RFI/EMI Automated Measurement System (REAMS)

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ABSTRACT

We live in a world that is fast becoming universally automated. As automation increases, so does our dependence on new computers, communications, and other electrical or electronic devices. The proliferation of new devices in turn causes an alarming rate of increase in Electromagnetic Interference (EMI) problems. In both the military and civilian sector, EMI problems can sometimes cause catastrophic equipment or system failures, which can in turn result in the destruction of life and property. To help ensure the safe inter-operation of equipment or systems operated and developed by the uniformed services and independent agencies, the Department of Defense (DoD)³ has directed the implementation of an Electromagnetic Compatibility Program (EMCP). This directive creates the need to measure, monitor, and characterize the effects of man-made and naturally occurring electromagnetic noise or interference.

To fill this need, the DoD Electromagnetic Compatibility Technical Center (ECTC) developed the RFI/EMI Automated Measurement System (REAMS). REAMS is a scientific, yet practical system for performing Electromagnetic (EM) Site Surveys, with frequency coverage from 100 Hz to 18 GHz, instead of the usual 10 KHz to 10 GHz¹. REAMS uses deployable field subsystems to collect first order noise statistics and spectrum occupancy data, and a minicomputer based noise data analysis subsystem (NDAS) for extraction of higher order noise statistics² and database management. REAMS deployments have resulted in the collection of high precision, real-time amplitude probability distribution curves of EMI disturbances commonly observed at DoD communication sites.

INTRODUCTION

The RFI/EMI Automated Measurement System (REAMS) was developed to perform Electromagnetic (EM) Site Surveys, with frequency coverage from 100 Hz to 18 GHz using commonly recommended measurement and analysis techniques¹. This paper presents a brief description of the REAMS employment in support of the DoD EMCP, the currently deployed REAMS equipment and planned upgrades, and finally, some results from the initial surveys conducted within the last six months.

Employment Concept

REAMS is employed for EMC site surveys in a process depicted in Figure 1. REAMS consists of two subsystems, the REAMS Field Subsystem (RFS), and the Noise Data Analysis Subsystem (NDAS). Site EMC data is collected using the deployable, shelter mounted RFS. Data collection involves the real time measurement of first order noise statistics⁴ and spectrum occupancy data. For further analysis² and database management, REAMS utilizes NDAS, which is located at the ECTC Fort Meade office. The analysis results and statistical data is then used to generate reports and formulate actions needed to mitigate, reduce, or eliminate harmful EMI. The reports and actions are the main interface to the DoD EMC program, as this step in the employment process involves the DoD operational and maintenance activities responsible for the sites surveyed.

Site Measurements

Before REAMS, field noise survey measurements were made using manual receivers with the noise data manually tabulated on worksheets. Typical noise surveys using a manual receiver require from two to four weeks to obtain the necessary measurements. Up to two hundred readings of noise samples at each of up to seven frequencies and at up to six site locations are typically required for a total of approximately 8,400 manually tabulated values. The field data is later manually input into a Personal Computer for processing. REAMS is designed to automate the EMC site survey process, to reduce the amount of time on site necessary for noise surveys, to provide greater accuracy in reading and faster processing of the collected data, and to provide a greater measurement capability than is available with a manual receiver.

The RFS is the deployable data collection unit of REAMS. It can be operated manually, or programmed to operate in an automatic (continuous 24 hour data collection capability) or semi-automatic mode. The RFS is capable of obtaining noise measurements from 100 Hz to 300 MHz and spectrum occupancy measurements from 9 KHz to 18 GHz. It is also capable of data reduction on site by performing first order and limited second order statistical analysis. Finally, the RFS is capable of generating preliminary noise survey reports on site.

Data Analysis, Database Management, and EMC Survey Reports

NDAS is the non-deployable, off-line analysis unit of REAMS. NDAS performs second and higher order statistical reduction of the RFS collected noise and spectrum occupancy data. NDAS also serves as the on-line database management system. The data contained within the database is used to identify noise encroachment problems, to form a historical database, predict future trends, inter-site comparisons, and to characterize noise types. The NDAS is also utilized in the generation of EMC survey reports.

Fig 1. REAMS Employment Concept

REAMS FIELD SUBSYSTEM

This section describes the REAMS Field Subsystem which is composed of the components shown in Figure 2. Functionally, the RFS can be subdivided into an antenna subsystem, a receiver subsystem, and a signal processing subsystem. Additionally, planned upgrades to improve the RFS performance are also discussed.

Fig 2. REAMS Field Subsystem (RFS) Block Diagram.

Antenna Subsystem

The RFS antenna subsystem includes the three reference antennas and remote low noise pre-amplifier modules. The RFS uses three calibrated, omni-directional antennas to measure the ambient EMC environment. Three antennas are necessary to cover the 100 Hz - 18 GHz frequency range. Coverage is divided into "Low Band" or 100 Hz - 30 MHz, "Mid-Band" or 30 MHz - 1 GHz band, and "High Band" or 0.5 - 18 GHz.

The antennas are connected to two "in-house" developed, low-noise pre-amplifier modules (low band - LO PA, mid/high band - MID/HI PA). The pre-amplifier modules also contain noise diodes for calibration and RF switches for test path selection. Octave band filtering and switching at the preamplifier boxes is used to reduce preamplifier loading from large signals.

The current RFS antenna subsystem provides at least 100 dB dynamic range and a noise sensitivity of $-40 \text{ dB}\mu\text{V}/\text{Hz}$ below 1 MHz, $-60 \text{ dB}\mu\text{V}/\text{Hz}$ from 1-30 MHz, 6 dB noise figure from 30-2000 MHz, and better than 9 dB overall system noise figure above 2 GHz. Planned upgrades will reduce the noise figures by 3-5 dB above 30 MHz.

Receiver Subsystem

The receiver subsystem consists of the RF matrix/switch control module, post amplifier/switch driver, preselector, and spectrum analyzer. Each individual component is controlled by an HP8236 desktop computer via an IEEE-488 bus. The desktop computer is being upgraded into an HP375CH workstation.

The switch controller allows connection of the receiver subsystem to the appropriate reference antenna, or a calibration noise diode. At existing sites, an internal 100-pole DC to VHF matrix switch provides the capability to interface with site antennas. Two auxiliary DC-18 GHz ports are also available for connection to site antennas.

The post amplifier unit provides a 20 dB gain, 4.5 dB noise figure amplifier at frequencies above 6 GHz. It is used to compensate for cable losses and improve the overall system noise figure at the higher frequencies. This box also connects the antenna paths to the correct HP85685A preselector input port at a transition frequency of 50 MHz.

The HP85685 RF Preselector is used to pre-process signals below 2 GHz. This unit introduces tuneable bandpass filters and preamplifiers before the spectrum analyzer to provide improved noise figure and reduced intermodulation distortion from 20 Hz to 2 GHz. Above 2 GHz, the preselector operates in "direct connect" or bypass mode, as the spectrum analyzer has a built-in 2 to 18 GHz tuneable YIG input filter.

The Spectrum Analyzer #1 (HP8566B) is the final component in the Receiver Subsystem. Each of the major subsystem's functions of Discrete Signal Cataloging, Noise Statistics Measurement, and RF Waveform Recording have been designed to take advantage of functions and outputs available from the spectrum analyzer. The spectrum analyzer can tune throughout the range from 20 Hz to 18 GHz (when coupled with the preselector). The Log Video port of the spectrum analyzer provides output signals for simultaneous Amplitude Probability Distribution (APD) measurements and the waveform recordings. Since the data collected from noise measurements is date and time stamped, taking APD and waveform measurements simultaneously allows for accurate correlation of data when performing off-line analysis.

Signal Processing Subsystem

The REAMS signal processing subsystem provides a capability for real time measurement and calculation of EMI first order statistics, spectrum occupancy data, and recording of EMI waveforms. This subsystem includes an Amplitude Probability Distribution (APD) monitor, an HP 5180 Waveform Recorder, and the HP computer/workstation.

The APD monitor is used to process noise or signal measurements into a short-term, real-time, statistical histogram of the signal amplitude distribution. This unit uses the spectrum analyzer's log-video output to drive a 10 MHz, 12-bit analog to digital converter. The 10 most significant bits of the ADC are then used to address and add "event" counts into a 1K-word, 32-bit accumulator. Hence, at the end of a measurement (1 to 300 seconds), the contents of the accumulator bins correspond to the input signal amplitude histogram. The histogram is then passed on to the RFS computer for further processing.

The HP5180A Waveform Recorder is a digital recorder used to save EMI waveform or signals for further analysis. This unit takes 16K-word, 10 bit samples of the spectrum video output independently or in conjunction with the APD monitor. We have used the waveform recordings to extract local man-made EMI statistical characteristics in the presence of intermittent, high level atmospherics.

The current RFS employs HP 8236 computers for equipment control, measurement scheduling, and first order statistical analysis. Equipment control implements the industry standard IEEE-488 bus. Measurement scheduling is performed in conformance with the diurnal time blocks discussed in past atmospheric noise measurements⁴. Site measurements usually last from seven to 15 days, with automatic measurements scheduled from 0000 to 1600, and 2000 to 2400 time blocks. The 1600-2000 time block is reserved for operating system maintenance and measurement data back-up.

The RFS computer performs first order statistical analysis on the APD monitor output during noise measurements and compiles spectrum data during spectrum occupancy measurements.

For noise data statistical analysis, the computer first calculates the noise envelope probability distribution function (PDF) by dividing the APD accumulator bin counts by the total number of samples measured. The APD curve and the following envelope statistics are then calculated for use, storage, and display:

Cumulative Distribution Function (CDF)

$$P(v) = \int_0^v p(x) dx \quad (1)$$

Amplitude Probability Distribution (APD)

$$APD(v) = 1 - CDF(v) \quad (2)$$

Average Envelope Voltage

$$V_{av} = \int_0^\infty vp(v)dv \quad (3)$$

RMS Voltage

$$V_{rms} = \left[\int_0^\infty v^2 p(v)dv \right]^{1/2} \quad (4)$$

Average Logarithm of the Envelope

$$V_{log} = \int_0^\infty \log v p(v)dv \quad (5)$$

Peak Voltage for Time Period T

$$\text{Maximum of } v(t) \text{ during } T \quad (6)$$

Average Envelope Referenced to RMS

$$V_d = -20 \log \left(\frac{V_{av}}{V_{rms}} \right) \quad (7)$$

Antilog of Average Log of the Envelope Referenced to V_{rms}

$$L_d = -20 \log \left(\frac{10^{V_d/20}}{V_{rms}} \right) \quad (8)$$

External Noise Factor

$$f_n = \frac{P_n}{kT_p B} \quad (9)$$

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Available Noise Power

$$P_N = \frac{V_{rms}^2}{Z_0} \quad (10)$$

External Noise Figure

$$F_a = 10 \log f_a \quad (11)$$

RFS Upgrades

In addition to the computer system upgrade mentioned above, we are currently upgrading the RFS by integrating a portable RF Head/Noise Analyzer module and miscellaneous EMI measurement instruments to the prototype shelters.

The prototype RFS configuration requires moving the entire equipment suite into a site for measurements using the site antennas. The Portable RF Head/Noise Analyzer will simplify site antenna measurements by reducing the amount of equipment to be moved. The Portable RF Head/Noise Analyzer consists of two IEEE-488 Bus Extenders that use fiber optic cables for control and data interchange. It also uses a matrix switch for switching between the various test paths from the site antennas to the Spectrum Analyzer #2. The HP8562A Portable Spectrum Analyzer #2 provide coverage from 9 KHz to 22 GHz and functions as an additional receiver subsystem.

This upgrade will also employ an HP3565S Signal Processor for real-time, higher order statistical data analysis. (In the current system, higher order statistics can only be performed using NDAS). The real-time statistical analysis obtained are the CDF, APD, V_{avg} , V_{rms} , V_{log} , V_{peak} , V_d , L_d , and F_a . The signal processor also produces real-time temporal and spectral records of the EMC environment.

The other upgrade is the inclusion of a Polarad ESH2 noise receiver and portable antennas to the RFS shelter. This upgrade will provide survey teams the capability of locating EMI sources while the RFS collects EMC data automatically.

NOISE DATA ANALYSIS SYSTEM

The NDAS is the off-line analysis unit of REAMS. It is used for reducing and consolidating collected data, computing noise statistics from waveform data, maintaining and managing the noise and large signal database, and generating the final noise survey report. In general, NDAS has a data analysis capability that provides statistical characterization of the EM environment for determining trends and EMI predictions. The following equations are the type of statistics produced by NDAS:

Pulse Spacing Distribution

$$PSD\left(\frac{t_s}{v_j}\right) = \int_{t_i}^{\infty} p_s\left(\frac{t}{v_j}\right) dt \quad (12)$$

Pulse Duration Distribution

$$PDD\left(\frac{t_b}{v_j}\right) = \int_{t_i}^{\infty} p_d\left(\frac{t}{v_j}\right) dt \quad (13)$$

Average Crossing Rate

$$ACR(v_j) = \frac{E(n(t_2 - t_1))}{(t_2 - t_1)} \quad (14)$$

Autocorrelation

$$\varphi(\tau) = \lim_{T \rightarrow \infty} \frac{1}{T} \int_0^T f(t) f(t+\tau) dt \quad (15)$$

Power Density Spectrum

$$S(v) = \lim_{T \rightarrow \infty} T^{-1} \left[\int_0^T f(t) e^{(-2\pi j v t)} dt \right]^2 \quad (16)$$

NDAS is comprised of an HP375CH Workstation that is connected to a DEC VAX 8200 via IEEE 802.3 LAN (Figure 3). The HP375CH Workstation is used as the primary data analysis computer. It is also used to generate the final survey report. The HP375CH contains a 32-bit MC68030 50 MHz CPU with a 50 MHz floating point coprocessor. It also has 16 MB of RAM and 32 KB of cache memory. HP-UX (similar to UNIX) is the operating system used with the HP375CH. The HP660 Mass Storage unit is used as the hard disk. The mass storage unit is comprised of a 660 MB fixed disk, a 650 MB removable optical drive, and a CD ROM drive. The output device is the HP Laserjet III printer.

FIGURE 3. Noise Data Analysis Subsystem (NDAS).

The DEC VAX 8200 is used as the primary data storage/retrieval system. It is comprised of three VT240 terminals, one removable and two fixed RA60 drives and two RA90 drives. The VAX has a total storage capacity of approximately 3.5 Gigabytes. In addition to being a storage/retrieval system, the VAX is also used to process and analyze digital waveform recordings. The digital recordings can be in linear form or log-envelope form.

NDAS operators can initiate RFS data analysis using the VAX from the VT240 terminals, or using the HP375CH with the VAX for database management.

Measurement Results

REAMS has been tested and deployed in at least five EMC measurement projects during the last six months. This paper discusses some of the results of these measurements and presents representative plots of the test data in Figures 4 thru 10. The results show short term statistics in the form of APD curves, first order calculations described above, and measurement summaries which can be used for comparing results with past predictions or inter site performance comparisons.

Amplitude Probability Distribution Curves

Figure 4 shows typical APD curves collected in the presence of EMI from thermal noise, motor boat ignition, and power line gap discharges. During the RFS tests, measurement times were varied from 1 to 300 seconds. However, results indicate that the V_{rms} values and APD curve shapes did not change significantly between 60 to 300 seconds. The APDs shown here resulted from 60 second duration, 3 KHz bandwidth measurements. APD from thermal noise is generated by terminating the antenna pre-amplifier module input ports. Thermal noise data is used mainly for checking the sensitivity of the RFS and serves as part of the system calibration procedures.

The APD curves are used to determine the impact of EMI effects in terms of amplitude severity, short term performance impact, and as input to NDAS for the calculation of site performance ratings. So far, ignition noise presents severe V_{rms} to peak noise ratios, but is intermittent and generally

Figure 4. APD curves from observed noise waveforms.

affects receivers less than 1% of the time. Power line noise has greater short term impact (30% here). Hence, it may be more practical to spend EMI resources in mitigating power line related noise in most sites. The Fa values for the first three APD curves are shown as 0.00 dB>kToB as we used uncalibrated site antennas for these measurements.

Atmospherics will always be present at some time during surveys. When local thunderstorms are present, the site noise power levels increase by as much as 10 to 60 dB^{5,6,7} above ambient levels. Before REAMS, measurements during thunderstorms were discarded and the survey time extended in order to collect more ambient site noise data. Close examination of the APD curves show the short term effects of atmospherics to be 15%-20% of the time or less. Therefore, if lightning effects can be excluded from the statistical analysis, extraction of the site noise characteristics should be possible.

Knowing the temporal structure of lightning discharges⁵, we have implemented an algorithm which extracts local thunderstorm effects during post analysis of RFS recordings. The algorithm examines an APD recorded data and excludes 1000 word blocks whenever the block Vrms value exceed predetermined thresholds for the entire ensemble.

In figure 5, we excluded blocks with Vrms values 10 dB above the minimum block Vrms observed. The 1000 point blocking preserves the statistical characteristics of EMI from local sources and distant thunderstorms. Results show that local thunderstorm effects predominate below 10 MHz.

Comparison of REAMS Data With CCIR Predictions and Polarad ESH2 Data

Part of the REAMS measurement validation is the comparison of Fa medians extracted from the APD measurements with data collected at the same location using a Polarad ESH2 test receiver. In Figure 6, we have observed a close correlation of measurement results between the two instruments in the HF range but have not taken ESH2 data below 2.5 MHz. Below HF, the REAMS data also compare favorably with CCIR predicted values for atmospheric noise in all sites surveyed.

Spectrum Occupancy Measurements

During spectrum occupancy measurements, the RFS collects EM signal data by initiating a pre-determined number of spectrum analyzer sweeps and calculating the statistical characteristics of the signals observed. A sample of a short term observation is shown as a "timegram" in figure 7. The timegram shows the maximum amplitudes vs frequency observed, and the % of time the signals exceed a software selected threshold.

In addition to "timegrams," the RFS also compiles a table of maximum signal amplitudes observed during spectrum occupancy measurements. NDAS subsequently combines these tables and generate large signal summary curves

Figure 5. APD with atmospheric noise data (left) is modified by excluding lightning noise to extract site EMI noise data (right).

like those shown in figure 8. For simplicity, the summaries only graph the largest signal observed at frequency increments equal to 1% of the observation frequency span. Finally, the results of the large signal summary are analyzed in conjunction with the noise data medians to generate performance ratings for the sites surveyed.

Site 3, Oct 1990, 0800-1200 Time Block

Fig. 6. Median Fa Data Comparison.

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TIMEGRAM SUMMARY

START ON:07/17/90, AT:10:40:52.41
STOP ON:07/17/90, AT:10:42:37.22
RUN LENGTH: 104.8 SEC

PERCENT OCCUPANCY (VS FREQUENCY)

MAX AMP (VS FREQUENCY)

Figure 7. "Timegram Summary" chart shows the relationship between maximum signal levels measured during an observation time and the percentage of time the signals have levels higher than a threshold 10 dB above the noise floor.

Figure 8. The large signal summary shows the maximum amplitudes observed during a survey. Coverage is programmable and can be from 100 Hz to 18 GHz.

Site Performance Comparisons

Site performance comparisons can be done either by comparing the signal to noise ratio available for fixed frequency communication systems, or by calculating a reception performance value for receiver sites operating in the HF spectrum. Figure 9 shows the hypothetical performance ratings of two HF sites. The curves are calculated using the following relationship:

$$Rating_{gr} = \left(1 - \frac{V_{noise} - MDS}{V_{max} - MDS}\right) 100\% \quad (17)$$

where V_{max} is the maximum signal in dBm observed in the vicinity of the

Fig. 9. HF Site Performance Ratings.

noise measurement frequency, V_{noise} is the median noise level in dBm extracted from the APD measurements, and MDS is the expected minimum discernable signal of the receivers for the site surveyed. The second term of the equation defines the percentage of signals masked by noise if the high level signal distribution is log linear.

Higher order statistics which are used to completely describe noise waveforms are also calculated during a survey. A sample calculation on a 20 second noise recording is shown in Figure 10.

Survey Reports

The implementation of DoD EMC Program actions depend on reports like those generated using REAMS survey data. For this reason, reports must not only be concise and technically correct, they must also be produced in a timely fashion. Final report generation is currently 60 days from conclusion of a survey. The goal is to produce a final report not more than 30 days after the conclusion of a survey. With planning and preparation taking up to 60 days, data collection from 10 to 20 days, analysis another 10-20 days, and report generation from 30-60 days, a current REAMS survey process currently takes from 110 to 150 days to complete.

Figure 10. Results on the higher order statistical analysis performed on a 20 second recording of the motor boat ignition noise with APD shown in Fig 4. Shown from left to right are the ACR, PSD and PDD statistics.

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Charts and recommendations from the REAMS reports are used to prioritize the implementation of EMCP actions. These actions include the mitigation of harmful EMI, or selection of candidate communications sites for activation, closure, or upgrades.

CONCLUSION

The REAMS prototype is a practical implementation of the IEEE Std 473-1985. REAMS has been thoroughly tested and is now operational. The prototype is undergoing upgrades to transform it into a state-of-the-art measurement system that can be used for worldwide measurements. REAMS has been deployed on several noise measurements and has proven to be an invaluable scientific tool for characterizing EMI and quantifying the effects of EMI on communication systems. REAMS survey results are also useful in selecting candidate communication sites. When fully upgraded, REAMS will provide DoD a quantum leap capability in measuring the radio frequency environment.

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