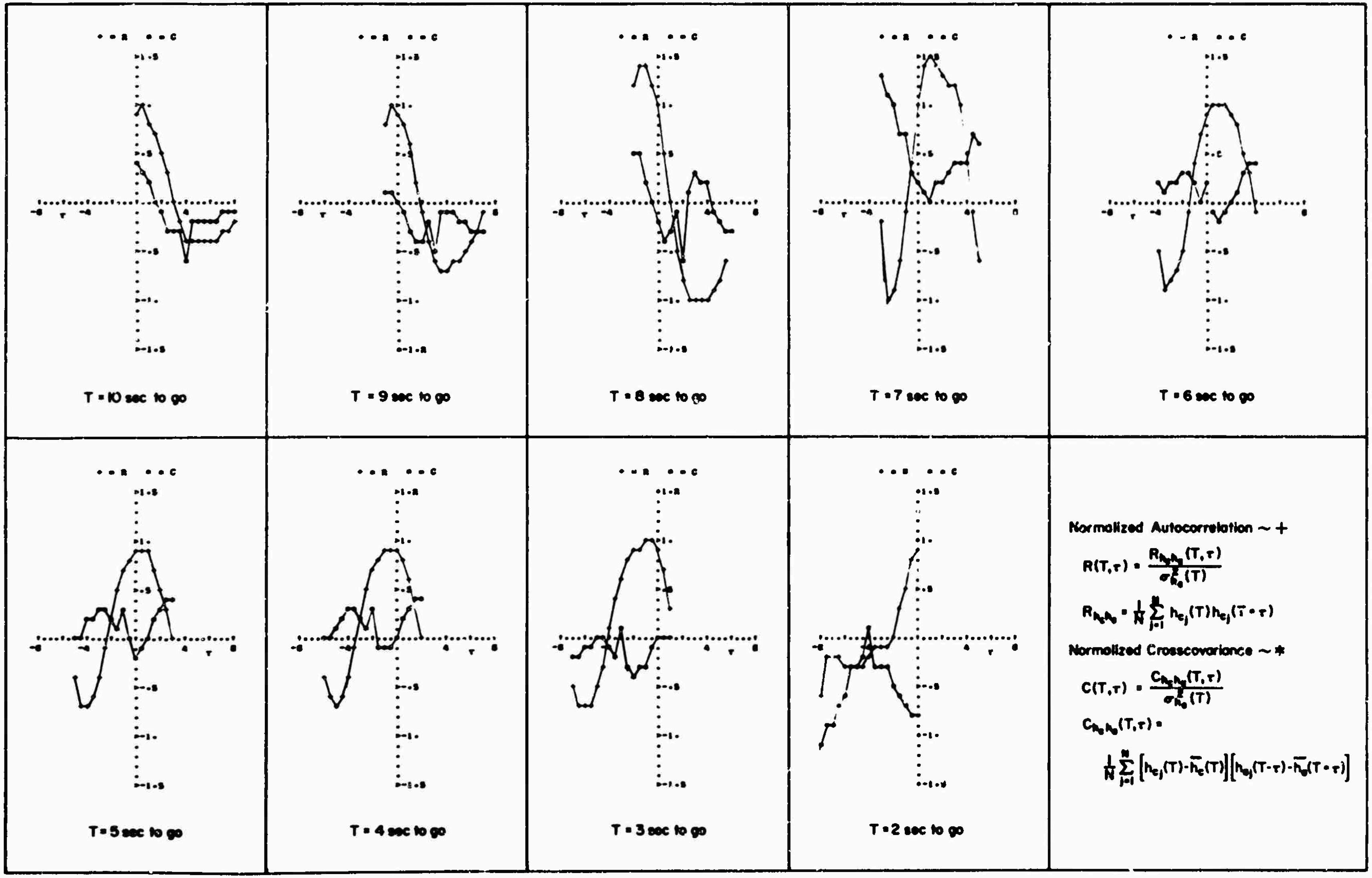


Figure 6 (Continued) (i) D and A/F-8/Day/APC On

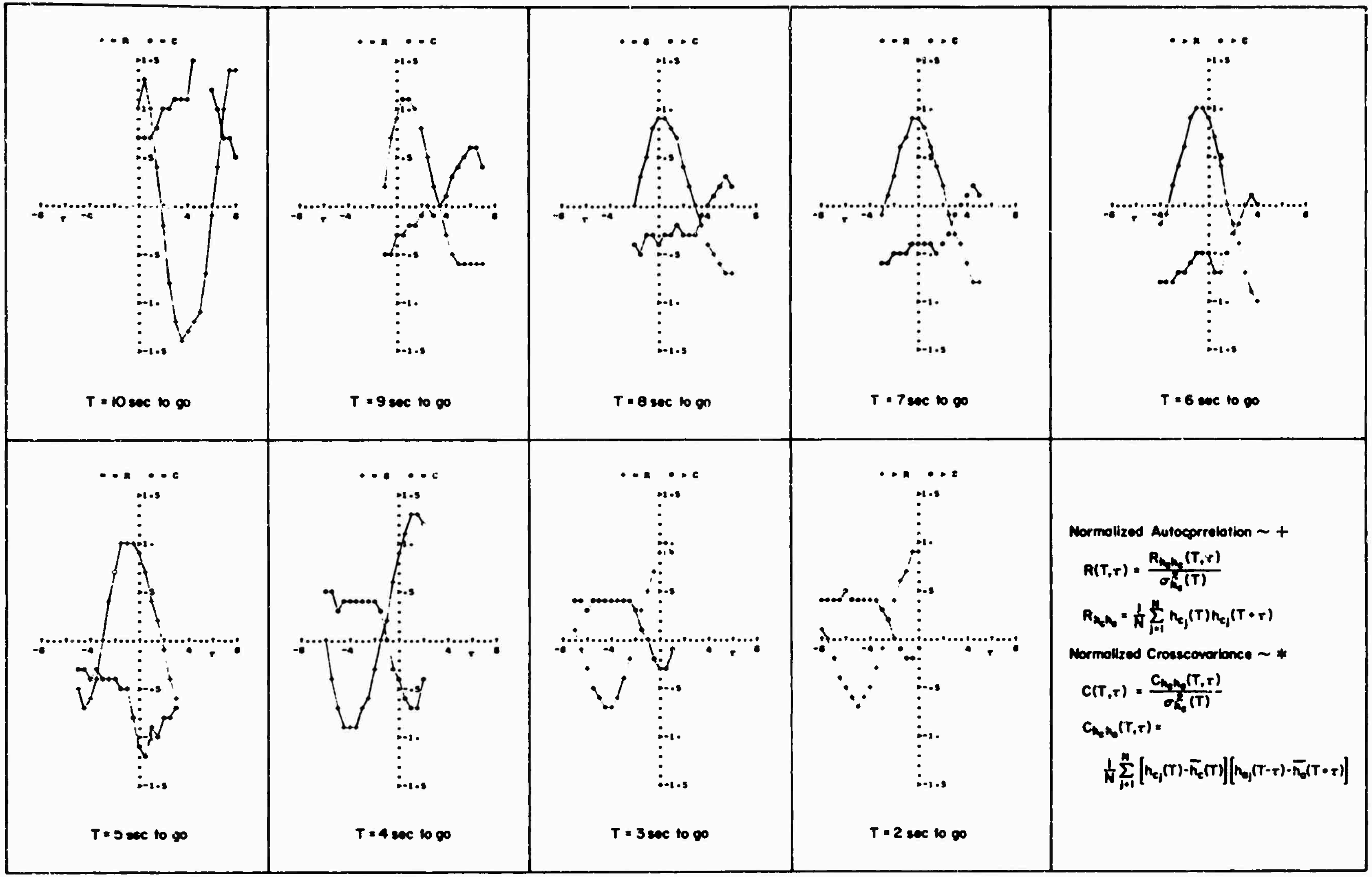


Figure 6 (Concluded) (j) D and A/F-8/Day/APC Off

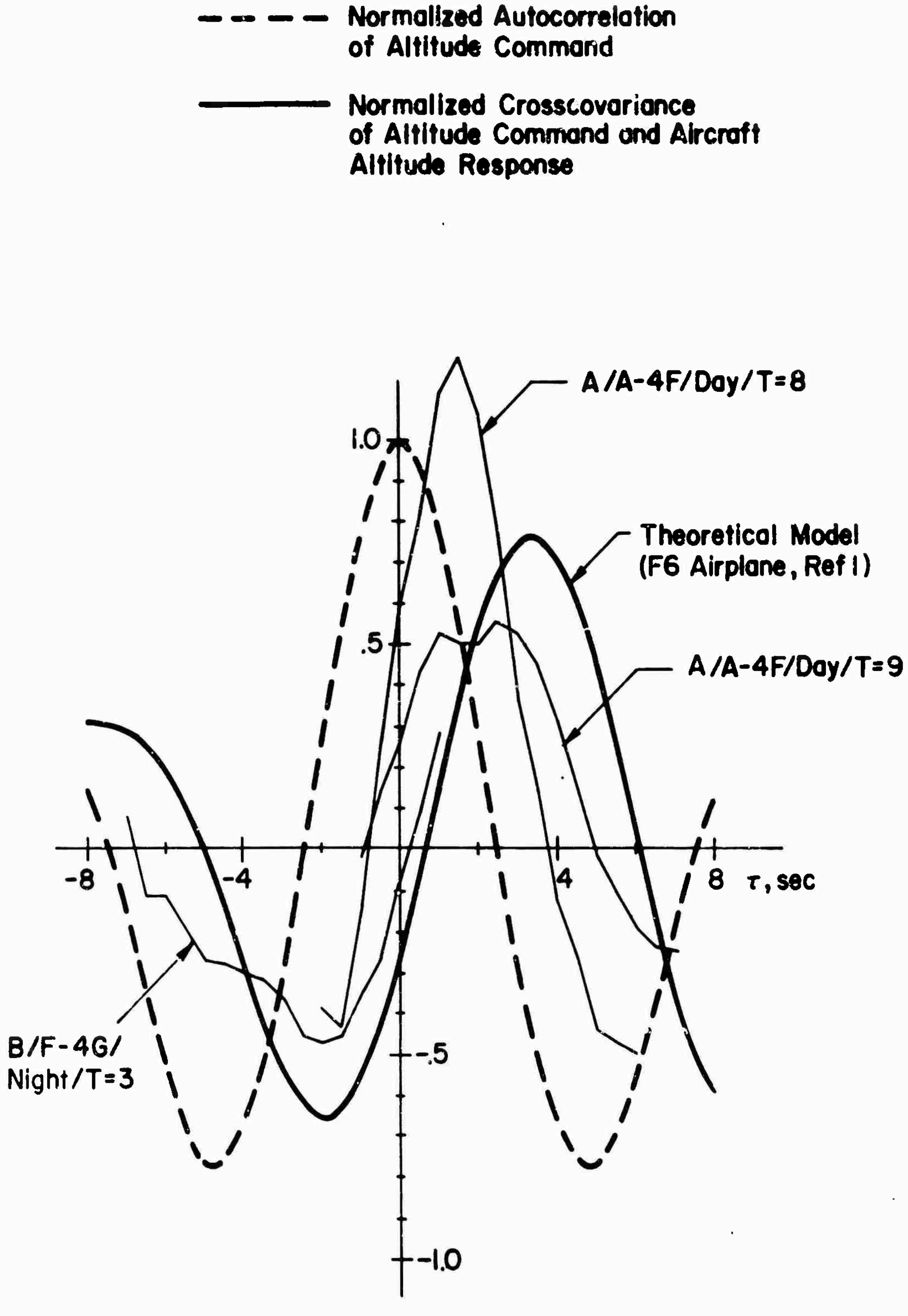


Figure 7. Comparison of Flight Test Data from "Good" Pilot/Aircraft with Theoretical Model of Ref. 1

b. Differences between Aircraft

1) A in A-4F/day versus F-8/day (Figs. 6a, g)

Good job in A-4F, $\tau_{min} \cong$ 1-1/2 sec, $|C| \cong 1.0$. Rather poor in F-8, $|C| \cong 0.3-0.5$, $\tau \cong 6$ sec

2) B in A-4F/day versus F-4G/night (Figs. 6b, c)

More evidence of tracking in close ($T = 2 \rightarrow 6$ sec to go) in F-4G/night, though slightly more delay (τ_{min} = 2-1/2 sec in F-4G versus 2 sec in A-4F).

3) C in A-3B/night versus F-4B/day (Figs. 6d, e)

Seems to do better, or pay more attention, in A-3B/night, at least for $T = 9 \rightarrow 10$ sec to go.

c. Difference between Pilots

1) A-4F: A/day versus B/day (Figs. 6a, b)

A does better job although τ_{min} = 2-1/2 sec versus 2 sec for B. Also evident that A following both $\omega_i = 0.5$ and 0.75 rad/sec input frequency versus B tracking mainly 0.5 rad/sec.

2) B/F-4G/night versus C/F-4B/day (Figs. 6c, e)

B does far better job, τ_{min} = 2-1/2 sec versus not very much evidence of C tracking at all. (There are known differences in the longitudinal control systems of the F-4B and F-4G. The extent, if any, to which they would affect these results could not be determined.)

3) D/F-8/day versus A/F-8/day (Figs. 6f, g)

D does slightly better job, though more than 180 deg out of phase.

d. Day versus Night

1) B/F-4G/night versus B/A-4F/day (see b.2)

2) C/A-3B/night versus C/F-4B/day (see b.3)

More tracking closer in at night.

e. APC On versus APC Off. Only comparison possible was with F-8 (Figs. 6i, j). Tracking with this airplane was poor in general and comparison required mixing pilots; unable to reach definite conclusions.

E. EFFECTS OF "IDEAL" CMS ON LANDING DISPERSIONS

The correlation functions discussed in the previous section show that the pilot, in certain aircraft, can and will track a moving meatball. It would be expected, therefore, that Compensated Meatball Stabilization (CMS) could reduce landing dispersion for these aircraft. The following will describe an idealized CMS* and our method of testing its feasibility using the actual flight test data.

The basic CMS concept is illustrated by the block diagram of Fig. 8a. In order to make the aircraft follow a desired path relative to the moving deck thus minimizing altitude dispersions, lead equalization (the CMS filter) is introduced between the deck and beam motions to compensate for the pilot/airframe lags. The form of lead shown and used in the subsequent analysis is an idealization in that it is assumed to provide pure time (phase) advance without attendant amplitude multiplication.

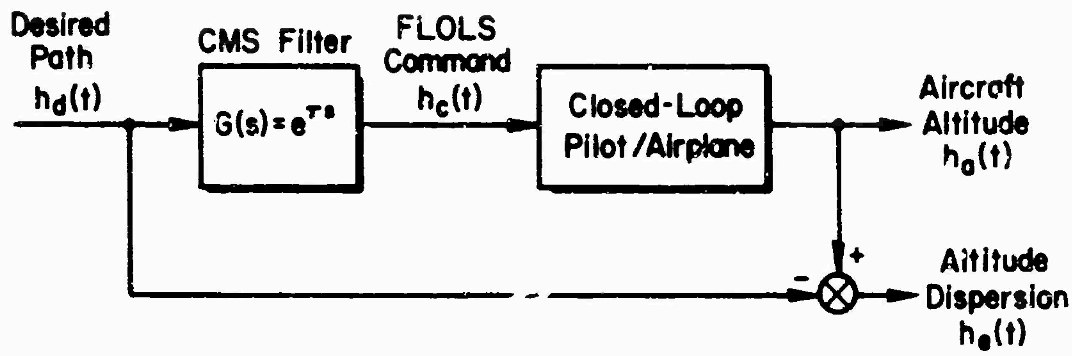
The flight test program provided samples of compatible command and aircraft altitude time histories. The manner in which the "derived" desired path was obtained is illustrated in Fig. 8b. Altitude dispersions relative to the desired (deck) motions are given by:

$$\begin{aligned} h_e(t,\tau) &= h_a(t) - h_d(t) \qquad (14) \\ &= h_a(t) - h_c(t-\tau) \end{aligned}$$

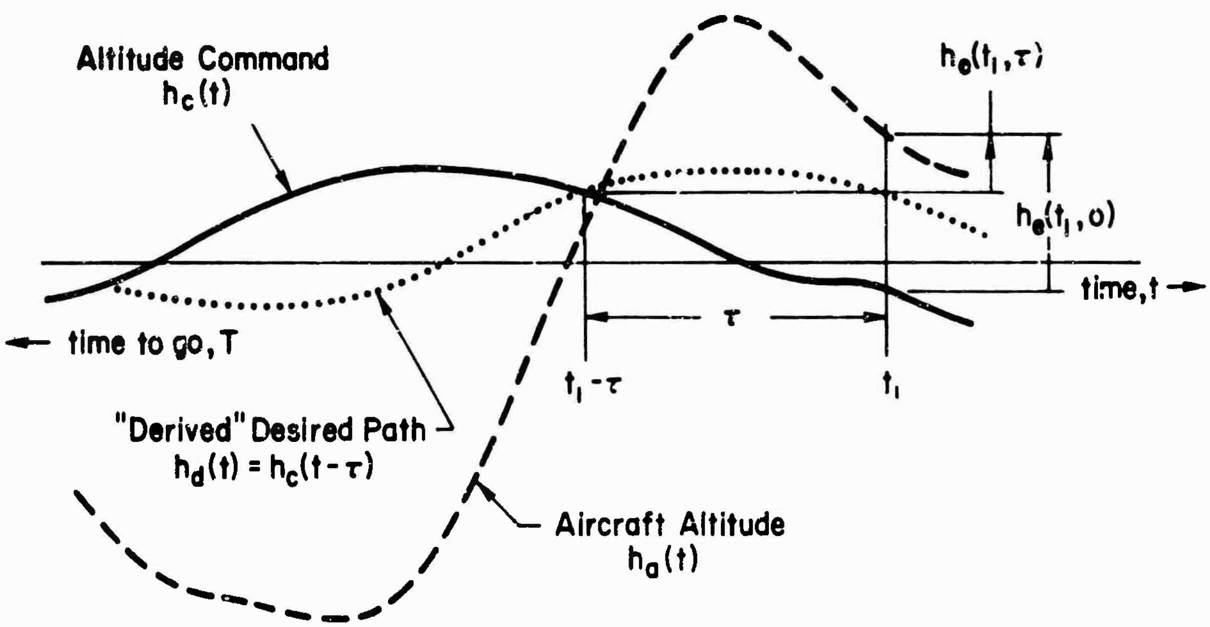
where t is the time along the flight path and τ the CMS filter parameter. For $\tau = 0$ this simply reduces to the difference between the aircraft altitude and the command as a function of time, t. The desired path for other τ's is obtained by simply lagging the command, i.e., the command now leads the desired path by an amount, τ, the CMS filter parameter.

Using this idealization, the altitutde dispersions as a function of time-to-go, T, and CMS parameter, τ, were computed for the passes representing the flight conditions of Table I. To obtain simple measures of the

*For a more complete discussion see Refs. 1, 2, and 13.



a) Block Diagram



b) Typical Time Histories of Altitude Command, Aircraft Attitude and Desired Path

Figure 8. Ideal Compensated Meatball Stabilization (CMS)

effectiveness of CMS for the various conditions the altitude dispersions were averaged over both the ensemble of passes and time; $T = 2$ to $T = 6$ secs to go was the period used in time averaging. The statistics computed were means and variances of the altitude error (relative to the deck), as follows:

$$\overline{h_e}(\tau) = \frac{1}{4}\int_{T=2}^{T=6} \left[\frac{1}{N}\sum_{j=1}^{N} h_{e_j}(T,\tau)\right] dT \qquad (15)$$

$$\sigma_{h_e}^2(\tau) = \frac{1}{4}\int_{T=2}^{T=6} \frac{1}{N-1}\left[h_{e_j}(T,\tau) - \overline{h_e}(\tau)\right]^2 dT \qquad (16)$$

where $h_{e_j}(T,\tau)$ is the altitude dispersion of the j^{th} pass at T sec-to-go with a CMS filter parameter of τ.

A reasonable interpretation of these measures is that the altitude dispersions in the vicinity of the ramp will have a random distribution with mean, $\overline{h_e}(\tau)$, and variance, $\sigma_{h_e}^2(\tau)$. As indicated by their dependence on τ these are a function of the CMS filter.

The effectiveness of the ideal CMS filter as measured by the procedure described above is shown in Fig. 9* for the 10 sets of conditions of Table I. Figure 9 confirms the expectations drawn from the correlation analysis; for certain aircraft (the A-4F and F-4G) CMS can substantially reduce terminal dispersions for τ's of the order of 3 sec. For other aircraft (F-8 and F-4B), where very little tracking was detected, relatively small but favorable changes in the dispersions are indicated for such τ's. Thus a fixed parameter CMS (constant τ) would provide equal or better performance than a noncompensated beam for any individual airplane (also a conclusion of Ref. 13). Across all airplanes it would, of course, provide better performance.

Based on Fig. 9a the reduction in dispersions for the A-4F for $\tau = 2.5$ sec is:

$$\frac{\sigma_{h_e}(2.5)}{\sigma_{h_e}(0)} = \frac{5.1}{6.9} = 0.74 \qquad (17)$$

*The reservations (see p. 23) as to the validity of the C/A3-B/night data are applicable to Fig. 9d also.

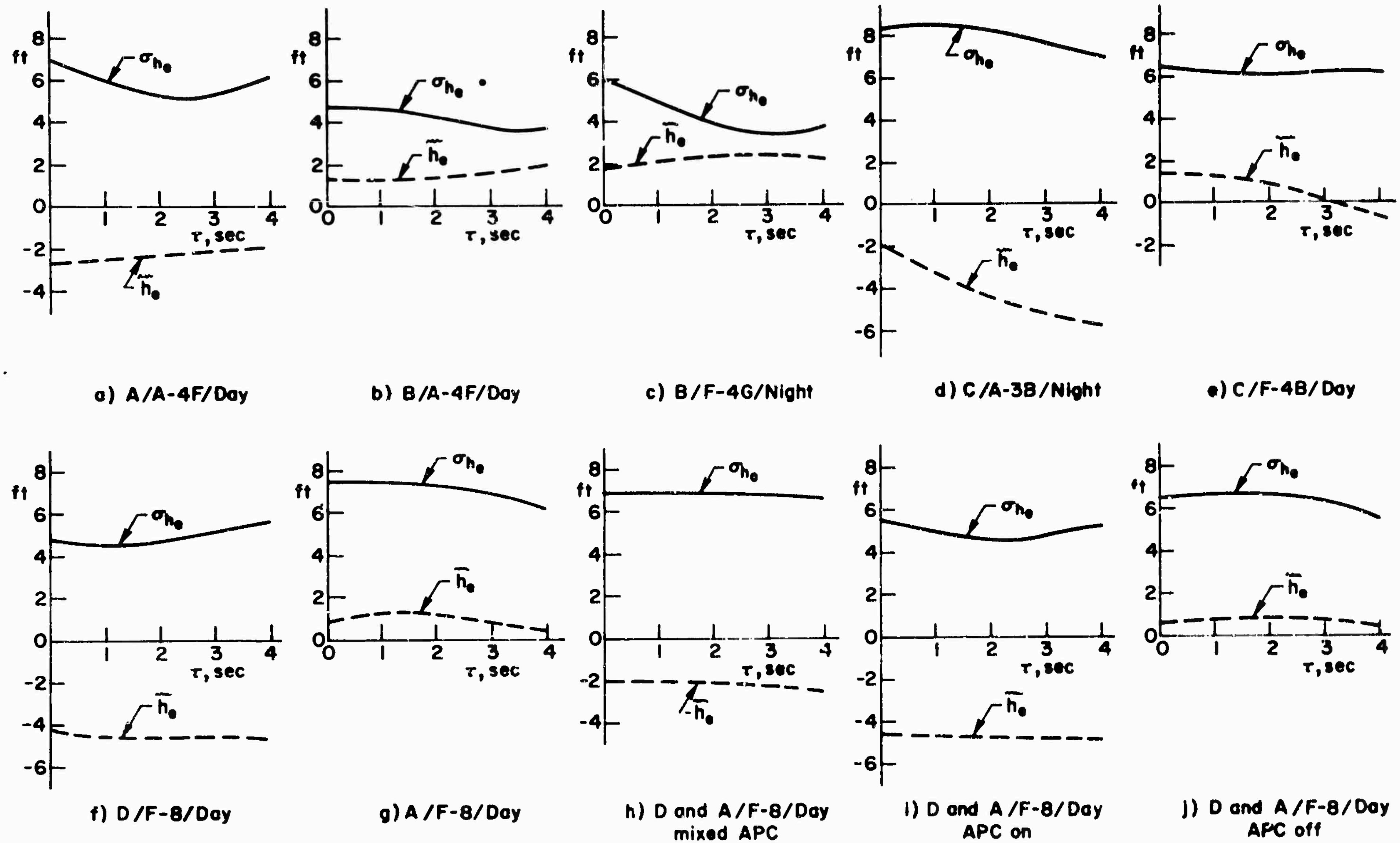


Figure 9. Effectiveness of Ideal CMS Filter

For the F-4G, Fig. 9c, the reduction in dispersion with $\tau = 3$ sec is:

$$\frac{\sigma_{h_e}(3)}{\sigma_{h_e}(0)} = \frac{3.3}{5.9} = 0.56 \qquad (18)$$

The corresponding reduction in errors predicted in Ref. 1 for the theoretical pilot/aircraft system and the optimum CMS filter was 0.74 at the ramp and 0.43 in the vicinity of the touchdown point. The desired path in that study was one which matched the motion of a point on the deck halfway between the ramp and the touchdown point. Note that this optimum CMS filter performance resulted in reducing the theoretical accident rate by a factor of 5.

The results of the "ideal" CMS analysis given here tend to complement the correlation analyses of the preceding subsection in that the latter are most applicable (e.g., truncation errors are smaller) prior to reaching the ramp ($T = 10 - 4$ sec), whereas the former apply reasonably close to the ramp ($T = 6 - 2$ sec). For some particular cases both sets of results are consistent; however, in other cases there are notable differences. For example:

- The correlation analysis indicated that there was little evidence of tracking for the F-8 aircraft. Figures 9f through 9j bear this out as little change is indicated with the use of CMS; however, these same figures show differences between pilots and with and without APC for this aircraft.

- Looking at pilot differences first, Fig. 9f and 9g, it is evident that D stays closer to his average path than A (the standard deviation, σ_{h_e}, is smaller). But D's average path, h_e, is about 4.5 ft low while A's is only about 1 ft high.

- In Fig. 9h the average path, $\bar{h}_e$, of both pilots is seen to be about 2 ft low. If there were no effect of APC it would be expected that h_e would be about 2 ft low for both APC on and APC off. In comparing Figs. 9i and 9j it is seen that this is not the case. With APC on, h_e, is about 4.5 ft low while the mean error with APC off is only 0.5 ft high. (The ratio of passes by A to passes by D is about the same, ± 1/2, whether we consider all passes, those with APC on, or only those with APC off.) On the other hand the differences in level indicated for the standard deviation of the altitude error do not appear significant; but their trend with r indicates that the pilot is tracking better with APC on.

Taking the point of view that the rms dispersions are more indicative of closed-loop tracking than the means (which could represent pilot, or real but unrecorded, biases), we can tentatively conclude from the above that APC has little effect on performance until near the ramp, where it becomes mildly beneficial.

F. PILOT COMMENTARY

The pilots felt that the meatball motions displayed were reasonably realistic and representative of the "pitching deck" conditions they had encountered. Furthermore they were impressed with the task as a means of rapidly separating "good" from "marginal" carrier-suitable longitudinal flight characteristics. For example, quoting Pilot A:

> "...Even in a bad airplane if you make correct transition to lens you have a fairly good approach. With moving lens this is not so. You must continuously command motions. Also it tells you whether or not you'd like to fly onto a carrier with the particular aircraft."

Another aspect of the setup that elicited comment was its possible potential as a training device. For example the pilots and observers noticed a marked improvement in performance within a relatively small number of trial passes. The general feeling was that regular use of a moving meatball at shore-based installations could serve to sharpen up and "refresh" pilot techniques.

G. SUMMARY

A pilot can and will track a moving meatball. Landing performance is a function mostly of the aircraft type and, somewhat, of the particular pilot. Slight performance improvement is indicated for the use of APC on the F-8 aircraft but, due to the limits of the data, this conclusion is only tentative. CMS can reduce landing dispersions for some of the tested and analyzed aircraft, the A-4F and F-4G; as expected, for other aircraft CMS use would be neutrally beneficial. The shore-based moving meatball (and its programmed inputs) provides a useful overall indication to the pilot of carrier-suitable longitudinal stability and control characteristics. It also appears to have potential as a training device.

SECTION III

PILOT'S PERCEPTION AND RESOLUTION OF FLOLS

To check the SPN-42 radar boresighting relative to the FCLP FLOLS, each pilot called the meatball location as he saw it (high, low, center, etc.) at regular intervals during his approaches. We used the "center ball" calls to eliminate boresight errors from the data presented in Section II, and also to estimate, from a limited sampling of the data, the pilot's ability to resolve indicated errors. The results and conclusions of the latter efforts are the subject of this section.

The pertinent optical geometry is shown in Fig. 10; the terminology and parameters which will be used are also defined in the figure. In Fig. 11 an example set of center meatball calls made by one pilot during 10 sequential daytime passes is shown. The altitude error (radar measured airplane altitude minus the altitude command) at the time of each call is plotted versus the measured range at the time of the call.

These errors can be considered as altitude errors, h_e, or transformed into visual angle errors, ϵ, or cell displacements, Z_e, by the relations given in Fig. 10. Regardless of which is the most suitable measure, the errors were found to have a normal distribution, e.g., as shown in Fig. 12.

The data of Fig. 11 were divided into two groups of 24 calls each, the first group corresponding to ranges between 0 and 4,300 ft, the second group corresponding to ranges greater than 4,3000 ft. The standard deviations, σ, were computed for each of the three measures as shown in Table II.

These data show that the pilot's error in called centerball, if measured by the cell displacement, Z_e, is independent of range. The other measures are not. Of special significance in this regard is the fact that the visual angle, ϵ, is <u>not</u> (as normally assumed, e.g., Refs. 1, 2, and 3) an appropriate measure of meatball error perception; i.e., it is <u>not</u> range-independent. Apparently the pilot can perceive a meatball displacement error of 0.17 ft or so, about a quarter cell, at ranges up to about 9,000 ft under good visibility, daytime conditions. That is, the probability that the pilot will perceive or not ignore errors greater that about a quarter cell is 0.68 for daytime operations.

$$\alpha \doteq \frac{h_e}{R + X_m}$$

$$Z_e \doteq \alpha X_m = \frac{X_m}{R + X_m} h_e$$

$$\epsilon \doteq \frac{Z_e}{R} \doteq \frac{X_m}{R(R + X_m)} h_e$$

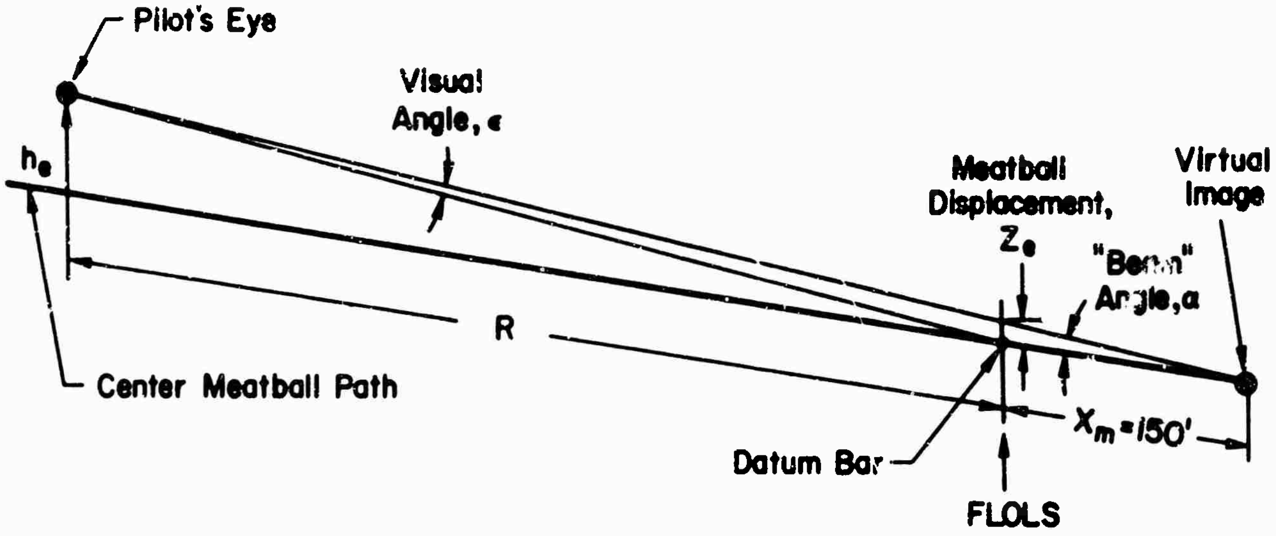


Figure 10. FLOLS Optical Geometry

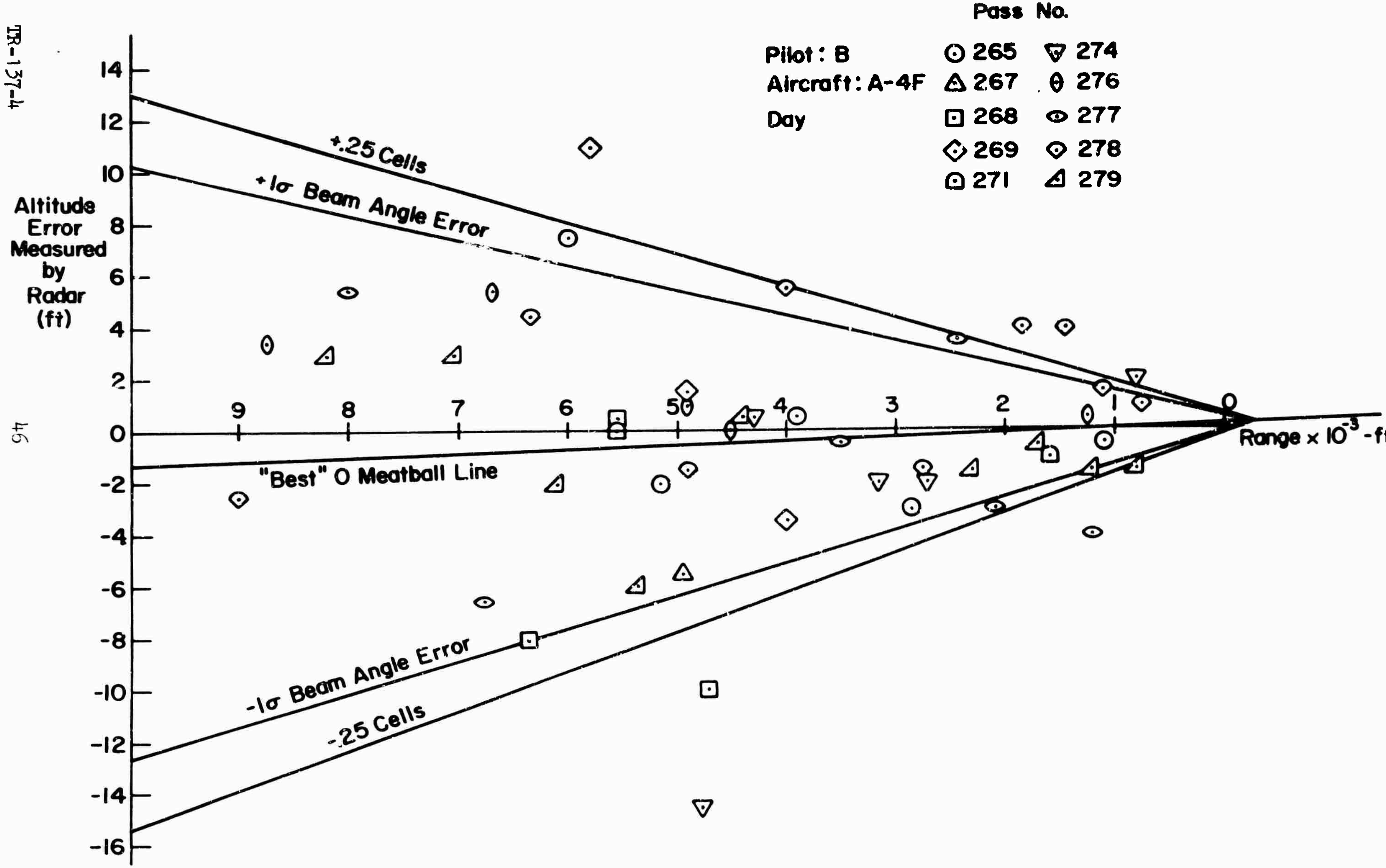
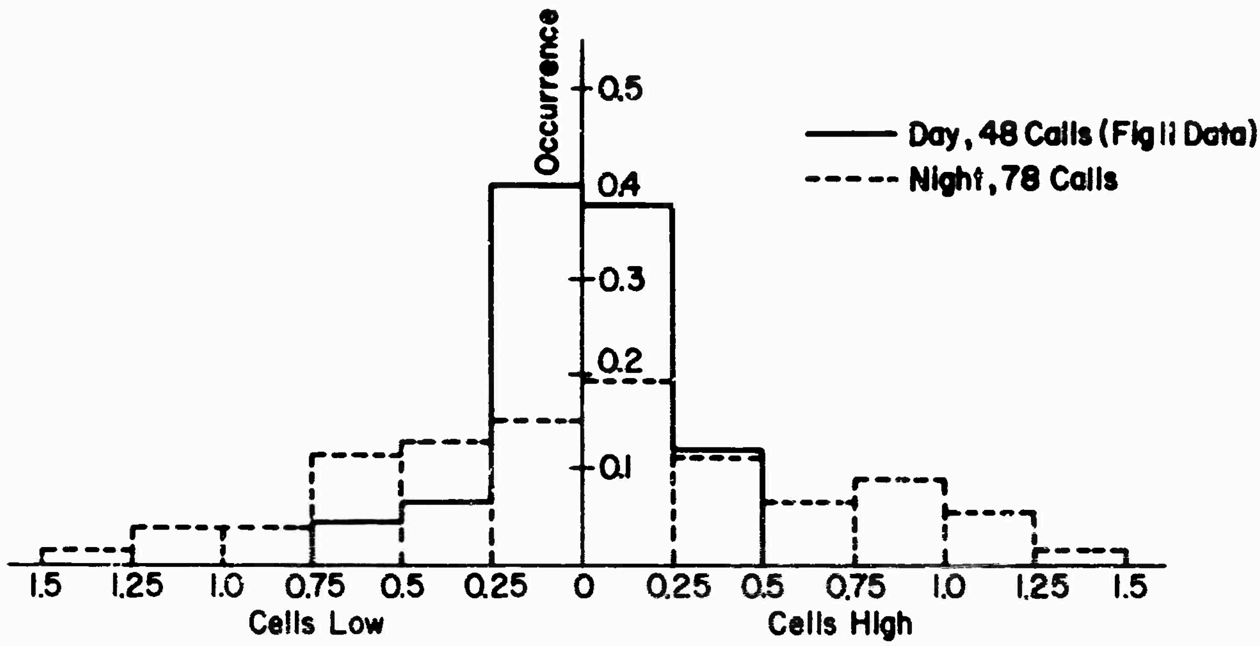
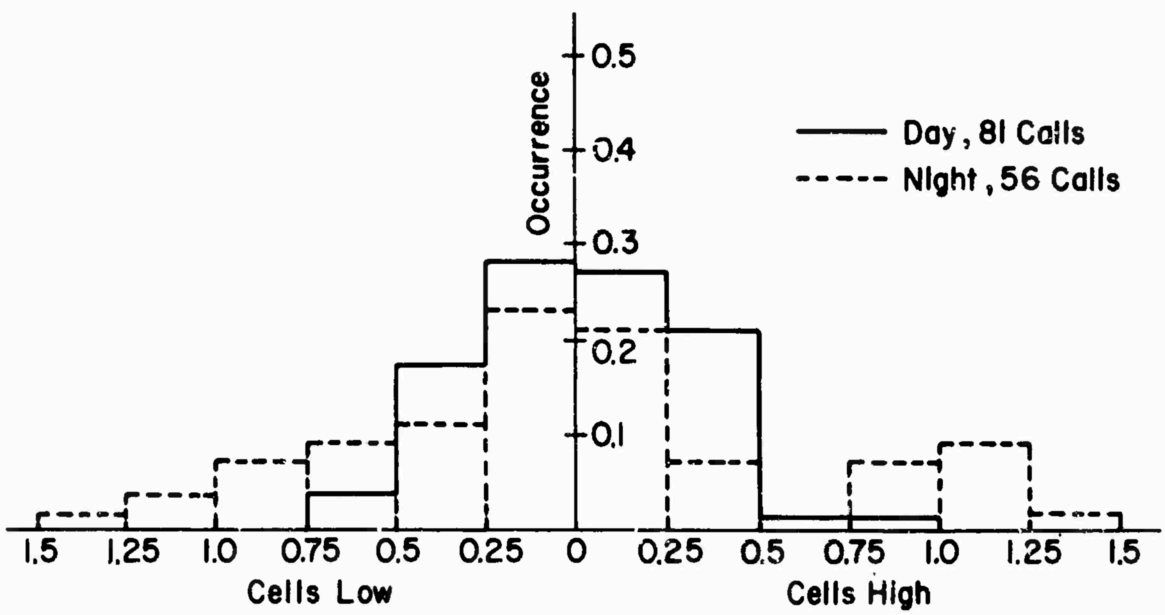


Figure 11. Center Meatball Calls — One Pilot, 10 Sequential Daytime Passes



a) B ; A-4F Day ; F-4G Night



b) A ; RA-5, F-4B Day ; A-3B Night

Figure 12. Pilot Error on "Center Ball" Calls — Day versus Night
(Normalized Distributions)

TABLE II

STANDARD DEVIATIONS OF CENTER MEATBALL CALLS

CALLS	ALL 48	24 $0 < R < 4300$ ft	24 $R > 4300$ ft
σ_{h_e}, ft	4.54	2.53	5.98
σ_{Z_e}, ft	0.17	0.18	0.16
σ_{ϵ}, millirad	0.092	0.13	0.029

Figure 12 shows the histograms of pilot's error in centerball calls obtained during day and night passes by two pilots. Nighttime errors are about twice those in the day. The perceivable errors with the Fresnel Lens at night appear, accordingly, to be about half a meatball.

A. IMPLICATIONS

Long range-discrimination of the FLOLS meatball is apparently better than previously assumed. The useful range of FLOLS is compared on the basis of two "laws" in Fig. 13. The first, conventionally assumed, says that the minimum detectable error is governed by a visual angle limitation, ϵ_{min}, of about 1 arc min. The second law, an outcome of the above data analysis, says that the limiting factor is meatball displacement, $\sigma_{Z_{e_{min}}} \doteq 0.17$ ft during the day and $\doteq 0.34$ ft during the night. In Fig. 13, these limitations have been transformed into minimum detectable altitude errors. As shown, at a range of about 1 mile, the conventional "law" indicates a minimum detectable error of 54 ft. The corresponding altitude error if governed by the meatball displacement law is 6 ft during the day and 12 ft at night. At closer ranges the differences are not significant but it should be noted that at ranges less than 1,000 ft the resolution indicated by the meatball displacement law at night is less than 1 arc min. Based on visual angle limits, the maximum range at which a 1 ft error can be detected is 719 ft; based on meatball displacement the maximum range would be 880 ft during the day and 440 ft at night.

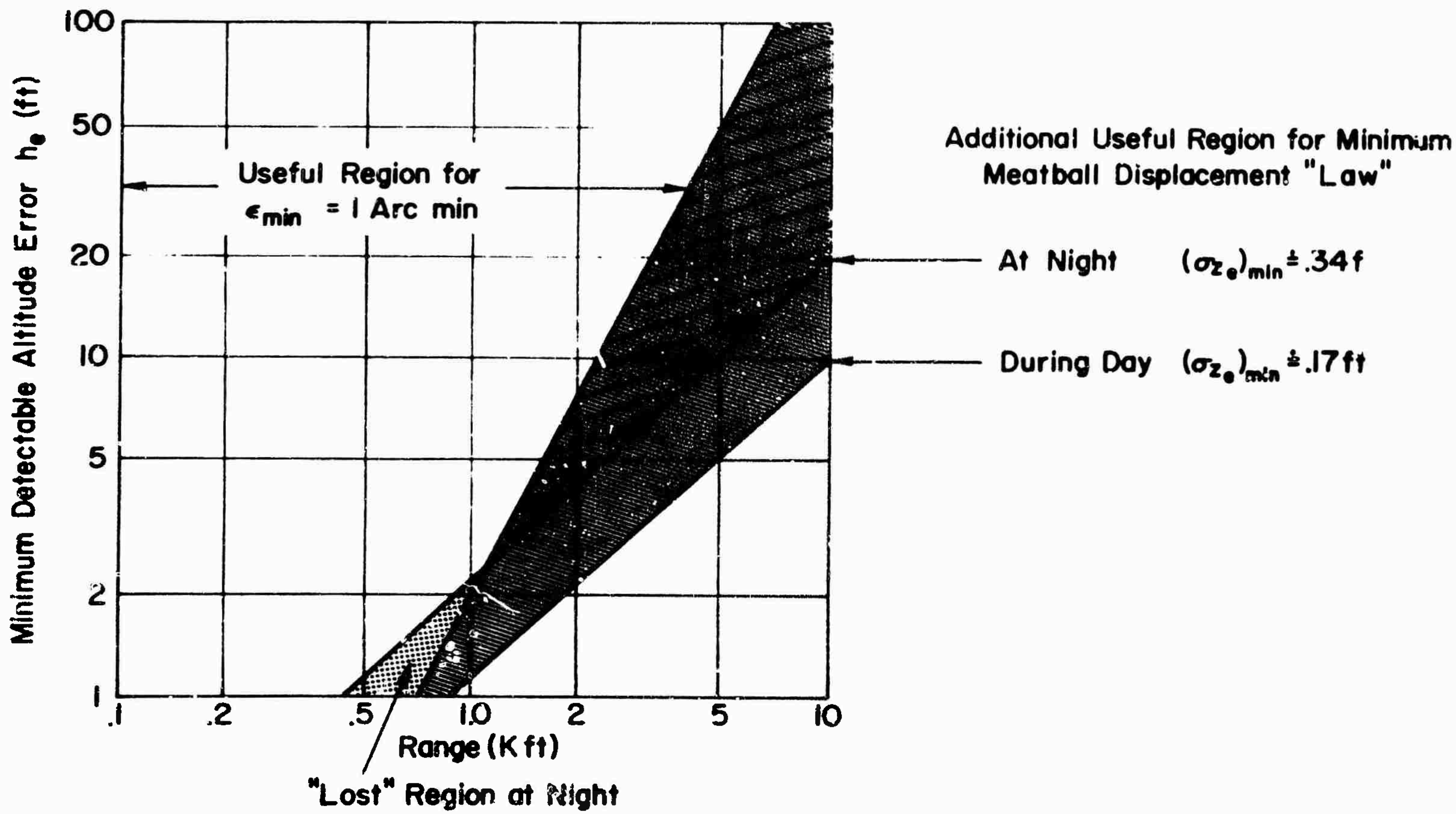


Figure 13. Useful Range of FLOLS, Comparison of Visual Angle Limit, ϵ_{min}, "Law" and Meatball Displacement Limit, $Z_{e_{min}}$, "Law"

B. SUMMARY

Limited data indicate that FLOLS error perception at long range is far better than expected. More definitive data should be obtained to verify this preliminary conclusion.

Pending more definitive tests, the minimum detectable meatball errors recorded here can serve as a guide to the design of stabilization equipment (e.g., CLASS) and also as a tentative standard for the design and testing of auxiliary VLA equipment now being developed. If eventual testing shows that there are large differences among the pilot population in their ability to discriminate meatball errors, such ability could be conceivably used in screening possible pilot applicants, or in sharpening up service pilots by proper training.

SECTION IV

CHARACTERISTICS OF THE FLOLS LENS DRIVE SERVO

The purpose of this series of tests was to obtain dynamic performance measurements for the lens drive servo system in both the pitch and roll axes.

A description of the test equipment used is given in subsection IV-A. The scope of the tests is described in subsection IV-B and the results in IV-C. A summary of the conclusions are given in IV-D.

A. TEST EQUIPMENT

The following equipment items were used for testing the FLOLS lens drive servos:

- Function generator (Exact Electronics)
- Signal-processing unit (Systems Technology, Inc.)
- Cathode ray oscilloscope (Tektronix)
- Six-channel strip chart recorder (Brush)

During normal operation, the lens drive servo amplifier operates on a basic 400 cps single-phase carrier signal which is suitably modulated, utilizing signals from the ship's gyros, to provide the appropriate stabilization commands to the lens drive servomotors.

It was necessary, therefore, to construct a signal-processing unit which, when used in conjunction with a standard sine wave function generator, would provide a modulated signal suitable for direct injection to the lens drive servo amplifier. It was also necessary to demodulate the command input signal and the pitch and roll servo feedback signals for recording purposes. Three demodulators were incorporated in the signal-processing unit for this purpose. This unit was constructed by Systems Technology, Inc. The CRT was part of the standard shipboard equipment and was used at various times throughout the test to check the modulated input signal, etc. All tests were conducted with the MK 6 system in the line mode in order to provide simultaneous activation of pitch and roll channels.

B. SCOPE OF THE TESTS

The following tests were conducted on the FLOLS lens box drive servo system.

1. Frequency Response, Roll Channel

Frequency range.............................. 0.01 cps to 3 cps

Amplitudes............................ ±0.5, ±1, ±2, ±4, ±6 deg

Roll angle bias (lens box clockwise as seen from aft end of the ship)........................ 1 deg

The frequency response test was repeated using ±6 deg amplitude about a mid-travel reference position of +5 deg.

2. Frequency Response, Pitch Channel

Frequency range.............................. 0.01 cps to 3 cps

Amplitudes.................................... ±0.5, ±1, ±2 deg

Basic angle (positive lens box rotation increases glide slope angle).......................... +4.3 deg

3. Step Response, Pitch and Roll Channels

Step magnitude...................................... ±2 deg

4. Hysteresis Tests, Pitch and Roll Channels

Examination of the frequency response data for evidence of frequency-independent phase lags.

Measurement of feedback potentiometer output in response to physical rotation of the lens box.

5. Rate Saturation

Peak servo rates estimated from the frequency response data.

6. **Amplitude Limits**

Maximum angular displacements measured for pitch and roll channels.

7. **Rate Test, Roll Angle and Pitch Basic Angle**

Rate of angular displacement measured using roll angle and basic angle controls on operator's console.

8. **Calibration Tests**

a. Pitch and roll angle calibration

Calibration in units of 10 min of arc up to 2 deg.

b. Unit indicator calibration

Unit indicators on operator's console versus angular displacement of lens box, pitch and roll.

c. Feedback potentiometers

Wiper voltage feedback potentiometer versus angular displacement of lens box, pitch and roll.

C. DISCUSSION OF RESULTS

1. **Frequency Response, Roll Channel**

Results of frequency response tests over the complete amplitude range using +1 deg bias reference are shown in Fig. 14. Phase lags at the highest estimated value of ship frequency (approximately 1 rad/sec) are of the order of 10 deg. Amplitude characteristics indicate 3 dB attentuation occurring at 1.5 cps

Figure 15 shows results of ±6 deg amplitude about the mid-range of total travel (approximately +5 deg). The data compare very closely with those of Fig. 14 for the same input amplitude.

During the above test, with the input to the pitch channel disconnected, the recorder gain in the pitch channel was set to maximum in order to check for crosstalk between channels. Crosstalk, if present, could not be distinguished from the low noise level appearing on the recorder trace. This noise level was less than 0.005 volts corresponding to a lens box rotation of ±0.8 min of arc.

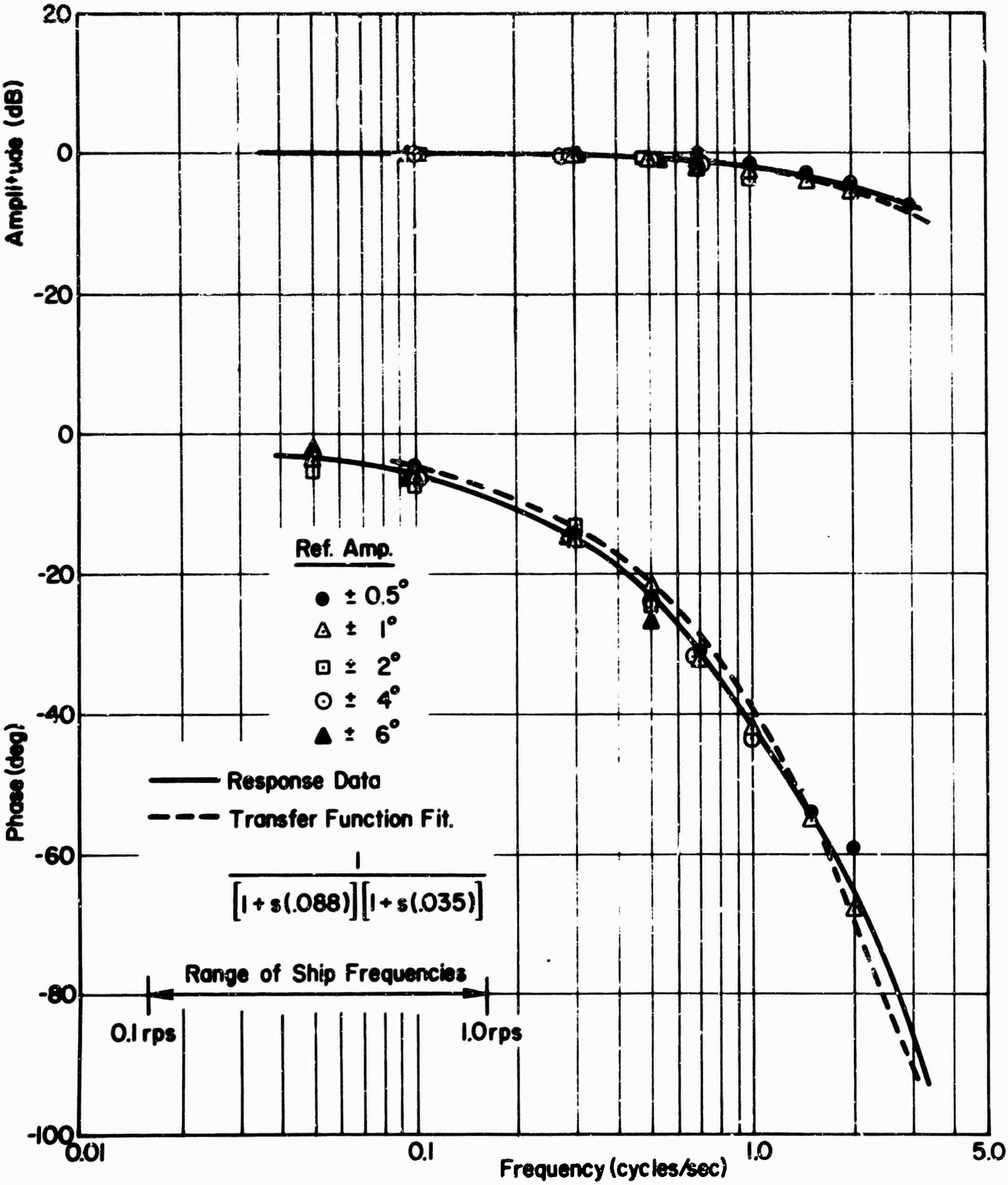


Figure 14. Roll Channel Frequency Response
(Roll Angle Bias 1°; Lens Box Clockwise)

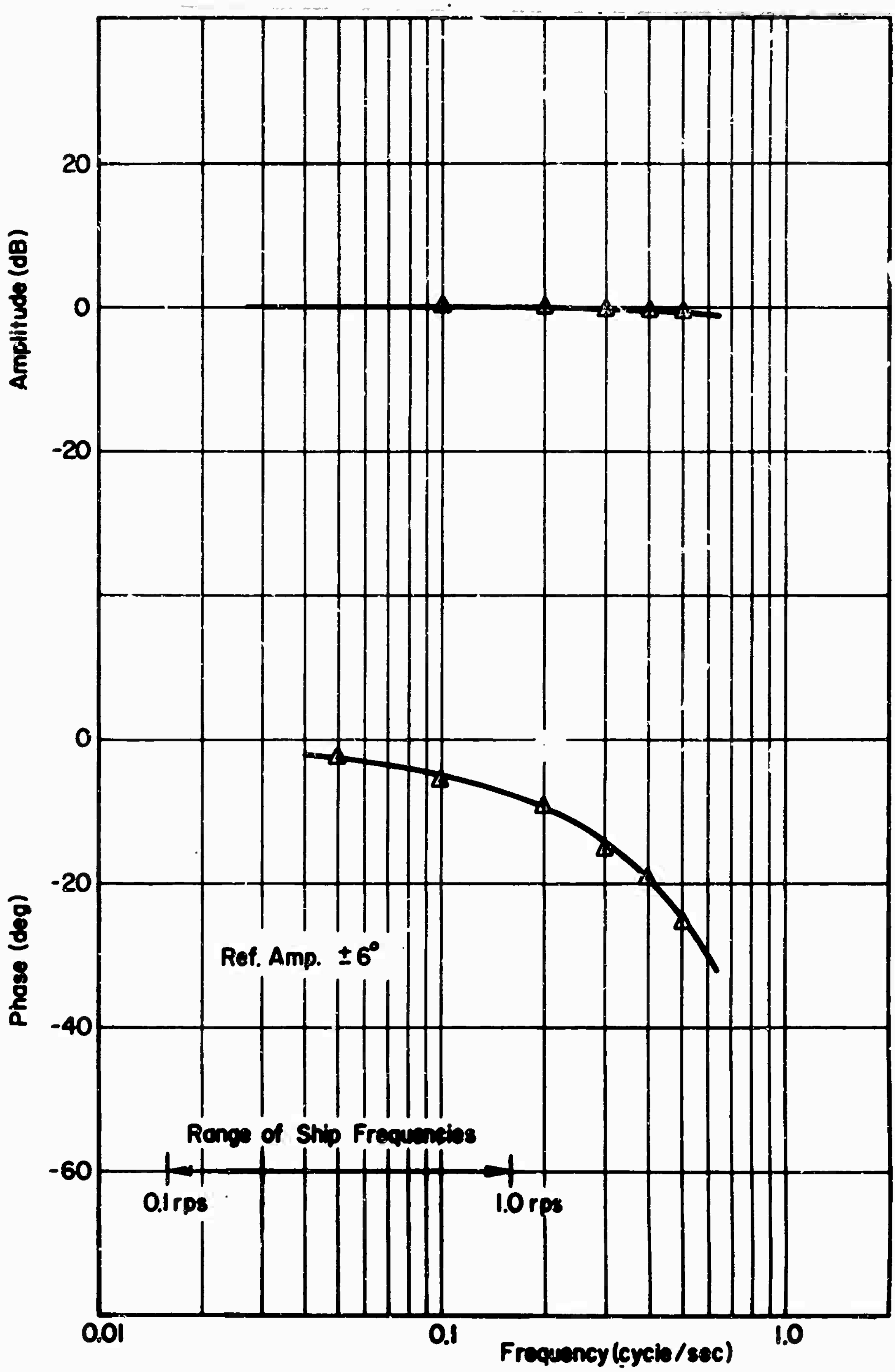


Figure 15. Roll Channel Frequency Response
(Roll Angle Bias 5°; Lens Box Clockwise)

It was observed that at servo rates greater than 20 deg/sec some distortion of the output waveform was evident. This was considered to be a rate saturation effect since the distortion was observed to occur at combinations of frequency and amplitude corresponding to a consistent value of peak servo rate. This is discussed in more detail under "rate saturation tests."

Since the distortion of the waveform occurred at values of frequency and amplitude well beyond the normal operating range of the system it was not considered to be detrimental to system performance.

2. Frequency Response, Pitch Channel

Results of frequency response tests up to ±2 deg amplitude using 4.3 deg basic angle are shown in Fig. 16. Phase lags are approximately 10 deg at 0.16 cps (1 rad/sec). Phase lags at frequencies of 0.01 cps are negligible. The amplitude characteristic in pitch shows 3 dB attenuation at 2.5 cps.

A distortion of the output waveform, similar to that experienced in the roll channel, also occurred in the pitch channel. This distortion effect appears to be due to a rate saturation type of nonlinearity as explained under "Rate Saturation Tests."

3. Step Response, Pitch and Roll Channels

A sample step response in pitch is shown in Fig. 17a. An equivalent step response was calculated from the best transfer function fit to the frequency response data and is superimposed on Fig. 17a. The measured transient characteristic exhibits a slower response with a larger overshoot.

This discrepancy in step response suggests that system nonlinear characteristics additional to those already discussed may be exerting an appreciable influence on the system under step input conditions.

A simplified schematic of the pitch drive servo system is shown in Fig. 18a together with a linearized block diagram of the major system components. The root locus diagram for the linearized system based on the transient and frequency response measurements is shown in Fig. 18b. The oscillatory mode characteristics corresponding to the frequency response measurements

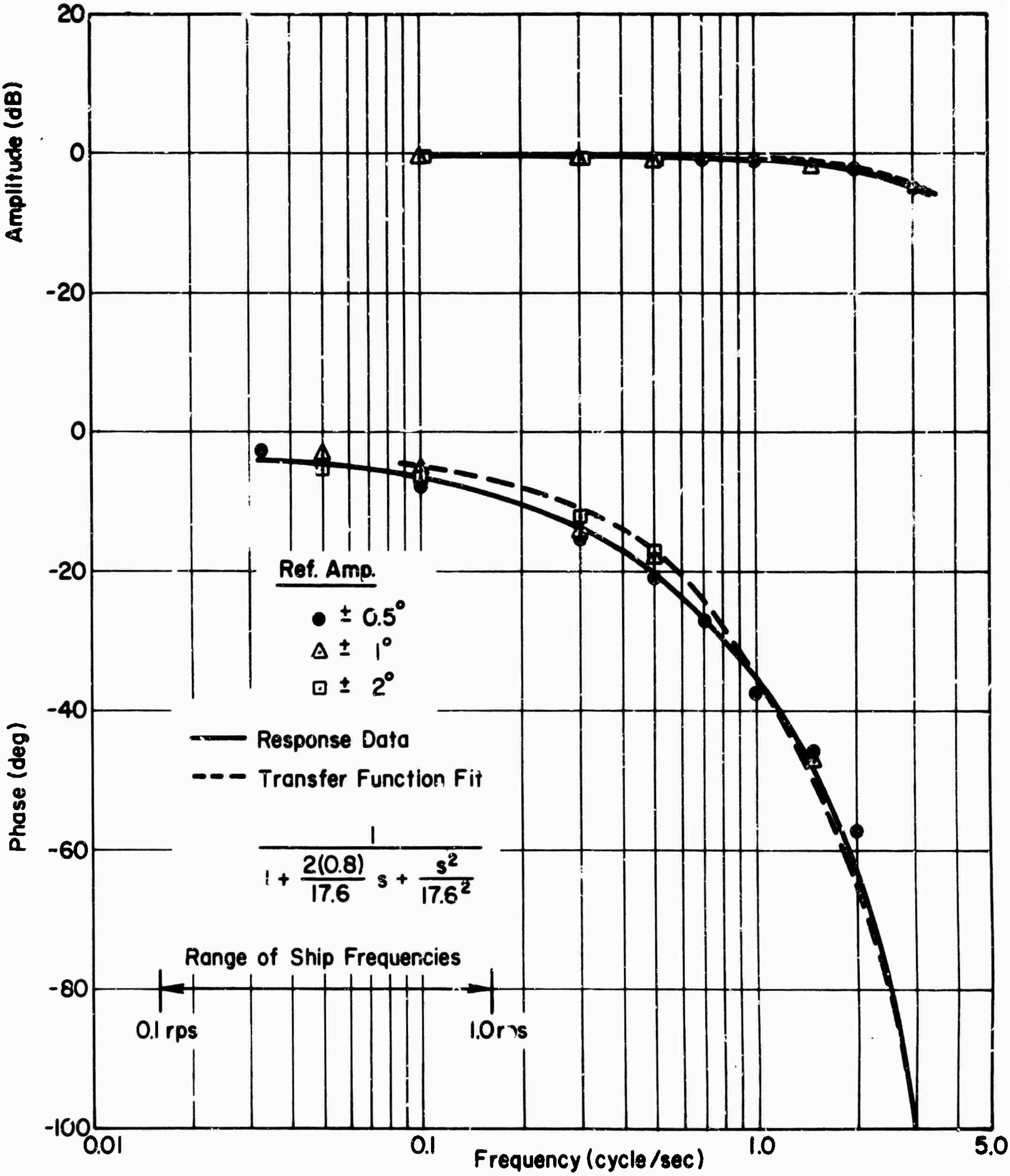


Figure 16. Pitch Channel Frequency Response
(Basic Angle 4.3°)

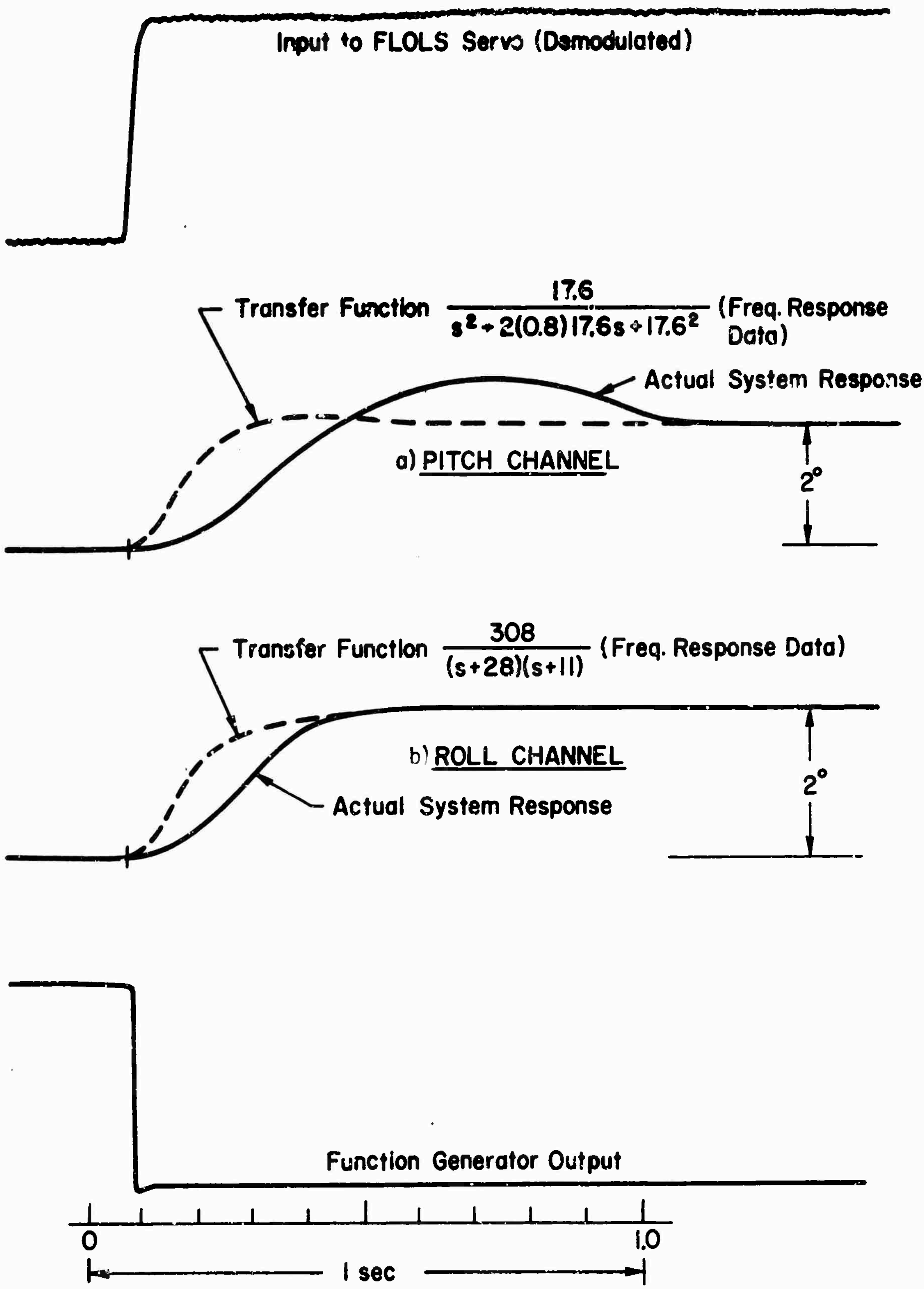
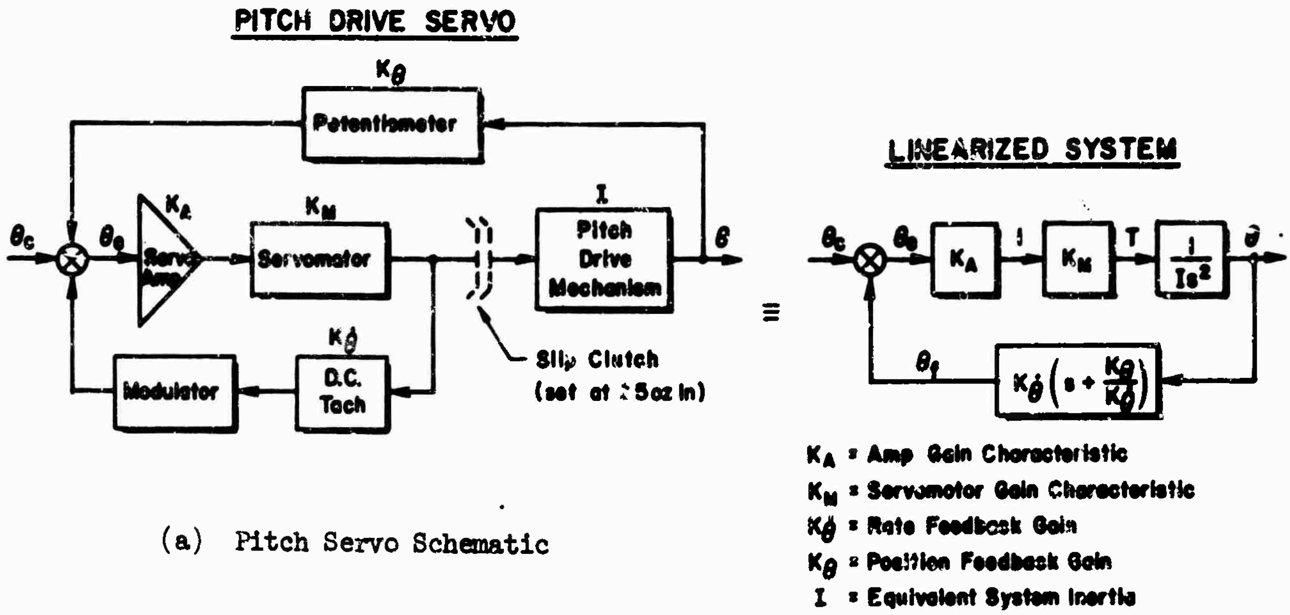
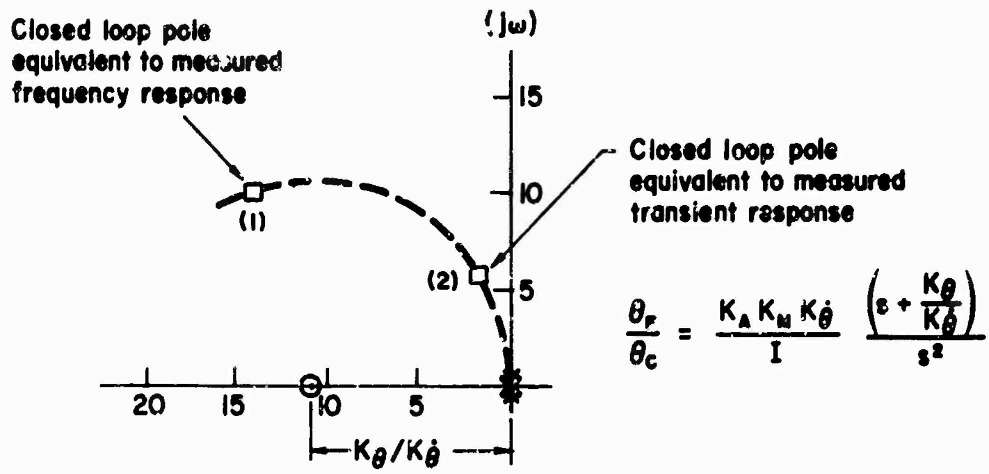


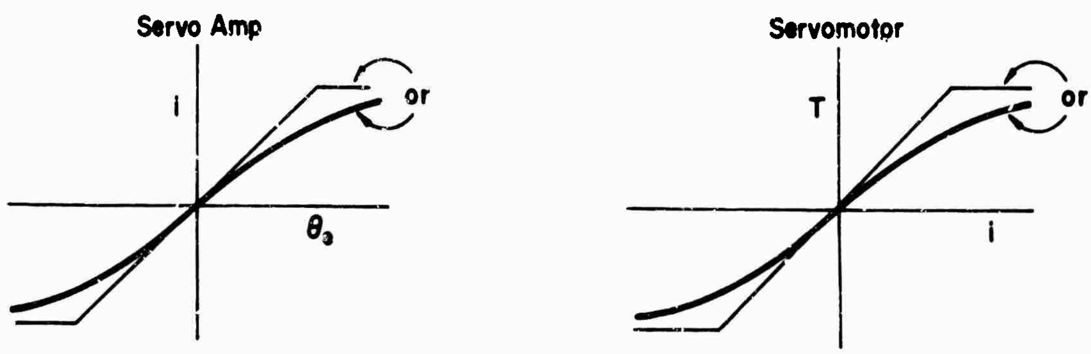
Figure 17. Step Response Pitch and Roll



(a) Pitch Servo Schematic



(b) Root Locus for Linearized System



(c) Possible Nonlinear Characteristics Causing Effective Loop Gain Reduction

Figure 18. Pitch Drive Servo

are indicated by the closed-loop pole at position 1. Reduction in the system loop gain will result in a decrease of natural frequency and damping ratio for the oscillatory mode. The resulting transient response will be less rapid and exhibit a larger overshoot. The corresponding closed-loop pole position which exhibits transient response features similar to the measured step response is indicated by position 2.

Nonlinear gain characteristics, as shown in Fig. 18c, associated with the servoamplifier or servomotor or both, could produce an effective reduction in loop gain for the initially large values of error (θ_e) associated with a step response. This effect may not be apparent for the smaller values of error amplitude associated with the frequency response measurements.

A sample step response in roll is shown in Fig. 17b. Superimposed is an equivalent step response estimated from frequency response data. A slower response is again demonstrated by the measured transient characteristic although the discrepancy is smaller than was the case for the pitch servo. This could also be due to nonlinear gain characteristics in the servoamplifier or servomotor.

Another factor which was considered as a possible explanation for the discrepancy between transient and frequency response data was the effect of the slip clutch located between the servomotor and the drive gear mechanism (see Fig. 18a). A slip clutch is incorporated in both the pitch and roll servo systems.

In the case of sufficiently large error signal applied to the servomotor, the clutch breakout torque can be exceeded initially resulting in reduced acceleration of the system. This is somewhat analogous to a reduction in amplifier or servomotor gain which tends to displace the closed-loop oscillatory mode to a position corresponding to lower values of frequency and damping ratio.

Values of initial acceleration estimated from the measured step response in roll together with estimates of the roll axis inertia indicated, however, that the corresponding torque was less than that required to slip the clutch (2.2 oz in estimated compared with 5 oz in required).

It would appear therefore that the more likely explanation for the mismatch is associated with nonlinear gain effects either in the servo-amplifier or servomotor. A more detailed study of these effects would require that additional response tests be conducted on individual system components.

4. Hysteresis Tests, Pitch and Roll Channels

The frequency response data for pitch and roll channels were examined, at low frequencies, for evidence of frequency-independent phase lags. Phase lags at low frequency (0.01 cps) appeared to be negligible; therefore, from this viewpoint threshold or hysteresis effects were also assumed to be negligible.

As an independent check the lens box was rotated physically in both pitch and roll axes in sequence while the output from feedback potentiometers was monitored on the recorder. Lens box rotation was monitored on the dial indicators in the FLOLS control room. The lens box could be rotated through amplitudes of ±2 minutes of arc, and a clear indication of movement was obtained on the recorder indicating that hysteresis effects in the gimbal system of the lens box was less than ±2 minutes of arc. This applied to both pitch and roll channels.

5. Rate Saturation Tests

Frequency response data were examined for evidence of rate saturation in terms of a triangular output waveform or other distortion effects. No evidence of distortion was found in the roll channel up to frequencies and amplitudes corresponding to a peak servo rate of 19 deg/sec. At frequency and amplitude combinations corresponding to higher servo rates, some distortion of the output waveform was evident.

No evidence of distortion was found in the pitch channel up to frequencies and amplitudes corresponding to a peak servo rate of 13 deg/sec. At frequency and amplitude combinations corresponding to higher servo rates, some distortion of the output waveform was evident.

6. Lens System Displacement Limits

Maximum angular displacement of the lens box was measured by increasing the amplitude of input signal until the displacement limits were reached.

In the roll channel displacement limits were +17.5 deg to -7 deg.

In the pitch channel displacement limits were +12 deg to -1 deg.

The lens box total travel in both pitch and roll axes appeared to be controlled by limit switches on the lens box gimbal system.

7. Rate Test, Roll Angle and Pitch Basic Angle

Operational angular rate of the lens box in pitch and roll axes was measured by activating the roll angle and basic angle rate controls on the operator's console.

Roll axis angular rate was measured as 0.5 deg/sec.

Pitch axis angular rate was measured as 0.3 deg/sec.

8. Calibration Tests

a. Pitch and roll angle calibration

Calibration between input command and lens box rotation is shown in Fig. 19 for the roll axis and in Fig. 20 for the pitch axis.

b. Unit indicator calibration

The unit indicators on the operator's console for monitoring roll angle, pitch basic angle, and hook-to-ramp clearance were calibrated against lens box angular displacement. The results are shown in Fig. 21.

c. Feedback potentiometers

Wiper voltage from the feedback potentiometers was calibrated against lens box angular displacement. The results are shown in Fig. 22.

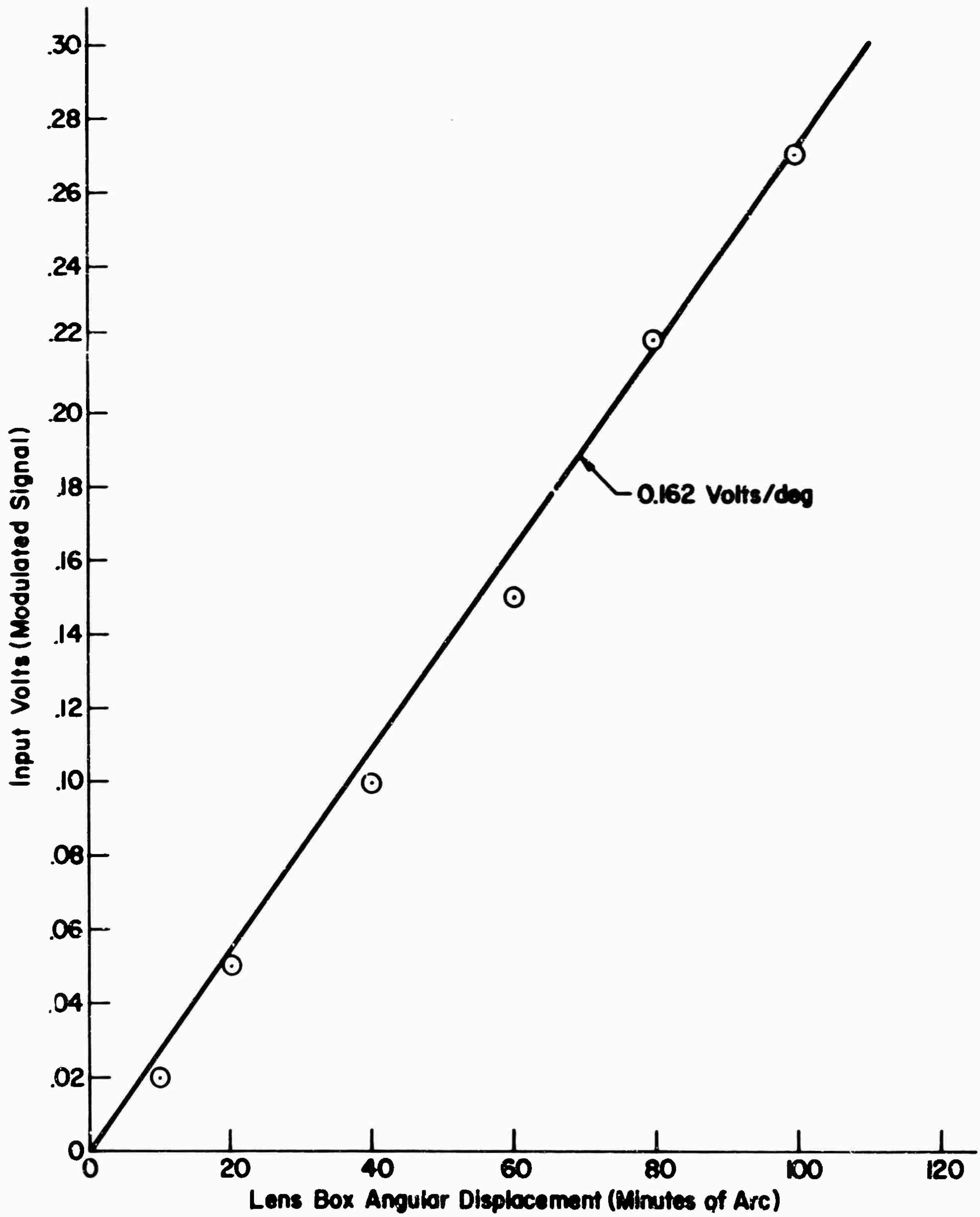


Figure 19. Roll Calibration

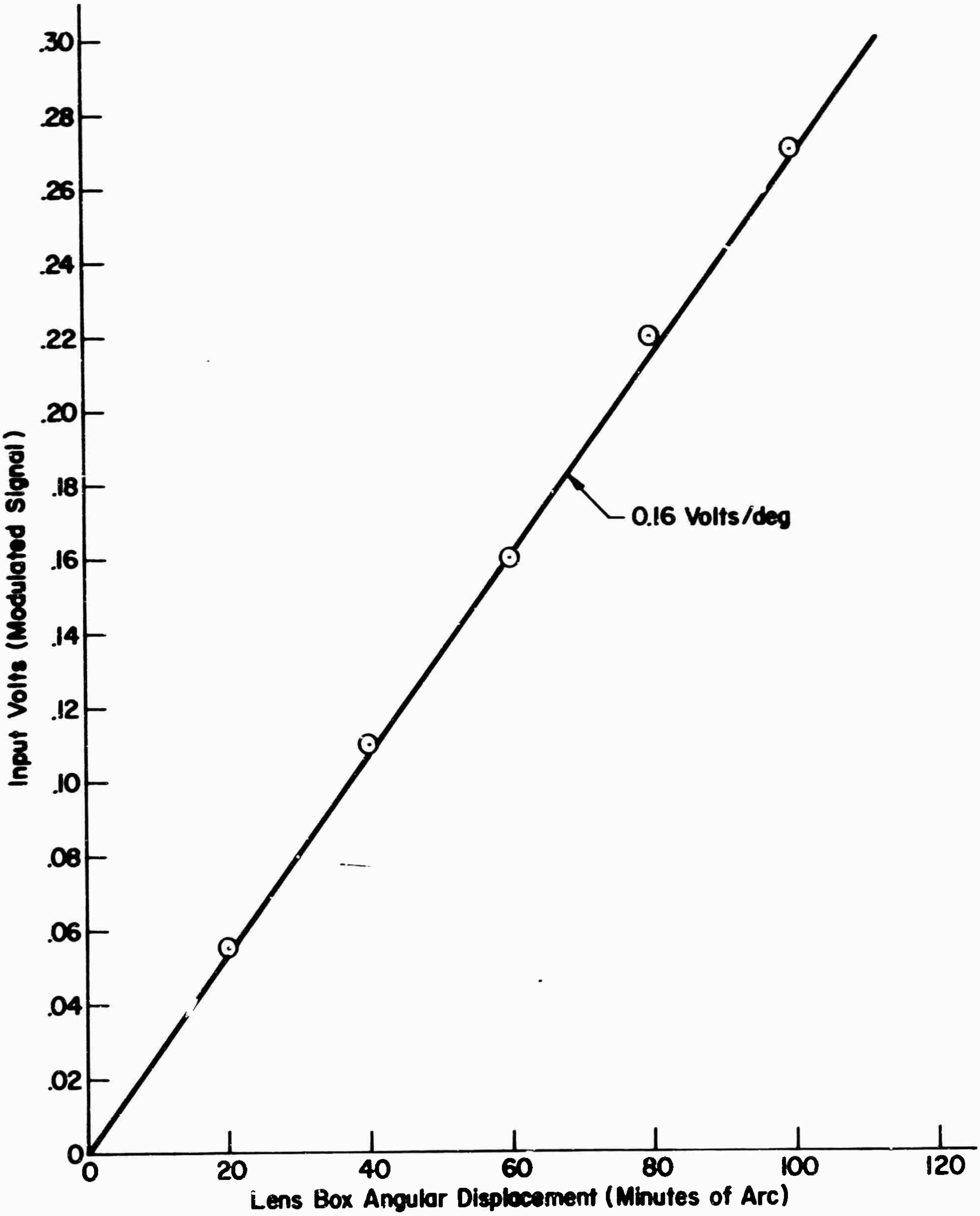
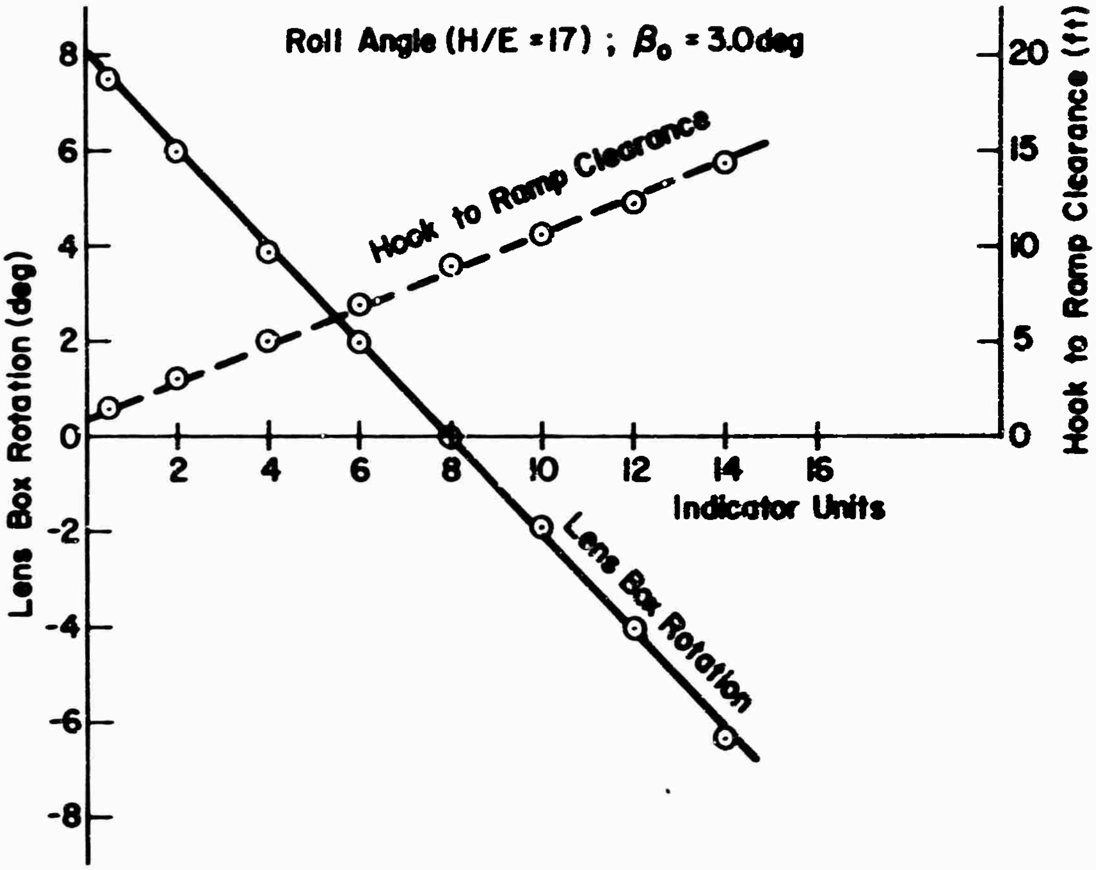


Figure 20. Pitch Calibration



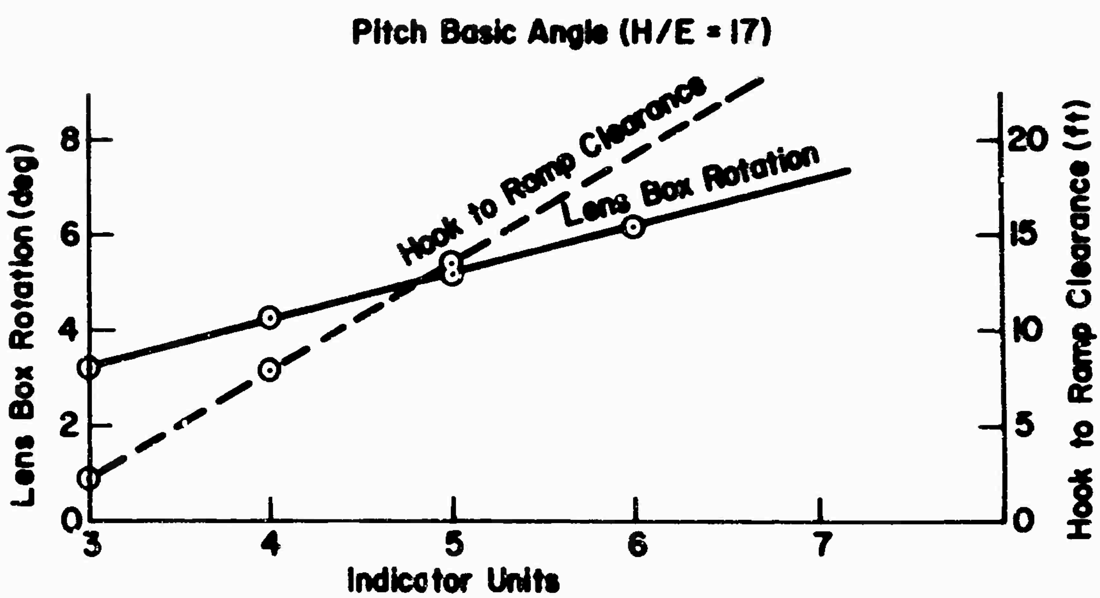


Figure 21. Calibration of Unit Indicators

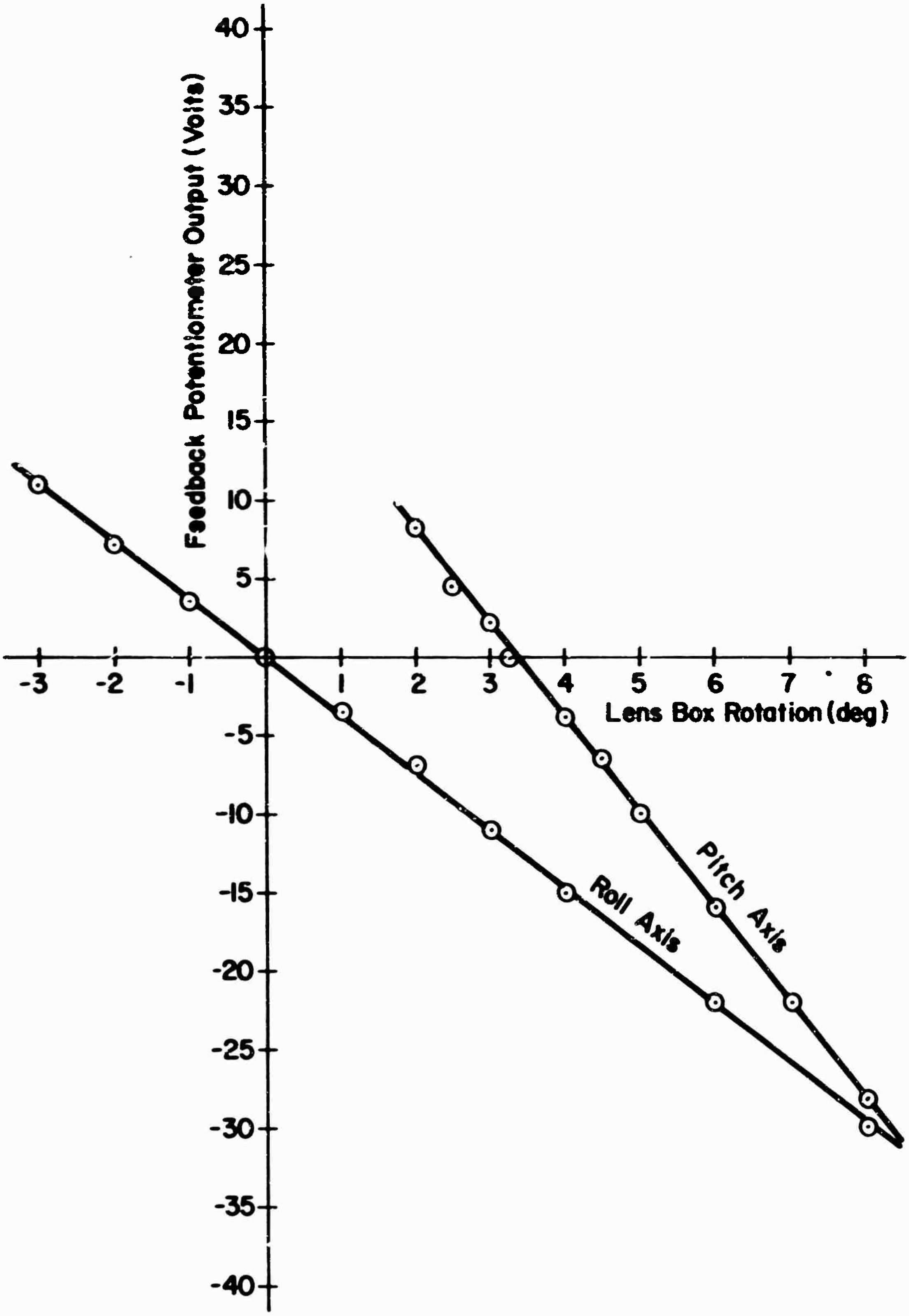


Figure 22. Calibration of Feedback Potentiometers

D. CONCLUSIONS

1. Pitch Servo

Phase lags in the pitch channel at 1 rad/sec are of the order of 10 deg. Phase lag variation with amplitude, in the region of ship frequencies, is of the order of 3 deg for input amplitudes between ±0.5 and ±2 deg. Attenuation of 3 dB occurs at approximately 2.4 cps.

Distortion of the output waveform, in response to sinusoidal inputs, occurs at peak servo rates greater than 13 deg/sec which could be due to a rate saturation type of nonlinearity.

Hysteresis effects in the pitch gimbal system appear to be less than ±2 minutes of arc, and frequency-independent phase lags were not apparent from the response data.

Displacement limits in the pitch channel occur at −1 and +12 deg. The measured transient characteristic demonstrates a slower rate of response with a larger overshoot than the equivalent characteristic estimated from frequency response data. This discrepancy could be due to the presence of nonlinear gain characteristics in the servoamplifier and/or the servomotor.

2. Roll Servo

Phase lags in the roll channel at the highest estimated value of ship frequency (1 rad/sec) are of the order of 10 deg. Phase lag variation with amplitude in this range of frequencies is of the order of 4 deg for amplitude variations between ±0.5 and ±6 deg. Attenuation of 3 dB occurs at approximately 1.5 cps.

Distortion of the output waveform, in response to sinusoidal inputs, occurs at peak servo rates greater than 19 deg/sec, which could be due to a rate saturation type of nonlinearity.

Threshold or hysteresis effects in the roll gimbal system appear to be less than ±2 minutes of arc, and overall hysteresis effects in the lens drive servo system appear to have negligible effect on the frequency response. Frequency-independent phase lags were not apparent from the response data.

Displacement limits in the roll channel occur at −7 deg and +17.5 deg.

The measured transient characteristic demonstrates a slower rate of response than the equivalent characteristic estimated from frequency response data. The mismatch is less, however, than was the case for the pitch servo. The same reasons for the response mismatch as discussed for the pitch servo are applicable to the roll servo.

3. General

The performance of the servo as indicated above is good, but, to avoid beam errors discernible by the pilot, will require improvements.

SECTION V

OPERATIONAL CONSIDERATIONS

It was part of the intent of this test and analysis program to provide background data or suggest additional flight-testing that would lead to improvements in current recovery practice. The particular areas of concern are:

A. Maximum deck motions for satisfactory recovery of each aircraft type tested using the current landing system

B. Optimum settings of FLOLS basic angle for the various aircraft types tested

C. Optimum flight control configuration for the aircraft types tested

With respect to the basic aspects of these areas of concern the available reduced and analyzed data show that:

1. The absolute levels of aircraft altitude motions measured during the test program are compatible with actual shipboard measurements (Ref. 12), thereby validating the basic flight-test procedures employed.

2. The measured data are not inconsistent with the predictions of the analytical models of Refs. 1, 2, and 13.

3. The measured pilot-aircraft characteristics (i.e., lags) are good agreement (see Fig. 7) with those predicted by the analytical model.

However in spite of these promising aspects of the data there is still, in our opinion, an insufficient data base for the positive resolution of the questions posed. That is, neither enough data to establish statistical trends, nor to provide incontrovertible verification of the theoretical models is available in either raw or analyzed form. Our treatment of the above noted areas of concern, as reflected below, is limited by this consideration.

A. MAXIMUM SHIP MOTION FOR VARIOUS AIRPLANE TYPES

The fact that some airplane types can be made to follow beam motions with more fidelity than others is clearly indicated in the data; and these data as noted above are not inconsistent with theoretical considerations. The significance of such beam following capability is that it can reduce the ramp clearance dispersions. For example, in Fig. 9 the σ_{h_e} for the A-4 is some 60 percent or so of that for the F-8. These dispersions are proportional to ship motion amplitude; and we would conclude, therefore, if we took this small sample seriously, that the A-4 could successfully recover under ship motion conditions that were 60 percent or so greater than those suitable for F-8 recoveries. That is, under such limiting circumstances both aircraft would show the same dispersions and, therefore, the same accident probabilities (Ref. 3). While the relative permissible ship motions could thus be established, the absolute allowable motions would require consideration of an associated acceptable accident rate. More and better data of the type used in the above illustration could be used either directly, as above, or indirectly to support accident probability calculations based on verification (or revision) of the system model (Ref. 1). For the present, we can only note that the data gathering and reduction techniques so far explored show considerable promise in connection with the problem of specifying relative limiting ship motion amplitudes as a function of airplane type.

B. IDEAL BASIC ANGLE

The notion of an ideal glide slope to minimize accidents due to both ramp strikes and hard landings is advanced in Refs. 2 and 13. Presumably (Ref. 2), changes in the ideal basic angle should occur whenever the relative dispersions of ramp clearance and impact velocity change due to such causes as airplane type, ship motion amplitude, carrier size, etc.

In order to establish such an ideal it is necessary to first establish the dispersions in both ramp clearance and vertical impact velocity. Because of the more pressing general aspects of the data reduction process, none of the data obtained were reduced or analyzed relative to impact velocity or rate of descent dispersions. Accordingly, it is not possible on the basis of the available reduced data to make any recommendations whatever relative to ideal basic angles.

C. OPTIMUM SELECTION OF FLIGHT CONTROL CONFIGURATION FOR TYPES OF AIRCRAFT TESTED

The "targets of opportunity" presented were restricted to three aircraft types:

F-8 The usable data consisted of 27 passes on which 10 were made with APC on, 15 with APC off, and 2 for which the status of the APC was uncertain. As observed in Section II, 16 passes were anlyzed and a slight improvement in tracking close to the ramp was noted with the use of APC. Because of the limited data any overall conclusions as to the desirability of APC on this aircraft would be premature.

A-7A Data on 29 passes were obtained with all combinations of APC on and off, and AFCS (control stick steering mode) on and off. This represents a potentially worthwhile data base which could yield information on the effects of APC and AFCS on approach flight characteristics. Unfortunately, limited funds prevented analysis of these data with the applicable time domain techniques developed during the current program.

F-111B Data on 9 passes were obtained, all with a single pilot. Approximately half were made with the use of DLC (Direct Lift Control). These data were the last obtained in the program and time and funds were, by then, not available to analyze this data.

D. SUMMARY

As pointed out above the major detriment to reaching firm conclusions as to practical improvements in current recovery operations is the lack of a sufficient data base. Usable data on about 180 passes were obtained during the current program representing 11 different pilots and 6 different aircraft types (one of which, the F-4, included 3 versions, the F-4B, F-4G, and F-4J which perhaps should be considered as distinct types). This spread of the data across the large number of aircraft types did not leave a sufficient number of passes in a given type with a reasonable (3 or more) number of different pilots such that incontrovertible conclusions could be reached as to characteristics which are truly associated with aircraft type, pilot technique, day versus night operation, or control system configuration, etc. For more practical results to be achieved more data, including reasonable samples of each condition tested, are required.

Although more data would be needed to reach final conclusions, the present data base, consisting of 180 passes obtained during the current program is not completely analyzed. Prior to obtaining more data it would be worthwhile to submit all the existing data to rigorous analysis.

It should be noted that all pilots partaking in the current program were test pilots. Any future program should consider using a more representative sample of the Navy's pilot population.

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APPENDIX A

DESCRIPTION OF SIMULATED CARRIER LANDING FLIGHT TESTS

GENERAL

The objective of the flight test program was to obtain data which would allow the identification of the characteristics of the pilot/aircraft/FLOLS system for conditions representative of actual carrier landings during pitching deck conditions. While the program was to be accomplished in the course of normal Field Carrier Landing Practice (FCLP) operations at the Naval Air Test Center (NATC), Patuxent River, Maryland, it was hoped that the opportunity would present itself to obtain data for a variety of aircraft types with several pilots under both day and night conditions and for both fully manual controlled approaches and approaches with whatever augmentation (approach power compensator and/or automatic flight control system) that existed on the given aircraft type.

FLIGHT TEST SYSTEM DESCRIPTION

Basic System Description

A flow diagram of the basic sys is shown in Fig. A-1. A center meatball flight path (commanded altitude) similar to that which would occur in an actual pitching deck carrier landing was generated by driving the FLOLS roll axis via a servo with a programmed command. The primary data recorded was the lens roll angle which was converted to an equivalent altitude command and the aircraft's altitude both with respect to a reference flight path. As indicated in Fig. A-1 the servo output and roll command were also recorded; this enabled a check on the servo and lens roll drive operation. In normal operation, the differences between lens roll, servo angle, and roll command were restricted to negligible high frequency dynamics. In addition to aircraft altitude the SPN-42 radar computer provided information on aircraft range along the flight path and lateral displacement from the nominal flight path. Pilot calls, i.e., high, center, low ball, etc., and comments by the test engineer

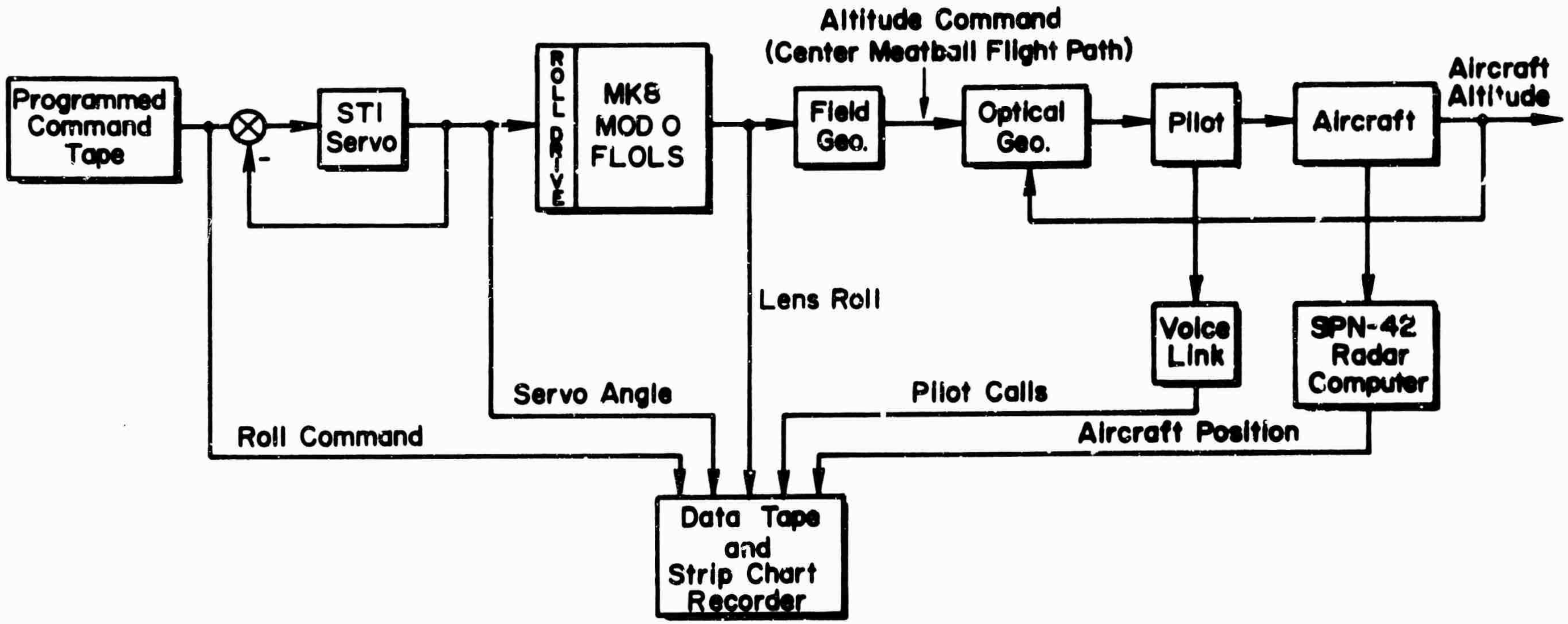

Figure A-1. Basic Flight Test System Flow Diagram were also recorded. All signals recorded on the data tape were also displayed on a strip chart recorder to enable the test engineer to monitor system operation.

Additional System Details

Field Geometry. The pertinent field geometry is shown in Fig. A-2. The location of the FLOLS unit (and, for reference, the SPN-42 Radar Computer) is indicated in Fig. A-2a. As a safety precaution the nominal touchdown point was elevated by about 30 ft. The relation between the altitude command as seen by the pilot in an approaching aircraft is shown in Fig. A-2b.

Altitude Command. Two taped altitude commands were used, each consisted of a sum of 5 sinusoids, i.e.,

$$h_c = \sum_{i=1}^{5} A_i \sin \frac{2\pi}{T_i} t$$

The amplitudes and periods of the components are given in Table A-I. Command I was designed for 15 sec data segments while Command II was designed for 25 sec data segments.

TABLE A-I

ALTITUDE COMMAND COMPONENTS

COMMAND	I		II	
i	A_i (ft)	T_i (sec)	A_i (ft)	T_i (sec)
1	3.25	15.	3.25	12.5
2	3.25	7.5	3.25	8.33
3	0.75	5.0	0.75	6.25
4	0.75	3.75	0.75	5.0
5	0.75	3.0	0.75	3.57

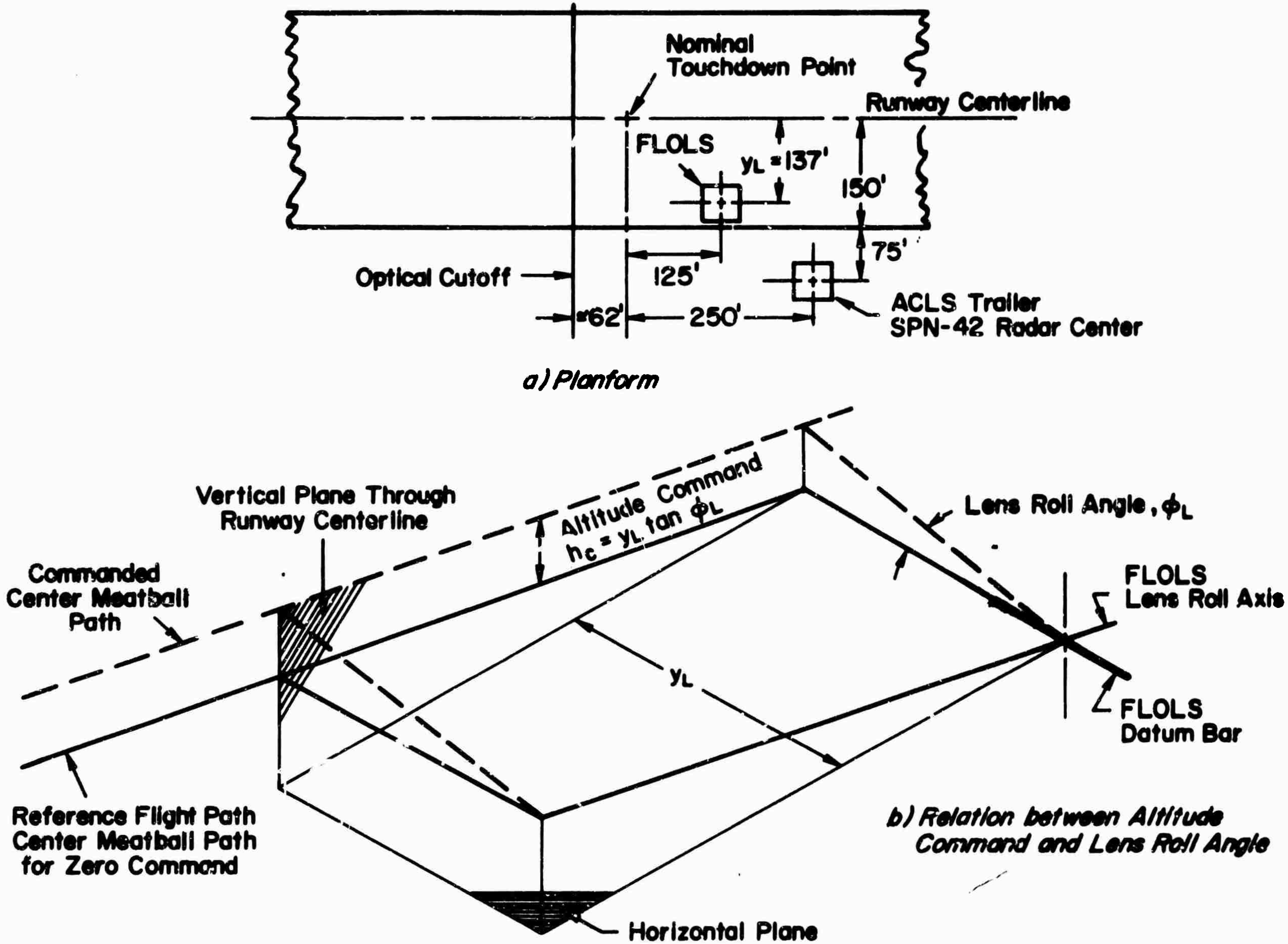

Figure A-2. Field Geometry

Optical Geometry. The FLOLS optical geometry is discussed in Section III of the main report.

FLIGHT TEST PROCEDURE

Pilot Briefing

The background and purpose of the program were reviewed. It was emphasized that the data sought were those representative of normal carrier landing technique with pitching deck conditions; and that, therefore, the desired practice of holding AOA, lineup, and meatball, applied here. All other considerations, such as meatball-averaging versus meatball chasing, spotting the deck versus flying the meatball, etc., would have utmost significance in the validity of the results. Accurate lineup was stressed as extremely important in these tests. (The effect of lateral flight path offset is to modify the effective input command structure into FLOLS due to its nonlevel beam-plane geometry.)

The pilot's objective was to stay on the FLOLS beam as long as possible. The pilot's ultimate achievement would be to have a roger-meatball all the way — but they were cautioned that this would be difficult to achieve since the motions of the FLOLS beam would be representative of actual Sea State 6 conditions.

Aircraft Types

The flight test program was essentially "piggybacked" onto existing operations at the Naval Air Test Center. As such the mix of aircraft types, pilots, control system configuration, etc., was not under our control. A wide variety of data were obtained as indicated in the flight test summary of the next section.

FLIGHT TEST DATA

A Summary of the flight test program is given in Table A-II. As noted, a number of these passes were eliminated from further consideration because of wave-offs, loss of radar lock-on, calibration, etc. The remaining usable data is summarized in Table A-III.

TABLE A-II

SUMMARY OF FLIGHT TEST PROGRAM

DATE	PASS NOS.	PILOT	AIRCRAFT	NO. OF PASSES	CALIB.	NO LOCK-ON NOISY	WAVE-OFF	PRACTICE	USABLE
4/21/68	1-56	E	A-7A No. 650	24	4	6			14
		F	A-7A No. 546	9		9			0
		?	Otter	3		3			0
		F	A-7A No. 650	20	2	3			15
5/24/68	57-106	L	H-34	14	14				0
		G	F-46 No. 481	20	2	2			16
		A	A-4	8	3			5	0
		M	F-4G	8	2			6	0
6/2/68	107-118	H	F-4G	12	3				9
6/3/68	119-125	N	F-4G	2	2				0
		C	A-4	5	5				0
6/4/68	126-149	M	F-4G No. 481	9	3	3		3	0
		O	F-4G No. 489	10	4	1		5	0
		P	T1	2				2	0
6/11/68	150-161	Q	A-4 No. 118	12	4			8	0
6/12/68	162-176	A	A-4 No. 118	15	3			2	10
6/13/68	177-202	C	RA-5C	9	2	1		6	0
		D	F-8 No. 218	17	3	2	1	1	10
6/14/68	203-228	D	F-8 No. 218	13	3			1	9
		A	F-8 No. 218	13	2	1	1	1	8
6/18/68	229-259	C	F-4B No. 426	17	5			2	10
		I	F-6A No. 177	14	5				9
6/21/68	260-279	B	A-4	20	3			2	15
7/1/68	280-319	A	A-3B	15	2			3	10
		K	F-4G No. 431	9		2	1	6	0
		J	F-4J	16			2		14
7/1/68 Night	320-358	B	F-4G No. 481	16	3			1	12
		K	F-4J No. 071	12	4			1	7
		C	A-3B No. 404	11	4				7
7/18/68	359-375	C	F-111B	16	7				9
TOTALS				371	94 25.3%	33 8.9%	5 1.3%	55 14.8%	184 49.6%

TABLE A-III

MATRIX OF USABLE DATA FROM FLIGHT TEST PROGRAM

PILOT	AIRCRAFT								
	A-7A	A-4	F-4B	F-4G	F-4J	A-3B	F-6A	F-8	F-111B
E	14/0*								
F	15/0*								
A		10/10				10/0*		8/7*	
B		15/10		12/11†					
C			10/8			7/7†,‡			9/0§
G				16/0					
H				9/0					
J					14/10*				
K					7/0†				
I							9/0		
O								19/9*	

Notes: 184/62 ← Passes analyzed during current program
↖ Estimated number of passes providing usable data

*Combinations of APC and AFCS on and off

†Night passes — all others day

‡Two of seven passes are questionable

§With and without DLC

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13. ABSTRACT

A shore-based flight test program was conducted at the Naval Air Test Center, Patuxent River, Maryland. Its objective was the determination of pilot/aircraft characteristics during simulated carrier landings with pitching deck conditions using the Fresnel Lens Optical Landing System (FLOLS). The results indicate that a pilot can and will track a moving FLOLS "meatball." Significant performance variations were found which were a function primarily of airplane type. Reductions of as much as 50 percent in the altitude dispersions of some airplane types were indicated for Compensated Meatball Stabilization (CMS) of FLOLS. Limited data also indicate that FLOLS error perception is far better than expected. At one mile range the pilots were able to resolve altitude errors as small as 6 ft during the day and 12 ft at night; it had previously been assumed that the minimum detectable altitude error at one mile was 54 ft.

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14 KEY WORDS	LINK A		LINK B		LINK C	
	ROLE	WT	ROLE	WT	ROLE	WT
Pilot/aircraft characteristics Carrier landing Flight test simulation FLOLS Compensated Meatball Stabilization Pitching Deck						

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