Research Report
UKTRP-83-10

# IMPROVED STRUCTURAL MONITORING WITH ACOUSTIC EMISSION PATTERN RECOGNITION

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for presentation at
14th Annual Symposium on
Nondestructive Evaluation
April 19-22, 1983
San Antonio, Texas

April 1983

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Abstract

A unique acoustic emission monitoring system originally developed for in-process weld monitoring has been used to monitor fatigue crack growth in a highway bridge during normal traffic loading. The system was able to clearly and reliably detect the presence of fatigue cracks that were adjacent to a row of bolts. The results of the brief experiment show that the signal processing used in this AE system may allow drastic improvements in the ability of acoustic emission to reliably detect propagating bridge flaws under adverse conditions.

## 1. INTRODUCTION

There is a growing need to insure the safety of the motoring public by performing periodic non-destructive evaluation (NDE) of in-service bridges. Older bridges are being subjected to loadings in excess of their original design capacity. Owing to the combined effects of age, atmosphere, and loading, these structures are prone to sub-critical, growing cracks. Newer bridges have employed ambitious designs, which often incorporate "fracture-critical" structural members. These bridges also rely on high-strength steels and welding fabrication processes to provide economical structures. These bridges have demonstrated a susceptibility to crack problems caused by fabrication-related defects. Unfortunately, the quality-assurance/quality-control measures used in recently constructed bridges have not precluded fracture problems.

A promising NDE technique entails monitoring of acoustic emissions (AE) from bridges and correlation of these emissions with the integrity of the structural members. However, the user of the AE methodology faces many problems due to the environment, complexity, and size of bridges. The uncertainty of internal defect excitation places even further limitations on the AE technique. However, the main limitation with present AE technology is the ability to relate AE signals to specific source events.

Currently available AE instrumentation can perform standard signal analysis, with well defined firmware using the signal in digital form. However, this equipment and methodology does not exploit currently developed signal-processing techniques to characterize defects and their locations. Recent laboratory signal-characterization tests have yielded promising results, but it is not known whether these techniques are viable in field applications. Also, little work has been done to optimize equipment, test methods and data analysis from bridge AE sources. The problem of positively identifying, locating, and assessing flaws is presently an active area of research in AE technology.

## 2. BACKGROUND

GARD, INC. has been actively pursuing the application of acoustic emission monitoring to the in-process NDT of welds for over eleven years. These efforts have culminated in the development of a microprocessor-based acoustic emission monitoring system that can detect, locate, and characterize flaws in welds during the welding process. The system has been evaluated and optimized for a wide range of commonly utilized welding processes and materials. An extensive evaluation program sponsored by FHWA (Contract No. DTFH61-80-C-00083) has just been completed in which the Acoustic Emission Weld Monitor (AEWM) was successfully tested on typical highway bridge materials and weld methods. The detailed results of this program are presented in Report No. FHWA/RD-83-006 to be published shortly. In over 350 feet of laboratory controlled welding in both A-36 and A-514 steel, using both GMAW and SAW welding methods, the GARD monitor detected 97% of the flaws (missing only one porosity). Furthermore it correctly characterized 92% of the cracks. No un-confirmed AE indications were produced, however 14 flaws which were predominantly cracks and lack of fusion were either un-detected or marginally detected by radiography and ultrasonics but were easily detected by the AEWM and confirmed by metallography. The key to this success is the AE signal processing methods developed by GARD. The welding environment is a very difficult area for application of acoustic emission monitoring due to the extremely high acoustic noise levels that exist. These high noise levels preclude the application of conventional acoustic emission monitoring techniques because of the high incidence of AE signals that result from benign or non-flaw related sources. The GARD signal processing technique uses an empirically developed pattern recognition method that keys on the AE signal characteristics resulting from flaw growth and allows the vast amount of non-flaw related AE to be rejected.

The problem of detection of flaw related AE that is imbedded in a high noise background is not unique to the in-process weld monitoring application. Rather, it is typical of a wide range of potential AE applications, one of which is the in-service monitoring of bridges for flaw growth. The belief that the AEWM might prove effective for this application led to the work described in this paper.

## 3. EXPERIMENTAL DESCRIPTION

The tests described herein were conducted on the I-24 Twin-Arch Bridges over the Tennessee River, near Paducah, Kentucky. The tests were performed by GARD with the assistance of both Kentucky Transportation Research Program (KTRP) and Kentucky Department of Highways (KYDOH) personnel.

KYDOH had previously determined that the bridge had suffered out-of-plane bending cracks near the connections in the deck cross beams in the vicinity of the upper flanges. This type of cracking is caused by design and construction problems and is somewhat generic for this bridge type. The cracking is fatigue-related and is not due to any fabrication defects in the steel weldments.

In an inspection performed just prior to the AE monitoring tests KTRP confirmed several crack sites in the cross beams over the piers. The cracks were located at the termini of the upper flanges, usually at the toes of the web-to-flange fillet weld. A typical site is shown in Figure 1. Dye penetrant and in some cases surface rust made the cracks easily visible.

The flaw sites chosen for testing purposes were all located near bolted angle splice plates that connected the cross beams to the tie-girders. It was felt that these locations would be very difficult to monitor because of large amounts of fretting noise resulting from the bolted connections. This assumption was borne out in the tests in that typically over 1000 AE events occurred per hour during the tests. The activity was in all cases associated with the passage of traffic over the portion of the bridge being tested.

Standard resonant AE sensors were used for these tests. The sensors had internal permanent magnets for attachment purposes. Silicone grease was used as a couplant. The sensors were mounted 64" apart along the edge of the angle splice plate. They were acoustically coupled to the cross beam, and the upper flange (which was the site of the crack) was located about 16" down from the top AE sensor (channel 1). The AEWM was used in a two channel linear source location mode. A third sensor was attached as near as practical to the crack site. This 3rd sensor was driven by a high power pulser and was periodically pulsed to produce a simulated AE burst to allow checkout of the AE systems performance. A typical sensor set up is shown in the lower portion of Figure 5. Each receiving sensor had a unity gain preamplifier attached to it. This pre-amp matches the high impedance of the sensor to the 50Ω cable so that cable length is not a factor. Signal cables were fed across the pier and up to the bridge deck where the AE equipment was mounted in a self-contained motor home that acted as a mobile laboratory. Figure 2 shows the mobile lab in place on the bridge.

The AEWM performs the required pattern recognition for flaw detection in real-time. The process consists of subjecting each AE event to a series of tests performed in sequence. The current flaw detection model is a three step process. A flow chart of the process is shown in Figure 3. After computing the ringdown count (RDC) for each event the first test is applied. If the RDC lies within pre-set limits the event is passed on to the next test which is rate. This test requires that there be some number N of events (that have passed the RDC test) within some pre-set $\Delta t$ or time interval. The final test is a test to see if all of the events that passed the previous two tests originate from the same location, or at least within some pre-set locational tolerance. The combination of the rate and location tests provides very high discrimination against interfering background acoustic signals, the assumption being that a growing flaw will produce higher rates of AE burst emission than other processes and that the flaw, being a localized phenomena will produce the high rate from a specific well defined location. Our use of source location as a flaw detection criteria differs radically from the traditional use of source location information. In conventional AE monitoring equipment, source location may be used to lock out given areas or regions of the structure under test, in other words, the system may be made to listen only to a specific location. This approach requires prior knowledge of the probable location of a flaw, and its degree of success depends on the flaws being locationally isolatable from potentially interfering sources (a condition that is seldom met in typical bridge structures). GARD's approach to the use of source location does not limit the monitor to a specific location. Any source location lying between the transducers is monitored. When a group of AE events has satisfied the first two criteria (i.e., ringdown count and event rate) a test is made to see that all of the group of events lie within preset locational limits of each other. For example, if a 1 inch tolerance is used, then the events that satisfied the first two tests must have the same order of receipt at transducers 1 and 2 and their locational clock indications must not differ by more than 16 counts (16μ seconds). If this criteria is met, then a flaw indication is shown at the appropriate location. Later in this paper, the importance of all three tests will be shown.

In addition to the detection of the flaw related AE, the AEWM applies an adaptive frequency analysis model to the flaw-related events and provides a 2 category classification of the source, crack or non-crack.

For these tests a floppy disc system was used in addition to the AEWM to allow post test analysis of data. In this mode of operation, the limits for the flaw detection criteria can be varied and raw AE data can be played back through the modified model thus allowing optimal monitoring parameters to be obtained.

A photograph of the AEWM in operation is shown in Figure 4.

## 4. RESULTS

A total of five sites were monitored over a three day period. Only one of these actually produced AE indications. These indications repeated on two consecutive days and were properly located in the known crack region. The first two sites tested were above the West Pier on the eastbound span. The first area (Location 1) had a 1½" long crack at the flange terminus. Considerable AE activity resulted during the two hour test. The activity occurred in conjunction with traffic and highest amounts of activity correlated with large heavy vehicles. None of the resulting activity produced any AE indications (valid AE). This test constituted monitoring a small crack under light loading conditions. After two hours, the sensors were moved to the passing lane side of the bridge in an attempt to get higher loading on a flaw (Location 2). This site had two 1" cracks visible in a location similar to the first. No valid indications resulted in a two hour test at this site, however, a relaxing of the flaw detection requirements (lowering rate from 4 to 2 Hz) did show some clustering of activity from the crack site along with some scattered background activity.

The next site tested was located on the west bound span (Location 3). This was the most severe flaw tested. There was a 2" long through crack at the toe of the web to flange fillet weld in addition to a second crack emanating from under the angle splice plate directly above the same region. This flaw was positioned under the passing lane of the bridge and so it received the maximum possible loading during the test. Figure 5 shows the results of two separate tests performed on this site over two successive days. Each test was approximately 2½ hours long. The model used for flaw detection had limits as follows:

| | |
|---|---|
| RDC | - 16 to 4000 |
| Rate | - 4 events in one second |
| Location | - 1" tolerance |

In the upper right corner of the printout, the total number of received AE events is shown. For these tests we see that the totals were 2130 for the first 2½ hour monitoring period and 818 for the second. These differences reflect the difference in the amount of traffic for the two monitoring periods. The AEWM Display prints sets of rectangular brackets to represent the two sensor positions with channel 1 at the left and channel 2 at the right. In this display, flaw indications will be shown at any location when the detection criteria are met. The edge of the angle splice runs along the line between the two sensors. The character, C,Ø, in the upper display indicates that at this location the flaw detection criterion was satisfied. Furthermore, the characterization model decided that the AE was crack related. The "Ø" following the comma is the truncated average of the ringdown counts for the four or more events that satisfied the detection model. In this case Ø signifies that the average ringdown count was between Ø and 99. Additional groups of events that satisfied the model are presented below the "C,Ø". Time of occurrance proceeds in a downward direction. The "S,:" indication is produced by our calibration pulser which was located adjacent to the bottom edge of the flange. The cracks extended around the end of the flange and above the end of the flange off toward the angle splice plate. The "S,3" indication occurs at about the end of the flange (S signifies non-crack related). One additional S,2 indication occurs near the midpoint of the monitoring region. Confirmation of a flaw in this region was not possible at the time the test was run.

The lower display was the result of another 2½ hour monitoring period the following day. There was considerably less traffic during this period which is reflected in the lowered AE event count (818). One indication (S,3) occurs from the lower edge region of the flange.

The photograph below the printouts shows the sensors in place. The actual orientation was vertical, however we rotated the picture 90° to place the significant features in approximately the same orientation as the printouts.

To summarize results for this site, all of the indications were grouped around the region of the known crack with the exception of one which occurred at just above the midpoint of the sensor array.

To further test the reliability of the AEWM to discriminate between the fastener noise and the crack emissions we positioned the sensors on an adjacent plate where the same pattern of fasteners existed, but no flaws were visible (Location 3A). A 2½ hour monitoring period from this site produced 700 AE events but no flaw indications. The final site tested contained a fillet weld with a longitudinal crack visible (Location 4). This crack was evidently a product of the fabrication shop and produced no AE activity since no growth was occurring.

To further illustrate the power of the three test flaw detection model, the illustrations in Figure 6, 7 and 8 show what happens when we relax the rate criteria. These figures utilize a different display mode feature of the AEWM. The monitor has provision for connection of an x, y, oscilloscope for the purpose of presenting source location information. In the figures shown, the sensor positions are represented by squares at each side of the display. A bright dot signifies an AE source location that satisfies the flaw detection model. Additional successive indications at the same location further brightens the spot.

In Figure 6 we see two scope displays produced by the same data that produced the printouts in Figure 5. Here the model still requires a rate of 4 Hz or higher from any source. In Figure 7 we see the result of playing back the same data as in Figures 5 and 6, however, the rate criteria has been defeated. The only restriction on data is the use of a ringdown count window (equivalent to an acceptance threshold). Here we see a great deal of clutter on the displays, most of which occurs in locations where no known flaw exists. Figure 8 shows similar results for the unflawed test area. The top display is produced with a normal 4 Hz rate criterion and a very wide open ringdown count window. The next two displays are the results for the same data with no rate test and varied RDC windows. Even though this area is probably flaw free, a multitude of AE sources results. The use of source location and fixed thresholds is obviously not sufficient to eliminate the fastener noise and allow reliable flaw detection.

## 5. SUMMARY

The AEWM was used to monitor several sites on a bridge where known fatigue cracks exist. The two channel linear location system suppressed the acoustic noise from fastener fretting and reliably and clearly detected crack-related activity even though the cracks were either immediately adjacent to or coincident with the bolt holes.

Besides proving that flaw growth related activity can be detected from noisy structural details, this work showed that very small amounts of fatigue crack growth can be detected when a bridge is subject to routine loadings. The volume of traffic on this bridge was not significant compared to bridges in more urban locations. Nor was the magnitude of the bridge loadings unusual. While the valid AE activity was usually correlated with one or two heavily loaded semi-trailer trucks, this type of traffic was very infrequent. Yet, it took no more than two and a half hours to excite the expected AE activity at flaw sites.

This work indicates that unusual load procedures such as heavy proofing loads are not necessary to excite AE activity from a crack which is already experiencing sub-critical growth due to service loading. In-service AE monitoring of a suspect area for a period of less than four hours should be sufficient to detect fatigue cracks on steel bridges subjected to normal structural loading patterns. Structural discontinuities which are harmless will not generate any AE activity and will be ignored.

AE testing, incorporating the equipment and techniques described in this paper, has demonstrated three attributes which make it a desirable NDE method for inspection structures such as bridges:

(1) Good operator productivity.
(2) The ability to detect and define bridge defects (cracks).
(3) The ability to compliment (confirm) other NDE methods.

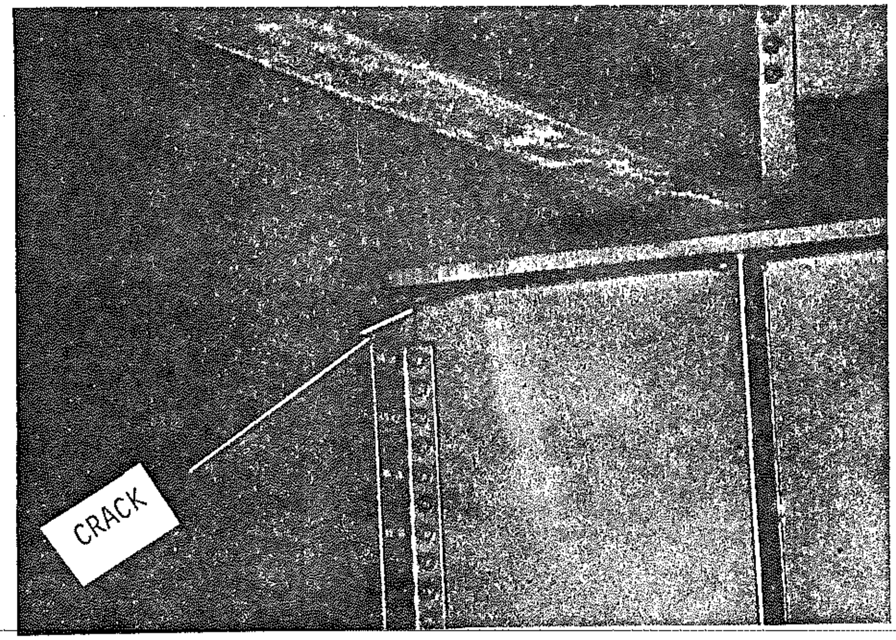



Figure 1 Photograph Shows Typical Crack Site in Cross Beam of I-24 Bridge

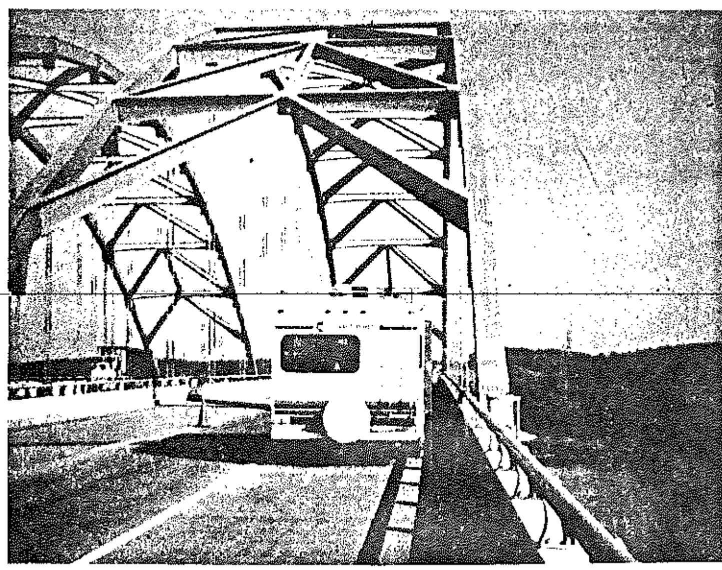


Figure 2 Mobile AE Test Laboratory in Operation on I-24 Bridge

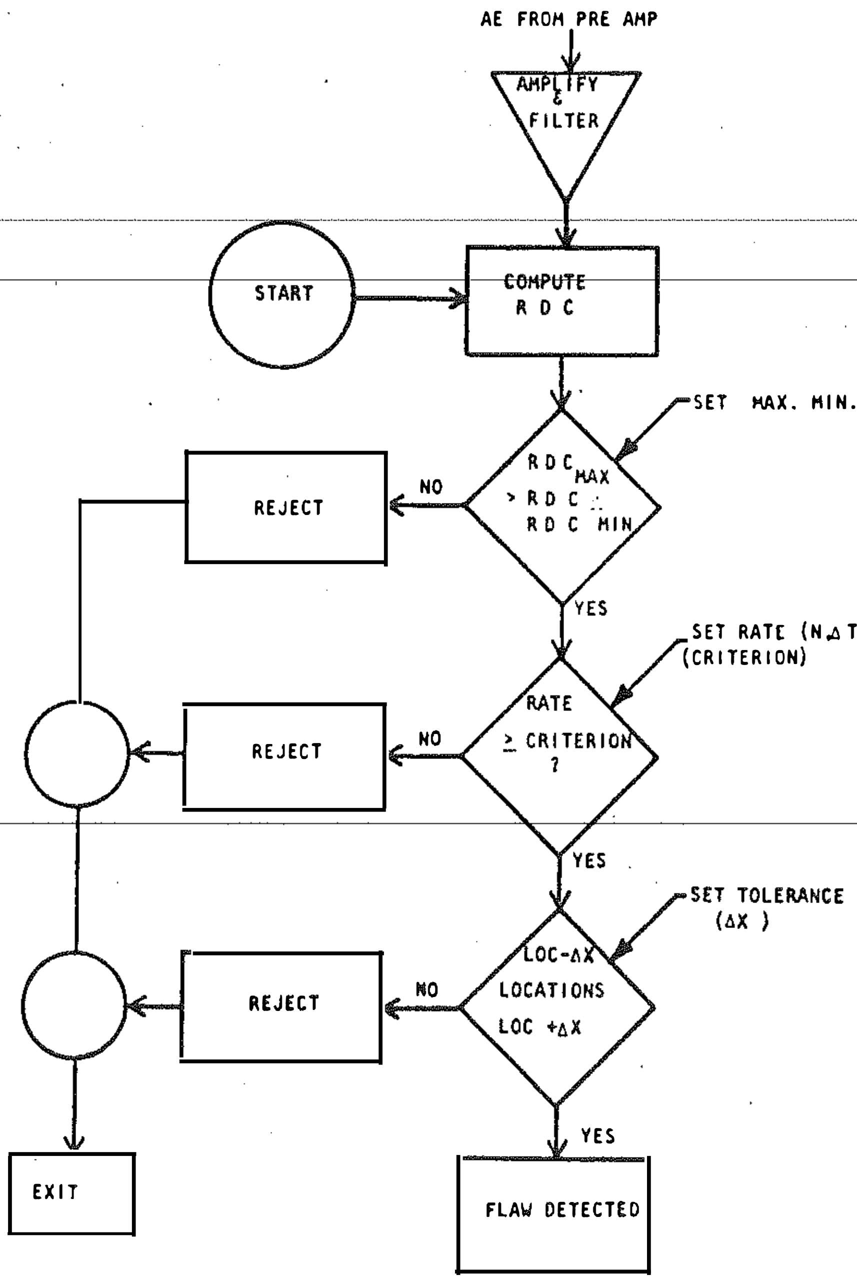



Figure 3 AEWM PROCESSING FLOW CHART FOR FLAW DETECTION

Figure 4  AEWM In Operation During Bridge Monitoring Test

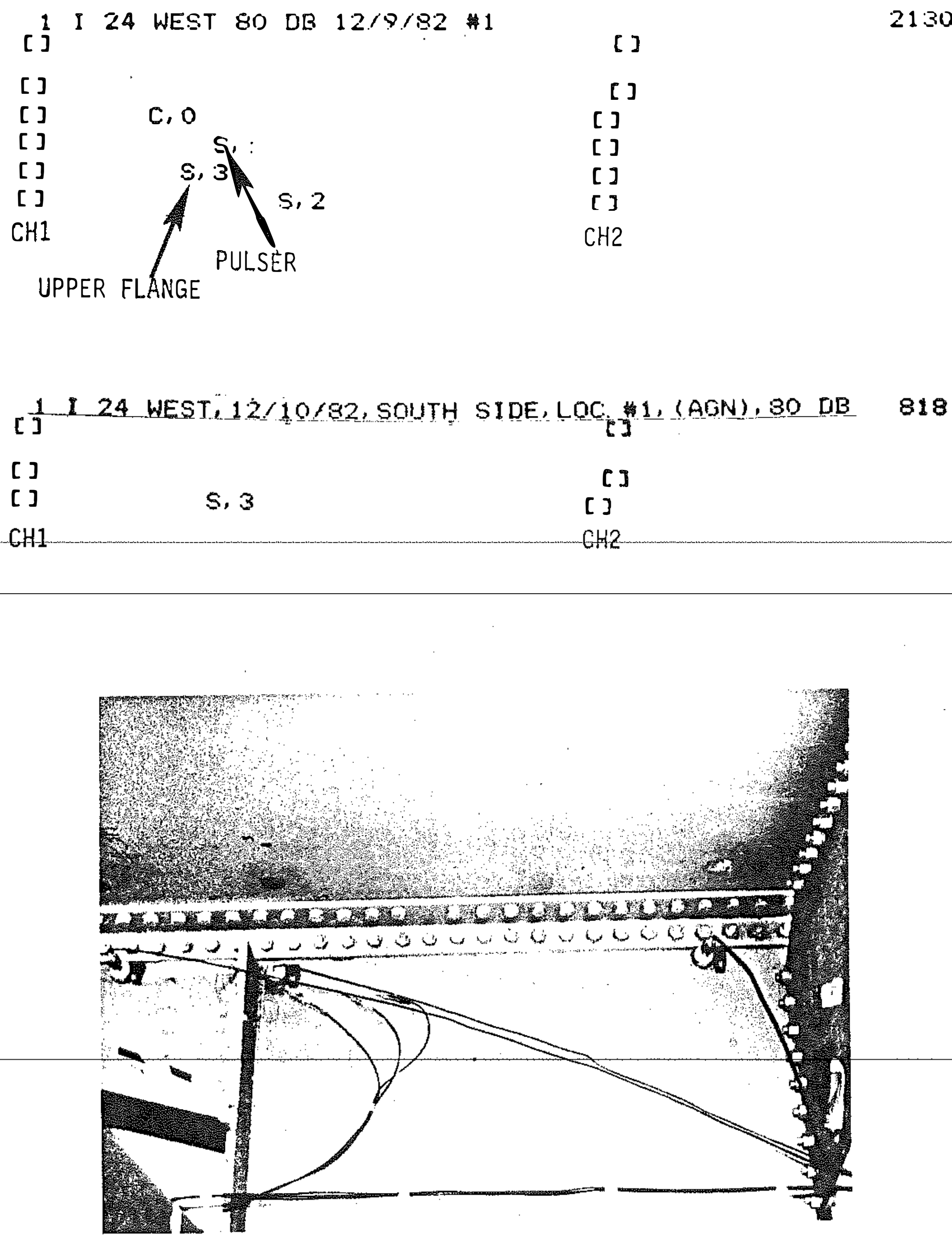
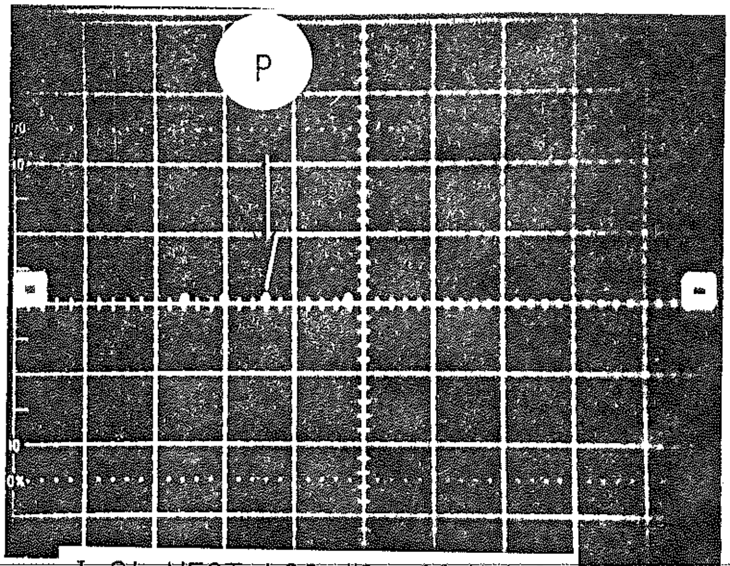
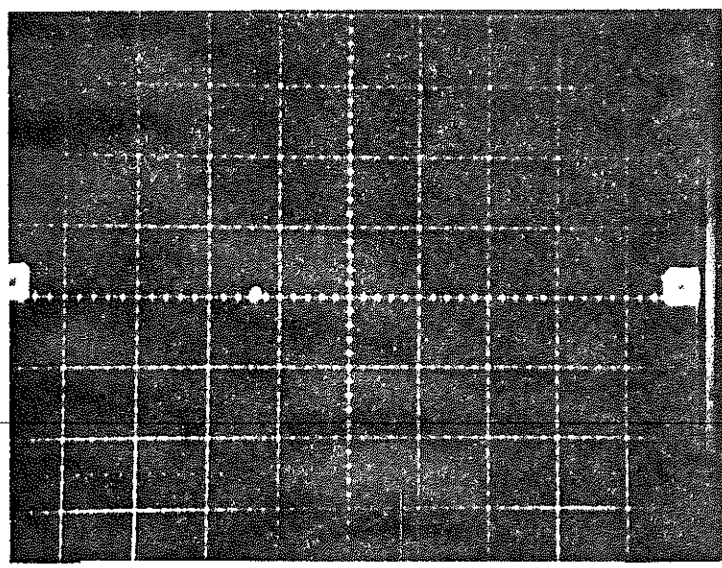



Figure 5 AE Results For Location #1 Westbound



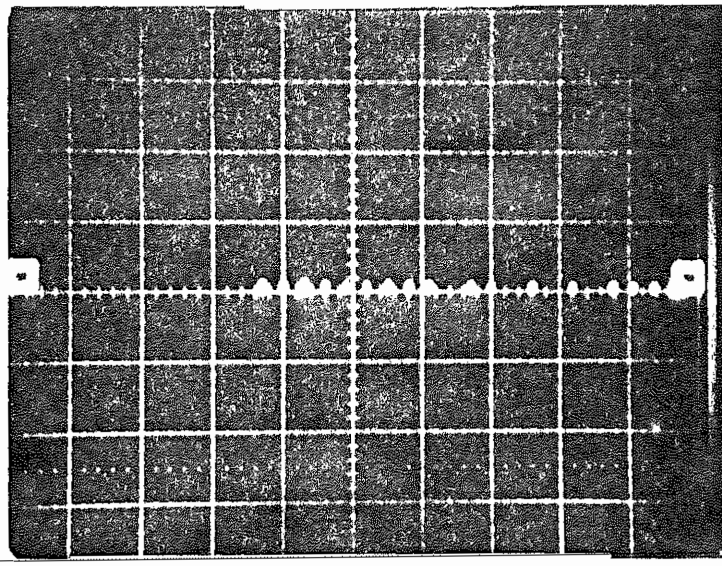

I-24 WEST LOC #1 12/9/82



I-24 WEST LOC #1 12/10/82

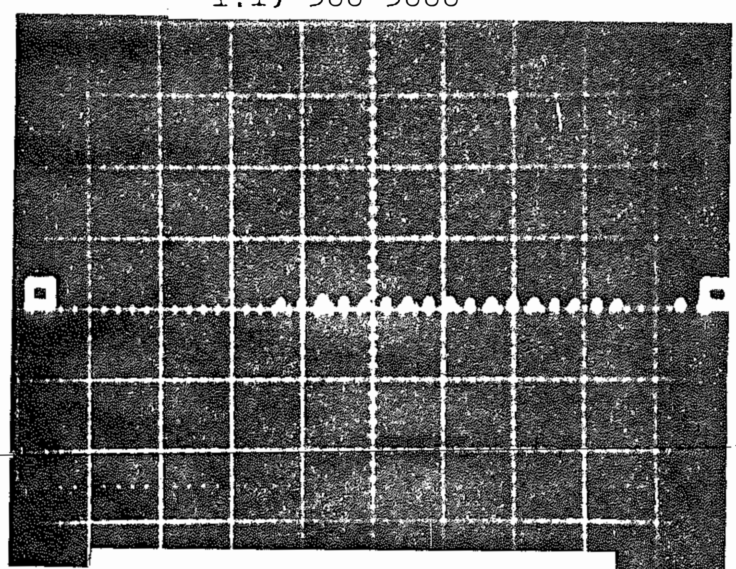
Figure 6 AE Source Location Plots

1:1, 100-1000



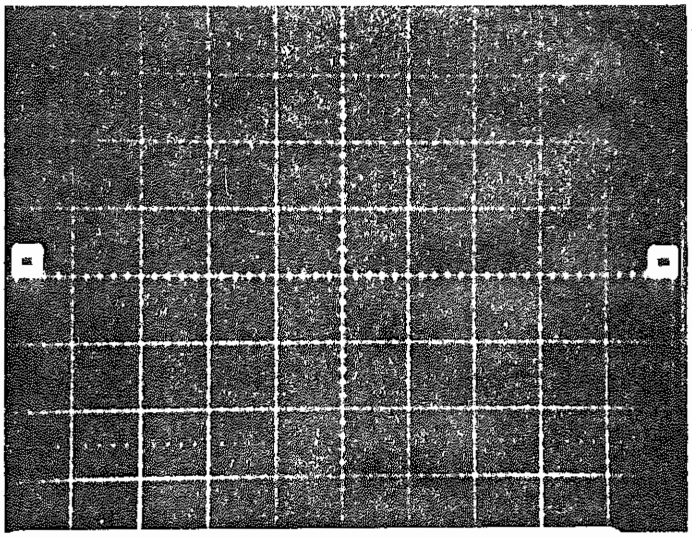
I-24 WEST LOC #1 12/10/82

1:1, 500-5000

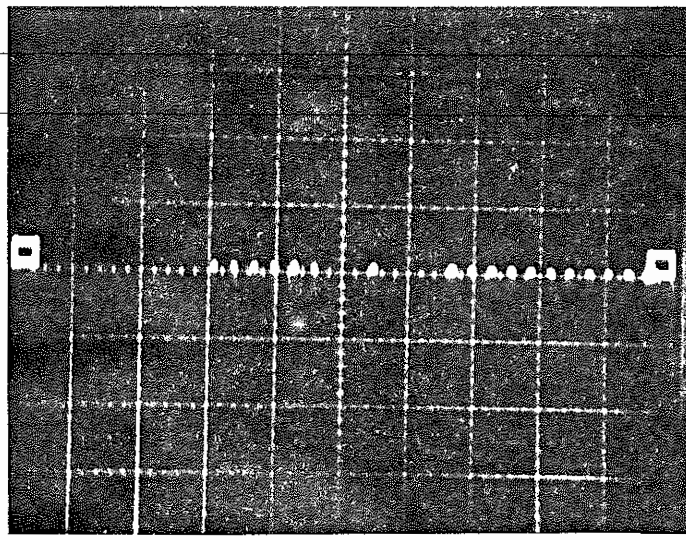


I-24 WEST LOC #1 12/10/82

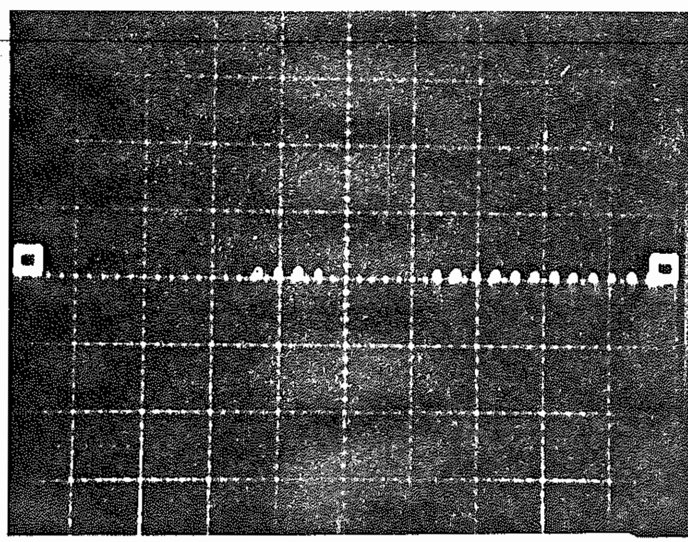
Figure 7 AE Source Location Plots



I-24 WEST CONTROL 4:1, 16-4000



I-24 WEST CONTROL 1:1, 100-4000



I-24 WEST CONTROL 1:1, 500-4000

Figure 8 AE Source Location Plots