# ERROR DETECTION AND CORRECTION --
# AN EMPERICAL METHOD FOR EVALUATING TECHNIQUES

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## ABSTRACT

This paper describes a method for evaluating error correction techniques for applicability to the flight testing of aircraft. Most prior work on forward error correction coding was predicated on stable or at least known statistics of the channel and other assumptions. While much work has been done for space applications, neither techniques nor hardware were developed in the past that were tailored and readily available for the aircraft flight test environment. Since the sources of error and dropouts in typical aircraft testing are never all known and frequently change during flight, an empirical method is shown which allows direct “with and without” comparative evaluation of correction techniques. The empirical method is used rather than mathematical methods that require various assumptions and caveats about the source of errors and often require narrowly defined, fixed, channel characteristics. A method was developed to extract error sequences from actual test data, independent of the source of the dropouts. Hardware was built to allow a stored error sequence to be repetitively applied to as many “unknowns” or new time slices of test data as desired. A test bed was assembled that:

- Utilizes only Reed-Solomon detection/correction with varying amounts of interleaving but provides an environment where future trials could be run using other candidate correction coding techniques and other hardware.
- Allows using real test data, machine generated random data or specific waveforms.
- Allows using actual recorded error sequences of unknown origin as well as specific selected error sequences that may have mathematical or project-based characteristics.
- Allows immediate visual and qualitative comparison of the effectiveness of a given technique versus bandwidth overhead involved.

Initial results are shown from a variety of actual aircraft test data error sequences. Test bed hardware configuration is described. Criteria are suggested for worthwhile correction techniques and suggestions are made for future investigation.

This work is supported by the Advanced Range Telemetry (ARTM) project under the DoD Central T&E Investment Program.

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## ABSTRACT

This paper describes a method for evaluating error correction techniques for applicability to the flight testing of aircraft. No statistical or math assumptions about the channel or sources of error are used. An empirical method is shown which allows direct "with and without" comparative evaluation of correction techniques. A method was developed to extract error sequences from actual test data independent of the source of the dropouts. Hardware was built to allow a stored error sequence to be repetitively applied to test data. Results are shown for error sequences extracted from a variety of actual test data. The effectiveness of Reed-Solomon (R-S) encoding and interleaving is shown. Test bed hardware configuration is described. Criteria are suggested for worthwhile correction techniques and suggestions are made for future investigation.

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## KEY WORDS

Error Correction, Error Sequence, Error Injection Circuit, Reed-Solomon, Interleaving

## INTRODUCTION

Data quality problems are extremely expensive in testing of new airframes, envelope expansion, flutter testing, weapons release runs and other critical test maneuvers. Every flight test center has painful examples of flights aborted and test objectives not met due to data quality. A standard parameter used by customers over the years for test planning is "30% re-fly" or having to fly test points over again. Certainly not all, but a significant number of normal flight test re-flies are because of unsatisfactory data quality. It is therefore economically and programmatically very important to find ways to reduce errors and increase the number of "test points made" per flight. This intensity and pressure is a fact of life for flight testing. Most prior work on error correction coding was predicated on statistics of the transmission channel and other assumptions. While much work has been done for space applications, neither Error Detection/Correction (ED/C) techniques nor commercial hardware were developed in the past that were optimized for the aircraft flight test environment. An existing feature of instrumentation on one recent test program involved CRC check bytes for PCM minor frames allowing the discarding of whole minor frames if they contained errors. The results were extremely graphic and "fixed" dropout problems in most cases because the data had generally been over sampled. It was not used because of customer concern about throwing away data at critical times. Error correction techniques would bypass such concerns. The potential has been so severely overlooked that ED/C techniques are *not currently being applied in real-time at any known major test facility.* Since the sources of error are many, Ref. [5], and dropouts in aircraft testing are never all known (and frequently change during flight,) an empirical method was chosen to allow direct "with and without" qualitative evaluation of correction techniques. The empirical method avoids mathematical dilemmas that require assumptions and caveats about sources of error and often require narrowly defined, fixed, channel characteristics. The approach is "try it." This empirical approach is intended to complement (and to fill in areas not accessible to) the more traditional statistical approaches. The test bed hardware, software and data gathering process used for this paper are described. Example plots with corrupted, corrected and "perfect original" data are presented. Effectiveness for the readily available Reed-Solomon and interleaving ED/C techniques are presented and recommendations are made for future effort.

## ERROR CORRECTION EFFECTIVENESS TEST BED

Figure (1) shows the basic configuration used for this project. Since it was not feasible to instrument an aircraft with error correction coding hardware, an error free digital on-board recorded tape was used as truth data. Error sequences were collected from many sources and stored as profiles of ones and zeros. Each bit in an incoming data stream is either left alone (a zero) or corrupted and changed in state (a one) by an "Error Injection Circuit," (EIC) Figure (2), built to apply a stored error sequence repetitively to a serial data stream.

The EIC modifies (corrupts) a correction encoded data stream in either of two ways. In the first, the circuitry compliments the data, sync, and check bytes of the (in this case R-S encoded) PCM stream according to error bits set in an eight-megabit error profile. The second way corrupts a bit stream in the same manner except that the correction coding bits are complemented to make correction impossible. This design permits comparison of corrected and uncorrected streams that have been identically corrupted by the same error profile while keeping the two streams in sync, bit-for-bit. The specially designed EIC board is pictured in Figure (3) and utilizes a field programmable gate array (FPGA), on-board microprocessor, Eprom and 1 MB of static RAM. Space prohibits more detailed description in this paper.

In the test bed, clean data is encoded by an Avtec Monarch-E board in a PC prior to the insertion of error sequences by the EIC. Two other identical off-the-shelf Avtec boards are used for decoding for both corrected and corrupted paths in Fig. (1). Application of the selected error correction technique is done by the Avtec board for serial data labeled "stream 1, source 2." This configuration allows concurrent viewing or electronic use of clean/original "truth data," data corrupted by a given error sequence and the same data corrected by a selected error correction technique. For added evaluation ease, minor frame lock indication was used in the form of an electronic time history (for both corrupted and corrected data) alongside "truth, corrupted and corrected" data on a time history chart. The truth data lock was "on" during all data runs and is not shown. The example runs in Figure (5) are from this configuration. The clean serial data stream prior to encoding can be "unknowns" or new time slices or an endless string of new test data applied in real-time. Delay through the EIC was insignificant for comparative visual evaluation on charts but is non-zero. Latency is not a focus of this paper but is certainly an issue precluding several kinds of correction measures (convolutional codes for example). In Ref. [2] a delay of 300 ms. is suggested as maximum allowable for real-time aircraft testing. As noted in Ref. [5], with current commercial hardware, we are forced to deal with interleaving and therefore some delay in order to do correction.

The configuration of Fig. 1 allows the use of real test data, machine generated random data or specific waveforms. It also supports the use of actual recorded error sequences of unknown origin as well as specific selected error sequences that may have mathematical or project-based characteristics. It can be used in the future to try other candidate ED/C techniques instead of Reed-Solomon and interleaving by developing modifications to (or substitutes for) the 3 Avtec boards that implement other error correction schemes.

## SOFTWARE DEVELOPED

Microsoft Visual C++ V6.0 and Windows NT 4.0 were used. Error sequence generation, error injection interface, and real-time error correction display programs were developed.

Error Sequence Generation is a Windows-dialog-box style program, used to compare on-board data with telemetered data. Bit-by-bit comparison is performed to yield an error sequence file broken into one-megabyte segments (memory limit of error injection hardware.) Another dialog box permitted the user to enter on-board and telemetry filenames, output error file name, and PCM parameter fields such as frame length, frame sync value, etc.

The Error Injection Interface, also a Windows style program, provided configuration loads to the error insertion hardware. User selection of error sequence, on/off for error insertion, amount of interleave, coding overhead, and upload of the error sequence are provided. User supplied values are transmitted from PC to error insertion hardware via a serial port.

Windows-based real-time error correction display software graphically illustrates effectiveness of a correction algorithm in real-time. Two PCs were required. Referring to Fig. 1, PC #1 was used to transmit an R-S encoded PCM stream to the error insertion hardware. PC #1 also received and decoded the degraded R-S stream, and sent the corrected stream to the real-time error correction display program via Ethernet. PC #2 received but did not decode the corrupted stream and sent it to the real-time error correction display program via Ethernet. The display program received and compared the corrected and uncorrected streams of data. Colored pixels were displayed for each bit received where a green pixel indicated that there was not an error in either stream, a red pixel indicated that both streams had the bit in error and a blue pixel indicated that the R-S decoded stream corrected the bit in error.

## DATA GATHERING PROCESS

The software above was used to collect error sequences from telemetered data in notorious test maneuvers where data was unsatisfactory as well as other cases selected at random. Aircraft tests were selected where a "good"digital on-board tape existed and where noisy data had been reported by customers. Data was gathered from two aircraft types under test at Patuxent River. Error sequences were also collected using BitAlyzer model BA25 hardware with the Advanced Range Telemetry (ARTM) testbed aircraft at Edwards AFB. From these real aircraft test sources, 508 error sequence segments were collected. Initial editing of these 508 error sequence segments was done using PC-based correction runs and a special-colored pixel graphics matrix display described above. This software allowed quick visual editing of a large number of error sequence trials in a single screen page. Tentatively interesting runs were then edited using bar charts of Errors per Segment vs Segment Number for various amounts of interleaving (example, Fig. 6). This process was not exhaustive nor guaranteed to statistically represent the characteristics of flight testing. The process was, however, done entirely using data collected in real flights where unsatisfactory data quality was or would be a problem for customers.

Very early in the project a profound (but not necessarily widely known among telemetry people) fact of error detection and correction theory became obvious: ***the data does not matter, only the error sequence matters in terms of an ED/C technique's ability to correct the errors.*** The project thus concentrated on selecting a variety of error sequences and looking at effectiveness in correcting those real error sequences. Since measurements ("the data") did not matter, only 2 parameters were chosen for time history chart illustrations from typical test aircraft for each empirical data run. Each error sequence was then applied per Fig. (1) to the serial PCM signal for a test aircraft and the two measurements were shown "clean, corrupted and corrected" along with lock indicators. This was narrowed to 33 runs. Interleave selections of 1, 4 and 8-way were used for various amounts of overhead. Due to hardware limitations in the test bed, only 14, 23 and 28% overhead cases were used. A French study Ref. [2] limited consideration to overhead less than 23% for flight test circumstances. It was judged that overhead greater than 15% would result in a veto for using ED/C at most busy Ranges because of the scarcity of spectrum resources. A 15% correction coding investment is hard to reject since manual detailed inspection of major test program formats regarding specific bit and word utilization revealed at more than 10% existing waste (bits not being used for anything other than filler, short words residing in long word locations, redundant copies of patterns, and the like). More than 10% of bandwidth could be dedicated to ED/C without adversely affecting anything else. This is reinforced by Ref. [12], which states that Data Cycle Map (format) "...designs tend to be inefficient in practice." The decision was made to run tests at the higher % overhead (e.g. 23 and 28%) primarily because of the poor overall performance of R-S in the aircraft test environment.

## RESULTS

Example time-histories from the Reed-Solomon (R-S) and interleaving trials are shown as Fig. (5). A summary of 33 selected data runs is shown as Table 1, "Selected Data Runs Using Reed-Solomon and Interleaving." The grading scheme (based only on lock loss and looking at selected measurements from a format) was A= fully corrected, B= OK for most users, C = improved but not great, D = little improvement, F = failed. Only 6 of this set of 33 runs (not statistically representative of anything) were graded "A". However, a single case of this level of improvement could more than pay for the instrumentation involved in supersonic release sorties, flutter and other critical or expensive cases. A grade of B would "save the test point" for most programs. The whole qualitative experience with 508 different error sequences showed that R-S correction, though with interleaving, was not very good, perhaps a "D average." This resulted in conclusions (1) that the R-S technique is not ideal for flight test data, (2) that grades did not correlate with the percentage of overhead (at least as these tests were set up), and (3) that grades were generally much better with higher amounts of interleaving but not always. Runs 7,8,21,24 and 32 were chosen for illustration in Fig. 5.1 through 5.5, because of the range of results (good, bad, medium) and other interesting features. The traces are in the same order left to right in Fig. 5 as they are top to bottom in the Fig. 1 Strip Chart Setup box. Note the minor frame Lock for corrected and Lock for corrupted are the two center traces in each chart. The object is *NOT* to try to read these shrunken traces but to allow visualization of the error spikes and lock loss comparisons.

| RUN NO. | ERROR FILE SOURCE | INTER-LEAVE | PERCENT OVERHEAD | SUBJECTIVE GRADE |
|---|---|---|---|---|
| 1 | EDWARDS T-39 | 1 | 14 | F |
| 2 | " | 4 | 14 | F |
| 3 | " | 8 | 14 | D |
| 4 | F-18 SPIN | 1 | 14 | F |
| 5 | " | 4 | 14 | B+ |
| 6 | " | 8 | 14 | A |
| 7 | " | 1 | 14 | F |
| 8 | " | 4 | 14 | C |
| 9 | " | 8 | 14 | B+ |
| 10 | V-22 | 1 | 14 | A |
| 11 | F-18 SPIN | 1 | 14 | F |
| 12 | " | 8 | 14 | C |
| 13 | " | 8 | 20 | D |
| 14 | " | 4 | 20 | F |
| 15 | " | 1 | 20 | F |
| 16 | EDWARDS T-39 | 1 | 28 | F |
| 17 | " | 4 | 23 | F |
| 18 | " | 8 | 23 | D- |
| 19 | F-18 SPIN | 1 | 28 | F |
| 20 | " | 4 | 23 | B+ |
| 21 | " | 8 | 23 | A |
| 22 | " | 1 | 28 | F |
| 23 | " | 4 | 23 | B |
| 24 | " | 8 | 23 | A & B |
| 25 | F-18 SPIN | 1 | 28 | F |
| 26 | " | 4 | 23 | D+ |
| 27 | " | 8 | 23 | D |
| 28 | V-22 | 1 | 28 | A- |
| 29 | " | 4 | 23 | C |
| 30 | " | 8 | 23 | A |
| 31 | V-22 | 1 | 28 | F |
| 32 | " | 4 | 23 | C |
| 33 | " | 8 | 23 | C |

**Table 1: "Selected Data Runs Using Reed-Solomon and Interleaving"**

## ANALYSIS OF FIVE SELECTED RUNS

Run 7 is a solid F with few if any errors corrected and lock loss just not improved by correction. Run 8 was graded C. There is significant improvement in Run 8 with nearly all short (fractional second) dropouts corrected where the corrupted data had shown a large number of lock losses and very marginal data quality. Run 8 was instructive in that it shows significant data quality improvement for the short dropouts but NO improvement for dropouts exceeding about 400 ms. in duration. Many non-critical tests would be supported adequately by this level of improvement. The periodic nature of *some* of the dropouts in Run 8 suggests some other kind of problem that remains unknown. Periodic dropouts are seen in both runs 8 and 24 and *may* have been related to the fact that these were of aircraft spin test origin. If that is the reason, these runs may illustrate that an error correction technique can greatly improve portions of a test maneuver but not be able to correct other portions (such as periodic blockage in spins.) "Transfer functions" (between corrected and clean data) were done on both Runs 7 and 8 with the expected "bad and good" indications. Run 21 was an example of a "terrible noise" case that was completely corrected using R-S with 8 way interleaving. Run 20 (not shown) was nearly as good with 4 way interleave using the same error sequence as Run 21. Run 24 has part of the run completely corrected and part of it "just improved well," thus the A & B grade. It should be recognized that with statistics and link margins and sources of error all changing in real flight circumstances, these kinds of mixed results are likely no matter what technique is used. Since Run 24 was based on a spin test error sequence, it is not surprising that there are many variables. Run 32 errors came from a catapult or arrested landing type of environment but not at the moment of touch down or launch. The Run 32 error sequence is more representative of "trees, brush, poles and changing multipath" very near the ground at low look angles. Run 32 was interesting because the data was very noticeably improved and yet the lock loss indicators were not as impressively improved. Further investigation revealed that these measurements used for illustration were from 128 deep PCM format subframes. Thus, the lock loss indicators were roughly 128 times as likely as the individual measurements to show dropout under burst error conditions. This kind of subtle factor often obscures the effectiveness of efforts to improve data quality, especially as seen by customers of telemetry data centers.

## OBSERVATIONS

It is considered significant that the Test Bed of Fig. 1 allows future investigation of better "tailored" ED/C techniques. "Troublesome error sequences" that repeatedly occur in individual test programs can be used as selection factors for ED/C techniques. For example, error sequences collected using an on-board recording versus recorded telemetry can be used in the Fig. 1 Test Bed to evaluate whether a given ED/C technique will "fix" the dropouts being experienced in a recent set of customer complaints or whether it should be used for an especially important upcoming test. This provides a potential solution for cases where a test program "never gets good data" from a certain section of the map of the Range or in a particular aircraft attitude or heading. The correction evaluation test bed use for problem solving would be even more attractive if ED/C encoders and decoders were programmable for a wide variety of techniques rather than fixed to a single correction algorithm.

For improving flight testing, some overall characteristics (dropout duration, data rates, etc. taken from a larger database of actual test data error sequences) should be fed to error correction theoreticians with a request to select ED/C techniques that would be most effective at lowest overhead for such data. It is quite possible that an effective correction algorithm could be developed specifically for flight test comparable to what was done for NASA and deep space work. These "tailored correction techniques" should then be tried using the test bed of Fig. (1). As Dr. George Cooper said in 1967, Ref. [4], "...a general procedure for constructing optimum codes is not known." Probably still true today but the population of codes and techniques tried are immense, particularly with modems over phone lines, TV cable, cell phones and other mass market bonanzas.

It is significant that the approach of Fig. (1) allows a candidate technique to be applied while feeding real data to the most sensitive, sophisticated or contrary real-time applications software. This is especially practical because sensitive, critical and hard-won applications software does not need to be changed in any way. This decouples extremely complex applications software and implied needs of that software (which often becomes untouchable) from the relatively academic sophistication of ED/C techniques. One can then quickly illustrate effectiveness or lack of it for a group of customers or specialists in a particular aircraft testing discipline without any change in their tools or methods of viewing data. This method with (essentially *required*) decoupling is practical because the serial PCM (both corrected and corrupted) retains the original instrumentation format already being handled and is usable electronically in real-time. Similar error sequence evaluation has been done in Europe by Aerospatiale, Ref. [2], but without the ability to apply a test bed in real time to unknown data. While Ref. [2] found that block codes and R-S with interleaving "held most promise" for flight testing, results here are not compelling. Note that experts, Ref. [3], suggest that spatial diversity reception may be better than ED/C when severe fading is encountered and delay of data must be minimized.

## CONCLUSIONS

Empirical methods in this project show effectiveness (and lack of it) on real flight test error sequences. A profound aspect of ED/C technology is that correction using most techniques is completely independent of test data and *depends only on the sequence of erroneous bits.* Test Bed feasibility was proven for feeding corrected and uncorrected data electronically to telemetry systems and real-time applications software *without any change in ground station, setup or software* while using candidate techniques. This allows the most sensitive or problematic processing to be used as the "proof" of correction effectiveness. Based on empirical observation using real error sequences from a variety of sources, R-S with interleaving is not very effective for errors in aircraft test data, yet can provide excellent correction in some cases. R-S was not effective at all for long dropouts (e.g. half-second or more) as tested. Results were not always better with higher % overhead nor with greater interleaving. It is probable that other optimized techniques, selected on the basis of flight test error sequence characteristics, can significantly improve quality of data to customers and save large amounts of resources and lost test points. Usable test points per flight are so important to economics and customer objectives that "fixing" (preventing) only a fraction of unsatisfactory test points could be very significant. Recommended future effort is to select the best of existing correction techniques for bursty errors that can perform well at 15 to 20% maximum overhead and to re-run this project using such selected techniques.

## ACKNOWLEDGEMENTS

Messrs. Brian Bailey, Bob Jordan, Walt Marusic and Bill Russell contributed significantly to the project, which could not have been done without their ingenuity and expertise.

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## CORRECTION EFFECTIVENESS TEST BED

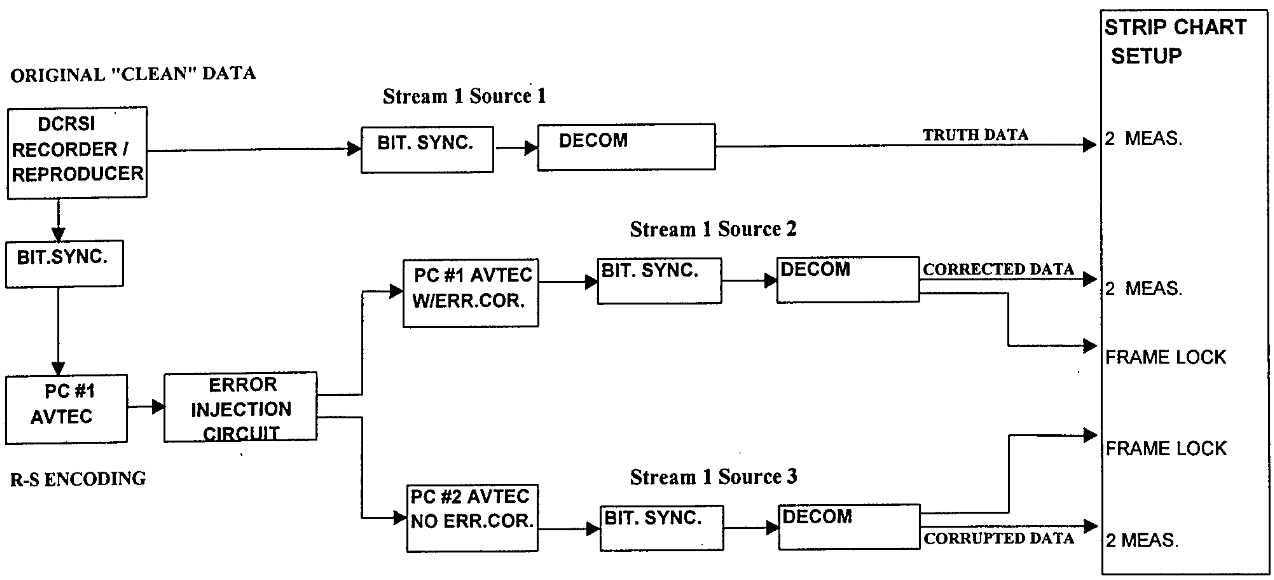


Figure 1

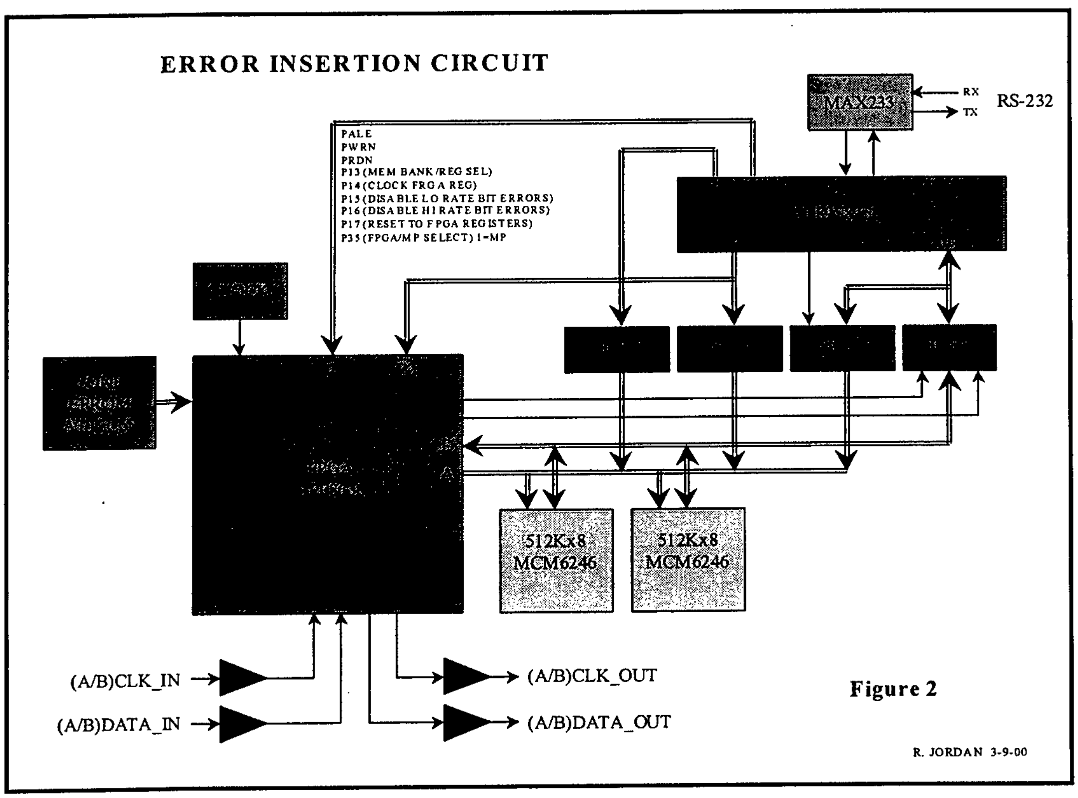


Figure 2

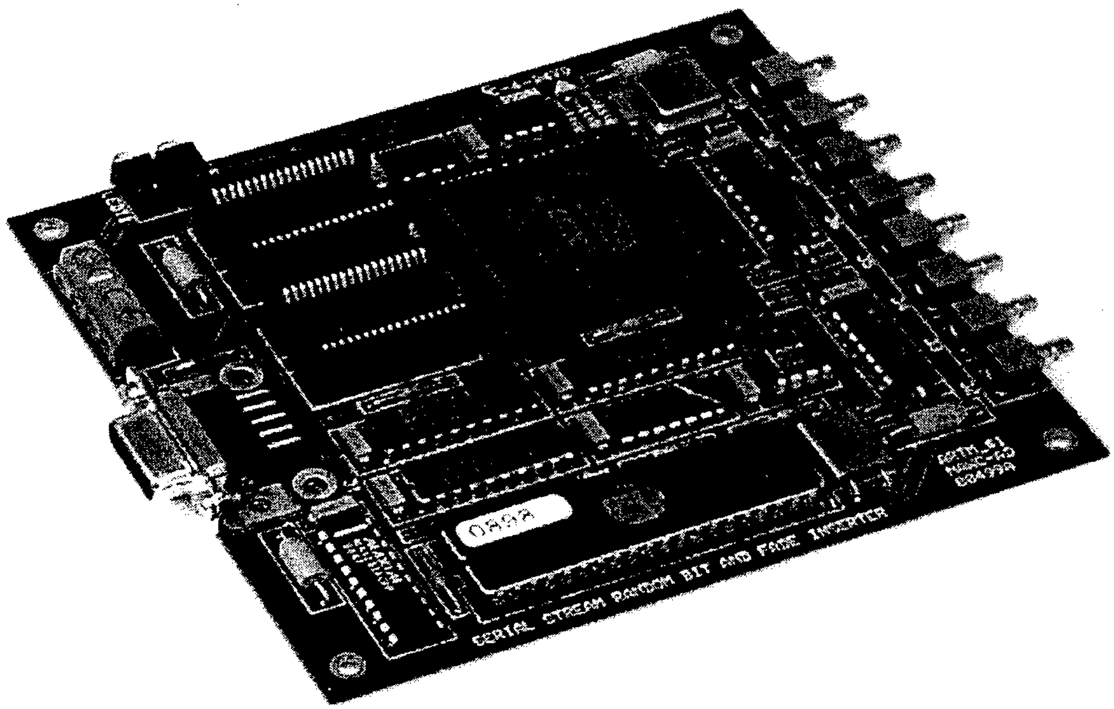


Figure 3 Photo of Error Insertion Circuit Board

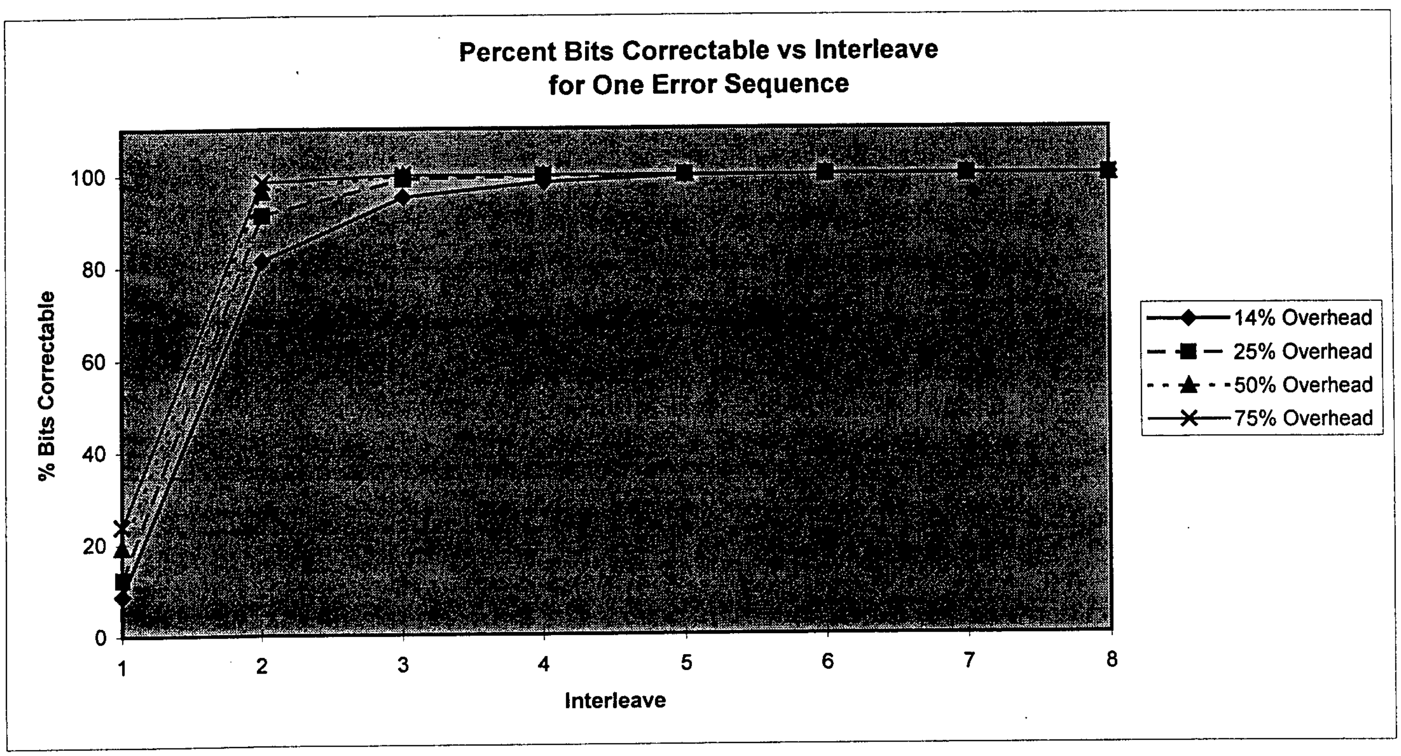


Figure 4 Percent Bits Correctable vs. Interleave for One Error Sequence

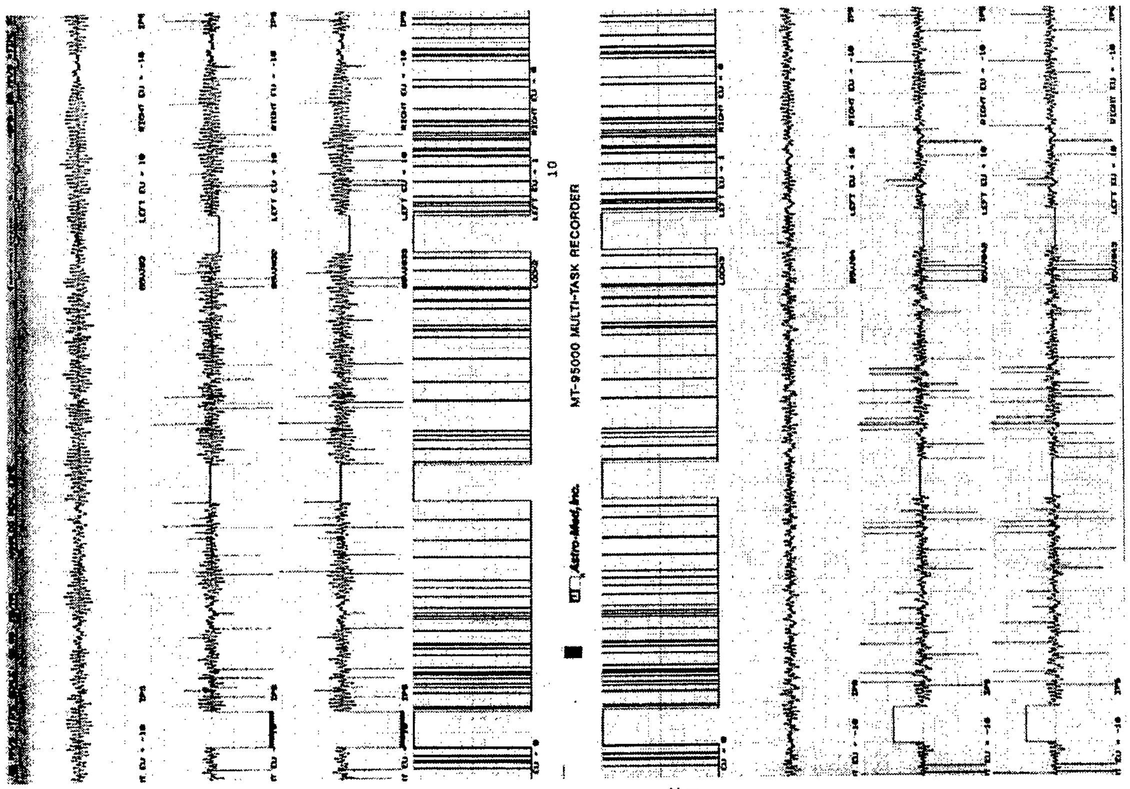


Figure 5.1 Run #7

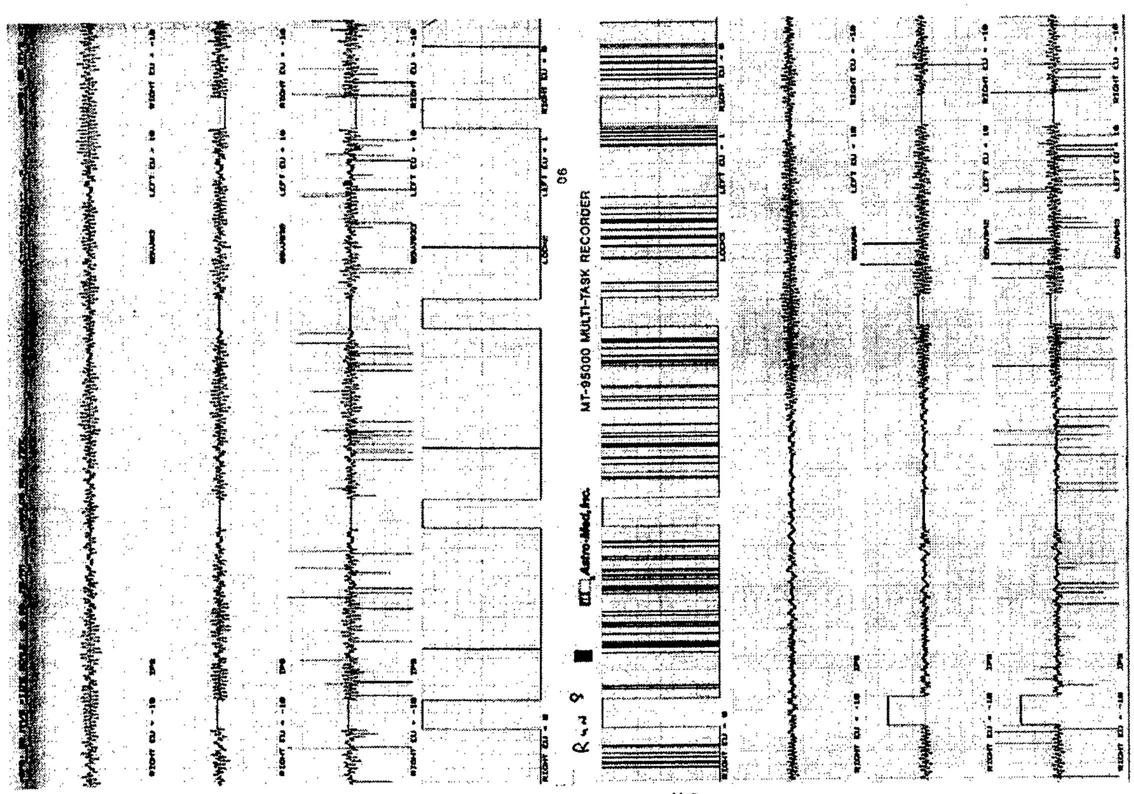


Figure 5.2 Run #8

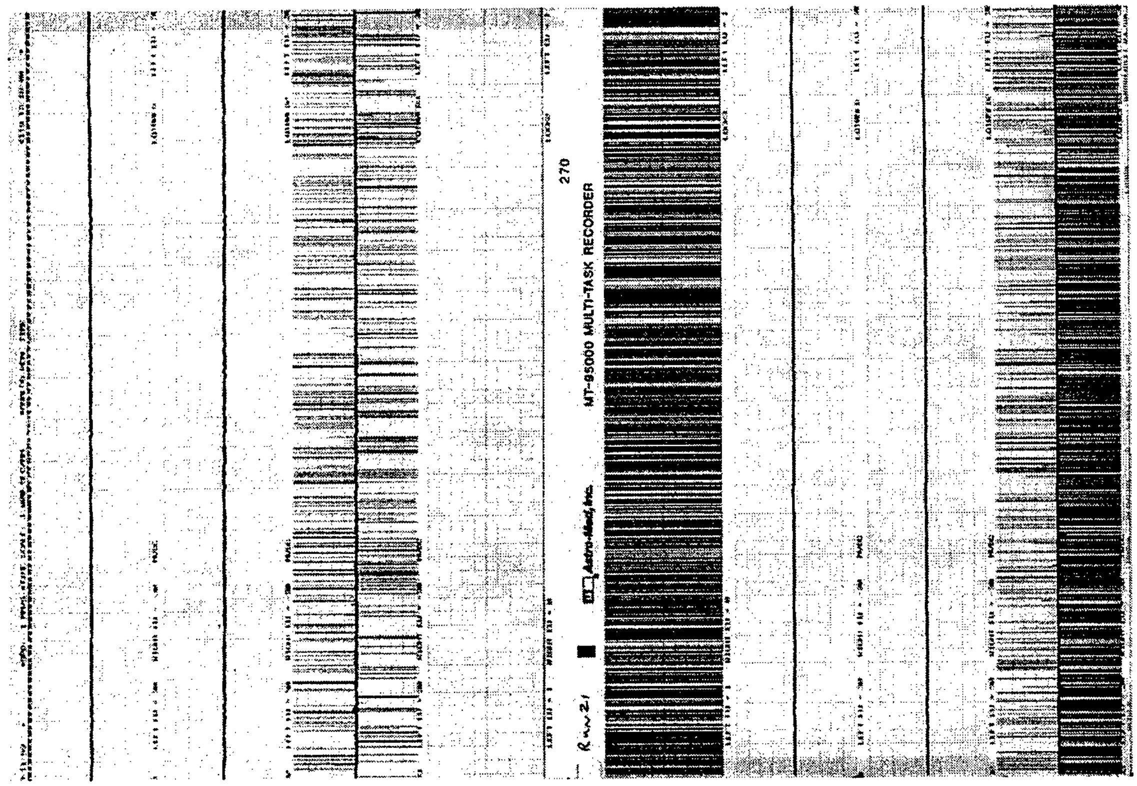


Figure 5.3 Run #21

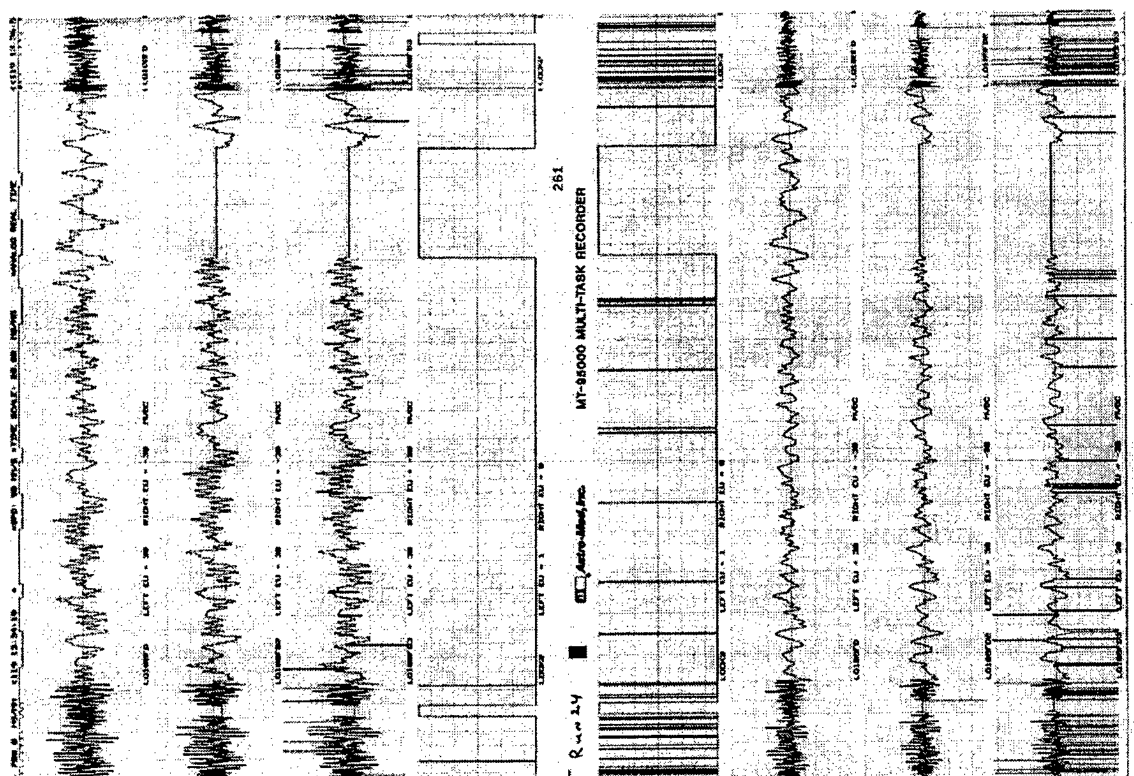


Figure 5.4 Run #24

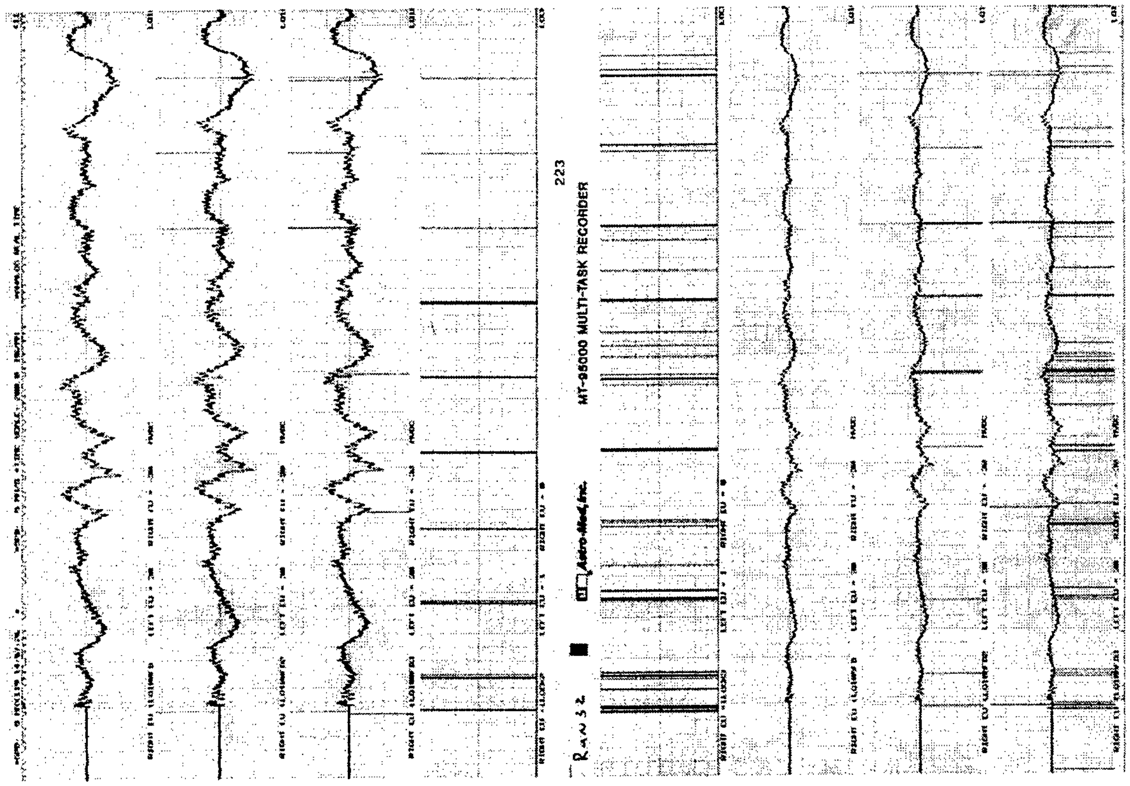


Figure 5.5 Run #32

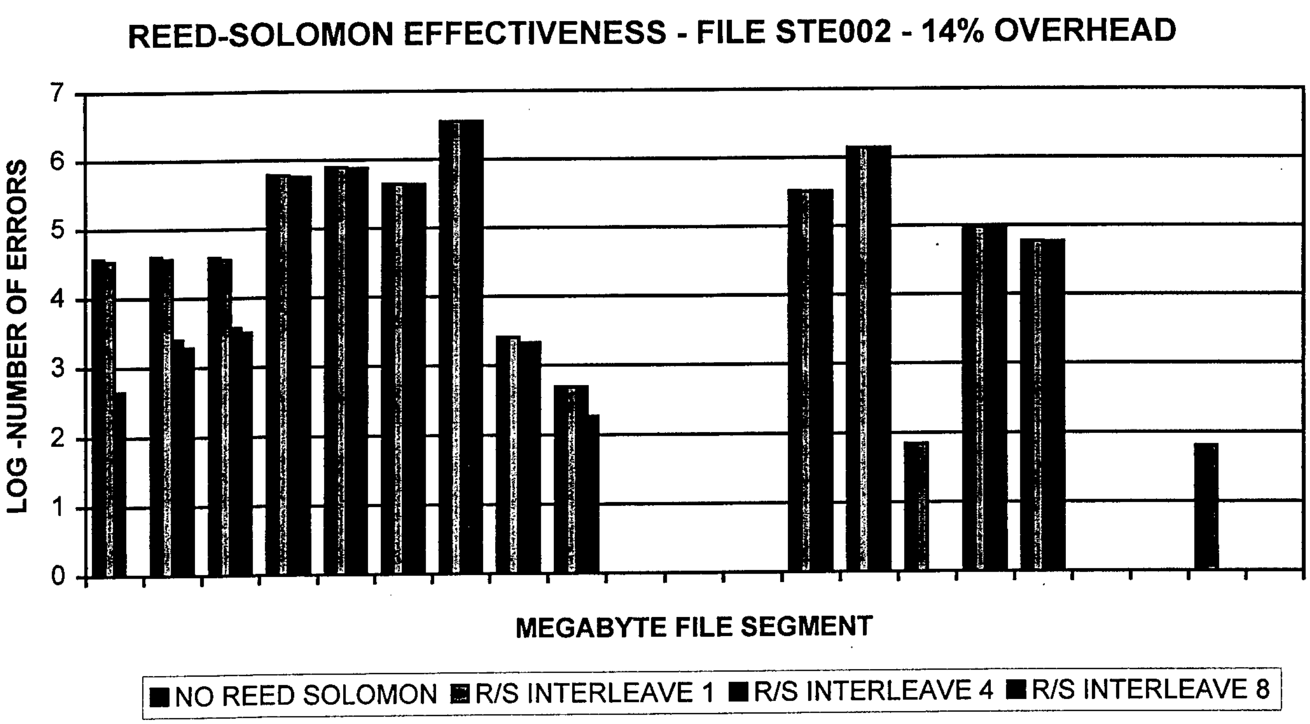


Figure 6

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|---|---|



| 1. REPORT DATE | 2. REPORT TYPE<br>Abstract and Professional Paper | 3. DATES COVERED |
|---|---|---|

| | |
|---|---|
| 4. TITLE AND SUBTITLE<br><br>Error Detection and Correction - An Emperical Method for Evaluating Techniques | 5a. CONTRACT NUMBER<br>5b. GRANT NUMBER<br>5c. PROGRAM ELEMENT NUMBER |
| 6. AUTHOR(S)<br><br>J. W. Rymer | 5d. PROJECT NUMBER<br>5e. TASK NUMBER<br>5f. WORK UNIT NUMBER |
| 7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)<br><br>Naval Air Warfare Center Aircraft Division<br>22347 Cedar Point Road, Unit #6<br>Patuxent River, Maryland 20670-1161 | 8. PERFORMING ORGANIZATION REPORT NUMBER |
| 9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)<br><br>Naval Air Systems Command<br>47123 Buse Road Unit IPT<br>Patuxent River, Maryland 20670-1547 | 10. SPONSOR/MONITOR'S ACRONYM(S)<br>11. SPONSOR/MONITOR'S REPORT NUMBER(S) |

12. DISTRIBUTION/AVAILABILITY STATEMENT

Approved for public release; distribution is unlimited.

13. SUPPLEMENTARY NOTES

14. ABSTRACT

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15. SUBJECT TERMS

Error correction, error sequence, error injection circuit, Reed-Solomon, Interleaving

| 16. SECURITY CLASSIFICATION OF: | | | 17. LIMITATION OF ABSTRACT | 18. NUMBER OF PAGES | 19a. NAME OF RESPONSIBLE PERSON<br>J. W. Rymer |
|---|---|---|---|---|---|
| a. REPORT | b. ABSTRACT | c. THIS PAGE | | | 19b. TELEPHONE NUMBER (include area code) |
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