Project Title: EMI Consultation and Testing.

Project No: A-1922

Project Director: Mr. W. R. Free

Sponsor: E-A Industrial Corporation

Agreement Period: From 11/15/76 Until 2/7/77

Type Agreement: Purchase Order No. 26388 & Standard Research Industrial Agreement.

Amount: $12,960

Reports Required: Monthly Status Reports, Final Report

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<table>
<thead>
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Defense Priority Rating: None

Assigned to: Electronics Technology (School/Laboratory)

COPIES TO:

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Other
Project Title: "EMI Consultation and Testing."

Project No: A-1922

Project Director: Mr. W. R. Free

Sponsor: E-A Industrial Corporation, Chamblee, GA 30341

Effective Termination Date: 3/15/77

Clearance of Accounting Charges: 3/31/77

Grant/Contract Closeout Actions Remaining:

- Final Invoice and Closing Documents
- Final Fiscal Report
- Final Report of Inventions
- Govt. Property Inventory & Related Certificate
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- Other
E-A Industrial Corporation  
4500 N. Shallowford Road  
Chamblee, Georgia 30341

Subject: Monthly Status Report No. 1, Purchase Order No. 26388,  
Titled "EMI Consultation and Testing", Georgia Tech Research  
Project No. A-1922.

Gentlemen:

This status report covers the period from 15 November 1976 to  
31 December 1976. Effort during this period was primarily expended  
in performing baseline EMI tests on the AN/AVQ-24-B Digital Data Computer and performing conducted measurements to locate the major sources of conducted EMI emissions and to evaluate EMI suppression techniques.

During the initial phase of the program, the measurement set-up was prepared in an 8' x 20' shielded enclosure and 115V, 400V, three-phase power was installed into the shielded enclosure to power the Digital Data Computer.

During the period 1 December through 8 December 1976, CEO3, CEO4, and REO2 measurements were performed on DDC serial no. GQZ 0114 to serve as baseline EMI data for the computer. The CEO3 and CEO4 measurements were performed over the frequency range from 14 KHz to 50 MHz. The REO2 measurements were performed over the 14 KHz to 1 Ghz frequency range. Copies of the data obtained from these measurements were given to E-A personnel at the conclusion of these measurements.

During the period 8 December through 10 December 1976, measurements were performed on a second computer to evaluate several modifications that had been performed on this unit. In addition, measurements were performed to evaluate the effectiveness of filter-pin connectors. Copies of the data resulting from these measurements were supplied to E-A personnel at the conclusion of the measurements.

During the period 13 December through 28 December 1976, conducted measurements were made on individual wires with various combinations of circuits disabled and activated in an effort to isolate and identify the major sources of conducted EMI. These measurements are continuing at the present time.
During the first week of January 1977, it is planned that a team of Georgia Tech engineers will meet with E-A personnel and recommend EMI suppression techniques which can be incorporated into the computer design. After the selected design changes are accomplished, EMI tests of the full AN/AVQ-24-B system will be performed to evaluate the effectiveness of the design changes.

Respectfully submitted,

William R. Free
Project Director, A-1922

Approved:

D. W. Robertson, Director
Electronics Technology Laboratory

WRF:phb
E-A Industrial Corporation
4500 N. Shallowford Road
Chamblee, Georgia 30341

Subject: Monthly Status Report No. 2, Purchase Order No. 26388,
   Titled "EMI Consultation and Testing", Georgia Tech
   Research Project No. A-1922.

Gentlemen:

This status report covers the period from 1 January 1977 through
31 January 1977. The primary effort during this period was directed
to isolating and identifying major sources of conducted EMI and evalu-
ating the effectiveness of several EMI reduction techniques.

On 4 January 1977, five EAIC staff members met with five Georgia
Tech staff members to discuss EMI suppression techniques which might
be considered in modifying the AN/AVQ-24-B system. Several recommen-
dations were made concerning improvements in the enclosures, circuit
boards, internal wiring, and interconnecting cables.

A project status review meeting was held at Georgia Tech on 31
January 1977. Derrick Coulson and Eric Yost of EAIC and H. W. Denny,
C. S. Wilson, and W. R. Free of Georgia Tech were present at this
meeting. The EAIC personnel indicated that a modified system would not
be available for testing before approximately 21 February 1977. On the
basis of this delivery date, it was mutually agreed that the program
should be extended from 7 February 1977 to 15 March 1977 to allow time
to test the modified system and process the test data for delivery. In
the time frame from 1 February to the delivery of the modified system,
the EAIC personnel requested that Georgia Tech: (1) construct a filter
box which will allow filters to be added to the modified system;
(2) bench test EMI filters with low and high, source and load imped-
dances; (3) investigate the characteristics of a typical TTL gate and
a typical line driver-receiver pair; and (4) develop and document a
shielding approach for the interconnecting digital lines. The approach
is to include balanced circuits, shielded twisted-pair lines, and gross
shielding.
Georgia Tech agreed to initiate action to extend the contract period to 15 March 1977 and to accomplish the tasks outlined above within the limitations of the funds remaining in the program budget. It is anticipated that the remaining funds will be adequate to cover the tasks as visualized at the present time.

Respectfully submitted,

W. R. Free
Project Director, A-1922

Approved:

D. W. Robertson, Director
Electronics Technology Laboratory

WRF: phb
EMI CONSULTATION AND TESTING

FINAL REPORT
PROJECT A-1922

BY
W. R. FREE

MARCH 1977

FOR
E-A INDUSTRIAL CORPORATION
ATLANTA, GEORGIA 30341
FINAL TECHNICAL REPORT
PROJECT A-1922
MARCH 1977

EMI CONSULTATION AND TESTING

BY

W. R. FREE

Standard Industrial Agreement
Purchase Order No. 26388
Dated November 12, 1976

Submitted to

E-A INDUSTRIAL CORPORATION
4500 N. Shallowford Road
Chamblee, Georgia  30341

Submitted by

Engineering Experiment Station
Georgia Institute of Technology
Atlanta, Georgia  30032
FOREWORD

This report was prepared by the Electronics Technology Laboratory of the Engineering Experiment Station of the Georgia Institute of Technology. The work was performed in accordance with the provisions of a Standard Industrial Agreement with E-A Industrial Corporation, dated 15 October 1976. The described work was conducted under the general supervision of Mr. D. W. Robertson, Director, Electronics Technology Laboratory, Mr. H. W. Denny, Head of the Electromagnetic Compatibility Group, and Mr. W. R. Free, Project Director. The report summarizes the objectives, activities, and results of an 18-week technical effort directed to assessing the EMI characteristics of the AN/AVQ-24-B Digital Data Computer and to providing technical consultation in developing modification techniques to improve the EMI characteristics of this unit.
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1. Introduction

This report presents the procedures followed and results obtained during an investigative program to determine the EMI emission characteristics of the AN/AVQ-24-B system, to develop modification techniques to improve the EMI emission characteristics, and to evaluate the effectiveness of implemented modifications.

The baseline measurement program is described in Section 2 of the report. The test configurations, test equipment, and test specimen system used to define the emission characteristics of the present AN/AVQ-24-B system are described in this section. The data resulting from the measurement program are also discussed.

A program to identify conducted EMI sources and evaluate modification techniques is described in Section 3. Conducted emissions tests performed on discrete power lines are described, and the data resulting from these tests are discussed. A series of tests performed to determine the major sources of conducted emissions are also discussed.

A program to evaluate the effectiveness of several types of filters and two types of filter-pin connectors is described in Section 4. In order to evaluate these devices under typical operating impedance conditions, the impedance characteristics of a typical TTL line driver-receiver pair were measured, and networks capable of approximating these impedances in the filter test setup were developed.

The tests performed to evaluate a modified Digital Data Computer are described in Section 5. Interference tests between the computer and an ARC-114 receiver were performed. These tests were performed with both an unmodified computer and a modified computer in order to evaluate the effectiveness of the modifications. The broadband and narrowband conducted emissions from the modified computer were measured, and the results from these measurements are discussed.
2. Baseline Measurement Program

2.1 Test Configuration

The initial effort on the program was directed to performing
tests in accordance with test methods CE03, CE04, and RE02 as defined in
MIL-STD-462, to determine the radiated and conducted EMI emission char-
acteristics of the AN/AVQ-24-B system.

The measurement setup was prepared in a 20' L x 8' W x 8' H shielded
enclosure as illustrated in Figure 1. The system to be tested, consisting
of the four equipment units listed in Table I, was positioned on a copper
ground plane on a test bench as shown in Figure 1.

<table>
<thead>
<tr>
<th>TABLE I</th>
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<tr>
<td>EQUIPMENT IN TEST SPECIMEN SYSTEM</td>
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</table>

<table>
<thead>
<tr>
<th>Digital Data Computer (DDC)</th>
<th>S/N GQZ 0014</th>
</tr>
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<tr>
<td>Video Amplifier (VA)</td>
<td>S/N GQZ 0062</td>
</tr>
<tr>
<td>High Voltage Power Supply (HVPS)</td>
<td>S/N GQZ 0068</td>
</tr>
<tr>
<td>Digital Data Display Indicator (DDI)</td>
<td>S/N GQZ 0074</td>
</tr>
</tbody>
</table>

The four subsystems were interconnected with a wiring harness supplied
by EAIC, and the six primary power leads were routed through six 10 μF
feed-through capacitors. The EMI receiver, X-Y recorder, calibrate sig-
nal generator, and coax transfer switch were set up on a bench outside
the shielded enclosure as shown in the figure. For the radiated tests,
the test antenna was positioned to be centered on the system under test
and at one meter from the front of the test bench. The output from the
test antenna was routed via coax cable through a coax penetration in the
enclosure wall to the EMI receiver outside the enclosure. A coax trans-
fer switch was used to switch the EMI receiver input between the test
Figure 1. Equipment Layout.
signal cable and the calibrate signal generator. For the conducted measurements, a current probe was used as the sampling device: the cable routing to the EMI receiver was the same as for the radiated measurements. A complete list of the test equipment used in the test configurations is presented in Table II.

<table>
<thead>
<tr>
<th>Equipment</th>
<th>Frequency Range</th>
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<tr>
<td>Fairchild EMC-25 EMI Receiver</td>
<td>14 KHz - 1 GHz</td>
</tr>
<tr>
<td>Fairchild PCL-24 Current Probe</td>
<td>1 KHz - 110 MHz</td>
</tr>
<tr>
<td>Fairchild RVR-25 Monopole Antenna</td>
<td>14 KHz - 24 MHz</td>
</tr>
<tr>
<td>Fairchild BIA-25 Bi-Conical Antenna</td>
<td>25 - 200 MHz</td>
</tr>
<tr>
<td>Fairchild LCC-25 Log Conical Antenna</td>
<td>200 - 1000 MHz</td>
</tr>
<tr>
<td>Empire Devices SU-105 Coax Transfer Switch</td>
<td>N/A</td>
</tr>
<tr>
<td>Hewlett Packard HP-703A X-Y Recorder</td>
<td>N/A</td>
</tr>
<tr>
<td>Houston Instrument Model 2000 X-Y Recorder</td>
<td>N/A</td>
</tr>
<tr>
<td>Hewlett Packard 8640B Signal Generator</td>
<td>N/A</td>
</tr>
</tbody>
</table>

2.2 Baseline Radiated Emissions Tests

Both narrowband and broadband radiated emissions tests in accordance with test method RE02 were conducted over the frequency range from 14 KHz to 1000 MHz. (A complete set of the data resulting from these tests was delivered to EAIC under a separate cover.)
The data from the narrowband radiated emissions tests indicate that the emissions exceed the limits in 10 of the 15 frequency bands over the 14 KHz to 1000 MHz frequency range. The most severe problems occur in the 14-50 KHz frequency range where in some cases the emissions exceed the limits of MIL-STD-461A by more than 40 dB, and in the 10-100 MHz frequency range where the emissions exceed the limits by 10 to 20 dB.

The data from the broadband radiated tests indicate that the emissions exceed the limits in 6 of the 15 frequency bands. The most severe problems occur in the 14-30 KHz range where in some cases the emissions exceed the limits by more than 20 dB, and in the 22-25 MHz range where the emissions exceed the limits by 10 to 12 dB.

2.3 Baseline Conducted Emissions Tests

Conducted emissions tests were performed at eight test points on the interconnecting harness. Both narrowband and broadband conducted emissions tests in accordance with test method C804 were performed on control and signal leads at test points A, B, and C as shown in Figure 2. Narrowband and broadband conducted emissions tests in accordance with test method C803 were performed on power leads at test points J, H, and F. Tests were also performed on the 400V primary power lines and the +28V DC primary power lines. All conducted emissions tests were performed over the 14 KHz to 50 MHz frequency range. (A complete set of the data resulting from these tests was delivered to EAIC under a separate cover.)

The data from the narrowband conducted emissions tests on control and signal leads indicate that the conducted emissions exceed the limits in 9 of the 11 frequency bands over the 14 KHz to 50 MHz frequency range. The most severe problems occur in the 14-50 KHz and the 1.5-4 MHz frequency ranges where conducted emission levels exceed the limits by 20 to 30 dB.

The data from the broadband conducted emissions tests on control and signal leads indicate that the conducted emissions exceed the limits in 3 of the 11 frequency bands at test point A, 9 of 11 bands at test
Figure 2. Cable Test Points.
point B, and 5 of 11 bands at test point C. The most severe problems occur in the 0.5-4 MHz frequency range where the emissions exceed the limits by more than 30 dB.

The data from the narrowband conducted emissions tests on power leads indicate that the conducted emissions on the HV lead between 1J3 and 4J3 are well below the limits over the entire range from 14 KHz to 50 MHz. The conducted emissions on the HV lead between 1J2 and 4J2 exceed the limits by approximately 5 dB between 0.9 and 1.8 MHz. The conducted emissions on the 3φ 400ν and 28V DC primary power leads at test point F exceed the limits in 5 of the 11 frequency bands. The major problem area is the 14-60 KHz frequency range where the emissions exceed the limits by as much as 45 dB. The conducted emissions on the 3φ 400ν primary power leads alone exceed the limits in 3 of the 11 frequency bands. The major problem area is the 14-60 KHz frequency range where the emissions exceed the limits by as much as 40 dB. The narrowband conducted emissions of the 28V DC primary power leads alone exceed the limits in the 20-60 KHz frequency range by approximately 20 dB.

The data from the broadband conducted emissions tests on power leads indicate that the broadband emissions on the HV lead between 1J3 and 4J3 are below the limits over the entire range. The broadband emissions on the HV lead between 1J2 and 4J2 exceed the limits by as much as 15 dB between 0.9 and 2.5 MHz. The broadband emissions on the 3φ 400ν and 28V DC primary power leads at test point F exceed the limits by as much as 20 dB in the 14-50 KHz range and by 10 dB in the 0.9-3.2 MHz range. The broadband emissions of the 3φ 400ν primary power leads alone exceed the limits by 20 dB in the 14-45 KHz range and by 5 dB in the 1-2.5 MHz range. The broadband emissions on the 28V DC primary power leads alone exceed the limits by as much as 3 dB in the 25-35 KHz region and by 5 dB in the 1-2.5 MHz region.
3. Program to Identify Conducted EMI Sources and Evaluate Modification Techniques

3.1 Tests with Modified Digital Data Computer

Digital Data Computer S/N GQZ 0059 was modified by incorporating additional power line filters; removing 2J3 connector, total time and fault indicators, and sealing holes; adding gaskets at seams; and modifying internal wiring. This modified unit was substituted for DDC S/N GQZ 0114 in the test specimen system. The R02, CE03, and CE04 tests were repeated over selected frequency ranges to evaluate the effectiveness of the modifications. The results from these measurements indicated there was no discernible reduction in either the radiated or conducted emissions as a result of these modifications.

3.2 Conducted Emissions Tests on Discrete Power Leads

In an effort to isolate and/or identify the major sources of conducted emissions, tests were performed on 10 discrete power leads between 3J1 and 2J2 over three frequency bands (14-30 KHz, 1.2-2.4 MHz, and 25-50 MHz). The discrete power leads measured are identified in Figure 3. (A complete set of the data resulting from these measurements was delivered to EAIC under a separate cover.)

The data from the narrowband conducted emissions tests on the 10 discrete power leads indicate that the conducted emissions on all 10 lines exceed the limits over the 14-30 KHz frequency range. The emissions on lines 1, 5, 8, and 9 (the 400V 115V fan lines and the +28V DC line) exceed the limits in the 14-30 KHz band by approximately 40 dB. The emissions on lines 2, 3, 6, and 7 (the 400V 70V lines) exceed the limits by approximately 30 dB in the 14-30 KHz band. The emissions on line 10 (the 400V 70V neutral line) exceed the limits in the 14-30 KHz band by approximately 40 dB. The emissions of line 4 (the +28V DC return line) exceed the limits by approximately 20 dB in the 14-30 KHz band. The conducted emissions on none of the discrete lines exceed the limits in either the 1,2-2.4 MHz or the 25-50 MHz frequency band.
Figure 3. Discrete Lines Measured.
The data from the broadband conducted emissions tests on the 10
discrete power leads indicate that the emissions on all lines except line
4 (the +28V DC return line) exceed the limits in the 14-30 KHz band.
The emissions on all lines except line 3 (the 4C 400V 70V line) exceed
the limits in the 1.2-2.4 MHz band. The broadband emissions on none
of the discrete lines exceed the limits in the 25-50 MHz band. The broad-
band emissions on lines 1, 5, 8, and 9 (the 400V 115V fan lines and the
+28V DC line) exceed the limits by approximately 15 dB in the 14-30 KHz
band. The emissions on lines 2, 3, 6, 7, and 10 (the 400V 70V lines)
exceed the limits in the 14-30 KHz band by 7-10 dB. The broadband emis-
sions on all lines except line 3 exceed the limits in the 1.2-2.4 band by
1-10 dB.

3.3 Tests to Identify EMI Sources and Evaluate EMI Reduction
Techniques

During the period from December 14, 1976 to January 11, 1977,
a number of tests were performed to determine the major sources of con-
ducted emissions. These tests were performed with various combinations
of circuit boards within the Digital Data Computer activated. In addition,
discrete EMI filters were installed in discrete lines, and filter pin con-
nectors from different manufacturers were installed in wire groups. Con-
ducted emissions tests were performed with and without the filters to
evaluate the effectiveness of these techniques in reducing the levels of
the conducted emissions. (A complete set of the data resulting from these
tests was supplied to EAIC under a separate cover.)

The results from these tests indicate that the "clock card" and the
"store care" are major sources of conducted emissions. It was also ap-
parent from these tests that filtering discrete wires in a bundle with
unfiltered wires resulted in very limited improvement due to the fact that
energy would couple from the unfiltered wires into the filtered wires.
It was also apparent that both the filter pin connectors and the discrete
filters provided considerably less insertion loss than the manufacturers
specified. It was concluded that this was partially due to energy by-
passing the filters on unfiltered wires and partially due to the fact that
the driving impedance and load impedance presented to the filters were significantly different from the design impedances of the filters.

4. Program to Evaluate Filters, Filter-Pin Connectors, and Impedance Characteristics of Typical TTL Driver-Receiver Pair

On the basis of the results from the baseline tests discussed in Section 2 and the exploratory tests discussed in Section 3, it was concluded that it would be necessary to filter as many of the wires entering and exiting the DDC as possible. To aid in accomplishing this filtering in the most efficient manner, a series of tests were performed to evaluate several types of filters and filter-pin connectors. In order to evaluate these devices under simulated operating conditions, the impedance characteristics of a typical TTL line driver-receiver pair were measured and networks capable of approximating these impedances in the filter test configurations were developed.

4.1 Impedance Measurements on Typical TTL Devices

Input and output impedance measurements were made on 9614 and 9615 (TTL) drivers and receivers for the purpose of developing a test procedure whereby the transfer characteristics of the various lowpass filters could be determined under dynamic conditions. Under "normal" conditions, the transfer characteristics of lowpass filters are measured under specific source and load impedances that match the design criterion of the filter. Generally, these source and load impedances are real (no imaginary part) with 50 and 75 ohms being typical. However, when the source and load are provided by TTL circuits, a significant departure from ideal driving and termination impedances can be expected.

In order to determine the impedances presented to the lowpass filters, a number of measurements were made on the 9614 and 9615 under pseudodynamic operating conditions. These dynamic conditions were established by providing test configurations that required the 9614 driver to sink and source currents approximately equal to the currents required when the driver is operating in conjunction with the companion 9615 receiver.
In a similar manner, measurements made on the 9615 receiver were made with input currents to the receiver being on the same order as when the receiver is interconnected with the driver. These impedance measurements were made over the frequency range from 0.5 to 100 MHz.

The schematic of Figure 4 presents the differential output circuit and the differential input circuit of the 9614 and 9615 respectively. As shown in the schematic, the active transistors in the 9614 are assumed to be Q2 and Q3. This condition causes the collector of Q2 to be at 0.2 volts and the collector of Q4 (Q4 being in an off state) to be at 3.2 volts. The differential input impedance of the 9615 is determined primarily by the 130 ohm resistor; therefore, the current sourced by Q3 and sunk by Q2 is approximately 20 mA.

In order to simulate this source and sink current condition with the 9614, the input to the driver (not shown in Figure 4) was biased to produce the output conditions depicted in Figure 4. Then the 9615 receiver was replaced with resistors connected to 40 volt supplies in the manner shown in Figure 5. Use of this high voltage (relative to the 5 volt supply used for the TTL circuits) permitted the use of resistors with large impedances as contrasted with the output impedances of the 9614 driver. This biasing technique results in sink and source currents approximating the conditions that exist when the driver and receiver are interconnected for normal operation. In Figure 5, the transistors in the active state are drawn with solid lines while the off transistors are indicated with dotted lines. The circled numbers indicate the pins on the DIP package.

The results of the 9614 output impedance measurements are presented in the graph of Figure 6. Note that the output impedance of the sink transistor (pins 1 and 2) is somewhat lower than the impedance of the source transistor (pins 3 and 4) at the lower frequencies and the real part of the output impedance continues to be lower at frequencies to 50 MHz. At frequencies above 50 MHz, the output impedance at pins 3 and 4 take on the larger value. In addition to the unbalanced output impedance measurements, a differential measurement of impedance was also made. The results of this test are also presented in Figure 6.
Figure 4. 9614 Driver and 9615 Receiver.
Figure 5. Impedance Measurement Test - 9614 Driver.
Figure 6. Output Impedance of a 9614 Driver.
In order to make input impedance measurements on the 9615 receiver, a bias condition similar to that used on the 9614 test was devised. A schematic diagram of the test setup is shown in Figure 7. For these measurements, the 40 volt power supplies were adjusted to produce a voltage of +3.2 volts at pin 5 and +0.2 volts at pins 6 and 7. These voltages, therefore, simulate the actual voltages produced by the driver under normal operating conditions. The results of these measurements are shown in the graph of Figure 8. The impedance seen at pin 5 was found to be virtually identical to the impedance looking into pins 6 and 7. These identical impedances result in the single curve presented in Figure 8. It is important to note that for these measurements, the bias resistors (1.5 K and 1.6 K ohms as shown in Figure 7) do enter into the measured value to some degree, primarily at the lower frequencies. For example, at 0.5 MHz, the measured impedance was 560 ohms which is, in fact, the parallel combination of the actual input impedance and 1.5 K ohm or 1.6 K ohm, depending on the specific input terminal. For this case, therefore, the actual impedance is somewhat greater than 560 ohms and is on the order of 875 ohms. From the curve of Figure 8 it is obvious that the bias network is significantly removed from the impedance measurements at the higher frequencies.

In addition to the impedance measurements presented in Figure 8, a differential impedance measurement between pins 5 and 6,7 of Figure 7 was also made. The results of these measurements showed a differential impedance of 130+ j0 ohms from 0.5 to 10 MHz and decreasing slightly to 119.9-j4.2 at 100 MHz.

Using the measured values of output and input impedances of the 9614 driver and 9615 receiver, networks were designed that would approximate these impedances over the frequency range from 0.5 to 100 MHz. No attempt was made to synthesize the impedances exactly since an investigation of the measured data shows a nonlinear impedance characteristic as a function of frequency. This nonlinearity is particularly noticeable in regard to the input impedance of the 9615 receiver. A single network was used to simulate the output impedance of the 9614 driver, whereas two networks were used to simulate the input impedance of the 9615 receiver; one network for the lower frequencies and a second network for the higher frequencies.
Figure 7. Impedance Measurement Test - 9615 Receiver.
Figure 8. Input Impedance of a 9615 Receiver.
The data used to design the network for simulation of the output impedance of the 9614 driver is simply that shown in the graph of Figure 9. The network for simulation of the input impedance to the 9615 receiver was derived by considering a combination of series and parallel impedances as depicted in Figure 9. In this figure, $Z_a$ and $Z_c$ are the impedances presented by Q5 and Q6 of Figure 4, $Z_b$ is the 130 ohm resistor and $Z_c$ is the output impedance of Q4 of Figure 4. Again, no attempt was made to exactly simulate the actual impedance over the full frequency range since any such complex simulation would be beyond the scope of this program.

The networks resulting from this measurement effort are shown in the schematic of Figure 10. Network I approximates the impedances at the lower frequencies and Network II represents the higher frequency impedances.

4.2 Measurements to Evaluate Filters and Filter-Pin Connectors

A series of measurements were performed to evaluate the effectiveness of two types of filter-pin connectors, three types of RC "T" filters, three types of LC "T" filters, and three commercially available "L", "π", and "T" filter types. The test setups and equipment used to perform these measurements are shown in Figure 11. The HP 8444A Tracking Generator and the HP141T/8552B/8554 Spectrum Analyzer were synchronized to sweep over the 0.5 to 1000 MHz frequency range. When a filter was inserted in the line between the output terminal of the tracking generator and the input terminal of the spectrum analyzer, the characteristics of the filter over the 0.5-1000 MHz frequency range were displayed on the CRT of the spectrum analyzer. The HP 9640B Signal Generator was used to inject a frequency marker on the CRT display. The Microlab PA-3FN "T" was used to combine the tracking generator output and the signal generator marker output. A 10 dB attenuator pad was connected at the input and output terminals of the filter under test to minimize the effects of the test cables and any mismatches between units of test equipment in the measurement setup.
Figure 9. Impedances Presented to the 9614 Driver.
Figure 10. Schematic Diagram of the Impedance Networks.
Figure 11. Test Setups for Filter and Filter-Pin Connector Measurements.
4.2.1 Evaluation of RC Filters

The three RC filter configurations shown in Figure 12 were measured over the 0-1000 MHz frequency range with: (1) no feed-thru capacitor; (2) a 1000 pF feed-thru capacitor; and (3) a 0.05 μF feed-thru capacitor.

The responses of the type 2 and type 3 filter configurations with no feed-thru capacitor over the 0.5 MHz to 1 GHz frequency range are shown in Figure 13. The upper curve shows that the type 2 filter cuts off below 0.5 MHz and exhibits an insertion loss of greater than 50 dB between 0.5 and 500 MHz. Above 500 MHz, the insertion loss decreases at a rate of approximately 6 dB per 100 MHz. At 1 GHz, the insertion loss is less than 20 dB. The lower curve shows that the type 3 filter cuts off below 0.5 MHz and exhibits an insertion loss greater than 50 dB between 0.5 and 200 MHz. Above 200 MHz, the insertion loss decreases at a rate of approximately 5 dB per 100 MHz. At 1 GHz, the insertion loss is again approximately 20 dB. For the type 1 filter, the response is similar with the roll-off starting at approximately 700 MHz. The roll-off in insertion loss at the higher frequency appears to be caused by the stray reactance associated with the leads of the disc capacitor.

The responses of the type 1 and type 3 filter configurations with a 1000 pF feed-thru capacitor are shown in Figure 14. The upper curve shows that the type 1 filter exhibits greater than 50 dB insertion loss between 0.5 and 850 MHz and decreases approximately 6 dB between 850 MHz and 1 GHz. The lower curve shows that the type 3 filter exhibits greater than 50 dB attenuation between 0.5 and 900 MHz and rolls off approximately 15 dB between 900 MHz and 1 GHz.

The response of the type 1 filter with a 0.05 μF feed-thru capacitor over the 0-200 MHz range is shown in Figure 15. This curve was measured with the 10 dB attenuators at the input and output of the filter removed to obtain 20 dB additional dynamic range. This was done primarily in an attempt to see the effect of the impedance simulation networks on the filter characteristics. The impedance networks exhibited a 20 dB insertion
Figure 12. RC Filter Types.
Figure 13. RC Filters with no Feed-Thru Capacitor.
Figure 14. RC Filters with 1000 pF Feed-Through Capacitor.
RC filter alone provides approximately 90 dB attenuation. Could see no change with Network II installed due to -90 dB limit of measurement.

Figure 15. RC Filter with .05 μF Feed-Thru Capacitor.
loss over the 0-200 MHz frequency range. Hence, the upper reference in the figure is -20 dB rather than 0 dB was the case in the previous figures. The curve shows that the type 1 filter with a 0.05 feed-thru capacitor exhibits greater than 90 dB attenuation between 0.5 and 900 MHz and decreases to approximately 85 dB between 900 MHz and 1 GHz. Impedance simulation networks II were installed at the input and output of the filter as shown in Figure 10 and the measurement was repeated. The attenuation of the filter and impedance networks exceed the dynamic range of the measurement setup over the entire 0.5 to 200 MHz range. Since the insertion loss of the networks is approximately 20 dB over this frequency range, it can be concluded that the attenuation of the filter operating with simulated typical operating impedances is greater than 70 dB.

4.2.2 Evaluation of LC Filters

The three LC filter configurations shown in Figure 16 were measured over the 0-1000 MHz frequency range with no feed-thru capacitor, with a 1000 pF feed-thru capacitor as shown in the figure, and with a 0.05 μF feed-thru capacitor.

The characteristics of the type 4 and type 5 filter configurations with no feed-thru capacitor over the 0.5 MHz to 1 GHz frequency range are shown in Figure 17. The upper curve shows that the type 4 filter with no feed-thru capacitor exhibits an insertion loss of approximately 42 dB between 0.5 and 150 MHz. The insertion loss decreases from 40 dB to 15 dB between 200 MHz and 650 MHz. The insertion loss starts increasing from 15 dB at 700 MHz and increases to 25 dB at 1 GHz. The lower curve shows that the insertion loss of the type 5 filter with no feed-thru capacitor is approximately 45 dB between 0.5 and 150 MHz and decreases from 43 dB at 200 MHz to 15 dB at 1 GHz.

The characteristics of the three types of LC filters with a 1000 pF feed-thru capacitor are shown in Figure 18. The insertion loss characteristics for all three filter types are greater than 50 dB between 50 and 500 MHz. Below 50 MHz and above 500 MHz the insertion loss characteristics are erratic due to resonances. The insertion loss characteristics
Figure 16. LC Filter Types.
Figure 17. LC Filters with no Feed-Thru Capacitor.
Figure 18. LC Filters with 1000 pF Feed-Thru Capacitor.
below 50 MHz are shown in more detail in Figure 19.

It was found that removing the disc capacitors and using a 0.05 μF feed-thru capacitor eliminated both the low frequency and high frequency resonances and resulted in the best stopband characteristics. The characteristics of this filter configuration are shown in Figure 20. Again, the 10 dB pads were removed to obtain more dynamic range to look for the effects of the impedance networks. The upper curve is for the filter alone operating in the 50 Ω test setup. The filter exhibits greater than 70 dB insertion loss between 30 and 200 MHz. The insertion loss is greater than 50 dB at 10 MHz and increases to 75 dB at 40 MHz. The lower curve shows the results obtained with the impedance networks in the setup. In the 0.5 to 20 MHz frequency range, the lower curve is approximately 20 dB below the upper curve which accounts for the 20 dB insertion loss of the impedance networks, and hence indicates that operating with the simulated impedances has little influence on the filter characteristics in this frequency range. In the 20 to 140 MHz range, the lower curve exceeds the dynamic range of the measurement setup, and the only conclusion that can be made is that the insertion loss of the filter operating with the impedance networks is greater than 70 dB over this frequency range. Above 140 MHz, the lower curve is only 3 to 10 dB below the upper curve, indicating that the simulated source and load impedances degrade the insertion loss characteristics of the filter by some 10 to 17 dB in this range. However, the insertion loss of the filter operating with the impedance networks is still better than 60 dB in the 140 to 200 MHz frequency range.

4.2.3 Evaluation of Filter-Pin Connectors

Measurements were made on a Deutsch and a Bendix filter-pin connector. The measured characteristics of the Deutsch filter-pin connector are illustrated in the photographs in Figure 21. The upper photograph shows the filter characteristics over the 0.5-1000 MHz frequency range. The insertion loss increases rapidly in the 0.5-60 MHz frequency range and reaches 40 dB at approximately 50 MHz. The insertion loss ripples in the range from 45 to 55 dB over the 60 to 1000 MHz frequency range. There are no serious resonances apparent over this frequency range.
Figure 19. LC Filters with 1000 pF Feed-Thru Capacitor, 1.0 - 100 MHz Frequency Range.
LC FILTER 0 - 200 MHz

-20 dB Ref.
20 MHz/Div.
10 dB/Div.

Lower Trace with
Network II

-90 dB Measurement Limit

Figure 20. LC Filter with 0.05 μF Feed-Thru Capacitor.
Figure 21. Characteristics of Deutsch Filter-Pin Connector.
range. The lower photograph in Figure 21 illustrates the low frequency response of the filter-pin connector over the 0-10 MHz region. The insertion loss is essentially zero in the 0-1 MHz region, increases to approximately 10 dB at 5 MHz, and is approximately 15 dB at 10 MHz.

The measured characteristics of the Bendix filter-pin connector are shown in Figure 22. The upper photograph shows the insertion loss characteristics over the 0.5-1000 MHz frequency range. The insertion loss increases rapidly in the 0.5-50 MHz frequency range and reaches 50 dB at approximately 40 MHz. The insertion loss is greater than 50 dB from 40 MHz to 1000 MHz except for a region in the 200 to 300 MHz frequency range where a resonance causes the insertion loss to decrease to approximately 30 dB. The lower photograph in Figure 22 shows the low frequency response of the Bendix filter-pin connector in the 1-10 MHz frequency range. The insertion loss is essentially zero in the low kilohertz region, increases to 10 dB at 5 MHz, and is greater than 20 dB at 10 MHz.

On the basis of these measurement results, the Bendix filter-pin connector has a sharper cutoff, provides insertion loss at lower frequencies, and provides higher attenuation in the stopband. However, the Bendix unit has resonances in the 200-300 MHz frequency range which degrades the stopband attenuation in this region to less than the Deutsch unit. The Deutsch connector does not exhibit any significant resonances over the 1-1000 MHz frequency range.

The results of measurements made to determine the effects of load impedances on the insertion loss characteristics of the filter-pin connectors are shown in Figure 23. The upper photograph shows the results obtained for the Bendix connector over the 0-200 MHz frequency range. The upper curve in the photograph was obtained with the filter-pin connector alone in the measurement setup while the lower curve was obtained with the impedance networks in the setup as illustrated at the bottom of the figure. If the insertion loss characteristics were identical under the two sets of conditions, two identical curves displaced by 20 dB would be obtained to account for the 20 dB insertion loss of the impedance networks. It is apparent from the photograph that the two curves are quite similar and are essentially displaced by 20 dB except in the 130-160 MHz...
Figure 22, Characteristics of Bendix Filter-Pin Connector.
Bendix Filter Pin
Top Trace Ref. @ -20 dB
-90 dB Measurement Limit
Middle Trace w/o Network
Lower Trace w/Network II

(-20)
(N)
(-90) -90 dB Limit
0 - 200 MHz
20 MHz/Div.
10 dB/Div.

(-20) Deutsch Filter Pin
w/o Network
w/Network II
(-90)

Without Network

Tracking Generator ➔ Filter Pin ➔ Spectrum Analyzer

With Network

Tracking Generator ➔ 1/2 Network II ➔ Filter Pin ➔ 1/2 Network II ➔ Spectrum Analyzer

Figure 23. Impedance Characteristics of Filter-Pin Connectors.
frequency range where a resonance was present in the upper curve. Similar results for the Deutsch filter-pin connector are shown in the lower photograph in Figure 23. From these results, it can be concluded that the source and load impedances have very little effect on the stopband characteristics of the filter-pin connectors.

Measurements were also made to determine the saturation characteristics of the filter-pin connectors. These measurements were made by measuring the stopband characteristics of the connectors while different amounts of DC currents were flowing through them. Measurements were made with 0, 1, 2, 3, and 4 amperes of current. The results from the measurements are shown in Figure 24. The center photograph shows the results obtained for the Bendix connector over the 0.5 MHz to 1 GHz frequency range. This photograph illustrates that the only significant effects of current loading occur in the 0-100 MHz frequency range. Similar results were obtained with the Deutsch connector.

The upper photograph shows the effects of current loading on the Bendix connector over the 0-100 MHz frequency range. The lower curve was obtained with no current loading. The next curve up was obtained with 1 ampere of current, and the next with 2 amps, the next with 3 amps, and the top curve with 4 amps. It is apparent from the photograph that 1 amp of current degrades the insertion loss approximately 10 dB between 10 and 40 MHz and gradually slopes off to zero degradation at 80 MHz. Two amps of current cause a degradation of 20 dB between 20 and 40 MHz and slopes off to approximately zero at 100 MHz. Three amps of current cause a maximum degradation of 23 dB at 30 MHz and 4 amps cause a maximum degradation of 27 dB at 40 MHz.

Similar results for the Deutsch connector are shown in the lower photograph of Figure 24. It is apparent from the photograph that saturation effects occur at the higher frequencies and are less severe in the Deutsch connector. For 4 amps of current, a maximum degradation of 20 dB occurs at 70 MHz.
1. Bendix Filter Pin
0 – 100 MHz
Bottom Trace @ φ Amp.
(4) 1A
(3) 2A
(2) 3A
(1) 4A
(B)
10 MHz/Div.
10 dB/Div.

2. Bendix & Deutsch Filters
No Appreciable change
with current applied
above 100 MHz
0.5 MHz – 1 GHz
300 MHz Bandwidth
100 MHz/Div.
10 dB/Div.

3. Deutsch Filter Pin
0 – 100 MHz
Bottom Trace @ Amp.
(4) 1A
(3) 2A
(2) 3A
(1) 4A
(B)
100 MHz/Div.
10 dB/Div.

Figure 24. Saturation Characteristics of Filter-Pin Connectors.
4.2.4 Evaluation of Commercial Filters

Three types of EMI filters commercially available from Spectrum Control were evaluated. The group included a "T" filter (Model 51-311-601), a "π" filter (Model 51-433-301), and a "L" filter (Model 51-353-232). The results of the measurements on the "T" and "π" filters over the 0-200 MHz frequency range are shown in Figure 25. The stopband characteristics of the "T" filter (Model 51-311-601) over the 0-200 MHz range are shown in the upper photograph. The insertion loss is approximately 60 dB at 3 MHz, increases to 80 dB at 10 MHz, and remains greater than 80 dB between 10 and 200 MHz. The filter was also tested with the impedance networks to determine the effects of source and load impedance variations on the characteristics, but the results exceeded the dynamic range of the measurement setup. It is only possible to conclude that the insertion loss of the filter operating with the impedance networks exceeds 70 dB over the 10-200 MHz frequency range.

The characteristics of the "π" filter (Model 51-433-301) are shown in the lower photograph of Figure 25. The two upper curves in the photograph were obtained with the filter alone in the measurement setup. The two curves were obtained by reversing the filter to check the symmetry of the "π" configuration. The insertion loss reaches 40 dB at 40 MHz, increases to 45 dB at 60 MHz, and remains greater than 45 dB between 60 and 200 MHz. The lower curve in the photograph was obtained by inserting the impedance networks in the measurement setup. It is apparent from the photograph that the upper and lower curves are displaced by 20 dB or more over the 40-200 MHz range, indicating that the source and load impedances have very little effect on the stopband characteristics of the filter.

The stopband characteristics of the "L" filter (Model 51-353-232) are shown in Figure 26. The two upper curves in the photograph were obtained with the filter alone in the setup. The two curves were obtained by reversing the filter in the setup. In the 50Ω - 50Ω measurement setup, reversing the filter had little effect on the stopband characteristics. The insertion loss is approximately 40 dB at 5 MHz and ripples down to
Type 51-311-601
"T" Filter 0 - 200 MHz
Top Ref. @ -20 dB
-90 dB Measurement Limit
0 - 200 MHz
20 MHz/Div.
10 dB/Div.

Type 51-433-301
"π" Filter 0 - 200 MHz
Top Ref. @ -20 dB
-90 dB Measurement Limit

with Network II

Figure 25. Characteristics of "T" and "π" Filters,
Type 51-353-232
"L" Filter

0 - 200 MHz
20 MHz/Div.
10 dB/Div.

Figure 26. Characteristics of "L" Filter.
30 dB at 100 MHz and increases to approximately 60 dB at 200 MHz. The lower curves in the photograph were obtained by inserting the impedance networks in the setup. The two curves were obtained by reversing the filter in the setup. The curve which starts lower was obtained with the choke end of the filter toward the source as illustrated in the lower portion of the figure. The measured impedance values looking into the filter at points A and B at 2, 5, and 10 MHz are also shown in the figure. It is apparent that the orientation of the filter has a significant effect on the stopband characteristics when operating with the simulated source and load impedances. When operating with the choke end of the filter toward the source, the change in impedance levels has little effect on the stopband characteristics; however, when operating in the other orientation, the impedance networks cause a significant degradation in the insertion loss characteristics in the 10-50 MHz frequency range.

5. Evaluation of Modified Computer

The final approach to modifying the Digital Data Computer was to build a shielded enclosure in which the computer could be inserted and mount 47 discrete RC and LC filters in one end wall of the enclosure which could be used to filter most of the lines from connector 2J2 of the computer. The test setup used to evaluate the modified computer is illustrated in Figure 27. The computer was installed in the shielded enclosure and positioned on a test bench in the 20' x 8' x 8' shielded room. The test set which powered the computer during these tests was also positioned on a test bench and the two units were connected with a wiring harness. A current probe was placed on the wiring harness between the units, and the output from the probe was routed by a coax cable through a coax penetration in the room wall to the EMI receiver outside the shielded room. A Fairchild BIA-25 Bi-conical Antenna was mounted one meter from the computer. The output from the antenna was routed by a coax cable through a coax penetration in the room wall to an ARC-114 receiver outside the shielded room.
Figure 27, Test Setup for Modified Computer.
The initial test was to operate the computer without the shielded enclosure and line filters to determine the effects of the unmodified computer on the ARC-114 receiver. The audio output of the ARC-114 receiver was monitored by means of ear phones and the AGC voltage was monitored with a digital voltmeter as the receiver was tuned through its channels with the computer in operation. Severe interference was present in the audio output for all the receiver channels and significant increases in the AGC voltages were noted on all channels. On several channels, the AGC voltages went into saturation.

The second test consisted of installing the computer in the shielded enclosure with the line filters and repeating the procedures described above to determine the effects of the modified computer on the ARC-114 receiver. With the modified computer operating, there was no discernible interference present in the audio output of the receiver on any of the channels. On most channels, there was no discernible difference in the AGC voltage when the computer was operating compared to the AGC voltage when the computer was off. On those channels where a difference was noted, the difference was too small to be considered significant.

The third test consisted of measuring the broadband and narrowband conducted emissions from the modified computer. The conducted emissions were picked up by means of a Fairchild PCL-24 current probe placed on the wiring harness between the computer and the test set. The current probe output was routed to an EMC-25 receiver located outside the shielded room. The receiver output was recorded on a X-Y plotter as the receiver was scanned over its bands.

The measured broadband conducted emissions from the modified computer over the 5 to 50 MHz frequency range are shown in Figures 28, 29, and 30. The data in Figure 29 indicate that the maximum conducted emission level in the 5 to 11 MHz band is approximately 46 dB below the limit level. Figure 29 indicates that the maximum broadband emission level in the 11 to 25 MHz band is approximately 50 dB below the limit. Figure 30 indicates that the maximum emission level in the 25 to 50 MHz band is approximately 87 dB below the limit.
Figure 28. Broadband Conducted Emissions from Modified Computer (5-11 MHz).
Figure 29. Broadband Conducted Emissions from Modified Computer (11-25 MHz).
Figure 30. Broadband Conducted Emissions from Modified Computer (25-50 MHz).
The broadband conducted emissions from the computer before it was modified (over the 11-25 MHz band) are shown in Figure 31. Comparing Figure 31 with Figure 30 reveals that the modification reduced the conducted emissions in the 11-25 MHz frequency range by more than 30 dB.

The narrowband conducted emissions from the modified computer over the 1 to 100 MHz frequency range are shown in Figures 32-37. It is apparent from these figures that the conducted emissions are well below the limits over most of the frequency range. In the frequency range from 4.5 to 13 MHz, the conducted emission levels do increase to within 10 dB of the limit and spikes actually exceed the limit at two discrete frequencies (5 and 6 MHz) by approximately 5 dB.

6. Conclusions

On the basis of the results from the baseline tests which indicated that both the radiated and conducted emissions from the Digital Data Computer exceeded the limits by more than 40 dB, it was concluded that it would be necessary to filter as many of the lines entering and exiting the DDC as possible. This was accomplished by building a shielded enclosure in which the computer could be inserted and installing 47 discrete filters in one end wall of the enclosure which could be used to filter most of the lines from connector 2J2 of the computer.

The modified computer was tested with an ARC-114 receiver and the results indicated that the modified computer caused no discernible interference in the ARC-114 receiver on any channel.
Figure 31. Broadband Conducted Emissions from Unmodified Computer (11-25 MHz).
Figure 32. Narrowband Conducted Emissions from Modified Computer (1.5-2.4 MHz).
Figure 33. Narrowband Conducted Emissions from Modified Computer (2.5-5 MHz).
Figure 34. Narrowband Conducted Emissions from Modified Computer (5-11 MHz).
Figure 35. Narrowband Conducted Emissions from Modified Computer (11-25 MHz).
Figure 36. Narrowband Conducted Emissions from Modified Computer (25-50 MHz).
Figure 37. Narrowband Conducted Emissions from Modified Computer (50-100 MHz).