University of Missouri-Rolla
Electromagnetic Compatibility Laboratory

Title: Investigation of Common-mode Radiation from the GM-Allison Electronic Control Unit

Report Number: TR94-9-027R

Author: J.L. Drewniak
T.P. Van Doren
R.L. Hill
Sha Fei

Date: June 1994

Contents

1 Introduction

Sources of common-mode current on the cables of the Allison Electronic Control Unit (ECU) are being investigated in order to reduce the resulting common-mode radiation. Fundamentally radiation requires an antenna and a feed or source. In printed circuits with attached cables, one half of the radiator is typically one or more conductors in the attached cable bundle. Locating the other half of the antenna is often difficult, as is locating the driving source. However, by determining the antenna (two halves) and/or driving source, design modifications can be introduced to render the antenna or source ineffective to eliminate or minimize the radiation.

Previous research has indicated that common-mode radiation from printed circuit boards with attached cables can be reduced to two primary source mechanisms denoted *voltage-* and *current-driven* [1]. A diagnostic procedure is under development utilizing these ideas to assist in more rapidly diagnosing and eliminating common-mode radiation from printed circuit boards. Elements of this diagnostic procedure were utilized in the investigation of the ECU to assist in determining the source of the common-mode radiation.

2 Experimental Investigations on the GM-Allison ECU

2.1 Summary of Results

The ECU was tested with the control keypad located at the end of a 15 ft. minimum cable bundle supplied by Allison. Twelve volt DC power was supplied to the ECU to operate the clocks. Attention was focussed on the two printed circuit boards (PCBs) connected by the ribbon cables of connectors J2 and J3. The lower board to which the connector is attached supplies the 5 V power for the circuit and is referred to as the *power* board. The majority of the logic is contained on the upper board and is referred to as the *logic* board. The primary contributors to common-mode current on the attached cable that have currently been determined are summarized below.

- A primary antenna and corresponding source are related to the address data lines AD0-AD7 that run through the ribbon cable attached to connector J3 from the logic to the power boards. These lines are switched at the full 5 V and the proximity of the ribbon cable to the chassis (case) allows for considerable capacitive coupling from the lines to the chassis. These lines capacitively coupling to the chassis provide the source for driving the chassis at one RF potential against the ground conductor in the attached cable bundle at another RF potential.

The difference in the RF potentials of these two portions of ground is a result of the high impedance (associated with inductance) connection of the EMC ground at the connector to the chassis.

- The signal return (or ground/reference) for the address data lines are conductors or lines near the opposite end of the ribbon cable from the address data lines AD0-AD7. This configuration produces significant "fringing" electric fields that contributes to capacitive coupling.
- The signal and digital grounds are isolated on the logic board and connected at the power board through a high inductance connection. These two grounds are routed through separate lines of the ribbon cable of J3. Further, in numerous places, signal lines are routed over the resulting gaps in the signal return or ground.
- Significant differential-mode noise voltages are developed between the RSI pins (as well as other pins that are not decoupled at the connector) and the ground in the cable bundle as well as the chassis.

Modifications were made to the ECU in an attempt to address each of the above concerns: 1) A modified planar ground structure approximately 3" × 5" constructed from copper tape was introduced to provide a low impedance connection between the ground at the connector and the chassis. The modified ground was soldered at approximately 20 points to the EMC ground, and soldered over a wide strip (approximately 1 cm) to the heatsink/chassis connection. 2) The signal and digital grounds on the logic board were connected through a short wire at the connector J3, as well as connecting the signal ground at the connector to the digital ground at a point on the board interior. 3) The RSI lines were decoupled with 0.01 μF capacitors at the connector. The common-mode current measured with the ECU in the initial configuration is compared with measurements after the described modifications were implemented in Figure 1. The strong single frequency peaks in the data (e.g., the -60 dBm signal at approximately 95 MHz) are ambients. Strong resonances associated with the cable length are apparent at 30 and 150 MHz in both cases. The measured common-mode current for the modified configuration indicates significant improvements at 30, 60, 120, and 150 MHz. These frequencies correspond approximately to the resonant lengths of the cable. The resulting antenna and noise sources after the modifications have a lower impedance at the resonance frequencies. As a result, a ferrite sleeve at the ECU connector can provide significant additional series impedance to further reduce the common-mode current on the attached cable. Measured results with a ferrite sleeve added at the ECU connector for the modified configuration are shown in Figure 2. The data for the black curve in Figure 2 is the same as the green curve

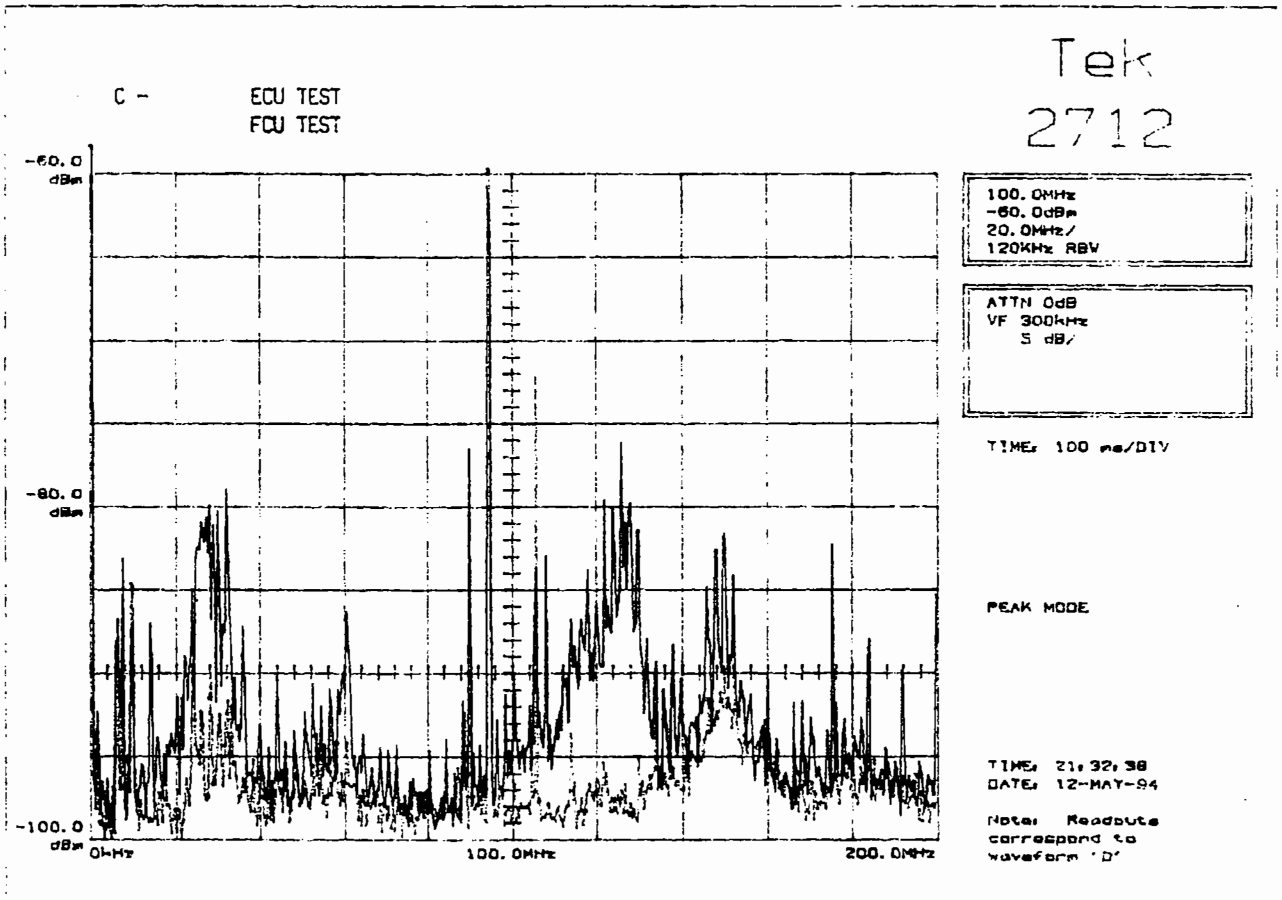

Figure 1: Common-mode current measurements on the cable bundled attached to the ECU before (green) and after (red) modifications to the ECU.

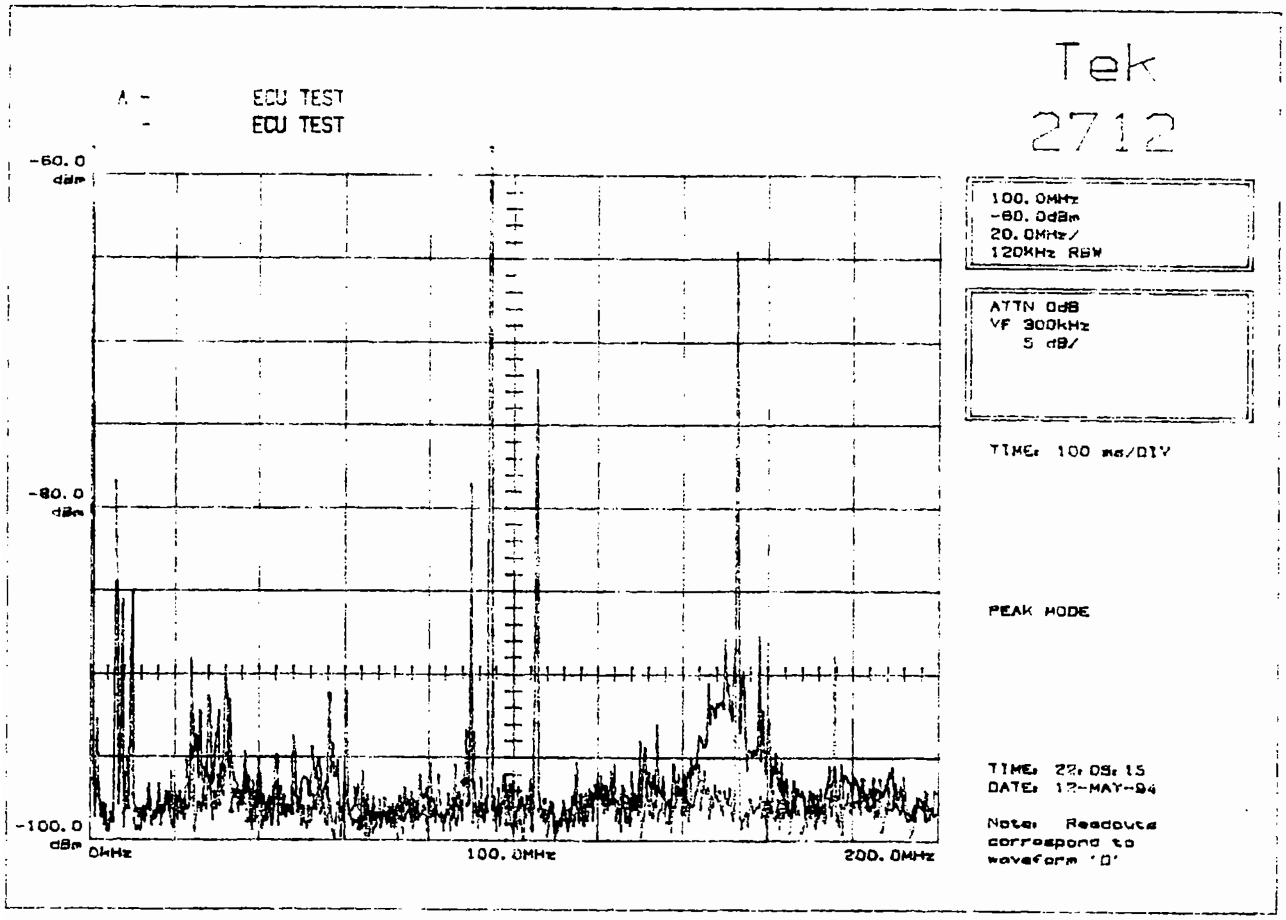

Figure 2: Common-mode current measurements on the cable bundled attached to the ECU before (black) and after (red) the addition of a ferrite sleeve at the ECU connector.

in Figure 1. The resulting measured common-mode current is outside the dynamic range of the measurements.

2.2 Measurement Procedures

The common-mode current on the ECU cable bundle was measured throughout the investigation on the initial configuration and as modifications were introduced. The relative improvements in the measured CM current on the attached cable bundle will translate into similar improvements in radiated EMI. The test configuration is shown in Figure 3. The measurements were performed with two cable bundles, a minimum cable bundle supplied by Allison (power and RSI lines), and a power cable bundle configured at UMR that included only lines necessary for powering the ECU. The RSI lines were not included in the UMR cable bundle configuration. The measurements were performed with the ECU on a metal-framed workbench with a molded top. The cables were extended approximately six feet from the ECU to the power supply, and the remaining lengths in

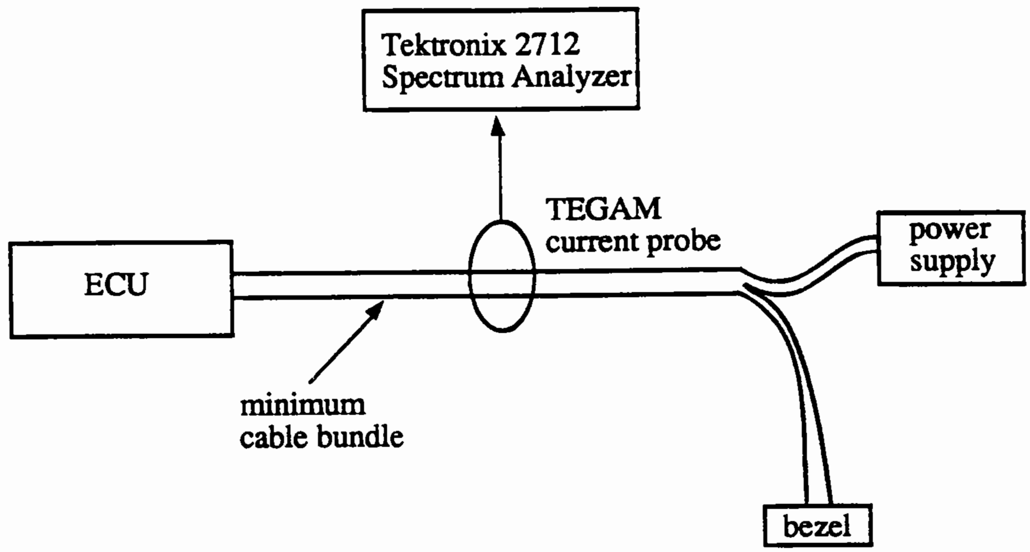

Figure 3: Test configuration for measuring the common-mode current on the ECU cable bundle.

the fifteen foot bundle were coiled and draped over the bench edge to the floor. The control keypad was attached at the end of the appropriate portion of the cable. The common-mode current was measured with a TEGAM current probe (Model 94111-1, $1 - 1000$ MHz) located midway between the power supply and the ECU. In most cases the midpoint was the CM current maximum. The measurements were not performed in a shielded room and as a result several large amplitude ambients are apparent in the data throughout. A plot of the measured common-mode current with the ECU unpowered illustrating the ambients is shown in Figure 4.

2.3 Measured Results

2.3.1 Address Data Lines Coupling to Chassis

One antenna and source discerned to date is related to the address data lines AD0-AD7, and the configuration of the EMC ground at the ECU connector B and heatsink. The address data lines AD0-AD7 run through the flexible cable connecting the power and logic boards at connector J3, and carry signals switched between 0 and 5 V. With the ECU out of the metal chassis, these lines form one half of an effective antenna that can be driven against the extended ground conductor in the attached cable bundle. Measurements of the common-mode current on the Allison minimum cable bundle with the ECU in and out of the chassis are shown in Figure 5. The radiation below 90 MHz is approximately $5 - 10$ dB greater when the ECU is out of the chassis. An equivalent circuit diagram in Figure 6 illustrates the benefits of the metal enclosure. With the ECU out of

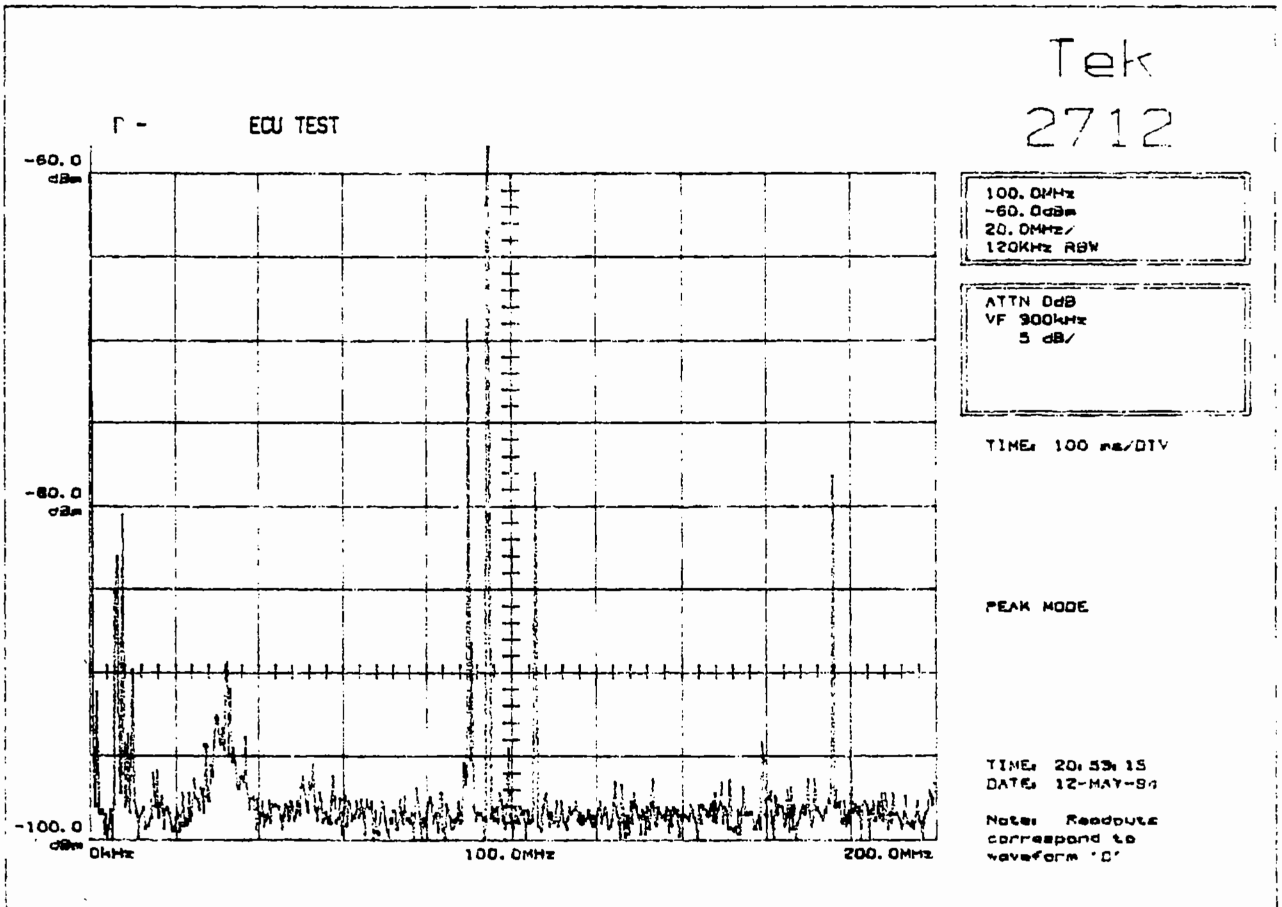

Figure 4: Common-mode current on the Allison minimum cable bundle with the ECU unpowered.

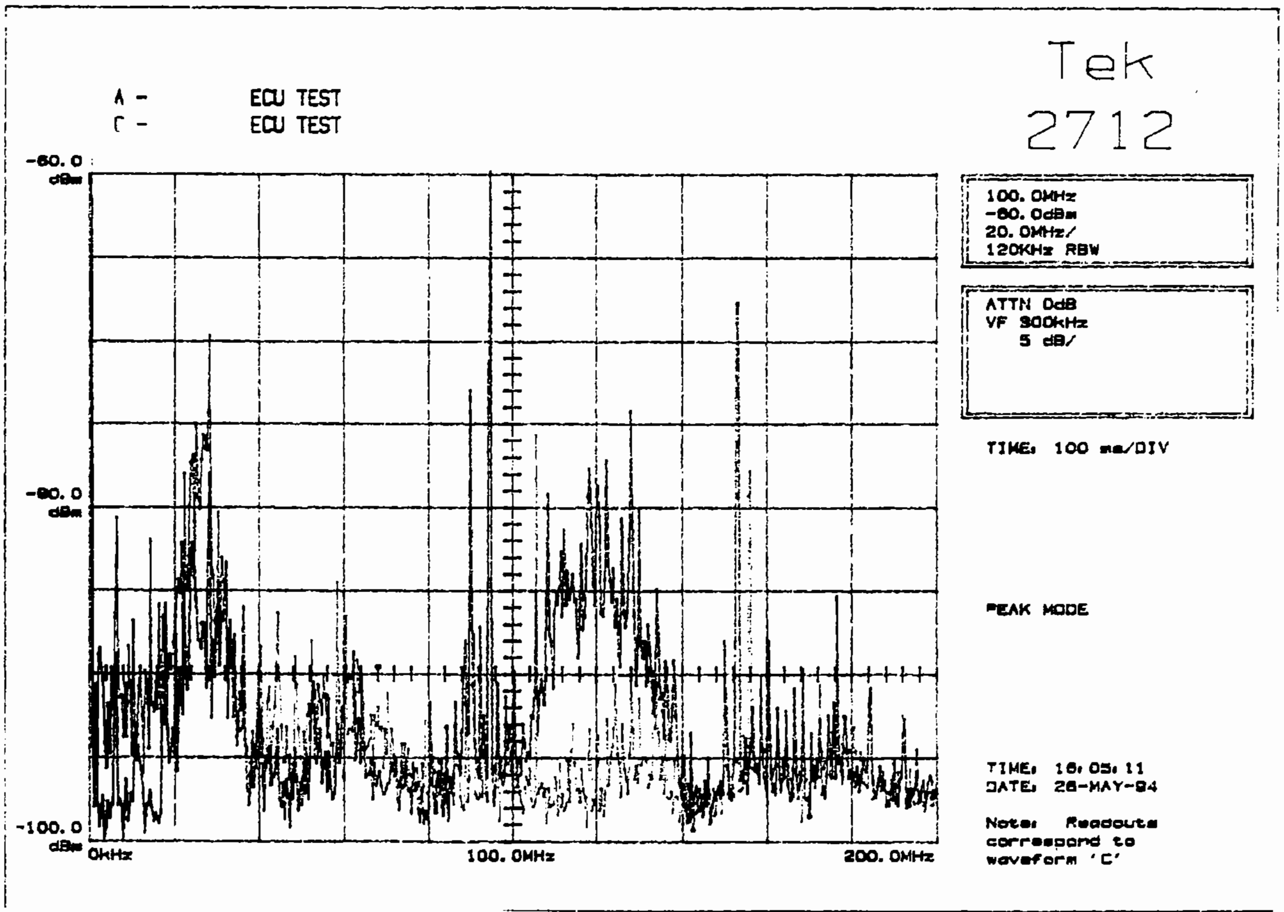

Figure 5: Common-mode current on the Allison minimum cable bundle in (blue) and out of (green) the chassis.

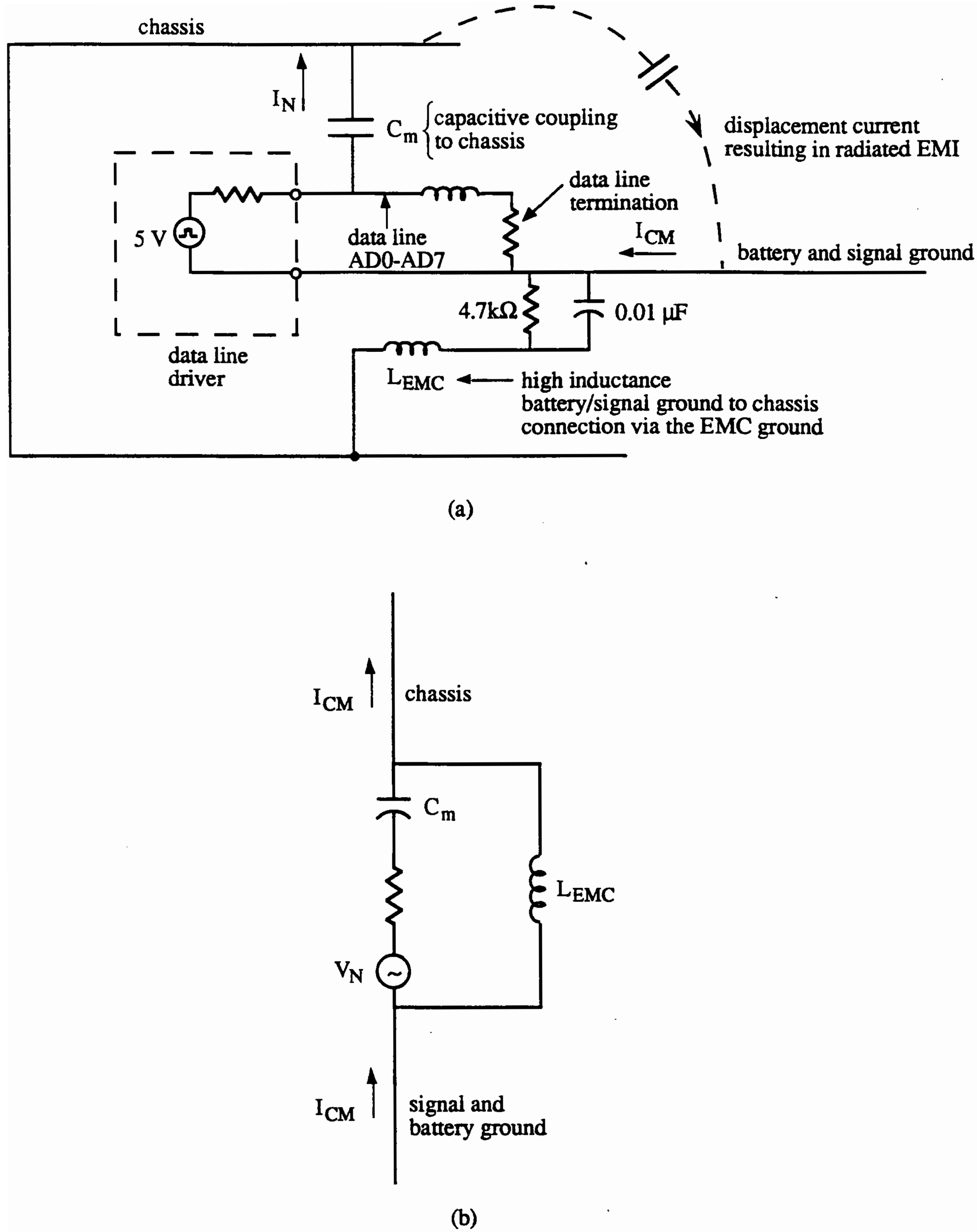

Figure 6: a) Equivalent circuit illustrating the coupling of the address data lines (source) to the chassis and the high impedance (inductance) EMC ground to chassis connection. b) Representative antenna with the ECU in the chassis.

the chassis, the address data lines are effectively driven directly against the ground in the cable bundle. Attaching a length of wire to any of the address data lines AD0-AD7, (or a finger on one of these lines) increases the measured common-mode current by greater than 15 dB. In addition, the spectrum of electric and magnetic field probe measurements in the vicinity of the address data lines was nearly identical to the spectrum of the common-mode current on the attached cable bundle for the ECU out of the chassis. When the ECU is in the chassis, the address data lines capacitively couple to the chassis. With no connection between the chassis and the EMC ground, the chassis can still be effectively driven against the ground in the cable bundle because of the capacitive coupling of the source to the chassis (voltage-driven mechanism). The EMC ground, which is attached directly to the ground conductor in the cable bundle, is attached to the heatsink/chassis. However, this connection has a high RF impedance as a result of the inductance associated with the limited ground conductor comprising the EMC ground. Further, the direct metallic connection between the EMC ground and the heatsink is through only three very narrow connections. The equivalent antenna structure, as illustrated in Figure 6 (b), is a series inductance between the chassis and ground in the cable bundle. Minimizing this inductance, or constructing a low impedance ground between the connector and the connection to the chassis (at the heatsink), can effectively short out the source of the common-mode current.

Also important for a low impedance path between the ground in the cable bundle and the chassis is the contact between the heatsink and the chassis. In the present ECU configuration a pressure contact is employed. Ensuring a good pressure contact is essential. The metal on the heatsink as well as the case was filed to remove any oxide that might increase the resistance, however, there was little or no difference in the measured common-mode current on the cable bundle between the two cases. The lower impedance planar EMC ground had been implemented prior to these tests.

A modified ground structure providing a low impedance connection between ground at the connector and the heatsink was introduced into the ECU. A solid copper tape ground plane of approximate dimensions 3" $\times$ 5" was soldered at approximately 20 points around the periphery of the EMC ground, including approximately 10 points at the connector. This modified ground was soldered to the heatsink over approximately a 1 cm wide strip. The connector opening in the chassis was enlarged to allow the modified ECU to be mounted in the chassis. The common-mode current with the modified EMC ground and heatsink/chassis connection is shown in Figure 7. The red data is the common-mode current on the Allison minimum cable bundle with only a modified EMC ground and heatsink/chassis connection. Comparing these results with those of the initial configuration (blue data), the reduction is approximately 5 dB for frequencies around

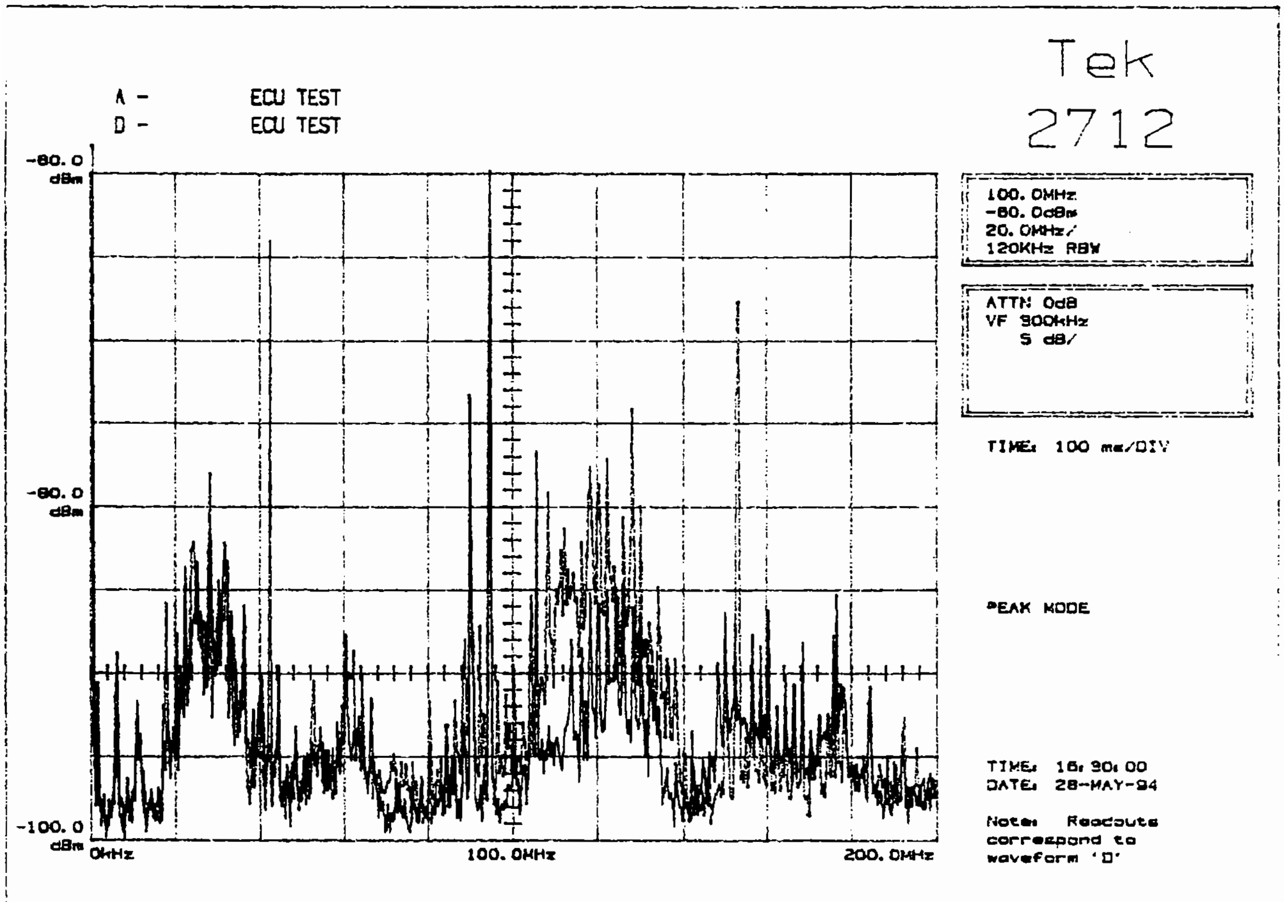

Figure 7: Common-mode current on the Allison minimum cable bundle with a modified EMC ground and heatsink/chassis connection. Modified EMC ground (red), and original configuration (blue).

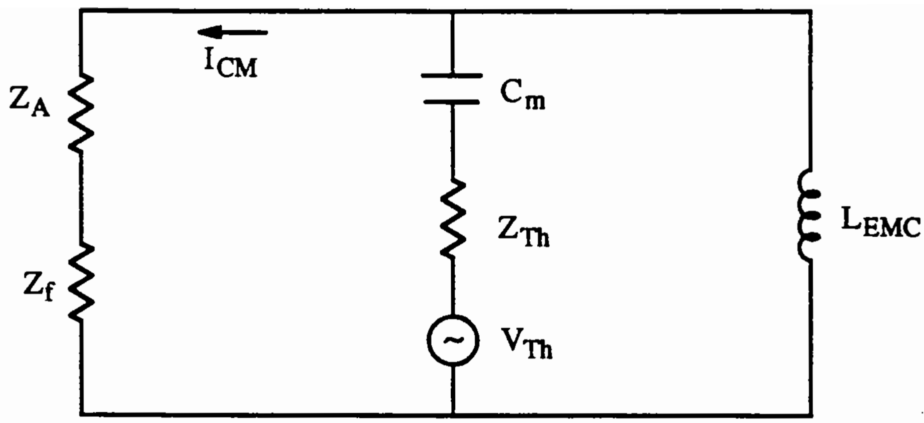

Figure 8: Equivalent circuit for evaluating the benefits of a ferrite with a low impedance versus a high impedance EMC ground and heatsink/chassis connection.

the resonances at 30 and 120 MHz. The measured common-mode current can be reduced by an additional 5 dB (approximately) with a ferrite sleeve placed at the connector. The potential benefit of adding a ferrite sleeve with a low impedance EMC ground is apparent from the equivalent circuit of Figure 6 (b). An equivalent circuit is shown in Figure 8, where V_{Th}, and Z_{Th} is the Thevenin equivalent noise source, C_m is the mutual capacitance between lines AD0-AD7 and the chassis, L_{EMC} is the inductance of the EMC ground and heatsink/chassis connection, Z_A is the antenna impedance, and $Z_f = R_f + j\omega L_f$ is the impedance of the ferrite. For a high impedance EMC ground, adding a modest impedance in the parallel branch corresponding to the antenna and common-mode current path, has minimal effect on the common-mode current. However, for a low impedance EMC ground, adding several hundred ohms with a ferrite can have a significant effect on the common-mode current, in particular around integer odd multiple half-wavelength frequencies where the input impedance of the antenna is moderately low ($68 - 73\ \Omega$ for a half-wavelength dipole of finite diameter).

The configuration of the signal return in the flexible cable between the logic and power boards can also affect the coupling between the address data lines AD0-AD7. In the current ECU configuration, the signal return lines are at pins 13 and 16, which are considerably remote from the signal lines. The large loop area results in considerable inductance and high impedance at the frequencies where common-mode radiation is significant. This high impedance path is in parallel with the path resulting in common-mode radiation on the attached cable bundle as seen in Figure 6. Reducing the impedance of the signal path by reducing the inductance (loop area), will result in less current through the common-mode path. A planar signal return the width of the flexible cable was constructed from copper tape and soldered to pins 3, 13, and 16 in J3 (signal and digital grounds

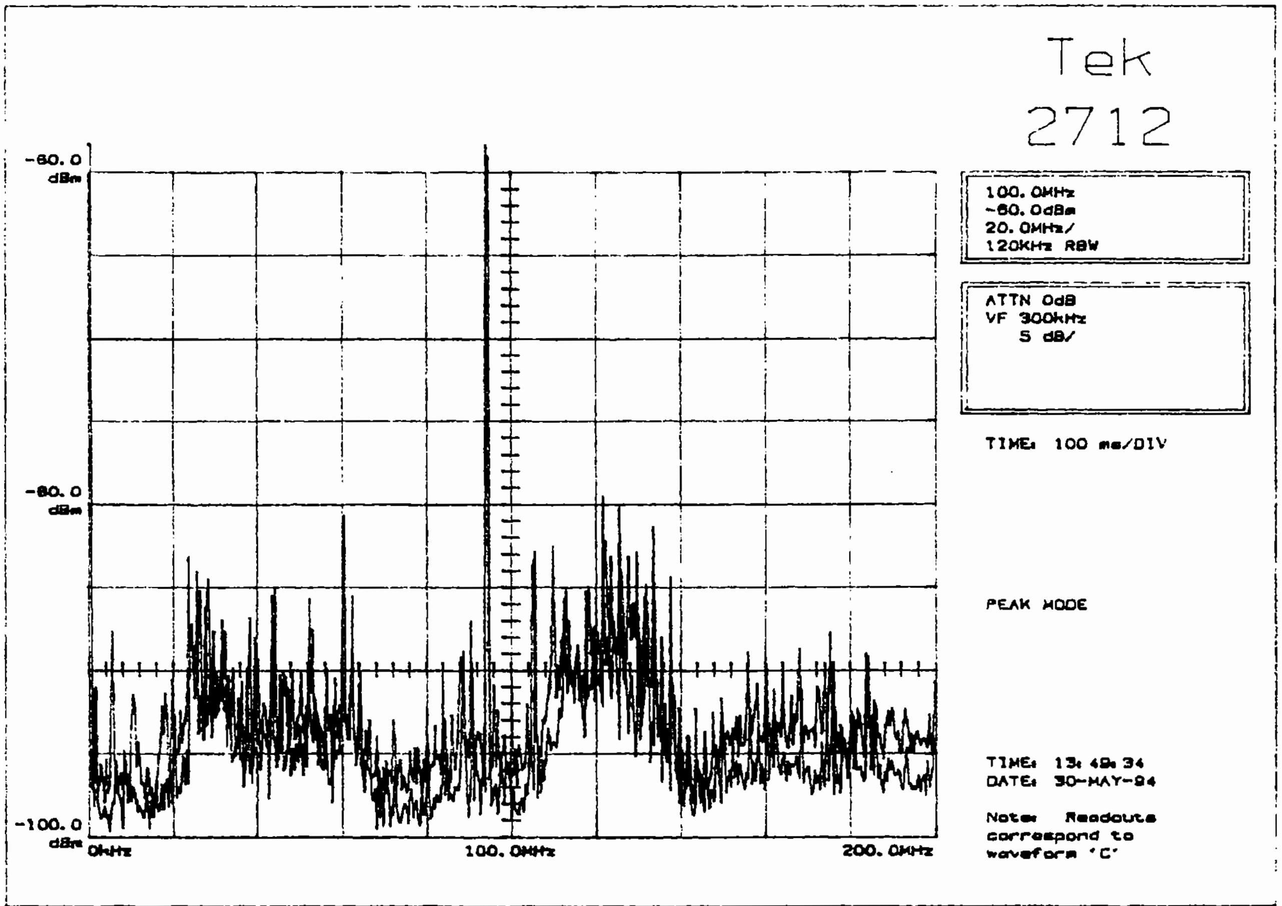

Figure 9: Measured common-mode current on the Allison minimum cable bundle with (green) and without (blue) a planar ground modification on the flex cable of connector J3. Other modifications are the planar EMC ground and the digital and signal grounds connected at J3.

connected on the logic board). The resulting measured common-mode current on the attached cable bundle is shown in Figure 9. There is a modest improvement of approximately 3 dB over the band 70 – 200 MHz even for the minimal connection at the three connector pins.

RECOMMENDATIONS

1. Improve the EMC ground and its connection to the heatsink/chassis. The high impedance of this ground is currently a primary contributor to the radiated emissions over the spectrum of 9 kHz-200 MHz, and in particular in the 30 – 60 MHz frequency range. A low impedance ground from the connector to the heatsink/chassis connection is essential. The high impedance results primarily from the limited extent of the EMC ground structure (moderately narrow traces) as well as the narrow traces connecting the EMC ground to the heatsink. Enlarging this ground between the connector and heatsink, and providing a low inductance

connection to the heat sink is recommended.

2. Modify the flexible cable configuration of connector J3 through which AD0-AD7 are routed to provide signal returns which minimize the loop area, and, hence inductance of the signal path. Possible modifications might include reassigning the current flexible cable pins such that the three current signal return conductors (pins 3, 13, and 16) are employed to minimize the signal loops of every address data line. Adding additional signal return conductors in order to alternate signal lines and signal return lines would be the optimal solution for the currently employed flexible cable. Another alternative would be a flexible cable with the signal lines over a solid (wide) signal return. Not only does this configuration provide a minimal inductance signal path, it also provides a certain amount of electric field (capacitive) shielding of the address data lines from the nearby chassis.

3. With the suggested EMC ground modifications, a ferrite sleeve can be employed to provide further modest reductions in the radiated emissions.

4. Since one source of the radiation is the address data lines AD0-AD7, slowing the rise times of these lines will reduce radiated emissions.

2.3.2 Multiple Grounds

The ground planes on both the logic and power boards are divided into several types of grounds. The difficulties that may arise as a result of a segmented signal return plane include traces that are inadvertently routed across the gaps in the ground plane, and that two different portions of ground may be unconnected or connected through a high impedance (as a result of inductance from a thin neck) at the connector. Both of these situations arise in the ECU. Current investigations have focussed on the gap in the ground plane at the connector J3 on the logic board. The two different grounds are denoted signal ground and digital ground on the schematic. The digital ground is routed through pins 13 and 16 of J3, and the signal ground is routed through pin 3. At the connector on the logic board, these two grounds are isolated. These two grounds are joined then through a via and narrow trace to the signal ground on the power board. The isolation and high impedance connections of the various grounds at the connector allows the distinct portions of ground to have different RF potentials. An effective antenna can be formed by the cable attached to one portion of the ground, and the remaining portion of ground at a different RF potential. Or one portion of the ground may have a significant mutual capacitance to the chassis to form the other half of the antenna.

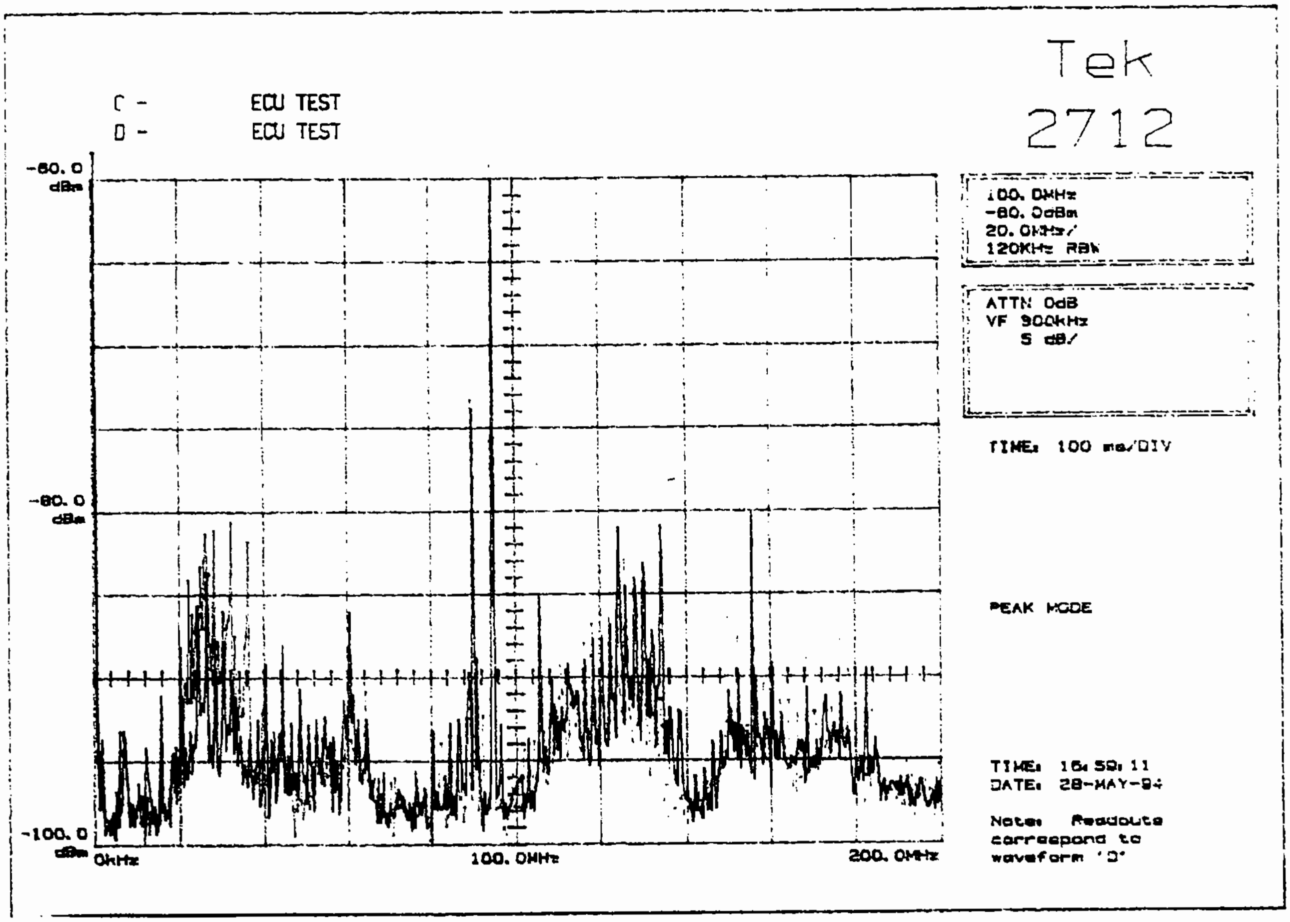

Figure 10: Common-mode current on the Allison minimum cable bundle with signal and digital grounds connected on the logic board at J3 (red); and, with no connection at J3 (green).

The signal and digital grounds were connected through minimal length stranded conductors at the connector J3 on the logic board. In addition, a connection between pin 2 of J3 and the bonding pad of C35 to digital ground was made with a stranded conductor. The common-mode current measured on the Allison minimum cable bundle is shown in Figure 10. The modified EMC ground is in place for these measurements. The green data curve is with no ground connection at J3, and the red data curve is with the digital and signal grounds connected on the logic board at J3. The improvement with the grounds connected even in this minimal fashion is approximately 5 dB at the 30 MHz resonance.

RECOMMENDATIONS

1. It is beneficial from an EMI point of view to have isolated grounds joined through a low impedance connection at a connector. In particular for the ECU, the digital and signal grounds could be connected on the logic board by filling the gap near the connector to

leave (at a minimum) a wide "neck" between the two grounds at the connector. The signal ground on the power board should then be directly connected at the connector J3, eliminating the via and trace. There may be circumstances where a segmented ground plane could be advantageous from an EMC standpoint, e.g., isolating low frequency (kilohertz), high current signals from high frequency (megahertz and above) low current signals. However, at high frequencies the benefits of segmenting the ground plane may be minimal. The UMR EMC group does not typically advocate split grounds for various high frequency signals. In the case of the ECU, however, with the exception of the split at the connector J3, the split grounds presently do not appear to be among the major contributing factors to the EMI. As such, it is usually prudent from an EMC standpoint "not to fix something that is clearly not broken".

2. The 8 MHz clock routing should be removed from the ground plane on the logic board. This would eliminate a significant gap in the ground plane of the logic board. Further, the signal return for the clocks should be adjacent to, or "shadow" the clock line. In particular, the *eclock* routing and return should be reviewed.

2.3.3 Differential Mode Noise at the Connector

After introducing the modifications to the EMC ground, and the grounds at the connector J3 discussed in the previous sections, measurable common-mode current still exists on the cable as seen in Figure 10. In particular, at frequencies corresponding approximately to resonances of the cable, the common-mode current is still significant. Extensive probing of the ground plane with a long wire to effectively provide a second antenna half to determine if two portions of ground might be functioning as an antenna indicated that a current-driven antenna was not a primary contributor to the radiation. High-frequency voltage measurements at the connector with an RF probe referenced to the battery and signal ground pin B27 showed significant differential-mode noise between B27 and connector pins which were not decoupled. I/O lines that are decoupled at the connector showed significantly less differential-mode noise. In particular, pins B5-B7, B14-16, and the RSI lines (pins B26 and B34) showed significant differential-mode noise. One half of the antenna is in the cable bundle. Placing a ferrite sleeve around all possible combinations of conductors in the Allison minimum cable bundle indicated that the potential antenna is the RSI lines being driven against the chassis. This conclusion, however, is preliminary. Decoupling the RSI lines to ground with 0.01 μF surface-mount capacitors reduces the common-mode current on the Allison minimum cable bundle by approximately 5 dB as shown in Figure 11. The green data is for the ECU with the modified planar EMC ground, digital and signal grounds connected at J3,

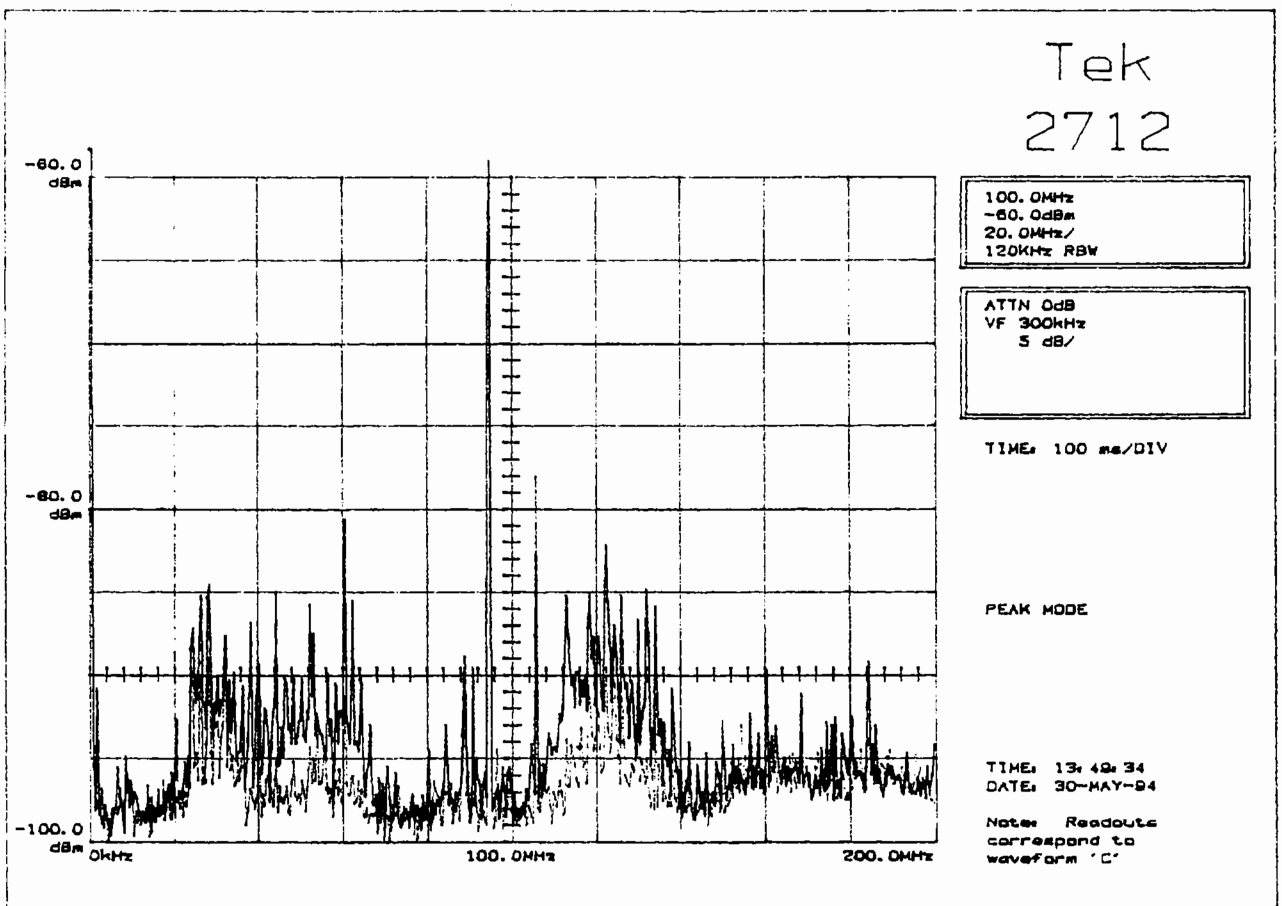

Figure 11: Common-mode current on the Allison minimum cable bundle with (blue) and without (green) 0.01 μF decoupling capacitors on the RSI lines at the connector. Other modifications are a planar EMC ground, planar ground on the flexible cable J3, and digital and signal grounds connected on the logic board.

and a planar signal return for the cable of J3. The blue data is with 0.01 μF decoupling on the two RSI lines.

While it is clear that the differential-mode noise voltage at the connector is a significant contributor to the remaining measured common-mode current, the source of the noise is not clear. One possibility is that the RSI lines, as well as other I/O lines are picking up noise as they run near the 8 MHz oscillator. The spectrum of a magnetic field probe in the vicinity of the RSI lines in the flexible cable attached to connector J2 is similar to the spectrum of the measured common-mode current on the Allison minimum cable bundle. Noise may be coupling from the 8 MHz clock to the RSI lines. This contribution to the common-mode current on the cable bundle requires considerable further investigation to specifically determine the source and possible solutions.

RECOMMENDATION

While the differential-mode noise at the connector requires further investigation, one recommendation at this juncture is to reroute the RSI lines as well as all other I/O lines to avoid the 8 MHz oscillator.

3 Summary and Preliminary Conclusions, and Future Work

Current investigations of the ECU have indicated that a primary source of the common-mode radiation is the address data lines AD0-AD7 in the flexible cable of connector J3. The proximity of these lines to the chassis allows for capacitive coupling to the chassis. The antenna is the chassis being driven against the signal and battery ground in the attached cable bundle. The high impedance of the EMC ground connection from the connector to the heatsink allows the chassis to be effectively driven against the ground in the cable bundle. Measurements indicate that addressing the design issues associated with this antenna and source, should significantly reduce the common-mode radiation over the measured frequency range of 9 kHz-200 MHz. The most significant measured improvements upon implementing modifications associated with this antenna and source were in the $30 - 60$ MHz band.

Another source of radiation is related to a differential-mode noise voltage at the connector that appears to drive the RSI lines in the Allison minimum cable bundle against the chassis. Conclusions on this source and antenna are, however, very preliminary and further investigation is required. Other potential modifications that might add to radiated EMI problems were also proposed. A summary of the experimental observations on the ECU and recommended modifications are listed in Table 1.

While the modifications introduced to date on the ECU have produced significant reductions in the measured common-mode current on the cable bundle, significant common-mode current is still produced in the frequency bands $30 - 60\ MHz$ and $120 - 160\ MHz$. Further, the investigations have considered only one configuration of the ECU, i.e., with the bezel at the cable end and not mounted on the ECU. Directions for future work include:

1. Shape the 2, 4, and 8 MHz clock waveforms to reduce high frequency spectral components.
2. Shape the address data line AD0-AD7 waveforms.
3. Investigate alternate configurations of the ECU, e.g., with the bezel mounted at the ECU.
4. Develope and evaluate an easily manufacturable EMC ground to heatsink connection.
5. Evaluate low impedance signal return for the address data lines.
6. Reroute RSI signal lines away from the 8 MHz oscillator.
7. Investigate sources of the differential mode noise at the connector.
8. Investigate noise on the +5 V DC power bus and evaluate the effectiveness of capacitive decoupling.
9. Measure the common-mode current on a cable with all wires present and connected.
10. Readdress the susceptibility problems associated with decoupling I/O lines B5-B7 and B14-B16 with the suggested modifications. Susceptibility and EMI problems are often of a reciprocal nature. Addressing problems that result in significant EMI can also reduce susceptibility difficulties. The removed decoupling capacitors on I/O lines B5-B7 and B14-B16 contribute to the differential-mode noise at the connector and the resulting common-mode current on the cable bundle. If the susceptibility problem can be surmounted, re-introducing these decoupling capacitors would reduce the common-mode current on the cable bundle.

As a potential follow-on project, testing a re-designed ECU with the recommended modifications could be pursued.

Table 1: OBSERVATIONS AND RECOMMENDATIONS FOR MODIFICATION OF THE ECU

	Observations	Recommendations
1.	AD0-AD7 couple to the case (30-60MHz), drives the case against the cable bundle	• improve the EMC ground and heatsink/chassis connection to lower the impedance
2.	AD0-AD7 signal return is remote from the signal lines (30-60MHz)	• improve the signal return -add more ground lines near the signal lines -planar ground in the flexible cable
3.	With modified EMC ground 30-60 and 120-160 MHz noise	• add a ferrite at the connector • slow the AD0-AD7 rise time • join the signal and digital grounds on the logic board at connector J3, provide a low impedance ground at J3 on the power board
4.	56 MHz noise	• reroute RSI lines to avoid the 8 MHz clock • reroute all I/O lines to avoid clocks
5.	Clock routing -8 MHz clock in ground plane -eclock return	• move 8 MHz clock off the ground plane • "shadow" the eclock for its return
6.	Connection of the digital and signal ground to the EMC ground is good	• remain as is

References

[1] J. L. Drewniak, T. H. Hubing, and T. P. Van Doren, "Investigation of fundamental mechanisms leading to common-mode radiation from printed circuit boards," UMR EMC Laboratory Technical Report TR93-4-012R, May 1993.