University of Missouri-Rolla
Electromagnetic Compatibility Laboratory

Title: Investigation of Common-Mode Radiation from the
GM-Allison Electronic Control Unit:
The Enhanced ECU vs. The ASIC ECU

Report
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Contents

1 Introduction 3

2 Experimental Investigations 6

3 Summary, Future Work, and Recommendations 18

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 from printed circuits can be broken into three components: 1) the specific IC source; 2) the antenna structure; and, 3) the parasitic coupling path by which energy is coupled from the IC source to the antenna. In printed circuits with attached cables, one portion of the radiator is often one or more conductors in the attached cable bundle. Locating the other piece(s) of the antenna can be tedious and time-consuming. However, since the number of conductors of sufficient electrical extent to suffice as an efficient antenna (by EMI standards) are few, use of ferrite sleeves, "wire antenna half" probes, connecting and disconnecting I/O lines, and voltage probing at the connector, can usually be employed to determine the antennas. Similarly, identifying the specific IC source resulting in EMI in a given frequency band is often tedious and time-consuming but can usually be accomplished by selective enabling and disabling of signals and devices. By determining the antenna, driving source, and coupling mechanism(s) leading to EMI, design modifications can be introduced to render the antenna, or coupling path 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], [2]. 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 are utilized in the investigation of the ECU to assist in determining the source of the common-mode radiation.

Previous investigations had identified several critical areas of the Enhanced ECU design that contributed to significant radiated emissions. First, the proximity to the chassis of the AD0-AD7 address/data lines in the flex-cable J3 between the logic and power boards provided a capacitive coupling path of these signals to potential antennas. Further, these signals were at the full 5 V. The source of these signals was the HC11 processor on the logic board, and the load is the I/O ASIC on the power board. There were three signal returns in the cable, but they were displaced from the high-speed data lines as well as the 2 MHz ECLK and AS lines leading to larger than necessary loop areas. As a result, the impedance of the return path was not as low as possible, thereby enhancing the parasitic coupling to the chassis. Noise currents returning to their source on the logic board from the chassis must traverse the chassis→ heat sink stud→EMI ground →J2 and J3 flex-cable→logic board ground. In this path the chassis connection to the EMI ground at the heatsink stud was a high inductance connection, hence, a high impedance at megahertz frequencies. As a result, there was an RF potential developed between the chassis, and the battery ground in the cable bundle that was DC connected directly to the EMI ground. EMI resulted from the potential difference across this antenna.

The second design area identified as contributing significantly to EMI in the Enhnaced ECU was the EMI ground. The EMI ground is a critical piece of the ground path that connects directly to the chassis and to the ground on the power board. The ground on the power board is then connected to the ground on the logic board through the J2 and J3 flex-cables. Each of these connections is inherently through a finite impedance (inductance associated with necking down currents in the ground structure), across which a potential difference can result from return currents. The source and antenna described in the previous paragraph is effectively shorted by a good RF connection between the chassis and EMI ground. The heatsink stud→EMI ground connection was found to have significant inductance, and thus failed to provide a sufficiently low impedance path to short out the described antenna. Further, since the EMI ground was not a low impedance ground, I/O lines that were decoupled to the EMI ground, saw a path of significant impedance to the chassis. As a result, decoupling the I/O lines, which were portions of the primary EMI antennas, at the connector was ineffective. This was found to be the case when attempting to decouple the $RSI^{\pm}$ and $SCI^{\pm}$ lines in the Enhanced ECU.

A third area identified as a potential contributor to the radiated emissions in the Enhanced ECU was the segmentation of the ground on the logic board. From an EMI perspective, ground segmentation is seldom helpful because of potential differences that can result between two different segments. Any conductors of sufficient electrical extent (such as I/O lines) directly connected or indirectly connected through parasitic coupling paths to each of these two segments results in an antenna driven by the potential difference. While grounds are typically connected at some point, these connections often have significant impedance above a few megahertz.

The major contributor to the radiated emissions for the ASIC ECU, which is detailed in the Phase 2 final report, is the noise voltage at the connector of the $RSI^{\pm}$, $SCI^{\pm}$, and speed lines relative to the battery ground (which is directly connected to the EMI ground at the connector). Upon modifying the EMI ground of the Enhanced ECU to provide a low impedance path to the chassis, and then decoupling the $RSI^{\pm}$ and $SCI^{\pm}$ lines, the radiated emissions are significantly reduced. The antenna has been effectively "shorted". However, until recently the source and coupling path of the noise voltage at the connector driving this antenna were unknown. Further investigations detailed in the final report of the ASIC ECU identify the IC source as the HC11 processor (address data line drivers). The coupling path is the result of a finite impedance between the logic board and power board grounds through the J3 and J2 flex-cables that leads to a potential difference between these two circuit boards.

The *current*-driven mechanism of radiation indicated previously results from return currents through ground structures that have a finite RF impedance associated with a "partial" inductance of a ground section. Return currents through these impedances result in potential differences across distinct segments of the ground layout in a design. Conductors of sufficient electrical extent either directly connected or parasitically coupled to two different segments of the ground structure form an antenna. An RF potential between these segments then drives the antenna resulting in radiation.

Measurements indicate that the layout of the ground in both the Enhanced ECU as well as the ASIC ECU is an underlying cause of the EMI. The ground layout includes the chassis, EMI ground, power board ground, logic ground, and the interconnection of these distinct ground structures.

Several design modifications were implemented in the next generation ASIC ECU as a result of Phase 1 of the EMI investigations. Among the significant changes from an EMI perspective was a solid (unsegmented) logic board ground, significant improvements in the EMI ground between the connector and the heatsink stud, as well as a 360° electrical contact between the heatsink stud and EMI ground. As a result of a new generation of ECU driven by a new logic ASIC, the layout on the logic board in particular was almost entirely new. In the ASIC ECU, the oscillator was ideally located, centered at the rear of the logic board (away from the connector) in the layout. Some difficulties with long clock lines resulted. However, tests and measurements indicated that the clock distribution and layout had little overall effect on EMI of the ASIC ECU. A continued significant problem area was the ground connection between the logic and power boards of the ASIC ECU. While some pins were reassigned, they were not ideally located for signal returns of the high-speed data lines or 2 MHz ECLK and AS lines. Finally, to achieve significant reduction in EMI, as well as greater immunity, decoupling all I/O lines at the input is essential. In particular, measurements show that with respect to common-mode currents on the cable bundle, decoupling the $RSI^{\pm}$ and $SCI^{\pm}$ lines is imperative.

One difficulty with the ASIC ECU is that vias and necking near the connection of the J3 flex-cable to the logic board ground eliminated a direct contact. As a result, the return for signals in the J3 flex-cable is through the grounds in the J2 flex-cable. This was discovered by Motorola and relayed to UMR. Further studies on the ASIC ECU have indicated that the primary noise source mechanism is a potential difference between the logic board ground and the power board ground (which is directly connected to the EMI ground, which then connects to the chassis). This lack of connection will result in a large loop area for return currents, leading to high inductance and a resulting potential difference. Measured results presented herein show that making this connection lowers the common-mode current on the cable bundle in the frequency range $60 - 90$ MHz where the primary antennas are known to be the $RSI^{\pm}$ and $SCI^{\pm}$ lines.

The measurement procedures described in the previous interim report on the Enhanced ECU were employed throughout this continuing investigation. Three cable bundles were utilized, a minimal three-wire power cable bundle configured at UMR, a minimum cable bundle supplied by Allison that included power and $RSI^{\pm}$ lines, and a full cable bundle supplied by Allison. In all cases the cables were unloaded with the exception of the keypad. Radiation from the ECU is primarily from the cable, and measuring the common-mode current on the cable bundle is indicative of relative levels of radiation over the frequency range of interest.

In this report, radiation from the Enhanced ECU and the ASIC ECU are compared via common-mode current measurements on the cable. Both full and minimum cables are employed. The benefits

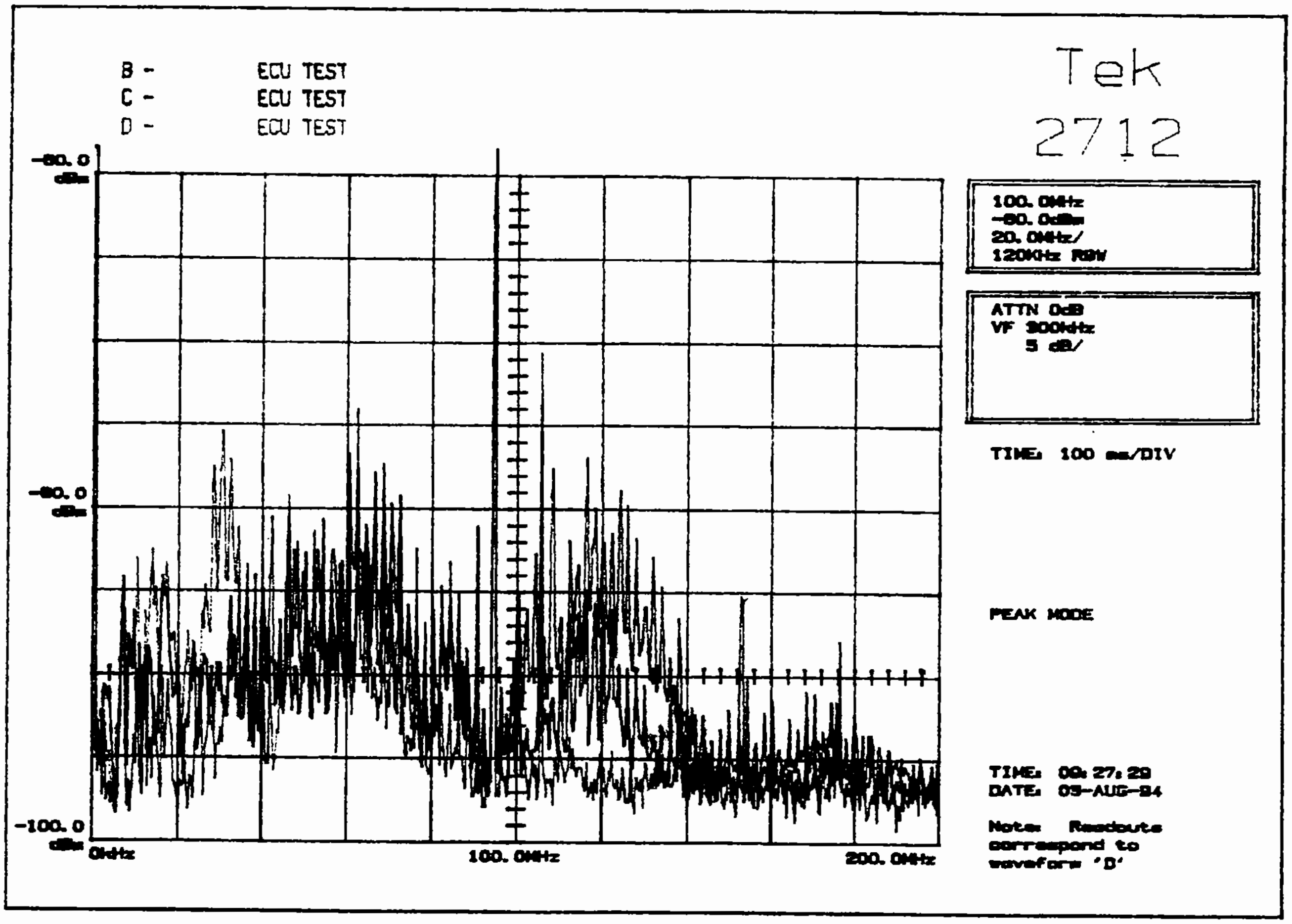


Figure 1: Common-mode current measurements on the full cable bundled attached to the ECU for the unmodified Enhanced ECU (blue), unmodified ASIC ECU (green), and, a modified Enhanced ECU (red).

of decoupling the $RSI^{\pm}$ and $SCI^{\pm}$ communications lines for reducing emissions are demonstrated even for small values of decoupling capacitors. The effectiveness of a ferrite sleeve in further reducing common-mode current on the cable bundle is also shown.

2 Experimental Investigations

Common-mode current measurements on the cable of three versions of the ECU, the Enhanced ECU, the ASIC ECU, and a version of the enhanced ECU modified at UMR are shown in Figure 1. The large peaks in the spectrum analyzer output around 100 MHz are ambients from local radio stations and communications bands, as is the single peak (green trace) around 155 MHz. The modifications to the Enhanced ECU are entirely in the extended ground structure throughout the ECU. A planar EMI ground was constructed from copper tape running from the connector to the heatsink stud. The ground was adhesively bonded to the ECU at the connector (conductive adhesive on the copper tape), and soldered 360° at the heat sink stud. The split ground plane on the logic board was joined (digital and analog grounds) at several points, and a solid ground return for the J3 flex-cable was constructed between the logic and power board grounds. While the connections of the J3 flex-cable to the both the logic and power board ground planes were of significant impedance, the ad hoc planar ground was shown previously to somewhat reduce the impedance between the logic and power board grounds. The modifications to the Enhanced ECU (red) did not include any decoupling at the connector.

In comparing the Enhanced ECU and the ASIC ECU, three frequency bands are distinct. First, the peak in common-mode current at approximately 30 MHz in the unmodified Enhanced ECU is reduced by approximately 15 dB in the ASIC ECU. The mechanism leading to this measured common-mode current was detailed in the Phase 1 interim report. Briefly, the 5 V AD0-7 signals of the J3 flex-cable in proximity to the case capacitively coupled noise currents to the chassis. These currents returning to their source through the high impedance connection between the heatsink stud and EMI ground resulted in an RF potential between the ground conductor in the cable bundle, and the chassis, and hence, common-mode current on the cable. The second distinct radiation band is in the frequency range $40 - 90$ MHz, and the third band is $100 - 140$ MHz. There is a reduction in the measured common-mode current in the band around 30 MHz of approximately 15 dB between the Enhanced ECU and ASIC ECU. This is the only frequency band in which emissions tests (stirred mode chamber) at the GM Proving Grounds showed a reduction in radiation of 10 dB or greater as shown in Figure 2. It should be noted that these radiated emissions tests were conducted prior to the discovery by Motorola that there was no ground connection in the J3 flex-cable to the logic board.

The second distinct frequency band of the common-mode current measurements of $40 - 90$ MHz shows no improvement in any of the three cases. It will be shown herein through experimental data that the the significant antenna structures in the cable bundle are the $RSI^{\pm}$ and $SCI^{\pm}$ lines being driven against the case and other extended ground structures. In all three ECU cases, Enhanced, ASIC, and modified Enhanced, these communications lines were not decoupled to the EMI ground at the input connector for the data of Figure 1. The third frequency band around $100 - 140$ MHz shows very modest reductions of $5 - 8$ dB of the ASIC ECU over the Enhanced ECU. Single sweep emissions data in the GM Proving Ground stirred mode chamber shown in Figure 3 indicates these reductions as well. The data for the UMR modified Enhanced ECU show significant reductions in the common-mode current on the cable bundle for $100 - 140$ MHz over both the Enhanced and ASIC ECUs. The underlying radiation mechanisms are currently being investigated. Preliminary testing indicates that the difference in the measured common-mode current levels between the UMR modified Enhanced ECU and the ASIC ECU is related to a good RF connection to the chassis. On the UMR modified Enhanced ECU, the chassis connection is *at the connector*, as compared to a connection to the heatsink stud approximately 2″ beyond the connector into the interior of the enclosure on the ASIC ECU.

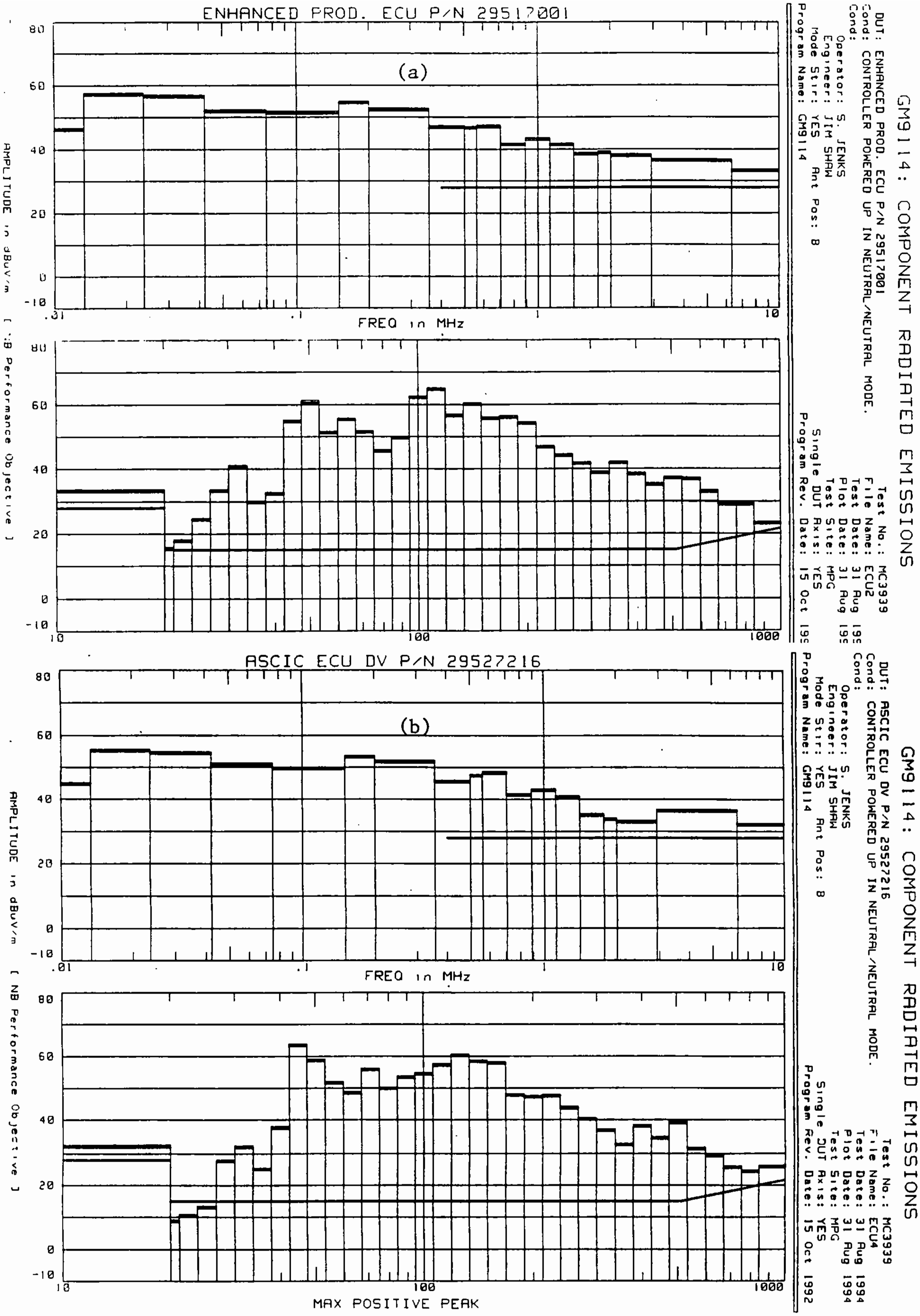
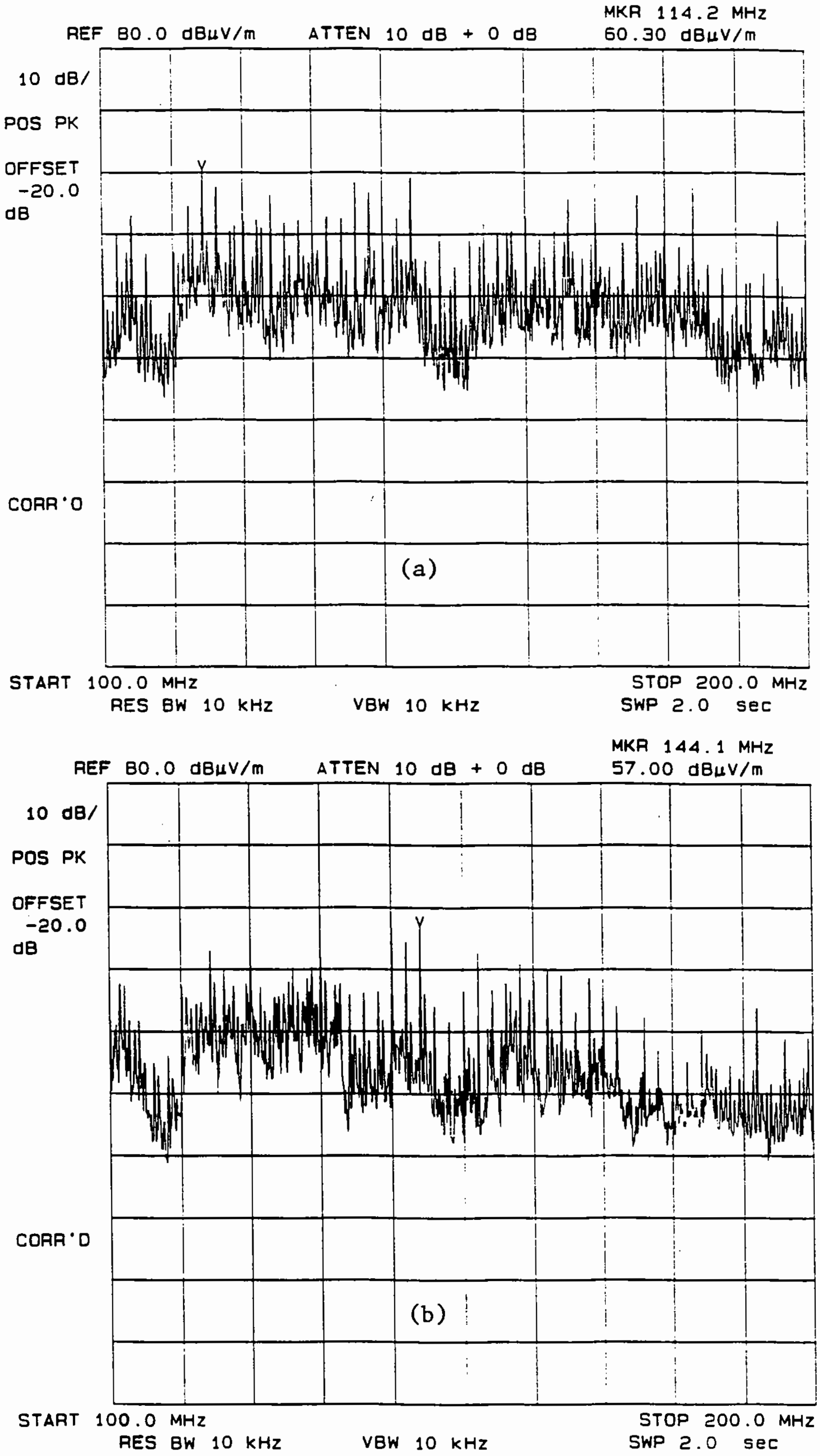


Figure 2: Radiated emissions measurements on the a) Enhanced ECU, and b) ASIC ECU in the GM Proving Grounds stirred mode chamber. Data is taken in a multiple sweep, maximum peak hold mode. Antennas employed are: biconical ($30 - 200\ MHz$), and log-periodic dipole array ($200 - 1000\ MHz$).



NOTES: *CONTROLLER POWERED UP IN N/N MODE*

Figure 3: Radiated emissions measurements on the a) Enhanced ECU, and b) ASIC ECU in the GM Proving Grounds stirred mode chamber. Data are taken in a single sweep mode with a biconical antenna.

A final observation regarding the data in Figure 1 is the "broadband" nature of the common-mode current peaks. Radiation resulting from a clock line coupling to antenna structures is expected to have peaks at the clock harmonics, but no signal level in between since the Fourier transform of a periodic signal has a discrete spectra. This is illustrated in Figure 4 (a). However, data lines are switched at the clock frequency in a psuedo-random fashion that "fills" in these intermediate frequencies. The result is an envelope with spectra corresponding to the clock harmonics superimposed as shown in Figure 4 (b). The data for the three ECUs indicate that the primary noise source(s) are data signals, and not clocks. Other work on the ASIC ECU supports this conclusion. Namely, filtering all 2, 4, and 8 MHz clocks and the 2 MHz AS signal had no effect in reducing the common-mode current on the cable bundle. However, filtering the data lines from the HC11 module did reduce the measured common-mode current on the attached cable. These measurements are presented in detail in the Phase 2 report on the ASIC ECU.

As indicated above, the $RSI^{\pm}$ and $SCI^{\pm}$ lines in the cable bundle are two of the primary antennas, driven by a noise voltage that appears at the connector between these I/O lines and the battery ground pin. The IC source and coupling mechanism to these antennas will be discussed in the Phase 2 report. The battery ground is directly connected (DC) to the EMI ground, which in turn is connected to the chassis at the heatsink stud. While bonding pads are available for high-frequency decoupling on these lines, no decoupling is specified in the design. Decoupling these lines to ground at the connector, effectively shorts the antenna. Figure 5 shows reductions in the measured common-mode current in the frequency range of 60 – 70 MHz when the $RSI^{\pm}$ lines are each decoupled with 0.001 μF capacitors. Reduction of 5 – 10 dB is obtained in the measured common-mode current. Measurements were also made with 0.01 μF decoupling and no difference observed from 0.001 μF. It should be noted that the logic ground was not connected to the signal returns in the J3 flex-cable for these measurements. Further improvements result when this connection is made.

Decoupling was also added to the $SCI^{\pm}$ lines. Figure 6 shows further reduction in the measured common-mode current on the full cable bundle with the $RSI^{\pm}$ and $SCI^{\pm}$ lines decoupled with 0.001 μF. Approximately 5 dB of reduction is obtained in the frequency range 75 – 85 MHz. While some improvements are obtained by decoupling the $RSI^{\pm}$ and $SCI^{\pm}$ communications lines, it is clear that the noise source must be eliminated in order to obtain significant reductions. Further improvements in the EMI ground to reduce the impedance from the connector to the heatsink stud, in particular along the current paths from the decoupled $RSI^{\pm}$ and $SCI^{\pm}$ lines, can be expected to help as well. Susceptibility testing at Motorola indicated that decoupling with 0.001 μF on the $RSI^{\pm}$ and $SCI^{\pm}$ passed at $140\frac{V}{m}$ [3].

Measurements were also made on an unmodified Enhanced ECU with and without decoupling on the $RSI^{\pm}$ and $SCI^{\pm}$ communications lines to determine the effect of the improved EMI ground in the ASIC ECU on emissions. Common-mode current measurements on the full cable bundle with and without decoupling on the communications lines are shown in Figure 7. There is little

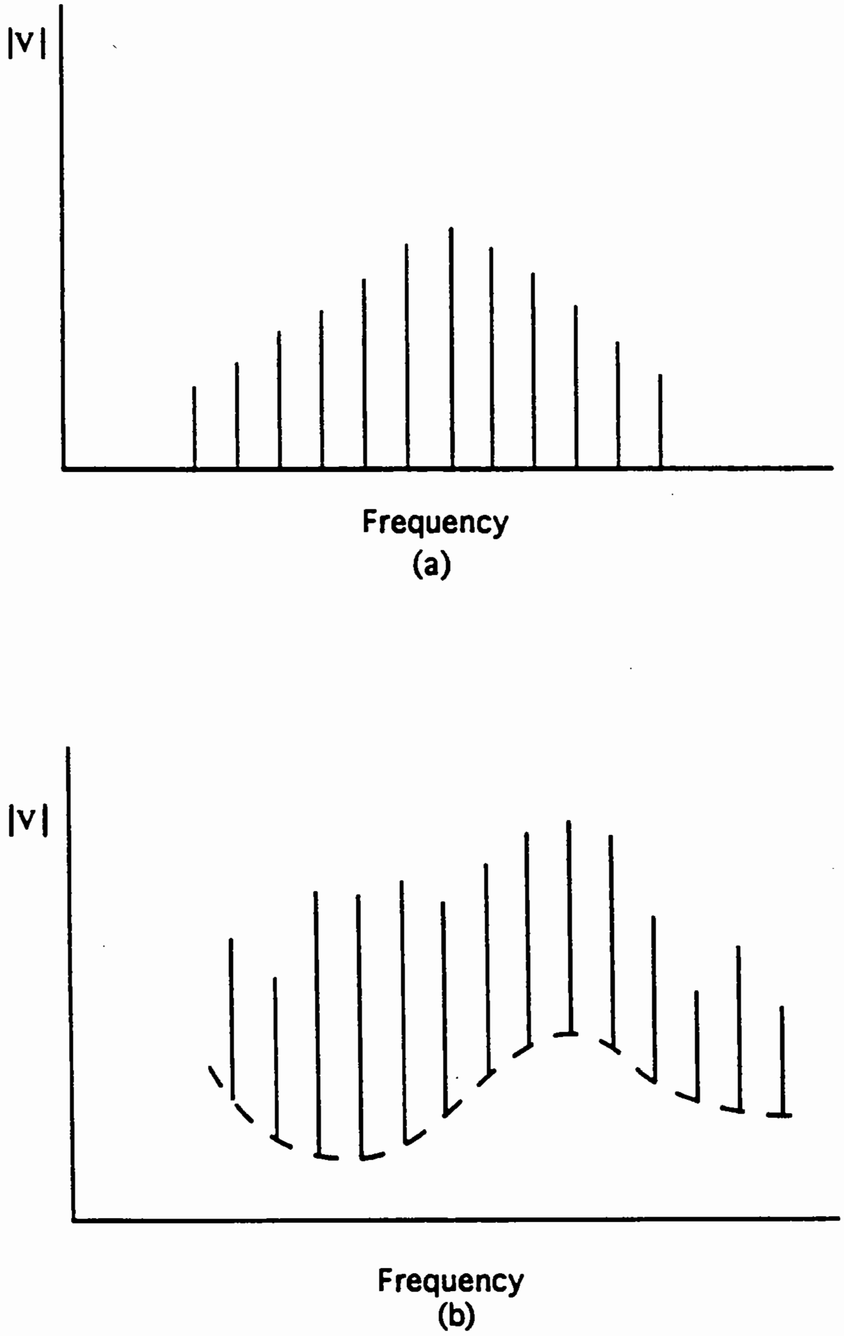


Figure 4: Radiation spectra from a) a purely periodic signal such as a clock, and, b) from a psuedo-random data signal initiated by the clock.

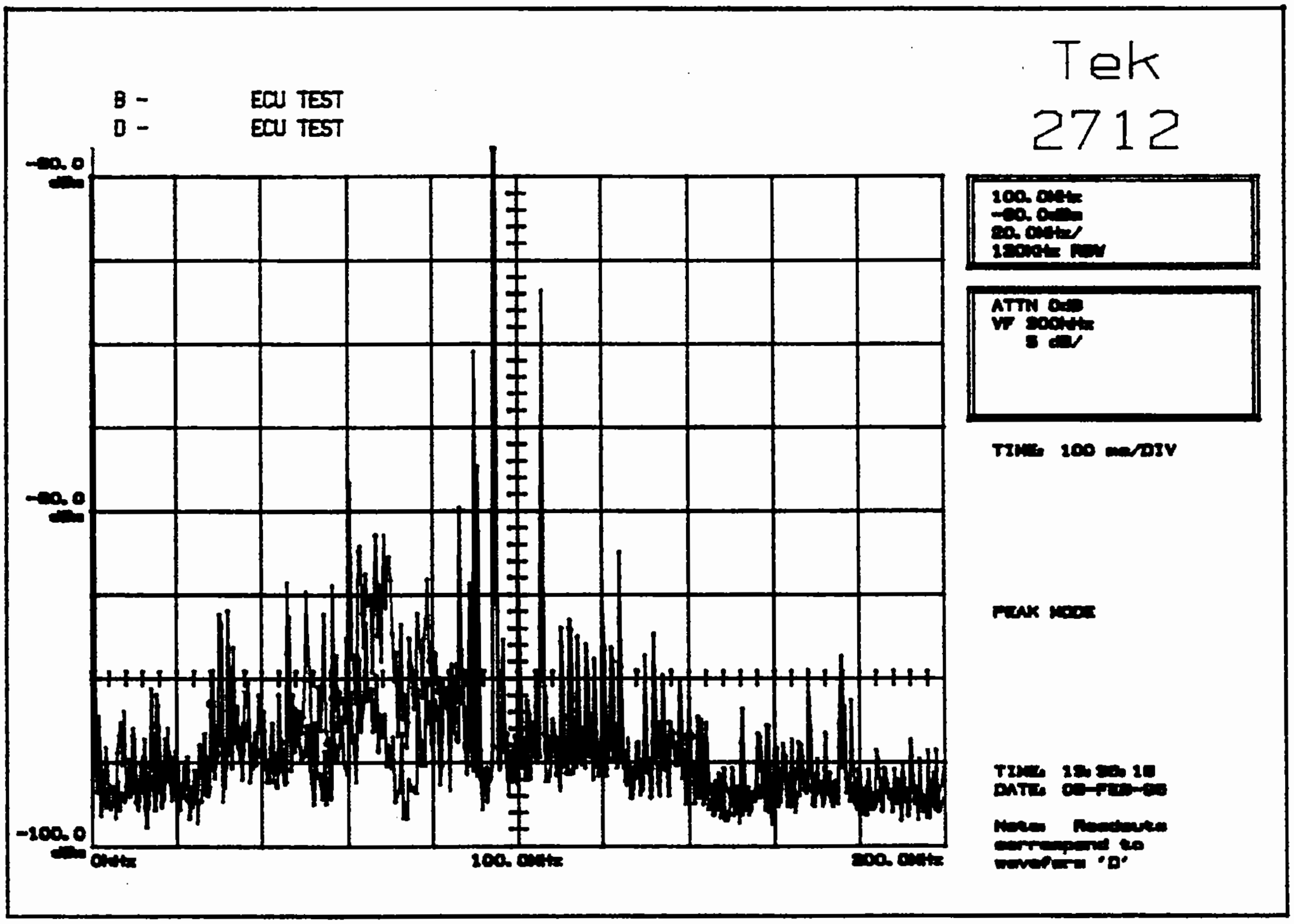


Figure 5: Measured common-mode current on the full cable bundle for the ASIC ECU in the original configuration (green), and with the $RSI^{\pm}$ lines decoupled with 0.001 μF capacitors (blue).

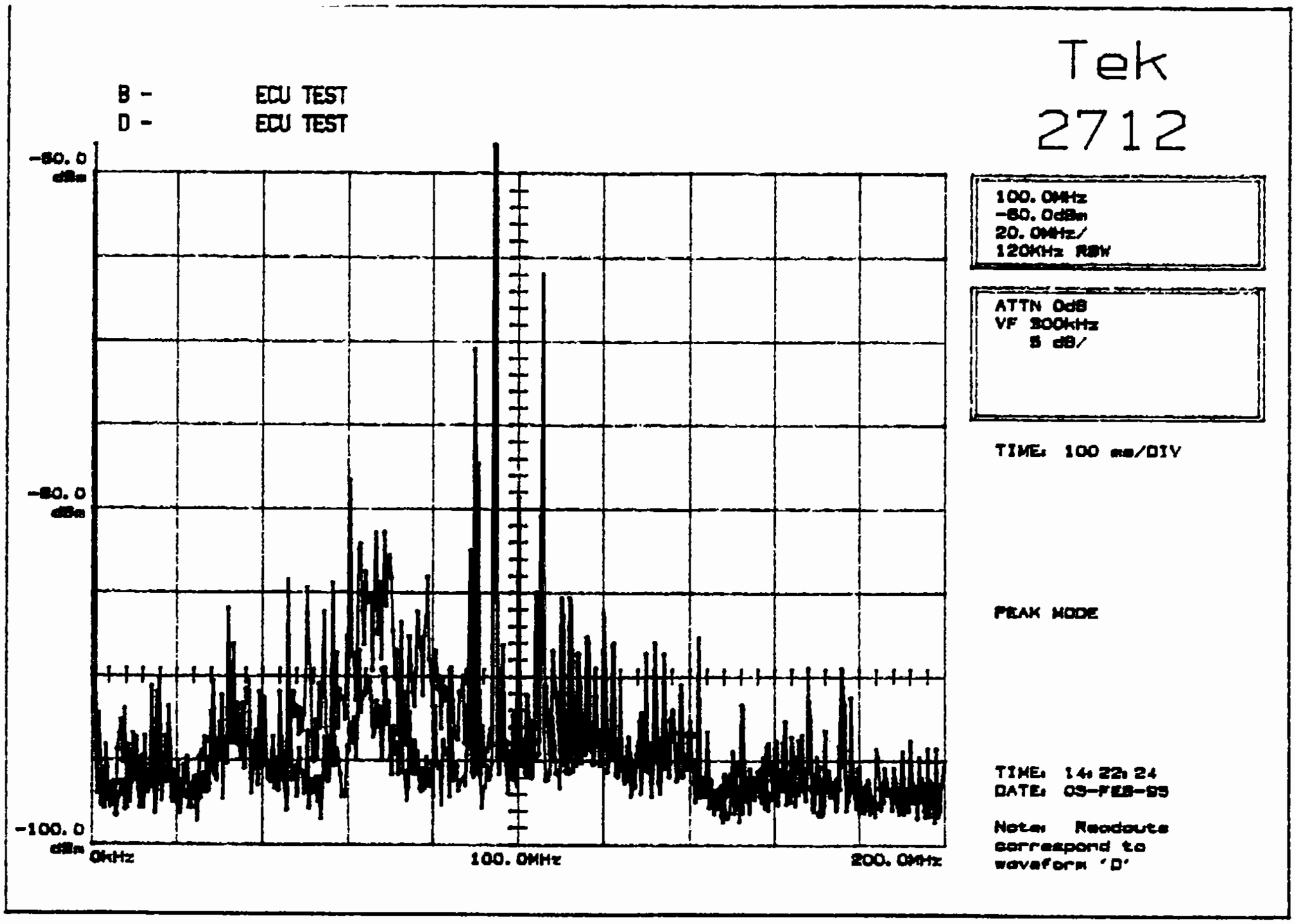


Figure 6: Measured common-mode current on the full cable bundle for the ASIC ECU in the original configuration (green), and with the $RSI^{\pm}$ and $SCI^{\pm}$ lines decoupled with 0.001 μF capacitors (blue).

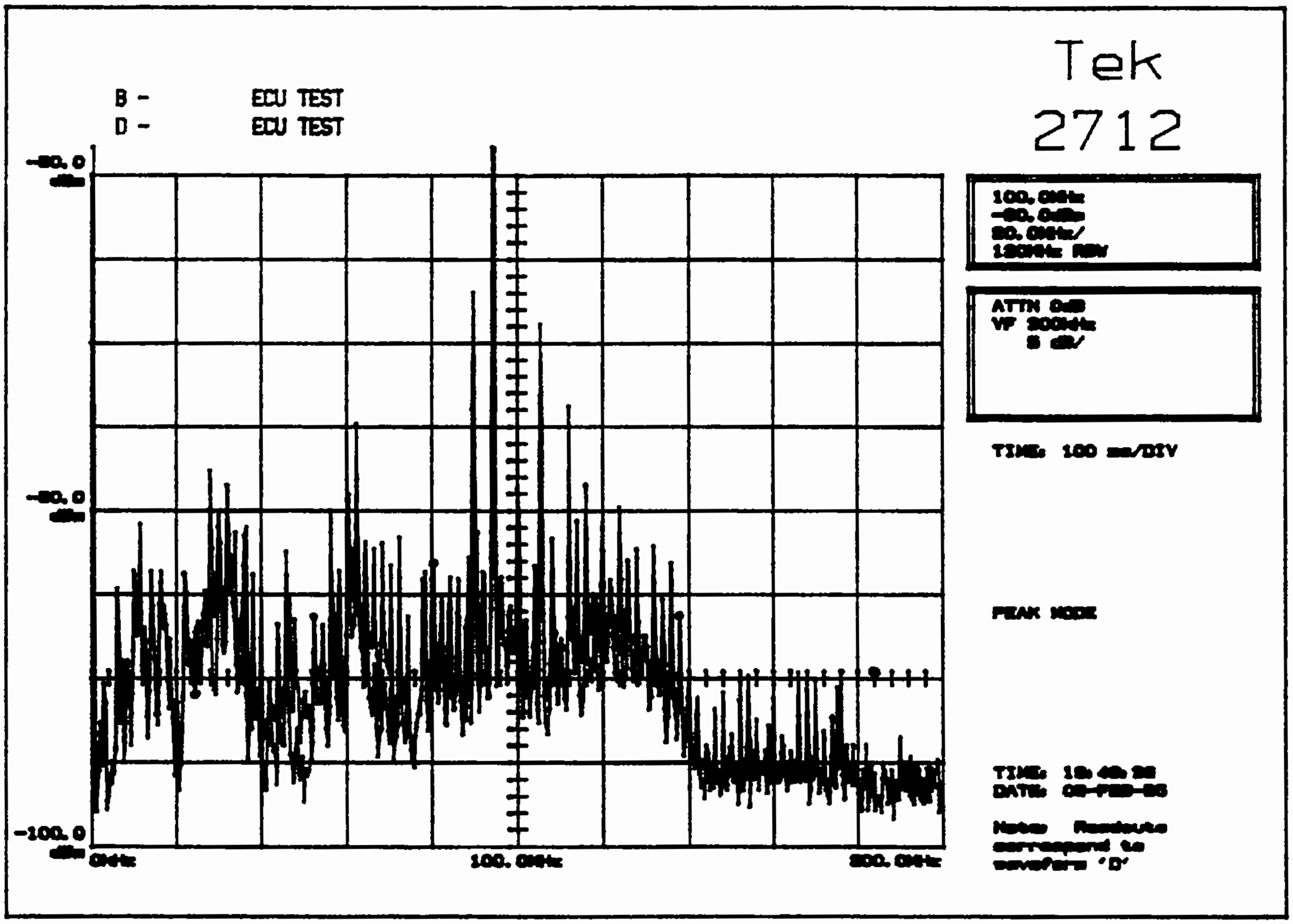


Figure 7: Measured common-mode current on the full cable bundle for the Enhanced ECU in the original configuration (green), and with the $RSI^{\pm}$ and $SCI^{\pm}$ lines decoupled with 0.001 μF capacitors (blue).

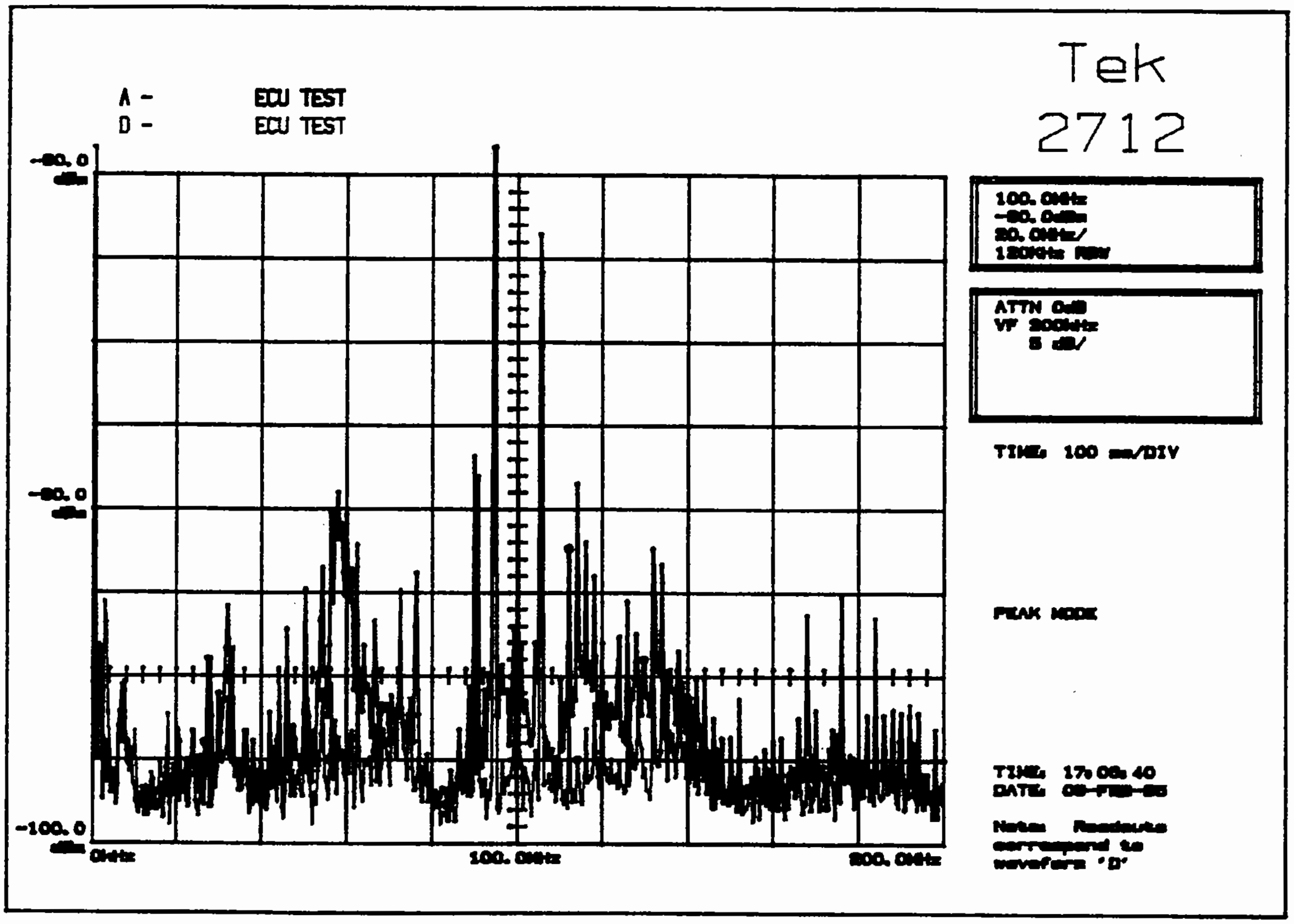


Figure 8: Measured common-mode current on the minimum cable bundle for the ASIC ECU in the original configuration (black), and with a ferrite sleeve at the connector (blue).

difference in the measurements except for an 8 dB reduction at two specific frequencies. Decoupling the communication lines has little effect because of the high impedance EMI ground path to the chassis. Larger values of decoupling, e.g., 0.01 μF showed no improvement either.

Improvements in the EMI ground for the ASIC ECU design also increased the effectiveness of adding a ferrite sleeve at the connector. A large diameter ferrite sleeve was not available for testing on the full cable bundle, so the minimum cable bundle was employed. Figure 8 shows the common-mode current on the minimum cable bundle for the unmodified ASIC ECU with and without a ferrite sleeve on the cable at the connector. The minimum cable bundle contains the primary antennas (with the exception of the $SCI^{\pm}$ lines) contributing to the radiation as indicated by comparing the spectra of Figure 8 with that for the full cable bundle in Figure 5. Figure 8 shows that adding a ferrite sleeve can reduce the common-mode current on the minimum cable by 5 – 15 dB at frequencies where it peaks.

Previous undocumented work in the laboratory had led the UMR team to the conclusion that a ferrite sleeve at the connector had little effect in reducing the common-mode current on the cable

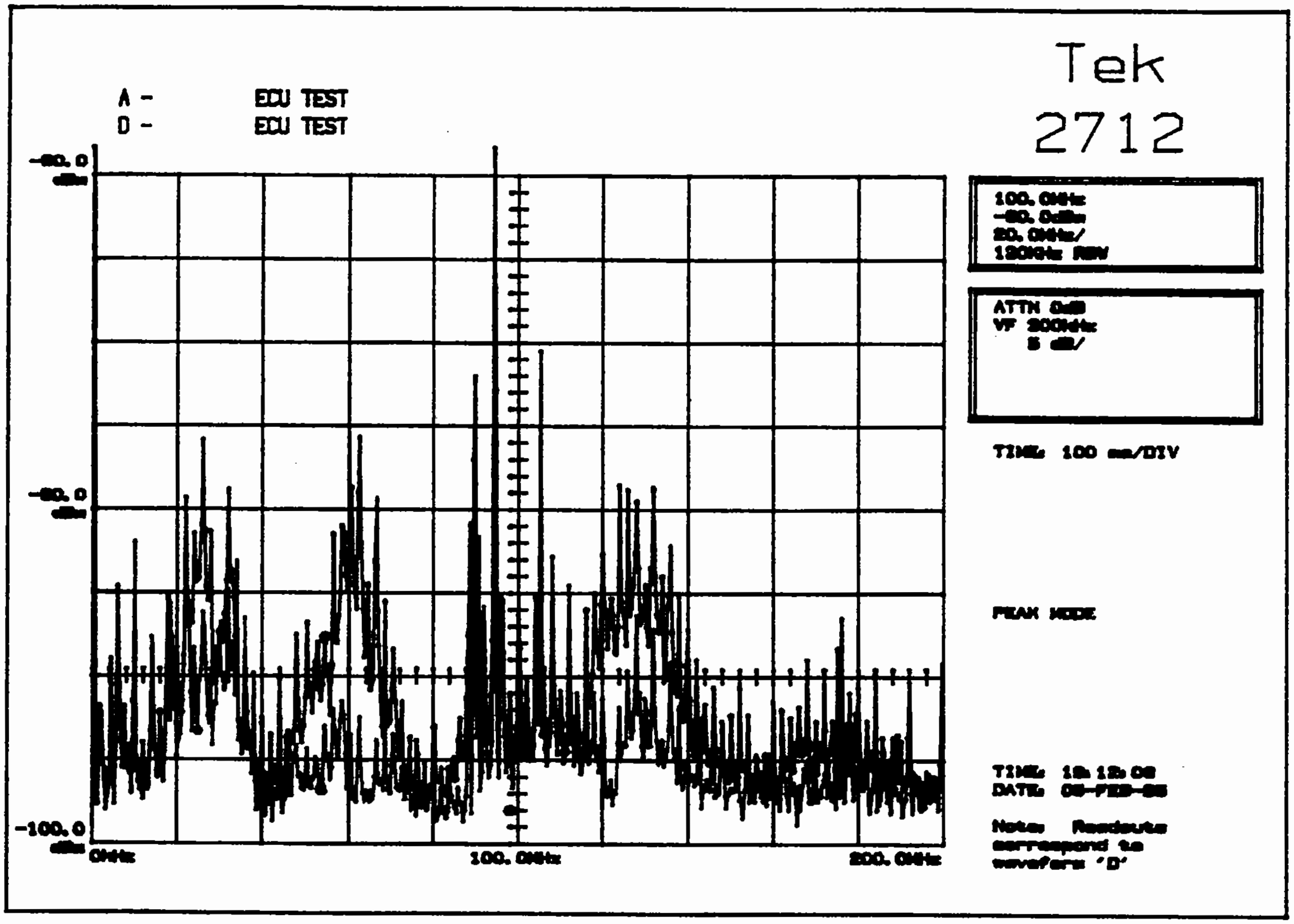


Figure 9: Measured common-mode current on the minimum cable bundle for the Enhanced ECU in the original configuration (black), and with a ferrite sleeve at the connector (blue).

for the Enhanced ECU. However, upon readdressing this issue, measurements shown in Figure 9 demonstrate reductions in the common-mode current on the minimum cable bundle with a ferrite sleeve at the connector. The improvement is modest at the first peak around 30 MHz. Although the cable may be near an integral half-wavelength resonance, it is fed off-center and will have an input impedance significantly higher than $68 - 73\ \Omega$ for a half-wave dipole. Further, the source coupling mechanism for this frequency is capacitive coupling from the AD0-7 signals in the J3 flex-cable to the chassis. This leads to a relatively high impedance for the Thevenin equivalent noise source. Adding a ferrite of $100 - 200\ \Omega$ in series with the relatively high source and antenna input impedance has a relatively marginal effect. However, at the 60 MHz peak, while the antenna input impedance still can be expected to be greater than $68 - 73\ \Omega$, the Thevenin source impedance is known not to be large, and the added impedance of the ferrite sleeve is significant relative to the source and antenna. The source mechanism at the 130 MHz peak is less well understood, but the improvements with a ferrite sleeve are clear.

A final frequency range at which significant differences in common-mode current on the cable be-

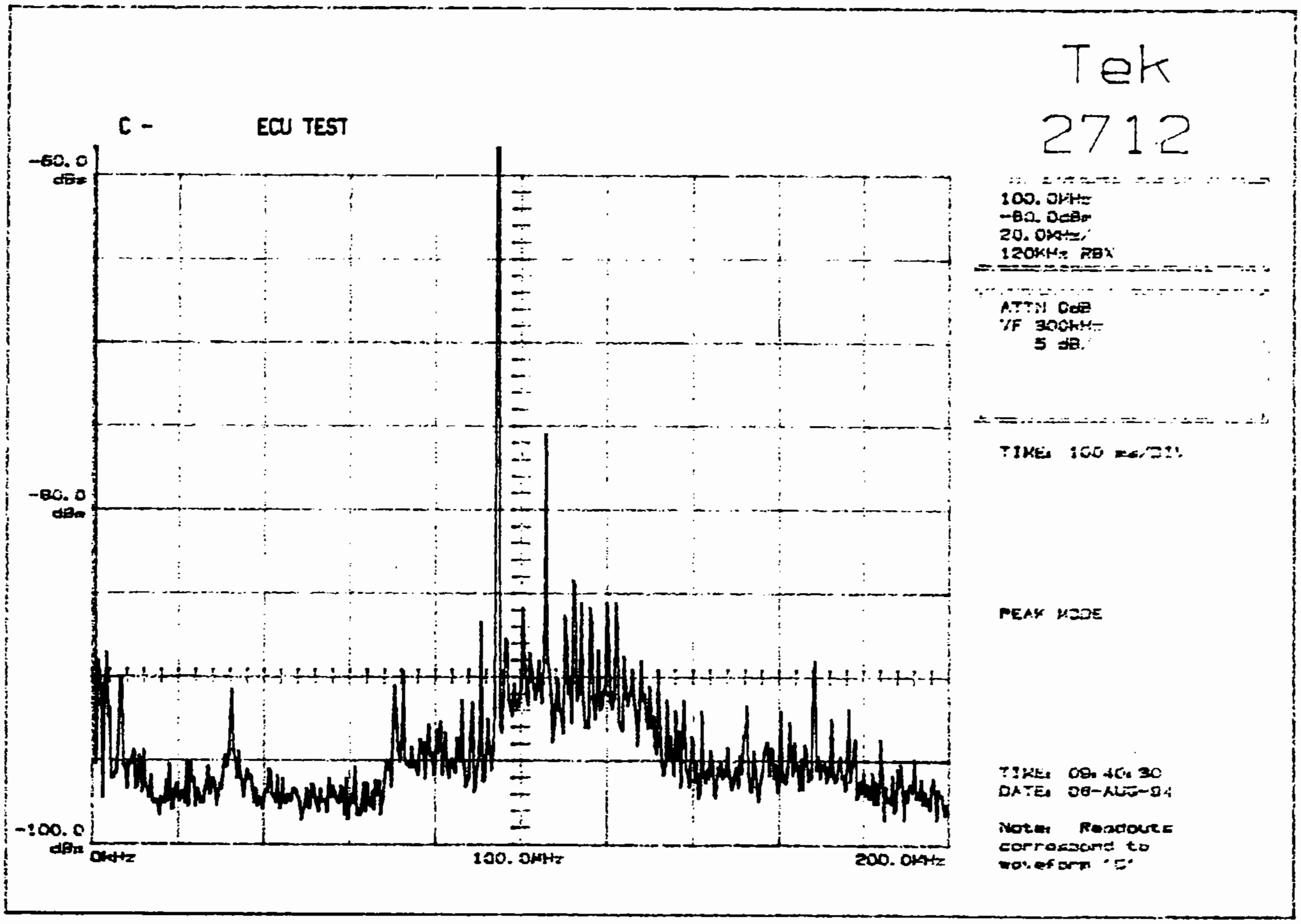


Figure 10: Measured common-mode current on a minimal three-wire power cable bundle for the unmodified ASIC ECU.

tween the Enhanced, ASIC, and UMR modified Enhanced ECUs were measured is $100 - 140$ MHz. Figure 1 illustrates the differences between these three ECUs in this frequency range. While the ASIC ECU is improved over the Enhanced ECU, it does not achieve the reduction of the UMR modified Enhanced ECU. The antenna(s) for this frequency range are believed to be primarily related to ground structures. Figure 10 shows the common-mode current measured on a minimal three-wire power cable bundle with connections only to B2 (battery positive), B9 (battery ground), and B12 (IGSN - battery positive). The measured common-mode current is in the range $100 - 140$ MHz. The specific IC source, and coupling mechanism to the antenna, however, are presently unknown.

Common-mode current measurements on the full cable bundle with and without the ground connection between the J3 flex-cable and the logic board are shown in Figure 11. In the frequency range $60 - 90$ MHz where the $RSI^{\pm}$ and $SCI^{\pm}$ lines are known to be the primary antennas, the measured common-mode current is reduced by approximately 5 dB. As discussed in the the Phase 2 ASIC ECU report, the coupling mechanism to these antennas is the RF potential developed between the logic and power board grounds. Making the ground connection from the J3 flex-cable to the logic board reduces the loop area of the return for signals in the cable, which otherwise return

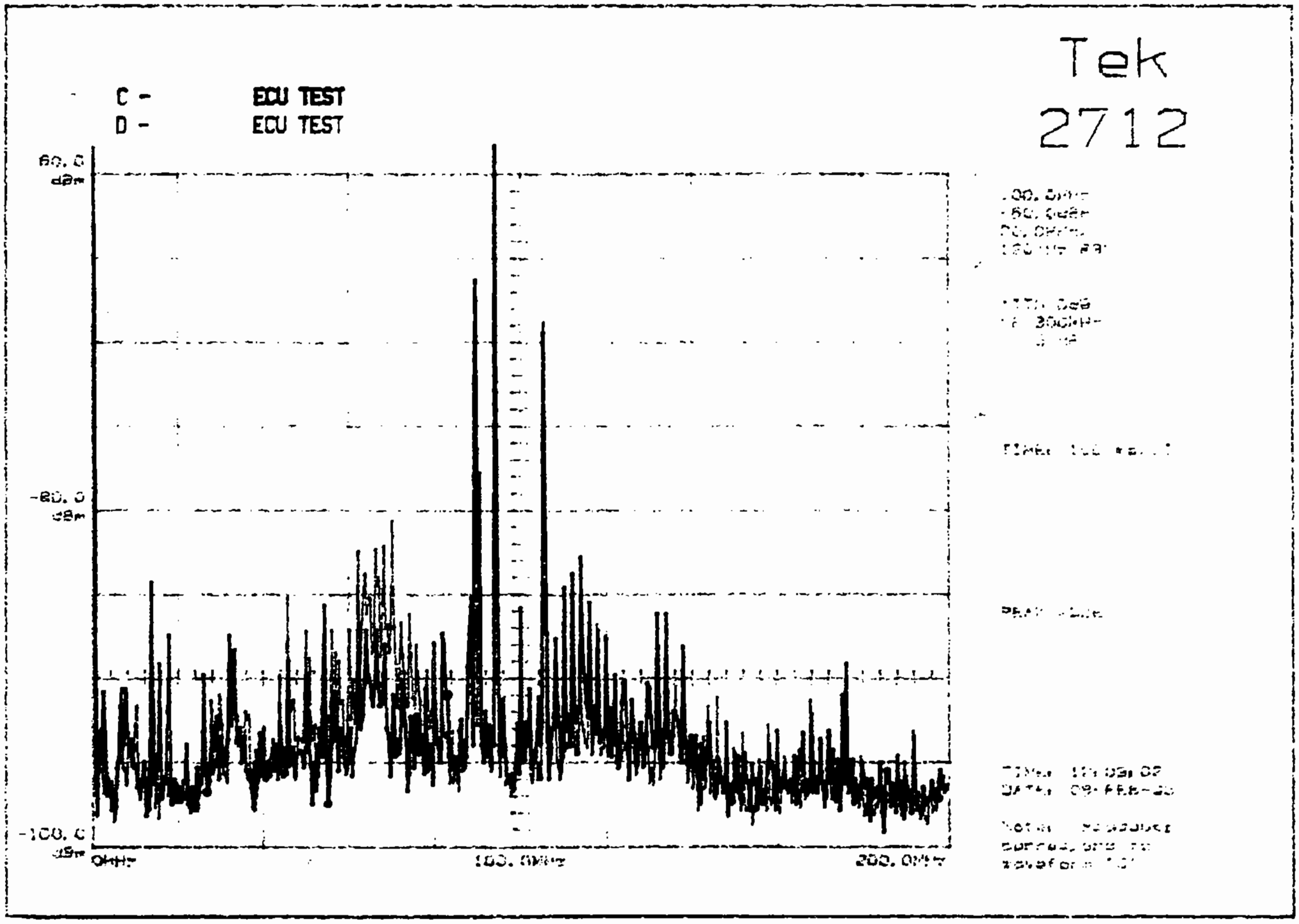


Figure 11: Measured common-mode current on the full cable bundle for the ASIC ECU in the original configuration (blue), and with the ground connection from the J3 flex-cable and logic board.

via the J2 flex-cable grounds. Reducing the loop area decreases the inductance and the resulting potential difference between the two grounds. The measured common-mode current is increased slightly in the frequency range 100 – 140 MHz when the J3 flex-cable ground is connected to the logic board. Since the IC source and coupling mechanism are unknown for this band of common-mode current, the increase is presently unexplainable.

3 Summary, Future Work, and Recommendations

In the final stage of the Phase 1 work of this project, the levels of radiation inferred from common-mode current measurements on the attached cable bundle were compared for the Enhanced and ASIC ECUs. Modifications that could be implemented without any redesign of the ASIC ECU were also investigated, *viz.*, decoupling the $RSI^{\pm}$ and $SCI^{\pm}$ communications lines, and adding a ferrite sleeve on the cable at the connector. A significantly improved EMI ground in the ASIC

ECU, capacitive decoupling of the $RSI^{\pm}$ and $SCI^{\pm}$ lines, and a ferrite sleeve were effective in significantly reducing common-mode current measured on the cable bundle.

A decoupling strategy for "shorting" one antenna, and a loading strategy employing a ferrite sleeve were shown to be effective in reducing common-mode current on the cable of the ASIC ECU. The primary antennas were determined in Phase 1 as well. However, of the three significant problem frequency bands of radiation identified with the Enhanced ECU, the source coupling path was identified and reduced in only one, at approximately 30 MHz. Reductions in measured common-mode current in this frequency range were corroborated by radiated emissions measurements.

Further work has focused on determining the specific IC sources and coupling mechanisms to the identified antennas. Specifically, this work included:

1. Determining the IC source and coupling mechanism resulting in the differential mode noise voltage at the connector that drives the $RSI^{\pm}$ and $SCI^{\pm}$ lines.
2. Determining the IC source and coupling mechanism resulting in the common-mode current on a minimal power cable bundle in the frequency band $100 - 140$ MHz.
3. Filtering the clocks to determine if clock lines are coupling energy to EMI antennas and are major contributors to the radiated emissions.
4. Filtering the AD0-7 lines to determine if the data lines are coupling energy to EMI antennas and are major contributors to the radiated emissions.

The above work has been completed, with the exception of determining IC sources and coupling mechanisms for the radiation in the range $100 - 140$ MHz, which is continuing. This work will be presented in the Phase 2 report on the ASIC ECU.

The recommendations for reducing the radiated emissions from the ASIC ECU are:

1. Implement a connection from the J3 flex-cable to the logic board ground that was inadvertently "cut" in the layout artwork. Motorola discovered this problem, and measurements shown in this report demonstrate that this will help reduce emissions.
2. Decouple the $RSI^{\pm}$ and $SCI^{\pm}$ communications lines with 0.001 μF capacitors. A value of 0.01 μF was found by Motorola and Allison to slow the communications lines to the point of ECU failure. However, 0.001 μF capacitors are employed in the filter connector being investigated by Motorola for the 12 V ECU (as well as potentially the Enhanced and ASIC ECUs as needed).
3. Employ a ferrite sleeve around the cable bundle at the connector. This has been found to reduce the common-mode current on the cable bundle for *both* the ASIC and Ehanced ECUs.

Decoupling the $RSI^{\pm}$ and $SCI^{\pm}$ lines and a ferrite sleeve can be implemented with no design modifications to the ASIC ECU. Other modifications that will be detailed in the Phase 2 report include further improvements on the EMI ground, filtering the address data lines and clocks, better ground connections between the logic and power boards, and better connection of the EMI ground to the chassis *at the connector.*

References

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[2] J. L. Drewniak, T. H. Hubing, and T. P. Van Doren, "Investigation of fundamental mechanisms of common-mode radiation from printed circuit boards with attached cables," *IEEE Electromagnetic Compatibility Symposium Proceedings*, Chicago, IL, pp. 110-115, 1994.

[3] Private communication from Sandy Walker, Motorola.