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**Missile Launch Detection
Electric Field Perturbation Experiment**

Final Report

**R. J. Kane
Dr. T. M. Rynne**

April 28, 1993

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Lawrence Livermore National Laboratory
University of California
Livermore, California 94550

Missile Launch Detection Electric Field Perturbation Experiment Final Report

April 28, 1993

R. J. Kane, LLNL
Dr. T. M. Rynne, SARA Inc.

APPLIED TECHNOLOGY PROGRAM

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1.0 Summary

The Lawrence Livermore National Laboratory (Livermore, CA) and SARA Inc. (Huntington Beach, CA) participated in the ATMD missile launch activities that occurred at WSMR during January 1993. LLNL and SARA deployed sensors for monitoring of basic phenomena.

An attempt was made to measure perturbations of the earth geo-potential during the launch of a Lance missile. The occurrence of the perturbation is expected from the conducting body of the missile and the exhaust plume. A set of voltage-probe antennas were used to monitor the local electric field perturbation from the launch at ranges of approximately 1 km.

Examination of the data acquired during the launch period failed to show identifiable correlation of the field variations with the launch event. Three reasons are ascribed to this lack of event data:

- 1) The electric field potential variations have a limited spatial correlation length — the fields measured in one region have little correlation to measurements made at distances of a kilometer away. The potential variations are related to localized atmospheric disturbances and are generally unpredictable. A value for the spatial correlation length is also not known.
- 2) The conductivity of the plume and missile body are not adequate to produce a field perturbation of adequate magnitude. Phenomena related to the exhaust plume and missile may exist and be outside of the collection range of the equipment employed for these measurements.
- 3) The presence of 60 Hz power line noise was of sufficient magnitude to irreversibly contaminate measurements.

2.0 Scientific Premise

The geo-potential field above the earth's surface is caused by cosmic ray and natural radiation ionization. The electric field gradient near the ground is approximately 150 V/m and exhibits variations due to local weather and diurnal effects. A conducting object placed within this field will alter the field gradient shape.

The premise for this experiment was that the presence of the missile body and exhaust plume conductivity would provide a perturbation that could be detected. It was known before the field operations that the spatial correlation of the field perturbation would be limited and that local variations may be larger than the desired signal.

The maximum signal anticipated during the launch would have been a voltage variation of 2 volts in a local field of approximately 300 volts. A time period measured in seconds to a few tens of seconds would occur during the detectable portion of the missile flight.

The hardware and geographic locations are discussed in the following section.

3.0 Measurement System

The measurement hardware consisted of low frequency voltage probe detectors, digital/analog tape (DAT) recorders, and a 12 bit ADC with Macintosh computer. The probes and recorders were placed at different locations during the launch events on 1/25/93 and 1/26/93. During the first launch event all sensors were placed at Chat site in a distributed array. The locations indicated as 473 and 237 as well as Chat were used for the later launch events. Figure 1 shows the locations in their positions relative to the launch site.

At the sites designated as 473 and 237 the data collection hardware included two antennas aligned radially from the launch site and separated a distance of 20 m. Data were acquired using the DAT recorders.

The sensor systems employ a vertically polarized antenna with a low frequency bandpass amplifier. Four of the five amplifier systems employ bandpass circuits from approximately 5 Hz to 800 Hz. The fifth unit had a 60 Hz notch filter to minimize the pickup of powerline noise. The 12 bit ADC and Macintosh computer were used with this last system for data acquisition. The antennas, amplifier circuits, digitizing hardware and Macintosh computer were equipment provided for this experiment by SARA Inc. (Huntington Beach, CA).

4.0 Data Analysis

The data collected during the launches were examined off-line. Powerlines near the data acquisition areas contaminated the data with noise which prevented simple visual examination of the results. The acquisition equipment was battery powered and therefore did not contribute to the source of the noise.

Filtering of the data records to eliminate the 60 Hz noise was performed by averaging data over a time window equivalent to the noise period. The result shows a significant reduction in powerline noise. The remaining variations in data are due to other manmade noise sources, local field variations possibly caused by the missile launch, and natural environmental variations.

Figures 2 through 5 are data taken during the missile launches on 1/26/93. A moving average filter of length 300 was used to smooth the data, the data acquisition rate was 1800 s/s (samples per second). The data shown have also been decimated by a factor of six and the horizontal axis is set to 300 s/s.

Figures 2 and 3 are data taken during the first launch and begin at approximately T-2 s (Two seconds before launch). Two data traces are shown on each figure and correspond to the two antennas at each location. In all figures the upper trace corresponds to the antenna positioned closer to the launch site. The amplitude offsets are due to the instrumentation and not the nature of the measurement. The launch time corresponds to approximately sample position 600 for these traces.

The data traces do not show evidence of a perturbing signal that could be attributed to the missile launch. Some identifiable trend in the data is necessary for the concept to be usable. Ideally the signal perturbation associated with the missile launch would be larger than the variations due to natural processes. This is not the case in the data acquired for these launches.

Comparison of the data taken at the 237 site shows that the signals from two antennas, in close proximity, fail to exhibit a reasonable correlation. The same problem exists for the data from the 473 site. This prevents two closely spaced antennas from being used as a gradiometer. The lack of correlation also prevents two widely separated sites from combining information. These data traces show similarity of some noise spikes from unknown sources. The larger rectangular pulses are likely manmade and radiated from the powerlines in the area.

The data acquired at the 237 and 473 sites was time-aligned to allow examination of similarities between sites. The larger pulse-like perturbations which appeared in a number of traces were used to determine the trace offsets due to starting the DAT recorders at different times. Figure 6 shows one trace from each of the sites with zero-padding added to align them in time. Comparison of these traces (best case) shows significant correlation in coarse and fine data. However, the large dip in the data prior to the launch time in the lower trace, and the opposite trends in both traces near the end of the records illustrate that the noise processes in the field are largely unpredictable. These variations may mask the presence of deterministic signals related

to the movement of the missile through the atmosphere.

In summary, the data acquired during these tests do not exhibit adequate evidence of signals related to the launch of the missile. The lack of feature changes at the time of launch and the unpredictable nature of the noise processes result in this experiment having a **null** result. The data sample acquired during these experiments is too small to definitively state that the process failed. Further examination of the concept is required before confirming or denying its appropriateness.

5.0 Conclusions

The lack of event-dependent data in our examination suggests a **null** result for this experiment. The factors that contribute to this assessment include the natural noise processes, manmade noise, and the possible lack of signal spatial correlation at ranges beyond a kilometer. Further investigation of the spatial correlation length is required.

The noise variations that are present during short term observations must also be investigated. The data collected suggests that these variations may be somewhat larger than the desired signal and are not predictable. Detection of a small event in this situation may not be possible.

Figure 1. Measurement Site Locations
figure is unclassified

The locations used for the E-Field measurements are indicated as *CHAT*, *237 Site*, and *473 Site*. At the 237 and 473 sites, pairs of antennas (probes) were positioned radially from the launch point and separated approximately 20 m. A DAT recorder was used for signal acquisition. The *CHAT* site had a single antenna with an ADC attached to the Macintosh computer.

Figure 2. Site 237, First Launch Data
figure is unclassified

The data acquired at Site 237 during the first missile launch are shown in this plot. The upper trace corresponds to the antenna positioned toward the launch site. Launch time is approximately sample 600. The source of the large perturbation is unknown but may have been a radiated powerline transient.

The basic trends in the data are not strongly correlated at the time of launch. This apparent lack of predictable signal is the primary cause of concern for this detection approach.

Figure 3. Site 473, First Launch
figure is unclassified

Data acquired at Site 473 during the first launch are shown in the figure. The upper trace corresponds to the antenna positioned closer to the launch site. The upper trace shows a number of long duration pulse-like noise signals. These may be powerline radiated signals.

Data trends near the time of launch do not exhibit signals that are indicative of an E-Field perturbation due to the missile plume.

Figure 4. Site 237, Second Launch
figure is unclassified

The data acquired during the second launch are shown. Variations in the change of the local electric field are visible toward the end of the record.

Figure 5. Site 473, Second Launch
figure is unclassified

The data acquired at the 473 Site still shows some evidence of periodic noise which is likely caused by powerline noise.

Figure 6. Time-Aligned Data
figure is unclassified

Zero-padding of the data records was used to align data from the 237 and 473 Sites. The pulse-like perturbation and spike noise was used to determine how they should be aligned. There is reasonable correlation between the measurements made at the two sites but a significant deviation is visible near the end of the data record.

Appendices

The purpose of these appendices is twofold. First, the concept of measuring the E-Field variations is examined from an atmospheric sciences point of view, and secondly, the contribution of SARA Inc. must be included. It is the opinion of the author (R. K.) that the natural atmospheric variations that occur in the same time scale will negate the use of this technique for detection of a missile launch. However, a number of unknowns exist which must be examined before the issue can be resolved. These issues should be of interest to the atmospheric sciences community.

Figures A1 -- A3 are taken from literature [1-3] and illustrate the vertical potential profile, variation with time, and lack of spatial correlation. These are only intended to show that some prior studies exist but do not address the particular interest of this activity. Further estimation of the potential of this concept is required prior to a final determination of its failure or success.

FIGURE 12.22 The atmospheric electric field versus altitude during fair weather (O), cloudiness without precipitation (●), and during haze: fog (∞, ≡). The black curves show typical measurements, the white curves show mean profiles and the hatched areas show the scattering of values (Fischer, 1977).

Figure A1.
figure is unclassified

Figure A1 shows the variation in the vertical electric field profile and how it may be perturbed by natural phenomena. Other local factors such as dust or dirt, trees and other foliage, and wind will cause short-term variations. Note that these effects are localized and may dominate the measurement process. [1]

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FIGURE 11.6 Average diurnal variations in potential gradient showing effect of afternoon turbulence mixing (from Israel, 1958).

Figure A2.
figure is unclassified

Diurnal and seasonal variations are illustrated in the figure. [2]

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FIGURE 12.21 Disturbed electric field near the ground in the neighborhood of a big city (black station). The electric-field pattern at the south is not disturbed and shows typical fair-weather values (Fischer, 1977).

Figure A3.
figure is unclassified

The lack of correlation between measurement sites is illustrated in this figure. The measured electric fields are affected by local processes which vary due to the soil or aerosols and wind conditions. [1]

References

1. **The Earth's Electrical Environment, Studies in Geophysics**, "Electrical Structure from 0 to 30 Kilometers", Gringel, Rosen, and Hofmann, Chapter 12, National Academy Press, 1986.
2. **The Earth's Electrical Environment, Studies in Geophysics**, "Atmospheric Electricity in the Planetary Boundary Layer", Hoppel, Anderson, and Willett, Chapter 11, National Academy Press, 1986.
3. **Atmospheric Electricity, 2nd Ed.**, Chalmers, J. A., Pergammon Press, 1967.

The following attachment is the report submitted by SARA, Inc. in response to a draft report provided by this author. Similarities are due to the merging of some sections of the draft report with the details provided by SARA.

The primary author of what follows is Dr. Timothy Rynne, CEO and Chief Scientist, of SARA Inc., Huntington Beach, CA, (714) 373-5509.

1.0 Introduction

The Lawrence Livermore National Laboratory (Livermore, CA) and SARA, Inc. (Huntington Beach, CA) participated in the ATMD missile launch activities that occurred at WSMR during January 1993. LLNL and SARA deployed sensors and monitoring of basic phenomena.

An attempt was made to measure low frequency electromagnetic signatures that may be produced during a missile launch. Hypothetical signature production mechanisms include

- 1) Perturbations of the earth geo-potential during the launch of the missile. This signature may arise from the interaction of the ambient electric field with the conducting body of the missile as well as the partially ionized exhaust plume.
- 2) Production of spatial charge sources from triboelectric - like mechanisms. Such effects may occur during the initial interaction of the missile plume with the ground material and lead to an initial "spike" output. Additionally, there may exist charge transfer mechanisms produced during the exhausting of the burnt fuel/oxidizer. This second type of mechanism may lead to a net dipole moment that may be significantly greater than the simple earth geo-potential induced electric field perturbation.
- 3) Production of signatures that are indicative of charge transfer effects in turbulent eddy zone of the exhaust plume. While the signature discussed in Item 1 above would have a relatively slow temporal behavior, this third mechanism might appear as high frequency components indicative of the turbulent effects.

A set of voltage-probe antennas were used to monitor the local electric field strength induced by geo-potential physics as well as modifications induced by the launch at ranges of approximately 1 kilometer.

Simple examination of the data acquired during the launch period failed to show a simple fiducial structure of field variations with the launch event. Several reasons can be ascribed to this lack of event data:

- 1) The sensors were not optimized for detection of the signatures induced by the missile launch. The sensors used for these measurements were originally designed for use in a personnel motion detection study conducted by SARA, Inc. for ARPA under its SBIR program. One of the sensors (designated ELF0) had a low pass cutoff frequency on the order of 100 Hz, a high pass cutoff frequency on the order of 3 Hz as well as notch filters for reducing the signature induced by the local power grid. The other sensors were prepared for the WSMR tests and had extended band ranges for detecting a wider range of signatures. These sensors (designated MLD 1, 2, 3, and 4) had internal cutoff frequencies of 2 kHz and 0.2 Hz, respectively. However, post test examination of the antennas on these second type of sensors showed that the potting antenna base potting compound had a conductivity which increased the high pass cutoff frequency from 0.2 Hz to the several Hz regime. The relatively high

frequency of the high pass cutoffs would basically eliminate the ability to detect the slow temporal variation induced by the interaction of the missile/plume with the earth geo-potential.

- 2) The electric field potential variations have a limited spatial correlation length - the fields measured in one region have little correlation to measurements made at distances of a kilometer away. The potential variations are related to localized atmospheric disturbances and are generally unpredictable. A value for the spatial correlation length is also not known.
- 3) The conductivity of the plume and missile body are not adequate to produce a field perturbation of adequate magnitude. However, phenomena related to the exhaust plume and missile may exist and be outside of the collection range of the equipment employed for these measurements as described in Item 1 above.
- 4) The presence of 60 Hz power line noise was of sufficient magnitude to irreversibly contaminate measurements. This was particularly true for data obtained with sensors at the site at the end of Road 237. A power distribution line was quite near to this site and no notch filters were available for these sensors.
- 5) The presence of fairly significant background noise probably induced by lightning physics in earth-ionosphere cavity. This leads to a large number of "impulse-like" signatures that make identification of a simple fiducial associated with the launch quite difficult.
- 6) Time - tying of the waveforms between the various detection sites was not handled in a very precise manner. This lead to time offsets in the waveforms (established by performing a cross correlation analysis) that was on the order of several seconds.

However, post processing of the data showed that a few of these difficulties could be eliminated. Cross-correlation techniques allowed for the determination of the appropriate time shift needed to synchronize the data and directly compare measured signals between the various sites. Additionally, spectral analysis of the data showed that the primary noise effects were associated with signals propagating in the earth-ionosphere cavity. This was indicated by numerous resonances starting at 7 to 8 Hz and progressing upward in steps of about 7 Hz. Numerical decimation of the data to below 10 Hz resulted in a waveform for the ELFO detector that readily shows a transient that occurred at the time of launch and which does not show extensive pulse-like contamination over the measurement window.

2.0 Scientific Premise

The simplest signal production mechanism that can be envisioned involves the perturbation induced by the missile and its plume interacting with the geo-potential field. The geo-potential field above the earth's surface is caused by cosmic ray and natural radiation leading to an ionization of the atmosphere as well as a small net current density. This in conjunction with additional currents induced by the distribution

of thundercells around the planet leads to an electric field distribution in the earth-ionosphere cavity. The electric field gradient near the ground and at sea level is approximately 150 V/m for fair weather conditions and exhibits variations due to local weather and diurnal effects. A conducting object placed within this field will locally alter the field distribution.

The primary premise for this experiment was that the presence of the missile body and exhaust plume conductivity would provide a perturbation that could be detected. Detection of this slow variation in field would depend on spatial correlation and magnitude of naturally occurring variations in the ambient field as contrasted against this slowly varying temporal field. SARA, Inc. measurements for personnel detection schemes had already shown that detection of fields down to one thousandth of ambient could be used for successful discrimination of personnel over ambient signatures. As part of the WSMR measurements, it would be necessary to characterize the ambient noise characteristics in temporal/frequency domains of interest to missile launch detection.

In Section 2.1 we provide a simple theoretical estimate for the temporal variation of the plume conductivity. This result along with simple transmission line propagation analysis implies that the missile plume provides a fairly long conductor which effectively shorts out the ambient geo-potential induced electric field. Accordingly, in Section 2.2 we provide a theoretical estimate for the field perturbation that would be produced by a missile that has a fixed vertical acceleration. The temporal variation can be contrasted against the bandwidth characteristics of the detection system in order to assess whether or not the present baseline instrumentation would be appropriate for measuring the predicted field perturbation.

Besides this simple physical mechanism, other processes may lead to signatures in the low frequency band. These include phenomena that relate to triboelectric effects (arising from interaction of the missile plume with either the ground or the missile/thruster structure) as well as turbulent eddy effects that lead to higher frequency excitations than those predicted by the simple quasi-static model for the interaction of the ambient geo-potential field with the missile/plume system. We have not developed a theoretical model of these signatures but have kept them in mind in examining the data for possible signatures that may be of use in detecting a missile launch.

2.1 Estimate for Plume Conductivity Versus Time

SARA, Inc. developed a simple model for estimating the conductivity of the plume material as a function of time after exhausting from the missile. This analysis assumes that the initial material is highly ionized after combustion and through electron attachment, electron-ion recombination, and ion-ion recombination eventually returns to ambient conductivity. For this analysis, nominal values for the various three parameter air chemistry parameters (i.e., electron plus single species positive and negative ions) were assumed in calculating carrier species densities as a function of time. Similarly, nominal mobility values for electron and fast ions were assumed in determining the total conductivity of carriers.

Figure 2.1-1 shows the resulting conductivity versus time profile provided by this analysis. The model does not include all of the complexities of exhaust expansion effects on the air chemistry, effects of turbulent mixing as well as evolution of the ion species to slow ions; however, the resulting curves do show that the plume takes a long time to return back to ambient conductivity values. Also note that while we assumed that the ionization fraction was very high for these specific results, parametric and asymptotic analyses show that the late time behavior is very insensitive to initial assumptions (i.e., the plume quickly loses memory of initial conditions).

Based on these results, we performed some additional analysis of the characteristic propagation length for signals along the plume based on a simple transmission line analysis. This analysis showed that the effect plume length in the few Hz regime would be on the order of a kilometer. Thus, we developed a model of the interaction of the ambient geo-potential induced electric field with the missile plume system based on a simple assumption that the plume appeared as a highly conducting channel (in comparison to the ambient air conductivity) and lead to an effective shorting of the electric field in the plume volume.

Page for transient conductivity analysis.

Figure 2.1-1: Estimate for Plume Conductivity Versus Time Since Exhaust for Various Initial Temperature. Note that ambient conductivity values (late time flat plateau) are not reached until well into the multi-second time regime. Plume temperatures vary from 300 °K (lowest curve) 30,000 °K (upper curve) in uniform logarithmic steps. For a Mach 3 vehicle, these results implies fairly long time regimes before the plume conductivity returns to ambient levels.

2.2 Nominal Estimate for Geo-Potential Perturbation

The estimate for the field perturbation versus range from the launch location was based on a simple prolate spheroid geometry. The launch was assumed to be vertical in direction and a constant velocity of Mach 3 was assumed for the missile. In an attempt to crudely account for the physical expansion of the plume, the plume diameter at the ground level was assumed to be 3 meters over the duration of the launch. Additionally, for the sake of simplicity, the plume conductivity was assumed to be much higher than ambient and be constant throughout the plume volume and throughout time.

Figure 2.2-1 shows the resulting estimate for the resulting electric field perturbation versus time seen by a ground observer at various ranges. The ambient geo-potential induced field was assumed to be 150 V/m. Note that the time to peak for these curves is somewhat dependent on range with peaks occurring in the hundreds of seconds regime. We must note that air chemistry effects will tend to heavily erode the increased conductivity by this time and therefore we expect that the actual waveform will likely peak in the seconds to tens of seconds regime. These results imply that an optimal detector for observing this phenomenon should have an excellent response down to at least 0.1 Hz. Additionally, from these results and the realization that the actual peaks will be moved back to earlier times, we find that the peak field perturbation for a ground observer at the 1 kilometer ranges should be on the order of 10 volts.

3.0 Measurement System

Two types of measurement systems were used for the ATMD tests. The first type of system (designated ELFO) was previously developed by SARA, Inc. in 1991 under private internal funds. This detector and associated electronics is described in detail in Section 3.1. Additionally, a second set of sensors were fabricated under SARA, Inc. internal private funds specifically for use in the ATMD tests. These detectors had extended bandwidths beyond the original DLF0 device. This redesign was intentionally effected in an attempt to monitor a broader range of phenomena than could be monitored by the bandwidth restricted ELFO device. A basic description of this device is supplied in Section 3.2.

3.1 ELFO Probe System

Figure 3.1-1 provides a layout of the sensor/preamplifier system that SARA, Inc. (originally developed under an internal SARA, Inc. activity) to measure near-field electric fields developed in the Sub VLF regime. The following is a description of the

Figure 2.2-1: Estimate for Field Perturbation Versus Time For Various Ranges from Launch Location. Plume Conductivity was assumed to be much higher than the ambient air conductivity.

Figure 3.1-1: Electrical Layout of Sensor/PreAmp Assembly. Output from this device is sent to a set of filters and subsequently to the Data Acquisition System and Controller. (Note on Indices: P is pico, N, is nano units. Note on Units: Resistances in Ohms, Capacitances in Farads.)

baseline design of the sensor and preamplifier unit.

The design is fairly straightforward once an understanding of the field production mechanisms and the atmospheric electrical properties are combined with the input preamplifier design. The output from the electric field sensor (antenna) is tied to the input of a JFET input operational amplifier. Figure 3.1-1 provides analytic estimates for the input capacitance and resistance of the antenna to a far field source as well as the parasitic capacitance of the antenna/preamplifier enclosure back to local ground. The high impedance ($10^{12} \Omega$) of the amplifier leads to a flat, approximately unity gain frequency response above a frequency which is proportional to the inverse of the antenna capacitance to near ground and the input impedance of the amplifier. Note that the preamplifier requires a small bias current (pA regime) in order to avoid drift and saturation effects. For this reason as well as to provide electrical protection, two back-to-back 1N914 diodes were placed at the front end of the LF 353. Note that the LF 351 model inherent in the electrical modeling code library that was used for numerical simulations was used to represent half of an LF 353 (there are two independent operational amplifiers on each LF 353 chip). This drops the preamplifier input impedance down to about $10^9 \Omega$. For the antenna size used in our prototype system the breakpoint frequency is on the order of 10 Hz.

The increased capacitive impedance at lower frequencies leads to a fall-off in the signal response of the preamplifier that is proportional to frequency. At very low frequencies (below roughly the inverse of the dielectric relaxation time of the atmosphere or about 3 mHz), the resistive loading of the antenna through the conductive air channel will dominate and the response flattens out to a gain value given by the ratio of the preamplifier input impedance to that of the input resistance

from the air to the antenna (see Figure 3.1-3 for the frequency domain transfer function of the full preamplifier/filter assembly). Such a behavior has the advantage of rejecting the relatively large "DC" component of the ambient atmospheric field while not greatly reducing signals in the several Hz and higher regime.

Finally, the preamplifier has an additional amplifier stage to ensure sufficient signal strength such that cable leakage between the preamplifier and the filter box does not significantly degrade, and to match the output line impedance. The $1\text{ G}\Omega$ resistor indicated in Figure 3.1-1 can be set to other discrete values allowing for a net gain of X1, X10, and X100. This allows for a boost in the output signal so that leakage in the cable run (RG-59 coaxial cable over a distance of about 10 m) between the sensor and the Data Acquisition system does not become significant.

Figure 3.1-2 provides a circuit layout of the filter assembly that was used in our test activities. This filter assembly was used to eliminate low frequency noise outside the range of interest for detecting personnel motion, remove strong power distribution induced signals (allowing for larger dynamic range for signals of interest) and to remove the possibility of frequency aliasing in the digitization process.

Active notch filters are included to reduce the 60 and 180 Hz signals produced by local power distribution systems. Without notching, the 60 and 180 Hz signals would push the peak-to-peak level of the time domain signal and thereby impose severe quantized limitations on the digitally converted signal. Both notch filters are based on active filters driven by a twin T filter, with an additional op amp included in a feedback loop so that the Qs of each filter can be adjusted. Since the components of the twin T are not exactly matched (2% components were used) adjustment of the Q is used to maximize rejection of a given frequency component.

Besides notch filters, we have also incorporated multipole high and low pass filters. The high pass filters are used to cancel out $1/f$ "popcorn" signals that are generated in the preamplifier, as well as DC offset signals that are produced by imbalances in the amplifiers and battery power source. The low pass filters are used to suppress high frequency signals (VLF and above) that would lead to aliasing in digitally sampling the signals. The output of the filter box is again actively amplified and matched to the signal line. As shown in Figure 3.1-2, the output cable capacitance, and Data Acquisition System (DAS) termination impedance has also been incorporated into the circuit model for estimating system response.

Figure 3.1-2: Electrical Layout of Filter Assembly. Input comes from the sensor/preamplifier assembly.

The analog-to-digital conversion box is a commercially available MACADIOS; 8 analog input channel DAS. We have modified the MACADIOS unit to take direct DC power instead of the original AC power required by the device. This unit has 8 channels and a maximum sampling rate of about 30,000 samples per second with a 12 bit resolution. This DAS has a sampling rate which is sufficient for measuring any S-VLF signals without causing undue aliasing. The DAS has a variable input gain that can be set to values of X1, X10, X100, X200, and X500.

The DAS is presently controlled by a Macintosh PowerBook 170 computer. This computer stores and post processes the data for identification of signal attributes that may be exploited for "target" identification. Besides the elements shown in Figure 3-1, the full signal acquisition system has been placed in a metal attache case with internal DC 12V battery power to eliminate grounding and noise effects from any AC power

source.

Besides the physical features of the analog electronics, we also select digitizing rates such that the Nyquist half-band frequency "folds" any higher harmonics of the 60 Hz power signals back onto the lower 60 Hz harmonics. This folding concentrates any aliased power signals into easily identifiable spectral lines for post-processing and removal.

Figure 3.1-3: Calculated Frequency Response of Monopole ELF0 Sensor with PreAmp and Filter Assembly Run into DAS.

3.2 Modified S-VLF Detectors

In order to look for wide bandwidth signature, we fabricated four detectors that had a low pass filter structure that would allow measurement to higher frequencies. Additionally, the high pass structure was modified to produce a smaller roll off in the sub Hertz regime. Figure 3.2-1 shows the predicted frequency response for these sensors. The sensors have an output buffer amplifier that can be adjusted from unity gain up to X10,000. The result shown in Figure 3.2-1 is for the specific case of unity gain in the output amplifier.

Figure 3.2-1: Response of Increased Bandwidth (MLD) Detectors.

These detectors were set up in pairs in a gradiometer configuration with a baseline separation of about 12 m between the vertical monopole antennas. Each antenna had a net vertical height of about 2.5 m. The output from these detectors were run to a Sony Digital Acquisition Tape (DAT) recorder. A single gradiometer configuration was deployed at both the 473 benchmark site as well as the site at the end of Road 237.

For final transfer to computer, the DAT was fed back into the MACADIOS DAS and the tapes were sampled over short windows of about 35 seconds duration around the time of launch of the two missiles. The tapes were sampled at a rate of 555.532 μ s per sample. This sample rate would ensure that any aliasing of 60 Hz harmonics would map back onto lower 60 Hz harmonic components. The record length was restricted by the 65536 sample length restriction of the MACADIOS DAS.

3.3 ATMD Measurements

The measurement hardware (probes and recorders) were placed at different locations during the launch events on 1/25/93 and 1/27/93. During the first launch event all sensors were placed at Chat site in a distributed array. The locations indicated as 473 and 237 as well as Chat were used for the later launch events. Figure 3.3-1 shows the locations of these measurement locations as well as the location of the launch site.

At the 237 and 473 sites, the gradiometer configurations were aligned radially from the launch site. The DATs at these sites were started at about 15 minutes prior to scheduled launch time. Subsequently, the tapes were recorded into a PowerBook 170 through the MACADIOS DAS for analysis. The record was roughly centered about the actual time of launch.

Note that time-tieing between the DAT recorded sensors was fairly crudely performed by synchronization by a simple watch. At the Chat site, the time-tieing was even cruder owing to the need to deploy the ELF0 sensor further away from the power line at Chat. This resulted in the need to have the countdown shouted to the DAS operator over a distance of a couple hundred meters. This plus reflex delays and actual launch time delays lead to significant uncertainty in synchronization of the various data records.

4.0 Data Analysis

The data collected during the launches was examined off-line. A significant amount of powerline noise was present in the data. The 60 Hz powerlines in the region resulted in contamination of all recordings with related noise. The acquisition equipment was battery powered and therefore did not contribute to the source of the noise.

4.1 Simple Time Domain Signal Comparison

Initially, a simple analysis was performed in an attempt to identify any signatures that may be produced by the missile launch. Figure 4.1-1 shows the resulting comparison of the data obtained at the three deployment sites centered around the first launch conducted on 1/26/93. The raw data was smoothed by a simple moving average in order to kick out the 60 Hz component. However, significant "noise" is still left in the data. While suspect peaks are indicated (???), such discrimination is questionable. Numerous peaks present themselves as candidates for consideration. Additionally, the peaks are offset by considerable times even though we attempted to

Figure 4.1-1: Simple Comparison of Three Measurement sites. Data has been smoothed by a simple moving average in order to eliminate the 60 Hz Noise Component. Also, the MLD detectors have been analyzed based on a gradiometer configuration.

synchronize by hand as closely as possible.

In order to determine if the identified peaks are appropriate candidates, we have performed additional analyses to optimize time tying between the data and to determine if the noise induced signals could be separated from possible launch induced signals.

4.2 Background Signal Analyses

Figure 4.2-1 shows the power spectrum calculated from the data obtained with the ELF0 sensor. The periodogram was obtained by segmenting the 65536 sample length record into 1024 bit segments, applying a Hanning window on each segment and then averaging the spectrum of all windows. The resulting spectrum clearly shows a set of resonances at approximately 7 to 8, 14, and 21 Hz. These values are clearly indicative of Schumann resonances in the earth-ionosphere cavity. This result implies that background noise of this type could be reduced by applying an appropriate filter to the data. If the missile launch signals lie outside the stop band filter, such signals may be enhanced. In Section 4.4.1 we provide the results of this analysis.

4.3 Cross Correlation (Time Synchronization) Analysis

In order to provide a better time tie of the data, we performed an analysis of the cross correlation between the waveforms obtained at the various sites. Note that this might appear risky since geo-potential noise at very low frequencies do not have excellent spatial coherence (site-to-site distances were on the order of a kilometer); however, we still performed this analysis using the standard cross correlation routine in the MATLAB toolbox. The cross correlation used the self normalization routine so that the autocorrelation function of a given waveform would yield unity at zero offset.

Figures 4.3-1 and 4.3.2 show the results of the cross correlation of the 237 and 473 sites against the ELF0 result. All of the waveforms were numerically decimated to eliminate 60 Hz effects on the cross correlation analysis. We see that the cross correlation generates a sharply peaked distribution for both cases. Thus, there is sufficient spatial coherence to obtain an estimate of the offset time developed by our primitive time-tying. Figures 4.3-3, 4.3-4, and 4.3-4 show the corresponding realigned waveforms for the three measurement sites. The overlap of the primary peaks in for the Chat and 473 sites are quite good. However, for the 237 site, the candidate peak (switched polarity) is imbedded in heavy noise. This may be due to the power distribution site near the 237 measurement site. The 473 site was the furthest from any power distribution and the Chat site detector used added active notch filters to help reduce power line effects.

Figure 4.2-1: Power Spectrum of Data from ELF0 at CHAT Site. Spectrum shows several peaks at frequencies in the 8 to 30 Hz regime that are induced by Schumann resonances in the earth-ionosphere cavity. Lightning activity in storms around the planet lead to this behavior.

Figure 4.3-1: Result of Cross Correlation Between Chat and 473 Benchmark Sites. Result shows an offset of about 196 bins or a time difference of about 6.5 seconds between the time windows for the CHAT and 473 benchmark sites.

Figure 4.3-2: Result of Cross Correlation Between CHAT Site Record and End of Road 237 Site. Result shows an offset of the time line that corresponds to 241 bins or a time difference of about 8 seconds between the two data records.

Figure 4.3-3: Baseline Time Line for ELF0 Detector. Primary peak at 10 seconds is possibly launch related. DAS operator kept running stop watch during launch and estimated launch time that coincides with the 10 second time to within 1 second.

Figure 4.3-4: Shifted Waveform for 473 Site. Waveform was shifted by time obtained through cross-correlation analysis.

Figure 4.3-5: Shifted Waveform for 237 Site. Waveform was shifted by time obtained through cross-correlation analysis.

4.4 Enhanced Low Frequency Signature Evaluation

Based on the spectral analysis of the noise (presented in Section 4.2), we reexamined the data in order to see if further decimation would enhance the peak observed in the ELF0 data with respect to the other peaks that were possibly due to Schumann resonance induced noise. In Figure 4.4-1 we show the raw data that was obtained at the Chat site with ELF0. This data includes the effect of power line signals and shows a wide band of noise with numerous spikes in response. Note that the large response at early time is due to the pickup of the motion of the DAS operator while the operator moved clear of the ELF0 probe.

In Figure 4.4-2 we show the resulting waveform for the case where the data has been decimated by a factor of two. For this specific measurement, the sample rate was 240 samples per second. Thus a decimation by a factor of two will lead to a high order cutoff frequency that is just a bit below 60 Hz. This amounts to eliminating the 60 Hz and any higher order aliased harmonics from the waveform. While the heavy band of noise has been somewhat diminished, there are still numerous peaks in the data. Thus identification of a unique signature associated with the missile launch is quite difficult.

According to the noise analysis, most of the Schumann resonance effects can be eliminated by low passing the data below 8 Hz. Thus, we further decimated the ELF0 waveform by a factor of eight. Figure 4.4-3 shows the resulting waveform. Other than the early time personnel motion effects (footfall for a walking individual has a primary frequency on the order of a couple Hertz), there are only two large peaks in the data. The first one corresponds to the onset of the first missile launch. Note that there is no clear signature associated with the time of the second launch (about 30 seconds later). We do not know whether this is due to the initial plume from the first launch suppressing the second launch's signal, the initial spike being produced by some spurious control signal that controlled initial launch onset, or that the signal is just an unusual naturally induced spike that coincided with the launch time.

Additionally, there is a large spike in the decimated data at a time of about 60 seconds after launch. The raw data shows a large transient at this time that has a strong damped sine wave appearance with interference effects. Spectral transform of this impulse again shows strong Schumann-like resonances. Because the transform also shows a strong "DC" component, it is not likely that the signal was produced by a distant source which would experience dispersive smearing and a loss of the DC component. This argues for a localized source. While there was a storm off the west coast of Mexico during the launch, we do not suspect that lightning transients at such a range would lead to this type of behavior. An alternate possibility may be that at this

Figure 4.4-1: Full Data Record for ELF0.

Figure 4.4-2: ELF0 Data Record Decimated by a Factor of 2.

Figure 4.4-3: ELF0 Data Record Decimated by a Factor of 16.

time the missile was reaching a high enough altitude that the missile/plume may have heavily interacted with the D-layer and initiated some unusual Schumann resonance excitation.

4.5 High Frequency Signature Evaluation

As discussed above, there is the possibility that other physical processes may lead to signatures that have rather high frequency components. These components may be tied to turbulent phenomena which also result in the acoustical emission of the missile. For this reason, we extended the low pass cutoff of the MLD filters in order to look for other signatures than those that could be detected with the ELFO detector. Accordingly, we developed some power spectrum periodograms of the 473 detector for times just prior to and directly after the initial missile launch. Figures 4.5-1 and 4.5-2 shows the resulting spectra for these two cases.

In Figure 4.5-1 (prior to launch) we see a broad band spectral response that has odd harmonics of the 60 Hz power distribution system as well as a "1/f" type noise signal at frequencies below about 400 Hz. Above 400 Hz the noise floor flattens out into a flat region that is possibly indicative of the dynamic range of the digitized data. Note that the sampling rate for the experimental runs was selected to ensure that additional power line harmonics beyond 900 Hz would be folded back down on one of the 60 Hz harmonics. Thus, we see that there is no apparent aliased peaks from high frequency sources that might exist above 900 Hz.

In contrast to this result, Figure 4.5-2 shows the resulting spectrum for the time period just after launch. This spectrum shows a number of high frequency peaks that are not present in data prior to launch. At this time we do not know whether or not this is a missile/plume induced effect or may be due to other operations signals in the WSMR area. It would be interesting to obtain data on the acoustical output of the Lance system to see if there is any correlation with the MLD spectrum. Of course with the restricted amount of data obtained during this test it is at present difficult to determine whether 1) this signal is due to turbulent effects cross coupling to an electromagnetic effect, 2) this signal is just a microphonic pickup of the acoustical output of the missile, or 3) is induced by some other source at WSMR.

5.0 Summary

The lack of excellent event-dependent data in our examination suggests a null result for this experiment. The factors that contribute to this assessment include the natural noise processes, manmade noise, and the possible lack of high spatial coherence in the signals across the time/frequency domain of interest for ranges on

Figure 4.5-1: Power Spectrum Prior to Launch for Site at End of Road 237. Narrow peaks correspond to harmonics of power line. Sampling rate ($555.532 \mu\text{s}$ per sample) selected to ensure wrapping of higher aliased power line harmonics back onto lower frequency harmonics.

Figure 4.5-2: Power Spectrum after Launch for Site at End of Road 237. Primary narrow peaks correspond to harmonics of power line. Sampling rate ($555.532 \mu\text{s}$ per sample) selected to ensure wrapping of higher aliased power line harmonics back onto lower frequency harmonics. Spectrum also shows additional peaks at 390, 430, and 500 Hz that did not appear in power spectrum of data measured just prior to launch.

the order of kilometers. Further investigation of spatial correlation length is required. Additionally, improved instrumentation with full spectral calibration would help resolve problems that may be associated with the equipment used for this test.

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