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Volume II: Suggested Test Procedures

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16. Abstract

The purpose of this report is to present a suggested test procedure for measuring the radiated electromagnetic interference (EMI) emanating from rail transit systems. This report points out that, unlike inductive and conductive EMI, radiated EMI has not been known to adversely affect the safety or reliability of rail transit operations. However, radiated interference from a rail transit system could potentially affect the neighbors of a rail transit system. It is indicated that testing rail systems for EMI poses unique problems not covered by existing EMI testing standards. The MIL-STD 461B and 462 describe in detail the testing of pieces of electrical equipment and vehicles sitting at rest in electromagnetically shielded enclosures essentially at arm's length. Other existing standards delineate procedures for testing equipment at greater distances out-of-doors, but still at rest. However, subway trains are large and must be tested while in motion. The suggested test procedure presented in this report describes standard physical and operational configurations for testing, along with recommended measuring equipment capable of rapid and automated data acquisition and analysis. The procedure has built-in steps to document the limits of accuracy and validity of the data obtained. The procedure presented in this report is generally consistent with procedures that have been used in the past to characterize radiated EMI from rail transit vehicles, but has been designed to provide greater consistence and speed in test performance and data interpretation

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PREFACE

Over the past eight years, a program has been undertaken under sponsorship of the Office of Systems Engineering, Urban Mass Transportation Administration, U.S. Dept. of Transportation, to delineate and mitigate the effects of electromagnetic interference (EMI) in rail transit operations. Cooperating in this venture have been U.S. manufacturers of rail transit propulsion and signaling equipment, rail transit system operators, members of the research and consulting community, and the technical staff of the DOT Transportation Systems Center in Cambridge, MA. Work has proceeded under the aegis of the Rail Transit EMI/EMC Technical Working Group, and has focused on three modes of EMI: Inductive, Conductive, and Radiated.

Inductive and conductive EMI, as defined in the rail transit context, result in one electrical subsystem of a rail transit system, namely propulsion and power, interfering with another electrical subsystem, namely signaling. Under this program, very specific inductive and conductive EMI problems have been identified and overcome.

Unlike inductive and conductive interference, radiated interference never has proven to be a problem in rail transit operations per se. That is, the occurrence of radiated EMI never has been shown to impact the operational safety or reliability of specific rail transit systems. However, radiated interference is the only one of the three types of EMI that either potentially or actually could affect the neighbors of rail transit systems. For that reason, effort has been made to develop accurate and cost-effective methods for measuring the radiated emissions from rail transit electrical subsystems. Based on review of other existing standards, the results of prior DOT-sponsored programs, and new work noted above, the Suggested Test Procedure for radiated EMI in rail transit systems contained in this report was developed.

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EXECUTIVE SUMMARY

The purpose of this report is to present a Suggested Test Procedure for measuring the radiated electromagnetic interference (EMI) emanating from rail transit systems. Unlike inductive and conductive EMI, raidiated EMI has not been known to adversely affect the safety or reliability of rail transit operations. However, radiated interference from a rail transit system at least potentially could affect a rail transit system's neighbors.

Testing rail transit systems for EMI poses unique problems not covered by existing EMI testing standards. The familiar MIL-STD 461B and 462 describe in detail the testing of pieces of electrical equipment and vehicles sitting at rest in electromagnetically shielded enclosures essentially at arm's length. Other existing standards delineate procedures for testing equipment at greater distances out-of-doors but still at rest. However, subway trains are big and they must be tested while in motion.

The Suggested Test Procedure presented in this report describes standard physicial and operational configurations for testing, along with recommended measuring equipment capable of rapid and automated data acquisition and analysis. The procedure has built-in steps to document the limits of accuracy and validity of the data obtained.

The procedure presented here generally is consistent with procedures that have been used in the past to characterize radiated EMI from rail transit vehicles, but has been designed to provide greater consistence and speed in test performance and data interpretation.

PART 1

INTRODUCTION TO RADIATED ELECTROMAGNETIC INTERFERENCE IN RAIL TRANSIT SYSTEMS

1. INTRODUCTION

Radiated emissions from rapid transit rail vehicles are a potential source of electromagnetic interference (EMI). These emissions are much like the unwanted electrical emanations that cause static and noise on radios and "snow" on television receivers. Radio-frequency noise, produced by many electrical devices, is radiated through space rather than travelling down rails or wires. Experience has indicated that these emissions are not likely to interfere with rail transit subsystems other than radio communications. The potential problems caused by radiated emissions from rail transit subsystems are mostly external to the transit system. Interference with AM raido reception near the right-of-way is possible. Potentially, these emanations can interfere with emergency communications such as police and fire radio networks.

A brief description of the theory of broadband EMI generation and observation is presented in Part 1 of this report, and the Suggested Test Procedure for its measurement in rail transit systems is presented in Part 2. More detailed information is available in the references listed in Part 2, Sec. 9 of this report, and in the companion document to this report.*

2. GENERATION OF RADIATED EMI

2.1 Electromagnetic Radiation

Physically, what gives rise to the radiation of either wanted or unwanted electromagnetic (EM) waves is a time-varying current in a conductor. The

* "Radiated Interference in Rapid Transit Systems - Volume I: Theory and Data", DOT Report No. UMTA-MA-06-0153-85-10, U.S. Dept. of Transportation, Urban Mass Transportation Administration, Washington, DC, June 1986.

greater the current, the faster its time variation, and the longer the conductor, the greater is the radiation of electromagnetic energy. Radio and TV transmitting antennas are designed to carry currents that vary in an accurately prescribed sinusoidal manner at very nearly a single frequency, thus keeping their EM emanations in well-defined frequency channels in the radio frequency (RF) spectrum.

2.2 Broadband EMI

Emanations having well-defined frequencies, such as radio and TV signals, are called "narrowband" emanations. Many sources of unwanted EM radiation, or EMI, are conductors carrying currents that vary in time in a transient or pulsed manner. Mathematically, non-sinusoidal or pulsed currents can be decomposed into a series of components at different frequencies covering a broad swath of the RF spectrum. A radio or TV receiver tuned to practically any single channel will receive some fraction of such an unwanted signal. Such signals are called "broadband" emanations.

In many respects, the tuned IF stage of a radio or TV receiver has the same frequency characteristics as a bell or crystal goblet. If narrow-band sound waves are incident on a bell or goblet at its natural frequency, it will sympathetically vibrate, and these vibrations can be heard as a pure tone after the exciting sound waves cease.

For a narrow-band signal to excite a bell, it must lie at or very near to its natural frequency of oscillation. However, transient signals applied to a bell, such as when the clapper strikes, also can excite ringing. Broadband EMI occurs when electrical transients hit a radio receiver's IF stage, causing it to ring at its center frequency. Each transient at the IF input causes a pulse in the envelope-detected IF output signal, that is heard as a click. A string of transients causes a burst of static.

Just as bells of various size all ring when hit with the same hammer, the same electrical transient incident on radio receivers tuned to various frequencies will cause each one to respond.

2.3 Sources of Broadband EMI

A number of notorious and familiar sources of such emanations are automobile ignition systems, and electric motors of the type called "universal motors", found in small household appliances. These motors are multi-pole commutator-type motors with brushes that rapidly switch motor current from winding to winding, and create pulsed waveforms in the line current as well. Present-day auto ignition systems generally employ resistor-type sparkplugs or high-resistance ignition wire to damp the oscillatory current pulses that fire the sparkplugs, thus reducing EMI. Some but not all appliances using universal motors include line filters to block the current pulsations caused by the motor from circulating in the power leads feeding the motor, thus reducing unwanted EMI emananating from the power leads.

Other common sources of EMI are fluorescent lighting systems, in which currents turn on very abruptly each current cycle instead of varying smoothly; and computers, in which all currents are abrupt pulses of varying duration. Another more obscure source of EMI is the electronic dimmer for household lighting, that works by abruptly switching on the current to a light circuit at some adjustable point in the middle of the normal current cycle, thus causing EMI-generating transients.

One natural and sometimes important source of EMI is lightning. Some devices that do not cause EMI are ac induction motors and electrical resistance heating units, no matter how large.

In rapid transit electrical systems, potential sources of radiated EMI are dc motors for propulsion and auxiliary power, and the electronic switches or "choppers" used in solid-state propulsion control systems. Both of these potential sources cause pulsating current through associated conductors. However, the amount of radiated EMI actually caused by any of these potential sources depends upon the filtering and shielding employed in system construction. Another potential cause of radiated EMI is third-rail shoe-bounce, that gives rise to transient current patterns in a car's propulsion current collection circuit.

2.4 Units of Measure of Broadband Radiated EMI

The power in continuously propagating electromagnetic waves in free space can be stated in watts per square meter of incident area. For such waves, the power density in W/m^2 is directly related to the electric and magnetic field strengths. Therefore, either E-field or H-field intensity can be used as an indication of the power density of the wave.

Nearby a source of electromagnetic waves, localized non-radiating E and H fields also are present. For physically small sources of radiation, the intensity of non-radiating fields decreases as $1/r^3$ with distance away from the source, whereas the intensity of radiating fields decreases as 1/r. The distance at which the localized field intensity becomes less than the radiating field intensity depends on the frequency in question, and the specific physical characteristics of the source of radiation.

For an ideal Hertzian dipole radiator, comprised of a signal source driving current along a short conductor between two open capacitor plates, the distance beyond which the radiating or "far" component of E-field becomes more intense than the localized or "near" component equals 48/f meters, where f is measured in MHz. Likewise, at a distance r away from an ideal Hertzian dipole radiator, the frequency above which the far-field intensity is greater than the near-field intensity is 48/r MHz.

To deal with the uncertainty of the precise electromagnetic circuit characteristics of sources of radiated EMI, it is convenient to prescribe a standard distance at which measurements of field strength will be made, and to prescribe which field component, E or H, will be measured. The Suggested Test Procedure presented in this document specifies measuring the E-field, at either 30 meters distance, or if that distance is inconvenient, at 15 meters. E-field has the dimensions of volts/meter.

Broadband EMI is caused by transients. The signal strength of a single transient is distributed in frequency in a continuous fashion. The greater the bandwith of a filter through which the transient passes, the greater will be the peak amplitude of the signal out of the filter. For narrow-band filters, the peak amplitude attained will be directly proportional to the filter bandwidth. The standard measure of intensity of one EMI transient is the peak amplitude produced on the observing apparatus - normally either a peak-reading voltmeter or oscilloscope screen. Therefore, to characterize broadband radiated EMI in a manner independent of specific receiver bandwidth, units of (volts/meter) per MHz of receiver bandwidth are used.

(Note that whereas peak amplitude is proportional to bandwidth, the time duration of an output signal in response to a transient input is inversely proportional to bandwidth. Thus the energy output, which roughly equals peak amplitude squared times duration, is also proportional to bandwidth. Since it is peak amplitude due to transients that is observed and recorded, the units are ones of signal amplitude per unit bandwidth, and not energy per unit bandwidth.)

To allow for mesurements of EMI over broad amplitude ranges, a logarithmic scale is used for amplitude, with broadband EMI given in the units of dBμV/m/MHz, i.e., dB relative to 1 (microvolt/meter)/MHz.

3. PRIOR BROADBAND RADIATED EMI TEST PROCEDURES

Several EMI standards were examined to determine their applicability to the measurement of rdiated emissions from rail transit vehicles. They are

- MIL-STD-461B and 462
- SAE J551F
- CISPR 2 and 18
- VDE 871/3.68, 877/1/12.59, and 877/2/12.55
- FCC Dockets 20780 and 80284
- ANSI C63.4
- IEEE Std 302-1969

These standards were reviewed by the National Bureau of Standards (Ref. 9.3, Part 2) to determine their applicability to measuring EMI from a moving electrically powered rail vehicle. It was concluded that none of these standards can be applied directly to assess EMI from a rail vehicle for the following reasons:

First, existing standards only provide for testing stationary objects. Only limited power cn be applied to a stationary electrically powered rapid transit vehicle. EMI usually increases as more power is applied, giving worst-case EMI levels at maximum acceleration (or deceleration for dynamic or regenerative braking). Thus, tests must be made on moving vehicles.

Additionally, rails are EMI transmission lines and form part of a car-rail radiating structure. None of the existing standards provides for testing vehicles on rails.

4. EMI EMISSIONS STANDARDS

MIL-STD 461B characterizes broadband EMI levels by peak amplitude of EMI transients, independent of the repetition rate of transients. The CISPR EMI standards, widely used in Europe, characterize broadband EMI not only by peak amplitude, but also by repetiton rate of EMI-producing transients. For voice or video communications, the CISPR criteria are probably more realistic, since isolated occurrences of transient interference generally do not disrupt the overall intelligibility of audio or video reception, and since the level of disruption due to repetitive transients is proportional to repetition rate.

The MIL-STD 461B criteria are more realistic when applied to interference with transmission of binary digital information over a presumably error-free channel. In that case, because of the binary nature of signals, any number of sufficiently small but discrete transients will not increase the error rate, but transients larger than some threshold size will cause bit errors in transmission.

In practice, the operator of broadband EMI measuring equipment exercises judgement, based on experience, as to what observed transient events constitute recordable EMI and what ones do not. The judgement and experience are correlated with common types of interference observed, and in a qualitative manner with the hazards to communication they pose. Therefore, an observer will characterize the steady emanations from an auto ignition system as "true broadband EMI"; whereas the observer might ignore the single isolated transient event due to a circuit breaker closing on a subway car, and regard it as spurious and inconsequential.

Because of the weight of prior practice and experience in the U.S. rail transit community, the Suggested Test Procedure in this document specifies characterization of broadband EMI according to the MIL-STD 461B formula.

MIL-STD 461B contains charts of broadband emission limits that must be met by military electrical and electronic systems having various applications. The rail transit industry has employed similar and related standards specifying allowed emission levels from rail transit vehicles in the past. However, such limits are neither a necessary nor a sufficient condition for civil applications under FCC jurisdiction. The FCC criterion is that a rail transit vehicle and its equipment shall not cause interference either on board or at wayside. The most important element of this standard is that non-broadcast radiated emissions must not interfere with legal radio communications.

5. CONCLUSION

In developing the Suggested Test Procedure found in this document, elements of recognized standards were adopted or modified to develop valid and repeatable measurement procedures. Where required, new elements were introduced. The result is a series of validated test procedures that may be applied to the measurement of radiated emissions from a moving rail rapid transit vehicle.

PART 2

RADIATED SUGGESTED TEST PROCEDURE - METHOD RT/RE01A

BROADBAND EMISSIONS OF RAPID TRANSIT VEHICLES - 140 KHZ TO 400 MHZ

1. PURPOSE

The purpose of this test is to measure the intensity of broadband radiated electromagnetic emissions from electrically propelled rapid transit vehicles. Broadband emissions arise from transient or pulsed currents and voltages as opposed to steady sinusoidal currents and voltages. Overall spectral widths of broadband emissions are broader than the bandwidths of measuring instruments. Broadband emissions arising from periodic transients or pulses have individual spectral components too close together to resolve with measuring instruments.

2. APPLICABILITY

This test is applicable to all electrically propelled rapid transit vehicles. The test was developed specifically for rail transit vehicles, but may be used as well for trolley buses.

3. APPARATUS

3.1 Antennas

The antennas listed below shall be used in the corresponding frequency ranges:

140 kHz - 30 MHz	Rod antenna
30 MHz - 200 MHz	Biconical antenna
200 MHz - 400 MHz	Log periodic antenna

Antennas shall conform to ANSI Standard C63.2-1980, Sec. 14. Antennas together with associated leads, baluns, matching devices, and/or amplifiers required to conect and match antennas to the 50-ohm input impedance of the EMI receiver shall have antenna factor calibration data provided.

3.2 EMI Receiver

The EMI receiver shall be one known to be suitable for performing measurements of broadband noise in the prescribed spectral range. If a receiver of the type generally referred to as a frequency-selective rf voltmeter or EMI meter is used, it shall conform to ANSI Standard C63.2-1980. As an alternative, an rf spectrum analyzer may be used as a receiver, provided it is of a type known to be suitable. See Note 8.5 concerning use of a spectrum analyzer as an EMI receiver.

4. EQUIPMENT PLACEMENT

4.1 Standard Equipment Placement

The standard equipment placement shall be with the receiving antenna positioned 30 meters (100') from the centerline of the vehicle's path. The ideal test configuration is the one recommended in ANSI Standard C63.4-1980, with F = 30 meters (100') taken as the distance from antenna to the centerline of the vehicle's path. Insofar as possible, specific test site and equipment placement shall be arranged to avoid proximity to interfering objects. Ideally the test site should be on level ground, and sites at which vehicles operate in cuts or on elevated embankments or guideways should be avoided. Gradually sloping terrain or sites at which track rests on ballast of normal depth are allowed.

Antennas shall be mounted on a tripod with mounting plate 2 meters above ground level. The rod antenna when used shall be oriented exactly vertically. The biconical antenna when used shall be oriented exactly vertically, or horizontally with its axis parallel to the vehicle's path. The log periodic antenna when used shall be aimed at a point 2 meters above ground level over the centerline of the vehicle's path.

4.2 Alternate Equipment Placement

The alternate equipment placement shall be with the receiving antenna positioned 15 meters (50') from the centerline of the vehicle's path. (See

Note 8.3 regarding scaling of observed interference levels from the standard 30-meter equipment placement distance to the alternate 15-meter distance.) Insofar as possible, specific test site and equipment placement shall be arranged to avoid proximity to interfering objects. Allowable grade and antenna placement shall be as stated in Sec. 4.1.

5. RECEIVER BANDWIDTH AND OPERATING MODE

5.1 Frequency-Selective RF Voltmeter Operation

If a frequency-selective rf voltmeter is used, it shall be operated in the peak mode, with impulse bandwidth of 10 kHz from 140 kHz to 30 MHz, and impulse bandwidth of 100 kHz from 30 MHz to 400 MHz.

5.2 Spectrum Analyzer Operation

If a spectrum analyzer is used, it shall be operated with resolution bandwidth of 10 kHz from 140 kHz to 30 MHz, and resolution bandwidth of 100 kHz from 30 MHz to 400 MHz.

5.3 Receiver Bandwidth Calibration

Standard techniques shall be used for assuring calibration of the impulse bandwidth of the receiver, whether an rf voltmeter or a spectrum analyzer is used. For spectrum analyzers whose IF stages have Gaussian passbands, the impulse bandwidth is 1.4 times the resolution bandwidth (-3dB bandwidth), and is approximately equal to the -6dB IF bandwidth.

6. PERFORMANCE OF TESTS

6.1 Fields and Polarities

Measurements of broadband E-field emissions shall be made for the following polarities:

140 kHz - 30 MHz	Vertical E-field
30 MHz - 200 MHz	Vertical E-field
30 MHz - 200 MHz	Horizontal E-field parallel to track
200 MHz- 400 MHz	Horizontal E-field parallel to track

6.2 Receiver Sensitivity and Spurious Response Levels

After the receiver and associated equipment are installed at the test site, and with the transit vehicle operating normally, receiver sensitivity and spurious pickup shall be measured by attaching a matched termination to the receiver's antenna input terminal and observing and recording receiver output levels across the entire frequency range. Data thus obtained shall be labelled "With Antenna Terminal Terminated". Any spurious receiver response shall be noted.

6.3 Ambient Level Determination

With the vehicle absent or de-energized, but with the electrical traction power feed energized, the ambient broadband and narrowband emission levels shall be measured and recorded for all stated frequency ranges and polarities. Data shall be labelled "Ambient Broadband Levels" and "Ambient Narrowband Levels".

6.4 Measurement of Vehicle Emissions

Known sources of narrowband emissions from the vehicle under test shall be disabled if possible without otherwise affecting the vehicle's operating characteristics. The vehicle then shall be operated over normal cycles of operation (e.g., acceleration, coast, dynamic braking), while broadband emission levels are recorded for all stated frequency ranges and polarities. As a minimum, measurements shall be made for the vehicular operating cycle for which the greatest emission levels are anticipated. Sufficient data shall be taken to assure that worst-case data are acquired. Data shall be labelled "Broadband Vehicle Emissions".

7. TABULATION OF RESULTS

7.1 Data Validity

For the broadband vehicle emission level observed at a particular frequency and polarization to be deemed valid, it must exceed the corresponding observed ambient broadband level by 10 dB or more. Furthermore, the frequency in question must be further than $2B_i$ from any ambient narrowband signal producing receiver output greater than the observed broadband vehicle emission.

Data for vehicle emissions and for ambient levels shall be regarded as invalid at those frequencies at which receiver accuracy is affected adversely by spurious response or lack of sufficient receiver sensitivity.

7.2 Data Presentation

Final broadband emisson levels shall be stated in dBμV/m/Mhz, i.e., dB relative to 1 (microvolt/meter)/MHz, for all required vehicluar operating modes, frequency ranges and polarizations. Data shall be presented in tabular format, or graphically in dB vs. log frequency plots, in a manner that allows immediate comparison of broadband emission levels, ambient levels, and receiver sensitivity levels. Any methods used to construct continuous curves from discrete data points shall be stated clearly, and discrete-frequency data from which curves were generated shall be given. Frequency ranges or frequencies for which data are valid and invalid shall be indicated.

The following additional data shall be presented:

- Characteristics of vehicle
- Test equipment certification information
- Antenna factors vs. frequency
- Cable attenuation vs. frequency
- Map of test site, noting terrain and potentially interfering objects

8. NOTES

8.1 Expanded Scope of Tests

If it is determined that the scope of tests be expanded to include H-field measurements and/or broader frequency coverage, the additional test configurations listed below may be considered:

14 kHz - 30 MHz	Loop antenna H-field sensor - measurement of H-field vertical and parallel to track
14 kHz - 140 kHz	Rod antenna vertical E-field sensor
400 MHz - 1 GHz	Log periodic antenna horizontally polarized

Suggested impulse or resolution bandwidths for expanded tests are as follows:

Frequency range	Bandwidth
14 kHz - 140 kHz	1 kHz
140 kHz - 30 MHz	10 kHz
30 MHz - 400 MHz	100 kHz
400 MHz - 1 GHz	1 MHz

8.2 Relation to Other Standards

The test procedures presented above generally are consistent with MIL-STDs 461B and 462; with ANSI Standard C63.2-1980 and C63.4-1980; and with SAE Recommended Practice ARP-1393 for measurement of broadband EMI. The test procedures outlined above are oriented specifically toward characterizing broadband EMI on the basis of field strength per Hertz of receiver impulse bandwidth, for a standardized set of receiver impulse bandwidths. In this regard, these tests differ from CISPR procedures that call for characterization of EMI in terms of quasi-peak values that take account of noise impulse repetition rates as well as impulse amplitudes.

8.3 Near-Field and Far-Field Distance Scaling Factors

Broadband emission limit specifications stated for standard distance F = 30 meters may be coverted for application at a new distance of 15 meters by means of the following procedure that is based on the known behavior of electric field intensity on the equatorial plane of a Hertzian dipole radiator. EdB_{std} and EdB_{new} are the standard and new specified field strength limits in dBμV/m/MHz.

$$EdB_{new} = EdB_{std} + 18\ dB \quad \text{for} \quad f \leq 1.6\ MHz$$

$$EdB_{new} = EdB_{std} + 6\ dB \quad \text{for} \quad f \geq 3.2\ MHz$$

Between 1.6 MHz and 3.2 MHz, the graph of the correction factor ($EdB_{new} - EdB_{std}$) follows a straight line on a dB vs. log frequency plot, from +18 dB at 1.6 MHz to +6 dB at 3.2 MHz.

8.4 Specification of Test Procedures and Broadband EMI Limits

Limits and/or specifications for broadband EMI are at the discretion of responsible authorities. In specifying test procedures and/or broadband EMI limits, responsible authorities citing this document as a reference shall specifically note allowed or required deviation from the standard test procedures as outlined in Sections 1 - 7 above.

8.5 Use of Spectrum Analyzers for Broadband EMI Analysis

Spectrum analyzers offer a speed advantage in data taking compared to the use of standard EMI receivers. General procedures for using spectrum analyzers for measuring broadband EMI are outlined in Ref. 9.2, and an example of past use in rapid transit applications is provided in Ref. 9.5. Use of a tracking rf preselector may be required with a spectrum analyzer to avoid spurious response, if ambient field strength is high. Such spurious response can cause readings of broadband emissions to be erroneously high. Ambient field strength high enough to necessitate use of a preselector generally is due to nearby rf transmitters or other narrowband sources.

Use of computer-coupled spectrum analyzers further decreases the time required to record and reduce data, and allows production of hard-copy plots of reduced data in the field. Reference 9.3 outlines their use.

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