THE KOREAN SEISMO-ACOUSTIC ARRAY

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ABSTRACT

The Korea Institute of Geology, Mining, and Materials (KIGAM) and Southern Methodist University (SMU) are jointly installing a four-element 1-km aperture seismo-acoustic array at 85 km northeast of Seoul, Korea, similar to the seismo-acoustic arrays at Lajitas, Texas (TXAR) and at Mina, Nevada (NVAR). This array will be used to identify and locate events associated with industrial blasting. These identified and located events will then be used to form a ground-truth database.

The Korean array uses Geotech Intelligent Communication Processing System Model 59660, similar to the prototype infrasound array at Los Alamos National Laboratory. Significant differences in the new system include the use of 2.4-GHz radios for inter-array communication and a link for the outgoing alpha protocol, use of three-channel digitizers with calibrators rather than single-channel digitizers, use of 40 SPS data, a modified alpha stream for weather data, omission of authenticators, and operation of a complete 12-volt system. Each array element includes solar power supplies, a GS-13 seismometer in a 10-meter borehole, and an infrasonic gauge similar to that used at NVAR.

The system was deployed and operated in a test configuration in McKinney, Texas. The primary purposes of the test were to build confidence in unfamiliar equipment, test installation procedures, and identify remote problem diagnosis procedures. The test deployment also demonstrated the characteristics of the infrasonic gauges and noise reducers under varying wind and weather conditions. Wind speed and temperature are measured at one infrasonic site and included in the data stream.

Infrasonic gauges were built using modified 2.5-inch Validyne DP250 sensors mounted in a 4-inch PVC pipe such that the sensor could be easily installed in the seismic borehole. The infrasound gauge included a backing volume of 1 liter, a fore volume designed to be fed from a _-inch hose, a remotely activated calibrator, thermal insulation of the backing volume, electrical and magnetic shielding of the sensor, and the capability to use long RC time constants in the capillary to push the response beyond 120 seconds.

Tests of the gauges at McKinney included self-noise under field conditions (equivalent to blocked mass seismometer tests), comparison and noise tests of systems driven from no or the same acoustic array, comparison tests of arrays of eleven 25-foot, five 25-foot, and one 25-foot 5/8-inch Moisture Master soaker hose. Initial tests of the remote calibrator were made. An alternative simple static field calibration procedure was also developed.

Final tests at SMU examine the capability of the system to send alpha data via mixed radio and wire telemetry to KIGAM to be forwarded over the internet to SMU.

Key Words: seismo-acoustic, array, industrial blasts, infrasound, noise

OBJECTIVE

The objective of this joint Southern Methodist University (SMU) and Korea Institute of Geology, Mining and Materials (KIGAM) program is to design, procure, integrate, test, install and operate a seismo-acoustic array in the Republic of Korea in order to create a ground truth database as has been done for TXAR.

RESEARCH ACCOMPLISHMENTS

Introduction

KIGAM and SMU are jointly installing and operating a four-element 1-km aperture seismo-acoustic array at Chulwon, 85 km north-northeast of Seoul, Korea (Figure 1). The Chulwon array (CHNAR) is similar to the Lajitas, Texas (TXAR) and Mina, Nevada (NVAR) seismo-acoustic arrays in its choice of sensors and geometry. The digitizer and data system, however, are similar to the LANL infrasound system. Waveforms from CHNAR are used to detect, identify, and locate events associated with industrial blasting. These events are then used to form a ground-truth database.

The cooperative cost sharing and operation of the array has been critical to the success of the project. SMU completed system design, instrument procurement, fabrication, testing, and training. KIGAM developed and tested the power and communication infrastructure, the site civil work, and the data integration into the current KIGAM seismic network processing. A joint KIGAM – SMU team made the site selection and initial installation. KIGAM will continue operation and maintenance of the array receiving real-time alpha data from CHNAR, integrating it into their automatic detection and location routines, and forwarding the alpha data stream and automatic locations to SMU for additional analysis.

The Chulwon Array is situated in an area of faulted metamorphic rocks overlain by quaternary alluvium and basalt flows. Geology of the individual 4 element sites varies from competent schist and gneiss to basalt over alluvium. All sites are remote from heavy traffic, although each site has a unique relation to topography. The central site CHN00 (Figure 2) is at the top of a lightly forested hill. Site CHN01 is within 5 m of a moderately traveled narrow unpaved road. Site CHN02 is near the 5-10 m banks of an entrenched river. Site CHN03 is near a 10 m high vertical wall.

The array hub is 4-5 km from the nearest commercial telephone service in the town of Daema-ri although commercial power service is available at the array hub. An existing concrete building is used to house the hub equipment.

Siting an array that was culturally quiet, was suited to microwave communication, was topographically acceptable, was within a reasonable distance of the acoustic sources, had sufficient land area for a pipe array, and was unfarmed proved to be difficult. The intensive farming of all level ground combined with rugged topography limited site selections. The final selection, near Chulwon, is nearly ideal. It is culturally quiet since there is neither through traffic nor much overhead air traffic. All sites are suited for direct radio communication to the hub. The array is well positioned to examine the industrial events associated with activity near Incheon and when combined with the existing KSAR and INCH stations will be well suited for locating events in the region.

Several minor modifications to the design were made to accommodate site conditions. The weather station, originally telemetered by radio from site 0, was moved to the hub and wired directly to the hub controller. This freed a set of radios such that a radio TCP/IP connection could be made between the hub and the nearby town. The original hose array, a six arm radial array of 50’ porous hoses, was modified to an 11 arm 25’ array to minimize the required land around the sites. Boreholes originally limited to 20’ depth were extended up to 30’ to allow better penetration of the bedrock.

Equipment Description

The overall configuration is a union of a modified LANL digitizer and infrastructure with SMU style sensors and power systems (Figure 3).

Each array element uses a GS-13 at the bottom of a 6-20 m deep borehole similar to the installation at NVAR and TXAR. Unlike NVAR and TXAR which used a poured concrete base at the bottom of the hole, at CHNAR the casing was closed with a welded steel bottom insuring that the base of the hole would stay dry, flat, and level. This simplified seismometer installation (NVAR required a down-hole camera).

The infrasonic subsystem used SMU style microbarographs, a modified version of the NVAR design. These use a modified Validyne DP250-14 gauge with P55D electronics. The modifications to the model were gauge improvements to allow a stress free mounting of the diaphragm in the down-hole package. The microbarograph is in a simple plastic pipe package 6 feet long and 4" in diameter with connections at the top for a standard 3/4" pipe thread and at the bottom a connector designed to plug into the digitizer. The design is simple with most components constructed from plastic plumbing parts purchased at the local hardware store. Unlike the NVAR package which used a traditional design of a hose connected to a closed bottle for the fore-volume, the CHNAR package uses a partial impedance match to help control hose resonance. Because the frequencies are low, it is difficult to build an ideal match and still maintain a reasonably small fore-volume. However the partial match does reduce the effect of reflections at the microbarograh connection to the pipe array.

To reduce the electronic noise, particularly when the systems were tested in the lab, the pressure sensor was heavily shielded in a three layer mu-metal cylinder and offset by 40-50 cm from the electronics. This also reduced sensor cross talk when multiple sensors must be operated close together (as for coherence measurements).

In addition to the modifications of the fore-volume, the backing volume of the CHNAR sensors was doubled from NVAR to 1 liter. This was then packed with stainless steel wool to increase the thermal mass and heavily insulated. The expanded backing volume helped stabilize the system for small temperature changes and allowed us to add a pump calibrator to the system.

The calibrator is a small impulse metering pump with a manually adjustable displacement. The magnetic and electrical shielding of the sensor was sufficient to eliminate most of the interference cased by pump operation. The pumps are set to produce a nominal signal of 0.6 Pa for each stroke when connected to their normal position at the backing volume. Since the pump may be left connected to the backing volume during normal operation, this permits remote calibrations. The pump impulse is essentially instantaneous (at 40 SPS) and thus produces a calibration step function that is modified by the microbarograph RC constant. The pump is driven through a small microprocessor controlled circuit that takes its input from the standard digitizer calibration signal. Although the calibration pump is only capable of producing a 0.6 Pa step, the driver can selectively operate it as a random binary telegraph spaced step or as multiples of 8, 16, or 64 rapidly pulsed steps. Thus, it is possible for the calibrator to drive the microbarograph at high outputs overriding any noise (or signal) being detected at the fore-volume.

The microbarograph is placed in the shallow borehole about 4 feet below the surface. A 1-inch pipe leading to a 3/4-inch hose connects the microbarograph to an off-the-shelf 12 port manifold. Eleven, 25-foot long soaker hoses are arranged in a radial pattern and connected to the manifold. The hose end caps are sealed with silicon caulk onto the distant ends of the hoses. This was done to prevent the caps from working themselves off as happened at TXAR.

The array uses Geotech Intelligent Communication Processing System Model 59660, similar to the prototype infrasound array at Los Alamos National Laboratory. Modifications to the LANL design were required to support the seismic portion of the seismo-acoustic system, to provide local data archiving for extended periods (up to 2 months), to eliminate the authenticators, and to accommodate the SMU style microbarograph. The following minor modifications were made during the integration and tests at Geotech and at SMU:

1. The system was configured for three digitizer channels per site rather than a single channel. While this was a minor hardware change, it caused a significant impact on parts of the software.
2. The system is sampled at 40 SPS rather than 20 SPS. This increase in sample rate increased the required throughput on the alpha stream and the amount of disk space required for local storage.
3. To accommodate the GS-13 sensor, it was necessary to add an impedance converter board to the digitizer front end and to increase the gain of the seismic channel by 20 dB.
4. A calibrator board was added to calibrate the GS-13. This hardware change required an associated software modification in the alpha sending software.

5. Changes were made to the way weather information is sent in the alpha data stream such that the alpha reader could correctly decode wind speed, direction, and air temperature. In addition, the weather station software was modified at SMU to use metric units.
6. Long distance WAN connections at Chulwon were felt to be uncertain enough that it was desirable to include local data storage for up to 6 weeks. A change in the software allowed us to save waveform files similar to CSS files on the local hard disk.
7. The system was modified at SMU to recover from a power cycle. Local archiving now starts automatically although starting the alpha data stream after power fail still requires manual intervention.
8. A software package to allow remote access to the console was added such that the manual alpha restart and state-of-health monitoring could be done remotely from either KIGAM or from SMU. In addition remote ftp services were added such that it is possible to remotely download or upload data and software.

The hub computer running windows NT4.0 gathers data from all four sites plus the weather station, displays the waveforms, saves it locally to CSS-like waveform files, and formats it to an alpha protocol TCP/IP stream over 10bT. A small Cisco router passes the data stream over a radio link to a second router at a convenient telephone site where it is forwarded to KIGAM and incorporated into the automated processing. KIGAM forwards the alpha stream over the internet to SMU for analysis and use in building the ground truth database. SMU records and archives the data stream with DCC-Lite on a small Sun workstation.

System Tests

Once the system was delivered from Geotech Instruments, two sets of tests were scheduled. One field test at McKinney, Texas was designed to locate problems in fielding the system and to field test the microbarographs. A set of tests at SMU was designed to test the alpha protocol. Field tests at McKinney were terminated after demonstrating successful operation of the microbarographs. Tests at SMU were terminated after demonstrating successful transmission of alpha data from the recording system over the internet to KIGAM and back to SMU's alpha reader.

The system was deployed and operated for six weeks in a test configuration in McKinney, Texas (Figure 4). The test goals were to build confidence in unfamiliar equipment, to test installation procedures, to identify remote problem diagnosis procedures, to make minor changes to the configuration to match field conditions (field tuning), to field test the microbarograph, and to demonstrate the system in a realistic configuration to KIGAM personnel. Results during the McKinney test led to minor changes in hardware (such as correcting the wiring on inverted GS13 cables), changes in hub software (such as correcting the local archiving software so it would function across a month rollover), minor changes in microbarograph design (such as increasing the low cut corner from 600 seconds to 20 seconds and modifying the calibrator logic), familiarity with various field configuration changes that might have to be made during installation (such as radio reconfiguration), and demonstration of the complexity of details involved in fielding even a simple system.

The test deployment also demonstrated the characteristics of the infrasonic gauges and noise reducers under varying wind and weather conditions. Wind speed and temperature are measured at one infrasonic site and included in the data stream. This portion of the test was useful in that it furnished information for analysis.

Tests at SMU were done to insure that alpha data could be sent from the hub to KIGAM and forwarded back to SMU. It required four weeks to reach a successful conclusion. Prior to testing, we had demonstrated that the system was able to transmit alpha data directly to a DCC-Lite system (a commercially available alpha reader) configured at SMU. The alpha tests were done to demonstrate that the system was able to send data to KIGAM's reader and back to SMU.

Tests of the infrasound gauges at McKinney included self-noise under field conditions (equivalent to blocked mass seismometer tests), comparison and noise tests of systems driven from no or the same acoustic array, comparison tests of arrays of 11 25-foot, 5 25-foot, and 1 75-foot 5/8" Moisture Master soaker hose. Initial tests of the remote calibrator were made and a simple alternative static field calibration procedure developed.

Analysis of two microbarographs driven from a Y-connector open to the air (no hose array) demonstrated that the microbarograph high frequency response even when connected to a 50' hose, is coherent and undisturbed to

8 Hz and that the microbarograph noise floor matches the calculations based on previous laboratory tests. The nominal noise floor is plotted in Figure 4a as a horizontal line below –50 dB relative to 1 Pa^2/Hz.

The effect of the 11-arm radial hose array of 25' radius was estimated by comparing the response of a collocated system without the hose array to the hose array. This was done under varying wind conditions. Figure 4a suggests that the hose array attenuates all signals by about 6 dB (since one would expect that the effect of a 25' array would be minimal for long wavelength signals). For signals of 1 Hz the small array offers a 12 dB improvement in the SNR. For the conditions examined, the open system recorded a difference in signal level of 12 dB from nearly 0 to 11 MPH winds. For the hose array, there is little difference in noise levels above 3 Hz for any of the observed wind conditions. For these conditions and frequencies, the array is apparently over sampled. In both cases, the background noise is above sensor noise up to 10 Hz.

Figure 4b shows the transfer function between the open system and hose array. The transfer function was calculated by using only time segments with zero wind. The phase delay is from a difference in the sampling points of the two systems and from the delay caused by propagation in the arms of the hose array. The array appears as a low pass filter with a corner at 3 Hz. Figure 4c shows an example time series of the two systems under zero wind conditions. The open system (lower plot 4c, dotted trace) has wider bandwidth than that of the pipe array and slightly higher amplitude.

A test of the remote calibrator (Figure 4d) demonstrated that the system could be calibrated under normal operate conditions. Five different calibration signals were tried. Under low wind conditions, an individual step calibration of 0.6 Pa is easily visible, but such a signal has insufficient SNR at the low frequency corner to verify the system RC time constant. Multiple pulses (Figure 4d, top three traces) produce enough energy (up to 20 Pa P-P) to be useful under windy conditions. The utility of the random binary calibration signal (Figure 4d, bottom two traces) has not been demonstrated to be superior to the simpler multiple step calibrations at least for the parameters tested. Lower clock rates for the RBT may be more useful in calibrate while operate configurations.

As a check on the calibrations, the absolute DC pressure response of the microbarographs was checked using a simple gravity method. Since the diaphragm is a known mass, inverting the sensor will cause a known equivalent pressure step. Since the gauges used here have a response flat to DC, this is easily read in the field to better than 5% using a multimeter. Although this does not guarantee the dynamic response of the system, it does provide a simple check.

CONCLUSIONS AND RECOMMENDATIONS

A seismo-acoustic array, the first of its particular configuration and design has been designed, tested, and installed in the Republic of Korea by KIGAM and SMU. Data from the array is being sent on the internet in alpha protocol to SMU.

Design, procurement, testing, site selection and installation of the array required approximately one year. Although many of the components were off-the-shelf, significant integration and design issues required field tests. Based on our experience with this array, it is unlikely that a similar design and installation task completed to the same degree of confidence, could be completed in less than 6 months.

Tests of the microbarograph and hose arrays at McKinney have demonstrated that the pipe array used in Korea causes little signal modification below 3 Hz other than an attenuation.

A test of the calibrator has demonstrated that it is possible to do remote calibrations of the microbarograph under normal conditions.

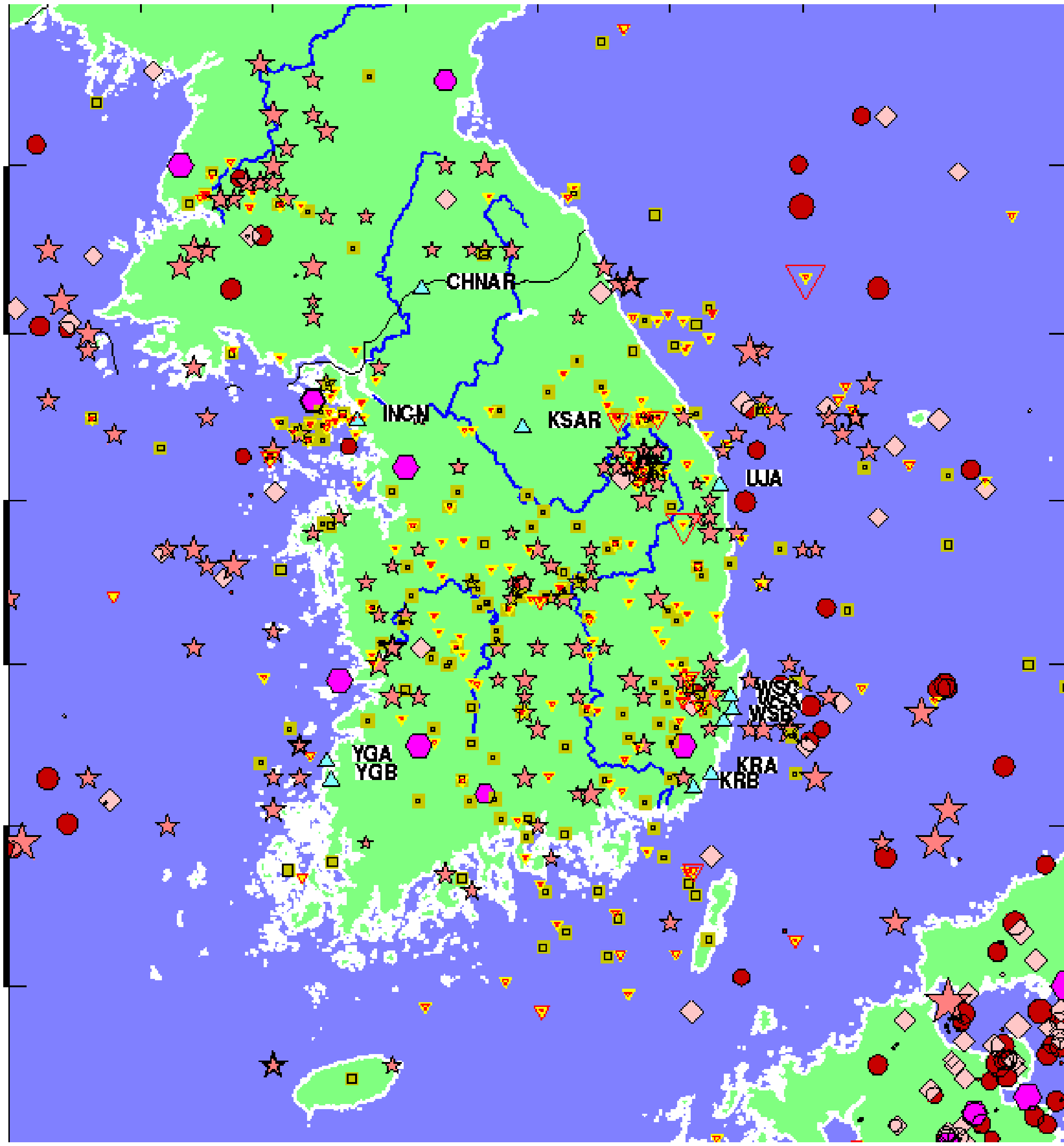

Figure 1. Seismicity of Korea.

Selected stations in the KIGAM network are labeled and shown as triangles. The station CHNAR is the new seismo-acoustic array. Other symbols, for example stars, indicate the epicenters of cataloged earthquakes. Symbol size in proportional to magnitude. The following symbols have been used to plot earthquakes:

Stars	KMA catalog locations from 1990-1999
Circles	USGS PDE locations from 1974
Squares	KSAR automatic locations from Feb 1999 to July 1999
Diamonds	PIDC locations from 1994 to July 1999
Inverted Triangles	KIGAM locations from Feb 1999 to July 1999
Hexagons	NOAA significant events catalog

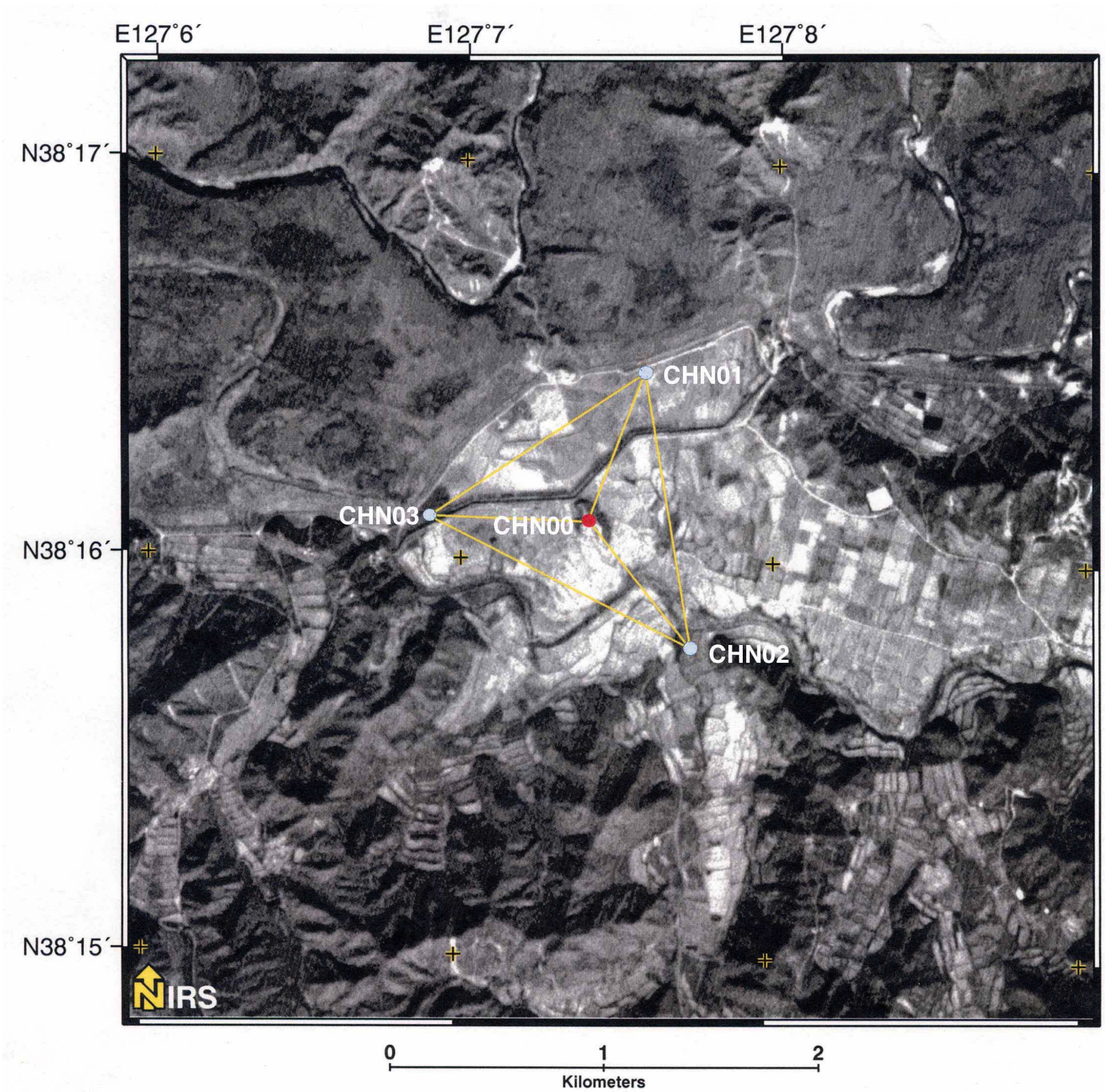

Figure 2. Overhead photo of CHNAR location. The area is in intensive rice farming. Site CHN00 is on top of a forested hill. The array is about 1.2 Km on a side.

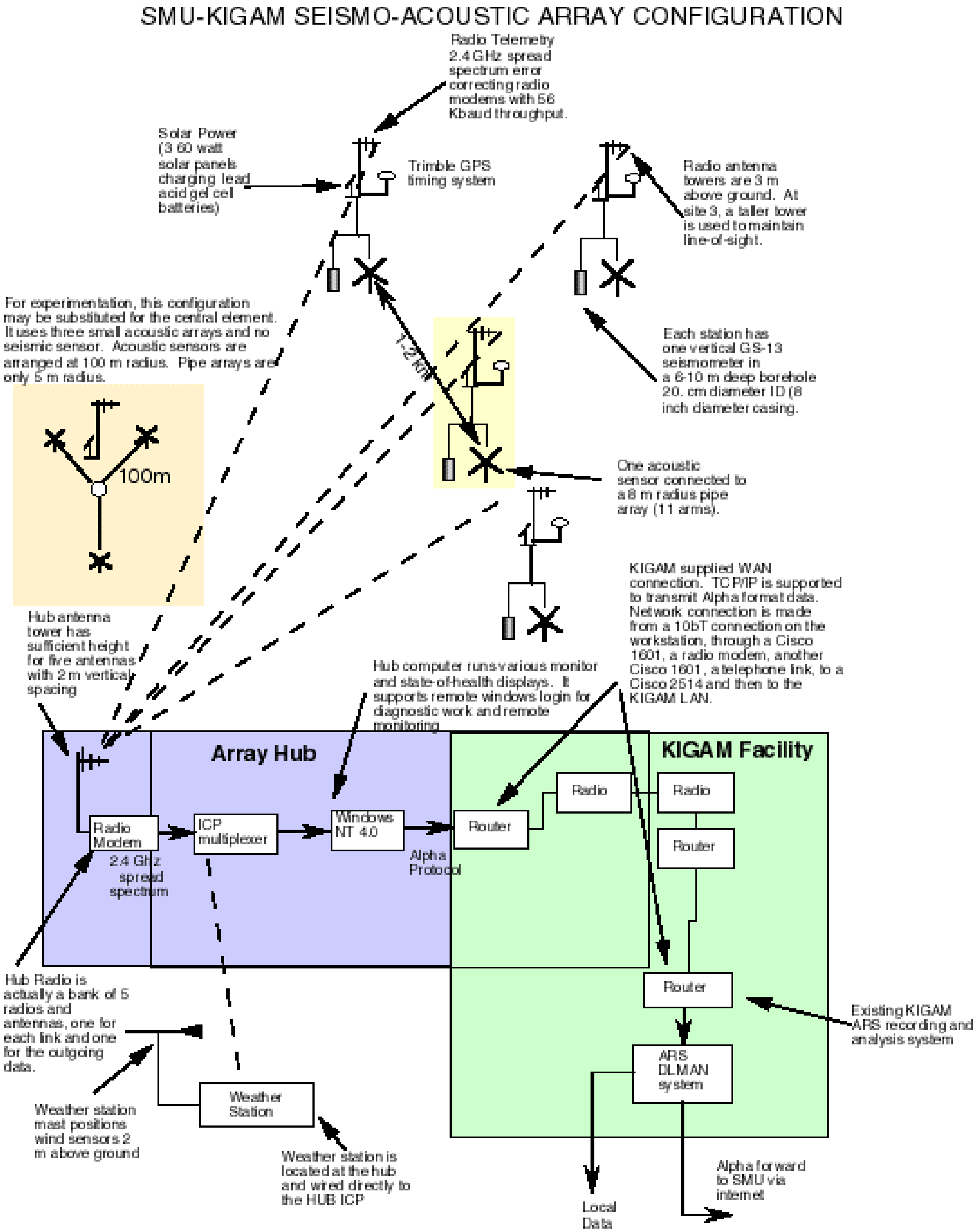

Figure 3. Schematic diagram of Korean array configuration.

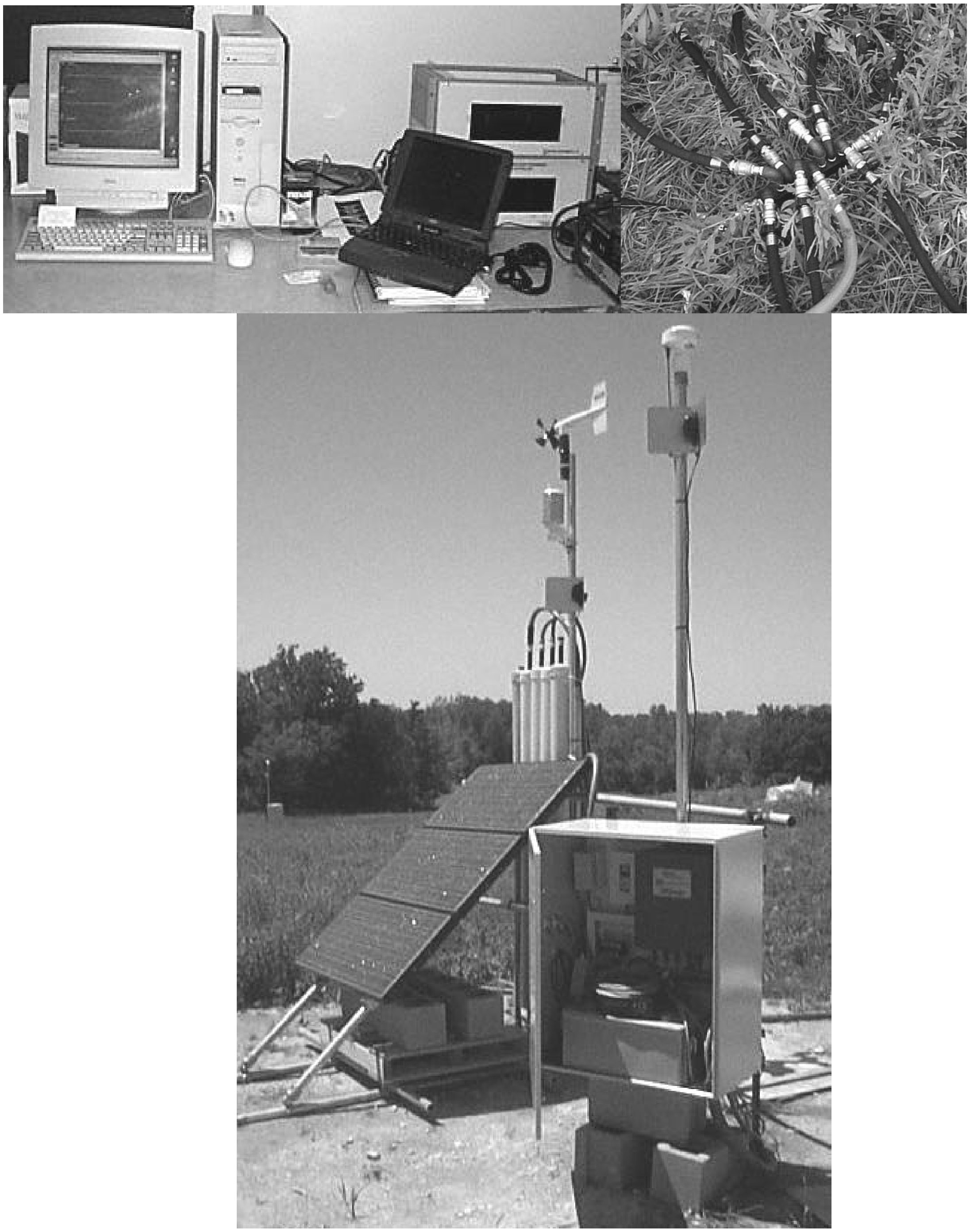

Figure 4. Photographs of the McKinney field test. Top, left photo is the hub computer and associated multiplexer and radio bank. Bottom photo is one test site with 5 microbarographs mounted to the solar panel supports for testing. The enclosure contains the digitizer, power supply, and weather station. A second site is visible in the background. Top, right photo shows the hose manifold for the 11 arm hose array.

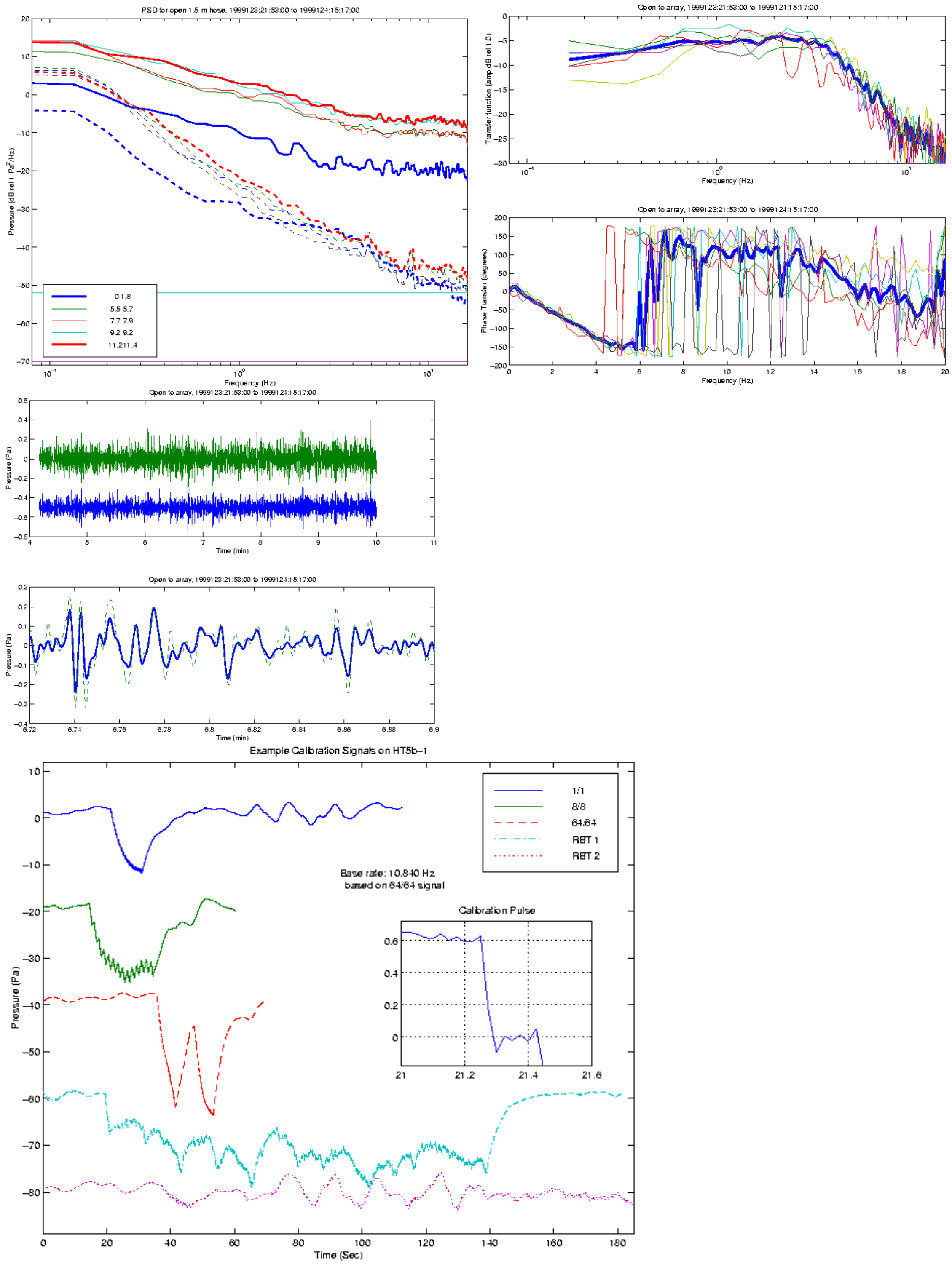

Figure 5. Microbarograph tests at McKinney, Texas. Figure 5a (top left) shows the power spectrum for an infrasound gauge without pipe array and with pipe array under varying wind conditions. Figure 5b (top right) shows the transfer function between the open infrasound gauge and pipe array under dead calm conditions. Figure 5c (middle plot) shows the time series of the two systems under these quiet conditions. Figure 5d (bottom plot) shows example remote calibration signals recorded under field conditions.