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**INDEPENDENT EVALUATION
OF
SHUTTLE FLIGHT CONTROL SYSTEM**

FINAL REPORT

CONTRACT NAS9-14915

14 OCTOBER 1977

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DEFENSE AND SPACE SYSTEMS GROUP

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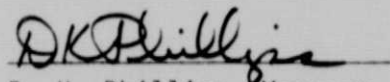
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ABSTRACT

This Final Report for NASA/JSC Contract NAS 9-14915, "Independent Evaluation of Shuttle Flight Control System," presents a brief summary of the work performed on the Approach and Landing Test (ALT) Shuttle flight control system (FCS) and references a bibliography of the formal reports generated during the contract period which document the activities in detail. In general, the activities were grouped in four categories: (1) independent evaluation of ALT FCS software design; (2) independent evaluation of Software Development Laboratory (SDL) testing of ALT FCS software; (3) independent evaluation of Shuttle Avionics Integration Laboratory (SAIL) ALT FCS testing; and (4) independent evaluation of ALT flight test results.

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1.0 INTRODUCTION

This final report provides a brief summary of the analyses performed for the Avionics Systems Engineering Division of NASA/JSC under Contract NAS 9-14915, "Independent Evaluation of the Shuttle Flight Control System," and references a bibliography of the formal reports, generated during the contract period, which document the activities in detail. The activities performed under this study fall into four general categories: (1) independent evaluation of ALT FCS software design; (2) independent evaluation of Software Development Laboratory (SDL) testing of the ALT FCS software; (3) independent evaluation of Shuttle Avionics Integration Laboratory (SAIL) ALT FCS testing; and (4) independent evaluation of ALT flight test results. Each of these activities is discussed in the following sections.

2.0 DISCUSSION

2.1 Independent Evaluation of ALT FCS Software Design

As a result of detailed investigations of the HAL code for the FCS, TRW developed HAL signal flow diagrams (Reference 1-1) to provide roadmaps through the complex hierarchy of the FCS application software modules. These signal flow diagrams were manually produced and would be quite expensive to modify as the software changed. In response to their inquiry, the Shuttle Program Assessment Office was informed of this difficulty (Reference 1-2) and they have contracted with Intermetrics Inc. to develop an automatic signal flow generator.

To effect a trace between the Functional Subsystem Software Requirements (FSSR) and the HAL code, TRW developed tables of Level C FCS FSSR signal traces to HAL code parameters and memory locations (References 1-3 through 1-6). These tables correlate the signals and constants in the ALT Level C FCS FSSRs to their corresponding HAL parameters and the memory locations of these HAL parameters. The internal units of the HAL parameters were derived and recorded in the tables. This tracing was performed for the aileron, elevator, body flap, and rudder/nosewheel control channels and proved valuable in monitoring FCS testing, defining and monitoring FCS troubleshooting procedures, and performing post-test analyses.

Based on our intimate knowledge of the FCS software, TRW performed several analyses to specify exactly how the software would perform in comparison to the FSSR specification (References 1-7 through 1-10). These analyses included a definition of the mechanization of the Program Test Input Program (stroking test); an evaluation of the automatic nosewheel steering gain; an evaluation of rudder transients during rollout; and the definition and proposed solution to GN&C sawtooth response due to navigation filter performance. In some cases, these analyses uncovered initialization-load (I-Load) errors which would cause unexpected and undesired responses. In the case of the GN&C sawtooth response, a GN&C interaction problem was uncovered and a solution was recommended. The solution was not implemented during ALT due to schedule constraints. However, the solution is being considered for the OFT design.

This analysis pointed out the need for system-level analyses of the GN&C system to uncover interaction problems.

A major analysis item began with detailed evaluation of the GN&C software and propagated to a general evaluation of the onboard flight software. The specific study was the evaluation of the use of the divide function in the GN&C software, from the standpoint of possible division by zero. TRW found that there were thirty-one divisions in the GN&C applications software which were not protected from division by zero (References 1-11 and 1-12). TRW determined that significant impact could result from such errors, not only from the standpoint of the erroneous numerical result of this operation, but also from the standpoint of software operation. It was found that if a sufficient number of such errors occur during a cycle of a given software process, that process would stop (forced closed) for the remainder of the process. It was further determined by TRW that a number of other errors (overflows, unnormalized input to floating-point divide, and overflow on conversion from floating-point to fixed-point) could result in similar problems. These susceptibilities were reported at the ALT and OFT Orbiter Avionics Software Control Board (OASCB) meetings. The decision was made by the OASCB to accept the risks of these vulnerabilities for ALT but to add protection for the OFT software design. TRW worked with IBM and RI OFT design personnel (Reference 1-13) to familiarize them with the nature of the problem and to establish a plan of action for OFT. TRW supported the development of a Technical Directive to RI for specific OFT action required to provide protection (Reference 1-14).

It should be noted that the vehicle encountered division by zero and negative square roots during several of the ALT captive-active and free flights which had not been predicted in SDL, ADL, or SAIL testing. The problems were not severe but the incidents dramatically highlight the fact that actual flights subject the system to a much wider range of conditions than those simulated at the verification facilities.

TRW also investigated the AP101 General Purpose Computer (GPC) system software to establish how the system software performed the input/output (I/O)

traffic through the GN&C application software (Reference 1-15). One specific FCS I/O transaction was examined to trace through the complex data transfers which are associated with the I/O traffic. The general observation from this examination is that the complexity of, and limited visibility into the system software appear to be inappropriate for safety-critical, single-point failure software.

2.2 Independent Evaluation of SDL Testing

TRW participated in the IBM dry-run presentations prior to the ALT software Configuration Inspection (CI). Module-level tests were reviewed and based on our insight into the FCS software, TRW recommended some additional testing (Reference 2-1). The total set of module-level tests and several GN&C system-level tests were evaluated at the ALT CI. This CI covered the SDL testing of the software for the tailcone-off vehicle configuration. TRW submitted a number of Review Item Dispositions (RIDs) which addressed the completeness of the testing; correlation of test cases to the elements of software that were exercised; and the need for evaluation of system software performance under multiple GPC conditions (Reference 2-2). The reference also cites major observations from the CI, including:

- a. The objectives of the CI were not clearly established;
- b. The volume of data and limited time available for its digestion precluded a meaningful review;
- c. Much testing that was assumed to be in the purview of SDL testing was deferred to ADL and SAIL testing and the capability of these facilities are extremely limited;
- d. The nature of the data presented at the CI did not allow a definitive assessment of the adequacy of the verification testing; and
- e. The fact that the SDL testing was limited to that defined in the Verification Test Specification (VTS) and the Verification Test Procedure (VTP) was not well known prior to the CI or at the time of issuance of these documents.

To provide a more comprehensive measure of expected GN&C performance for assessing SDL and other GN&C verification testing, TRW collected a set of GN&C performance requirements from various sources including the System Design Manuals (SDMs) and Certification Requirements (CRs) and provided this compilation to the technical community (Reference 2-3). These performance requirements were subsequently used by TRW in assessing the Δ CI test results as well as SAIL test results.

In response to the RID that we submitted at the CI concerning correlation of testing to specific software elements, TRW generated examples of this correlation. Since the Shuttle system software design precludes a precise definition of all execution paths, "all" paths through the software cannot be verified. TRW recommends that, at a minimum, the GN&C software verification effort address exercising each executable statement in the GN&C applications software at least once. TRW provided two techniques for systematically correlating the test cases to the software code to establish that this requirement has been met (Reference 2-4).

Preparatory to the Δ CI (tailcone-on vehicle configuration), TRW reviewed the results of software performance testing at the Orbiter Aerodynamic Simulator (OAS). As described in Reference 2-5, only limited information could be extracted from these runs since the available data was restricted primarily to the downlink data and the runs were not flown by skilled crewmen.

Also preparatory to the Δ CI, TRW performed detailed evaluations of eighteen GN&C system performance cases implemented on the SDL. The GN&C performance requirements assimilated by TRW were applied and violations were noted. Response characteristics which did not violate any constraints but were unexpected were identified. The results of this review and a summary of the TRW Δ CI participation are documented in Reference 2-6. The major facts from this review, the RIDs submitted by TRW, and evaluation of the testing philosophy include:

- a. Undesirable navigation/guidance/flight control transient interactions result from design deficiencies both in the requirements definition and in the software implementation;
- b. System performance requirements, as applied by TRW, were not accepted by the CI Board as criteria for software verification;
- c. Comparison between the SDL and CSDL Statement Level Simulator (SLS) results yielded valuable qualitative information on the software compatibility with requirements but is extremely expensive to implement;
- d. There is a need to establish realistic stress cases which establish the GN&C system performance envelope and it is not economically feasible to implement this work on the SDL, ADL, or SAIL; and

- e. The CPU stress testing was inadequate to establish the impact on GN&C performance of cycle overruns.

IBM received an action from the Δ CI to perform additional CPU stress tests. TRW reviewed the results of these tests to establish the effect on GN&C performance. These reviews indicated that in one set of the stress cases, the initial conditions varied sufficiently among the test cases to preclude a meaningful comparison among the runs. In a second set, the initial conditions were more similar but the results did not demonstrate the "graceful degradation" of GN&C performance that had been advertised. TRW's position is that the impact of cycle overruns on GN&C performance is not well understood nor easily predictable.

TRW continued to monitor the I-Load regression tests performed on the SDL by IBM to verify that the software would perform adequately for each ALT flight I-Load. TRW established a technique for correlating the I-Load changes with the method for verification, which was adopted by IBM (Reference 2-7). Some results of TRW's review of the test results are documented in Reference 2-8.

2.3 Independent Evaluation of SAIL Testing

TRW was a member of the ALT Certification Team created by the Avionics Systems Engineering Division. One of our major roles in this team was a review of SAIL test plans and test results and, prior to formal testing, active participation in SAIL testing.

TRW reviewed the SAIL Test and Checkout Procedures (TCPs) and provided corrections and additions for these detailed procedures (References 3-1 and 3-2). TRW participated in coordinated ADL/SAIL test planning for the ALT FCS (Reference 3-3).

Prior to formal certification testing, TRW provided active participation in SAIL testing and performed analyses of several Interim Discrepancy Reports (IDRs) and defined and supported a number of troubleshooting procedures to resolve IDRs. This participation included:

- a. Nosewheel Steering Troubleshooting (Reference 3-4);
- b. Evaluation of SAIL roll and pitch step responses (References 3-5);
- c. Evaluation of the Dedicated Display tests (Reference 3-6);
- d. Definition of IMU discretets associated with IMU initialization (Reference 3-7);
- e. Evaluation of incorrect mode response to PHC activity (Reference 3-8);
- f. Analysis of SAIL navigation errors (Reference 3-9); and
- g. Evaluation of SAIL area navigation test (Reference 3-10).

A number of these analyses required evaluation of the math models within the SAIL simulation.

TRW was a principal investigator of the two SAIL certification runs for Free-Flight 1 (Reference 3-11). We established the procedures and data requirements for this analysis which were used by the ALT Certification Team for analyses of subsequent SAIL runs. Additional evaluations of these two runs were documented in Reference 3-12.

As a member of the ALT Certification Team, TRW performed detailed analyses of certification runs for Free-Flights 2, 3, and 4. To assure timeliness, documentation of these analyses was made directly through the NASA/JSC reporting system. Special reporting of problems generally was contained under the standard reporting with exceptions such as the reporting of non-stationary aerosurface positions during a four second period when the primary GPCs were frozen and the Backup Flight Control System (BFCS) had not been engaged (Reference 3-13).

In anticipation of OFT activities, TRW participated in several meetings in which verification/certification testing at the SAIL and other facilities were discussed. These meetings were reported in References 3-14, 3-15, and 3-16.

2.4 Independent Evaluation of ALT Flight Test Results

To provide a correlation of actual flight performance to the predicted performance, TRW supported the ALT Free-Flights 1 through 4 in the Mission

Evaluation Room and performed postflight analyses of specific anomalies or specific response characteristics. These analyses included:

- a. Evaluation of elevon drift during CA-1A (Reference 4-1);
- b. Evaluation of FCS command compatibility with rate gyro feedback (References 4-2);
- c. Analysis of rudder lag during CA-1A (Reference 4-3);
- d. Evaluation of erratic Horizontal Situation Indicator displays during CA-3 (Reference 4-4);
- e. Evaluation of FF-1 onboard state vectors (Reference 4-5);
- f. Observations of navigation state transients in FF-1 due to navigation and MLS SOP computation frequency mismatch (Reference 4-6);
- g. Analysis of FCS transport delays in the CSS mode (Reference 4-7);
- h. Analysis of FF-3 onboard state vectors (Reference 4-8).

The major observation on the ALT flight results is that the flights subjected the onboard system to a much broader range of conditions than was used in the preflight verification/certification testing at the SDL, APL, and SAIL. This was particularly true of the navigation system. Indeed, there were a significant number of transients in the navigation state which had not been observed during preflight testing. Postflight analyses indicated that, for most cases, the transients resulted from unique flight conditions. The concern is that these transients are generally undesirable and, in flight, proved to be the rule rather than the exception.

2.5 Work Plan Reporting

The work plan and progress of the work were reported monthly in progress reports. These are documented in References 5-1 through 5-12.

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1-1	23 Dec 1976	TRW 76:2511.7-102 (76:2511.7-103)	HAL Signal Flow Diagram
1-2	11 Nov 1976	TRW 76:2511.7-89	Meeting with Program Assessment Office
1-3	22 Dec 1976	TRW 76:2511.7-101	Transmittal of Level C Flight Control System FSSR Signal Trace to HAL Code Parameters and Memory Locations
1-4	31 Jan 1977	TRW 77:2511.7-19	Transmittal of Level C Flight Control System FSSR Signal Trace to HAL Code Parameters and Memory Locations
1-5	4 Mar 1977	TRW 77:2511.7-36	Transmittal of Level C Flight Control System FSSR Signal Trace to HAL Code Parameters and Memory Locations
1-6	25 May 1977	TRW 77:2511.7-76	Transmittal of Updated Level C Flight Control System FSSR Signal Trace to HAL Code Parameters and Memory Locations for ALT 23.0
1-7	14 Jan 1977	TRW 77:2511.7-3	Program Test Input (Stroking Test) Response
1-8	18 Mar 1977	TRW 77:2511.7-46	I/O Transactions for FCS, an Example
1-9	26 May 1977	TRW 77:2511.7-78 (77:2511.7-91)	Rudder Transients During Rollout
1-10	26 May 1977	TRW 77:2511.7-79 (77:2511.7-80)	Solution to the NAV Filter/FCS Interaction Problem
1-11	10 Mar 1977	TRW 77:2511.7-40 (77:2511.7-41)	Review of Program Divides in ALT Software (Version 20)

<u>Reference Number</u>	<u>Date</u>	<u>Letter Number</u>	<u>Subject</u>
1-12	7 Apr 1977	TRW 77:2511.7-58 (77:2511.7-59)	Review of Protection of Program Divides in ALT Software
1-13	8 Jun 1977	TRW 77:2511.7-89	Review Comments on RI Presentation to OFT OASCB on Program Check Protection
1-14	14 Sep 1977	TRW 77:2511.7-129 (77:2511.7-130)	Software Error Conditions
1-15	19 Mar 1977	TRW 77:2511.7-47 (77:2511.7-61)	I/O Transactions for FCS, an Example
2-1	27 Jan 1977	TRW 77:2511.7-17 (77:2511.7-18)	Comments on IBM Briefings on SDL Testing of ALT Flight Control Software
2-2	11 Mar 1977	TRW 77:2511.7-31	ALT Configuration Inspection
2-3	1 Mar 1977	TRW 77:2511.7-34 (77:2511.7-37)	GN&C Performance Requirements
2-4	25 Mar 1977	TRW 77:2511.7-51 (77:2511.7-52)	ALT Software Verification
2-5	29 Mar 1977	TRW 77:2511.7-55 (77:2511.7-60)	Review of SW Performance Runs Performed for IBM at the OAS Facility
2-6	19 May 1977	TRW 77:3511.7-72 (77:2511.7-75)	ΔCI Summary
2-7	7 Jun 1977	TRW 77:2511.7-86 (77:2511.7-88)	GN&C I-Load Parameter Variations from I-Load 6.1 to 11.1
2-8	15 Jun 1977	TRW 77:2511.7-93 (77:2511.7-94)	Evaluation of Captive Active (CA1) I-Load Regression Tests
3-1	16 Nov 1976	TRW 76:2511.7-92	SAIL Test and Checkout Procedures Reviews
3-2	2 Feb 1977	TRW 77:2511.7-23 (77:2511.7-25)	Expected BFCS Commands during Sequence 8 Tests in TCP 2002, Volume 2

<u>Reference Number</u>	<u>Date</u>	<u>Letter Number</u>	<u>Subject</u>
3-3	18 Nov 1976	TRW 76:2511.7-95 (76:2511.7-96)	Rockwell FCS Verification Plan
3-4	14 Jan 1977	TRW 77:2511.7-4	Nosewheel Steering Troubleshooting Procedure
3-5	17 Jan 1977	TRW 77:2511.7-5 (77:2511.7-7)	SAIL Run Analysis
3-6	18 Jan 1977	TRW 77:2511.7-9 (77:2511.7-10)	Dedicated Display Tests
3-7	18 Jan 1977	TRW 77:2511.7-8 (77:2511.7-11)	Review of IMU Related Discretes which would be Supplied by the IMU Math Models when Performing SAIL "Fast Initialization"
3-8	25 Jan 1977	TRW 77:2511.7-14 (77:2511.7-15)	SAIL Anomalies 213-216 and IDR 8BCF76064
3-9	2 Feb 1977	TRW 77:2511.7-22 (77:2511.7-24)	Investigation of Navigation Error Observed during Special Nav Test on 16 January 1977
3-10	3 Mar 1977	TRW 77:2511.7-35 (77:2511.7-38)	SAIL Anomaly 270 and IDR 8BCF76078, Area Navigation
3-11	19 May 1977	TRW 77:2511.7-73 (77:2511.7-74)	Review of SAIL Certification Runs 131-2 and 131-4 in Support of FMC
3-12	13 Jun 1977	TRW 77:2511.7-90 (77:2511.7-92)	Analysis of Rudder Transients during Rollout
3-13	18 Aug 1977	TRW 77:2511.7-118 (77:2511.7-120)	SAIL Run No. 23, One Generic Fail
3-14	30 Sep 1977	TRW 77:2511.7-131 (77:2511.7-134)	FCS Meeting on Element Interface Tests for OFT
3-15	30 Sep 1977	TRW 77:2511.7-132 (77:2511.7-135)	SIGFLO Meeting
3-16	3 Oct 1977	TRW 77:2511.7-133 (77:2511.7-138)	Trip Report; TRW and RI, 20-23 September 1977

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4-1	7 Jul 1977	TRW 77:2511.7-100 (77:2511.7-101)	Elevator Drift Observed on Captive-Active Flight 1A
4-2	14 Jul 1977	TRW 77:2511.7-103 (77:2511.7-105)	FCS Response to 747 "S" Turn Inputs on Flight CA-1A
4-3	25 Jul 1977	TRW 77:2511.7-107 (77:2511.7-108)	Rudder Lag in CSS Mode during CA-1A CSS Stability and Polarity Checks
4-4	10 Aug 1977	TRW 77:2511.7-114 (77:2511.7-116)	HSI Heading Card and Bearing Needle Erratic Behavior Observed on Mission CA-3
4-5	2 Sep 1977	TRW 77:2511.7-122 (77:2511.7-125)	Evaluation of FF1 Onboard State Vectors
4-6	7 Sep 1977	TRW 77:2511.7-123 (77:2511.7-124)	Periodic 48-Second Glitches in the Navigated State during FF-1
4-7	9 Sep 1977	TRW 77:2511.7-126 (77:2511.7-128)	FCS Transport Delays - CSS
4-8	11 Oct 1977	TRW 77:2511.7-140	FF3 Onboard State Vectors
5-1	13 Oct 1976	TRW 76:2511.7-80	Study Plan for Independent Evaluation of Shuttle Flight Control System
5-2	13 Oct 1976	TRW 76:2511.7-81	NAS 9-14915 Progress Report for Period Ending 15 October 1976
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5-11	18 Jul 1977	TRW 77:2511.7-104	NAS 9-14915 Progress Report for Period Ending 15 July 1977
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