SMU-R-93-500

COMPLETE AND DEPLOY THE GERESS SEISMIC ARRAY IN SOUTHEAST GERMANY, ESTABLISH WORKSTATIONS WHICH ACCEPT THE ARRAY DATA AT BOCHUM AND NORSAR, AND PROVIDE THE INTERFACE TO THE INTELLIGENT ARRAY SYSTEM AT NORSAR...

SMU STAFF

Southern Methodist University

Dallas, TX 75275

December 1993

C-Contract Final Technical Report

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ABSTRACT

SMU was awarded DARPA Contract #MDA 972-89-C-0054 in January 1989 to (1) Complete and deploy the GERESS (GERman Experimental Seismic System) Seismic Array in southeast Germany (FRG), establish workstations which accept the array data at Bochum FRG and at NORSAR, and provide the interface to the Intelligent Array System at NORSAR, (2) Acquire commercial communication links as required for the GERESS Array, (3) Acquire 6 (six) new exportable CD Stations and provide assistance in installation of these Stations at 6 (six) foreign locations, to be designated by the COTR, (4) Provide 6 (six) domestic CD Stations (4 [four] new and 2 [two] upgraded from contract MDA972-88-K-0001) and establish the six-station U. S. GSE Network with capability to transmit data from each station to the archive facility at the University of California at San Diego, (5) Acquire commercial communication links to handle the data for the 6 (six) CD Stations located in the United States, (6) Provide operational maintenance for the equipment at each of the 6 (six) CS Stations located in the U. S., (7) Acquire 2 (two) workstations to be located at the National Data Center in Washington, DC to interface with the U. S. GSE Network. Provide maintenance for these 2 (two) workstations, (8) Operate the CD Stations at Lajitas, TX and Blacksburg, VA.,(9) Support U. S. participation in the initial 1990 GSE experiment, and (10) Transfer equipment from MDA972-88-K-0001 as necessary to combine with equipment acquired on this contract in order to provide the complete system described above.

GERESS was patterned after the Scandinavian arrays of NORESS, ARCESS, and FINESA; however, several improvements and unique features in the instrumentation and data systems have been implemented at GERESS. These features include (1) signal sampling using a 24-bit analog-to-digital converter (ADC) to extend the dynamic range of the seismometers, (2) selectable sampling frequencies of the ADC, (3) simultaneous transmission of data to NORSAR and RUB, (4) data acquisition and timing system controls inter-element time-skew to less than 50 microseconds, and (5) modular sensors and data-acquisition systems. GERESS Acceptance Tests were held in August of 1990, and the Inteleseis Array Controller (IAC) was deemed acceptable by

SMU/RUB in September 1993. GERESS is considered to be the most sensitive seismological station in Central Europe.

In addition to the GERESS tasks, accomplishments regarding participation in GSETT-2 were as follows: (1) Installed, tested, and operated US GSE Network, consisting of 6 CD stations, during GSETT-2, (2) Installed, tested, and operated US GSE satellite communications network during GSETT-2.,(3) Conducted training seminars for US GSE station operators and analysts, (4) Installed CD station in Pakistan, including INMARSET communications equipment, within weeks of request, enabling their participation in GSETT-2, (5) Trained Pakistani personnel on the use of CD station hardware and software for data acquisition and analysis during GSETT-2, (6) Provided two CD stations to Poland enabling their participation in GSETT-2, (7) Developed prototype US National Data Center (NDC) for use in GSETT-2, (8) Provided technical support to all US GSE station personnel including US NDC staff during GSETT-2, and (9) Operated and maintained SMU experimental seismic station, LTX through 1992.

SMU-R-93-500

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The views and conclusions contained in this document are those of the authors and should not be interpreted as representing the official policies, either expressed or implied, of the Advanced Research Projects Agency or the U. S. Gopvernment.

DEFENSE ADVANCED RESEARCH PROJECTS AGENCY

CONTRACT # MDA 972-89-C-0054

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INTRODUCTION

Work on "Development and Deployment of a Prototype Regional Array," was begun under Contract # MDA 972-88-K-001 in October 1987. This task and the array-controller-development subtask was underway at Teledyne Geotech by January 1989 when the GERESS task of the new Contract # MDA 972-89-C-0054 called for the completion and deployment of the GERESS array in the Bavarian Forest [*Bayerischer Wald*] of Southeast Federal Republic of Germany near the Austrian and Czechoslovakian border This task superseded the Prototype Regional Array task of the former contract. Most of the equipment -- seismometers, RDAS's, amplifiers, and array controller -- came from the K contract. In addition to the array installation, Workstations were installed at NORESS and at Bochum and respective communication links from the array to these remote locations were established. GERESS acceptance tests were held in August 1990. There were several other tasks in Contract # MDA 972-89-C-0054 that called for the acquisition and operation of CD Stations in the United States and in foreign countries for GSETT-2.

Chapter One is entitled GERESS -- *GERman Experimental Seismic System*. Chapter Two is entitled Ten CD Seismic Stations. Chapter Three is entitled Support US Participation in GSE Experiment. Chapter Four is entitled Operate and Maintain Systems Through 1992. Chapter Five is entitled Conclusions and Recommendations. Chapters are followed by References including Contract Reports and Selected References. Appendices 1 and 2 are the Contract Statement of Work and GERESS Facts, respectively.

CHAPTER ONE

Background

In January 1989, Contract # MDA 972-89-C-0054 called for the completion and deployment of the GERESS array in the Bavarian Forest [*Bayerischer Wald*] of Southeast Federal Republic of Germany near the Czechoslovakian border as well as other tasks that were begun under Contract # MDA 972-88-K-001. Workstations were to be installed at NORESS and at Bochum (see Quarterly Technical Report QTR-89-C-4, 15 October 1989 to 15 January 1990). The plan was to develop, manufacture, transport, and install the array equipment during the Summer of 1989. One of the tasks of the original 88-K contract was the "Development and Deployment of a Prototype Regional Array," and the array-controller-development subtask was underway at Teledyne Geotech by January 1989 when the GERESS task of the new 89-C contract superseded the Prototype Regional Array task of the 88-K Contract. Appendix 1 is the Statement of Work for the C contract.

SMU-RUB MOU

A Memorandum of Understanding (MOU) between Ruhr-University Bochum (RUB) and Southern Methodist University (SMU) for an International Cooperative Research Program supported by DARPA was executed in May of 1989. The following is is a verbatim description of Item 2, Cooperative Program to be Undertaken, from the MOU:

> The intended joint and cooperative program that is agreed to in this memorandum consists of the study, design, development, installation, operation, and evaluation of an experimental seismic array facility in the Federal Republic of Germany, the establishment of an inter-linked experimental signal processing facility at the Institute of Geophysics (RUB) and the Laboratory of Geophysics (SMU), and the establishment of a joint

cooperative research effort based on the preliminary results of the experimental program.

The general goal of this program, as provided for in this MOU, is the establishment of a joint cooperative scientific research effort to develop, install, test and evaluate an experimental advanced seismic array facility in the Federal Republic of Germany and to develop signal processing methods to enhance the effectiveness of such arrays.

The experimental seismic facility will be installed at a site in the southeastern area of the State of Bavaria.

An experimental signal processing facility will be established at the Institute of Geophysics of RUB for the purpose of receiving and analyzing the array data.

FRG Noise Survey

The original equipment acquisition from Teledyne Geotech consisted of a three-component set of S-13 short-period seismometers, a Portable Data Acquisition System (PDAS-100) with 1.5 Mb of memory and a 16-bit digitizer, and a Portable Setup and Analysis Computer (PSAC-100), which was a Toshiba laptop. This system was shipped to Dr. Hans-Peter Harjes of Ruhr University at Bochum (RUB), Germany, who made the original noise survey in 1987. Eight more vertical G-13 PDAS-100 systems were subsequently delivered to establish a 9-element array for the study of both signals and noise on the Bohemian Massif in Southeastern Germany in 1988. The results of the signal and noise surveys are presented by Harjes (1990). As reported by Harjes (1990), the local noise level was comparable to NORESS, perhaps lower for frequencies around 1 Hz but about a decade higher beyond 10 Hz.

System Specifications

The Scope of the GERESS System Specification, released by Teledyne Geotech on 6 September 1989, is as follows:

This specification covers the operational and functional requirements for GERESS. The GERESS System Specification is the performance baseline for the system, and as such, will be maintained and adhered to throughout the development and deployment of the system. The specification will be under the control of the designated System Engineer as directed by the Teledyne Geotech GERESS Program Manager. All specification changes will be performed in accordance with Section 3.5.2 of this specification. An "as built" final version of the specification will be delivered on completion of the GERESS project. The release at the bottom of the first page of any copy of the specification will be the revision date of that copy. All specification illustrations are contained in Appendix A.

Array Installation

Ground was broken at GERESS on 18 September 1989, and excavation for vaults and trenching for cables began in October. Because of the late start, winter weather and the resulting snows caused a 6 month delay in installation. Figure 1 is a map of the array showing the array geometry and locations of the hub and sites. GERESS consists of 39 seismometers in 26 vaults. The installation is similar to NORESS and ARCESS in Scandinavia. A central hub sends power to each underground vault on buried cable in conduit. Timing signals and inter-array communications are carried on buried fiber-optic cables. GERESS Facts, a compilation of information on site preparation, vault construction instrumentation, and operations, is presented in Appendix 2. Recent GERESS status is reported by Jost (1993).

Communications

For array applications such as GERESS, Teledyne Geotech's Inteleseis III Seismograph System was designed to consist of up to 32 RDAS (Remote Data Acquisition Systems) units, an Inteleseis Array Controller, and one or more local or remote Workstations. An RDAS is employed at each remote site, and can be configured to accommodate a single channel of short-period data, a three-component set of short-period seismometers, or a three-component set of broadband seismometers. Each RDAS was to be be controlled and operated from a remote Inteleseis Array Controller (IAC) or a Workstation. Principles of operation of the Inteleseis III System are covered in the *Operation and Maintenance Manual for the Inteleseis III System* published by Teledyne Geotech in July 1989.

RDAS-200

The RDAS-200 is basically an IBM PC, configured without a monitor and keyboard, that is designed to digitize, time-tag, and transmit seismic data to an Inteleseis Array Controller (IAC). Data processing is performed using Microsoft's MS-DOS operating system, and Teledyne Geotech's applications software. Preliminary specifications are presented in SMU-R-89-125, p. 39-65, and the RDAS is described in detail in SMU-R-898-226, p. 32-39. Hardware and software details are presented in *RDAS-200 Remote Data Acquisition System Models 58440 and 58450 Technical Reference* published by Teledyne Geotech as Document Number 990-58440-9801. Principles of operation are covered in *RDAS-200 Remote Data Acquisition System User's Guide* published by Teledyne Geotech as Document Number 990-59231-0101

IAC-200

As with the RDAS-200, the IAC-200 is basically an IBM PC. The IAC accepts digital data from RDAS's of the array, and these data are synchronized and time-tagged therein for retransmission to RUB and NORSAR. Preliminary specifications are covered in Semi-Annual Technical Report, SMU-R-89-125, April 1989, p. 54-65. Principles of operation are covered in Teledyne Geotech's *Operations and Maintenance Manual for the IAC-200.*

Protocol

The communication link between the host workstation and the array controller is through a serial communication link using Synchronous Data Link Control (SDLC) protocol. This link will operate a speeds between 1200 bps and 22K bps.

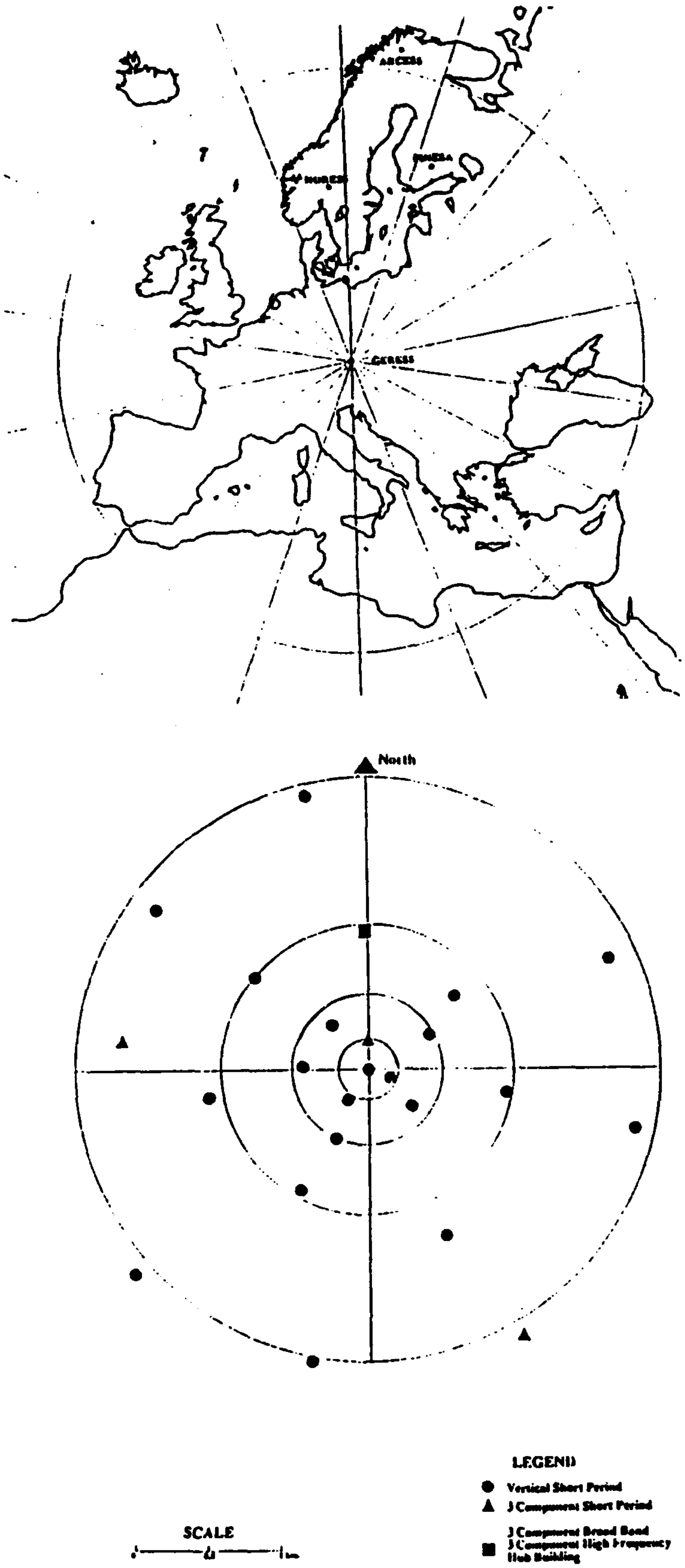


Figure 1. GERESS array geometry and design.

Workstations

The Intelligent Monitoring System (IMS)

The IMS is a computer system for processing data from seismic arrays and simpler stations to detect, locate, and identify seismic events. Prior to bringing GERESS on-line, the IMS processed data from NORESS and ARCESS. The NORESS and ARCESS processing computers are Sun 4/2xx workstations similar to the Sun 4/330 (SPARCstation) acquired for the processing of GERESS data. The SPARCstation is in addition to the eseis III Workstation configuration described below. The IMS computers and functions are distributed between the NORSAR Data Analysis Center (NDAS) near Oslo and the Center for Seismic Studies (CSS) in Rosslyn, Virginia. According to Harjes, it will be interesting to see if the IMS automated-analysis software for the two arrays on the stable Scandinavian shield can handle the increase in seismicity expected for the GERESS array, which is nearer to quarries, mines, and two active orogenic zones (The Alpine earthquake belt and the Mediterranean earthquake zone).

General

GERESS Inteleseis III workstations consist of a Sun 3/280S computer at NORSAR and a receive-only Science Horizon's SH-3E computer at RUB. The GERESS-to-NORSAR communication is a duplex link by satellite, and the GERESS-to-Bochum communication link is by land line. GERESS will provide data to the Intelligent Monitoring System (IMS) at NORSAR through a simplex interface.

NORSAR Workstation Configuration

The Inteleseis III graphics configuration at NORSAR consists of the following Workstation components plus the State-of-Health Display System:

Workstation

1. Sun 3/280S computer,
2. 8 Mb Expansion Board,
3. Exabyte 2.3 Gb Tape Drive,
4. 1600/6250 bpi, 1/2-in. Tape Drive, and
5. 1.23 Gb Disk.

State-of-Health Display System

In addition to the Sun 3/280S, the State-of-Health Display System from Science Horizons for NORSAR consists of the following components:

1. Sun 3/60 Color Subsystem,
   Sun 3/60FC-8 Workstation,
   International SunOS,
   OS Documentation and Two (2) User RTU Licenses,
2. Science Horizons SH-600M/TA60 Subsystem,
   600 Mb Disk,
   1/4-in. Tape Drive, and
3. Ethernet Cable.

Bochum Workstation Configuration

The Inteleseis III graphics configuration at RUB consists of the following components:

1. Science Horizon SH-3E computer,
2. Monochrome Monitor,
3. Keyboard and Mouse,
4. 12 Mb Expansion Board,
5. Exabyte 2.3 Gb Disk Drive,
6. Communication Interface Module (CIM), and
7. 60 Mb, 1/4-in. Tape Drive.

SMU Trip To GERESS

Gene Herrin, Paul Golden, and Chris Hayward arrived at GERESS on 13 August 1990 to perform the "limited" GERESS Acceptance Test from 14 through 16 August 1990. The reason that the tests were limited was because Teledyne Geotech failed to provide all of the required test equipment. At the time, they documented at least 30 deficiences with GERESS including the RDAS's, Array Controller, and Workstations. These and other deficiencies were documented by Combix Controls in their GERESS Test Incident Report dated 11 September 1990. As mentioned in the introduction, the *GERESS Test Summary Report* is included as Appendix 2. In addition to the tests at GERESS, Chris Hayward performed some fault isolation at NORSAR.

Technical Interchange Meeting Re GERESS Problems

On 13 September 1990, SMU principals met with Teledyne Geotech personnel as a follow-up on SMU's report to Geotech concerning problems at GERESS. At this meeting, Teledyne Geotech presented their *GERESS Array Corrective Action Plan* (Mulcahy, 1990). The Plan was to "resolve outstanding problems to bring the GERESS array to full operation." The following deficiency list is a summary of the list presented in the Geotech's Action Plan. The key to classifications is as follows:
1. CRITICAL: Any problem which precludes effective operation of the array and/or will prevent participation in the November GSETT-2 experiment,
2. NON-CRITICAL: Any problem which detracts from efficient operation of the array or which reduces data quality from optimum, and
3. ENHANCEMENT: Any item which will improve/enhance operation of the array, improve data quality, and which is not within the scope of the contract.

TABLE 1. -- GERESS DEFICIENCY LIST

DEFICIENCY	DESCRIPTION	CLASSIFICATION
1	INTEGER SECOND TIME ERRORS	CRITICAL
2	TIME SET COMMAND FAILURE	CRITICAL
3	CLOCK DRIFT COMPENSATION	ENHANCEMENT

4	INITIALIZATION FAILURES	CRITICAL
5	CALIBRATION COMMAND FAILURE	NON-CRITICAL
6	HIGH-FREQUENCY CHANNEL LAG TIME	NON-CRITICAL
7	SINGLE CHANNEL DATA LOSS	NON-CRITICAL
8	RDAS READY MESSAGE	NON-CRITICAL
9	VAULT INTRUSION ALARM	NON-CRITICAL
10	DIGIBOARD FAILURES	CRITICAL
11	ADCCP PROTOCOL/REDUCE "SUPER" FRAME	NON-CRITICAL
12	COMMUNICATION LINKS	CRITICAL
13	RDAS POWER ANALYSIS	NON-CRITICAL
14	DC OFFSET	NON-CRITICAL
15	SHI EXABYTE DRIVES	NON-CRITICAL
16	GERESS DOCUMENTATION	NON-CRITICAL
17	"ICI" LOSES RDAS S/N'S AT RESTART	NON-CRITICAL
18	HIGH-FREQUENCY 'E' CHANNEL NOISE	NON-CRITICAL
19	HORIZONTAL CHANNEL POLARITIES	CRITICAL
20	METEOLROLOGICAL SYSTEM INOPERATIVE	NON-CRITICAL
21	AUXILIARY DATA FRAME TRANSMISSION INTERVAL	NON-CRITICAL
22	SPIKES IN BB AND GS CHANNEL SPECTRA	TBD
23	RDAS RATE SET COMMAND ERROR MESSAGE	NON-CRITICAL
24	IAC UNSOLICITED ERROR MESSAGES	NON-CRITICAL
25	FIBER OPTIC REPEATERS NOT INSTALLED	N/A
26	EXCESSIVE FRAME DROPS ON SITE D7	N/A
27	IAC STATE-OF-HEALTH NOT DISPLAYED	NON-CRITICAL
28	RDAS WILL NOT CALIBRATE BELOW 1 HZ	NON-CRITICAL
29	IAC WILL NOT AUTOSTART	NON-CRITICAL
30	"ICI" WILL NOT ACCEPT S/N "ALL"	ENHANCEMENT

GERESS Array Status

Mike Browne and Rodney Bartholomew visited SMU to make a presentation on the technical status of GERESS on 8 May. Accordingly, all data sites and the array controller are currently operational :

1. Data gaps occur randomly,
2. Defective fiber optic repeater power cable to site D9,

3. All channels reporting "on-time,"
4. All RDAS units running with Version 2.20 software,
5. All RDAS units contain updated CPU BIOS and GSD software.

Teledyne Geotech considers that communication links to Bochum and NORSAR are operational:

1. Bochum link meets specification,
2. NORSAR link changed from satellite link to land line, but operation still experiences an excessive error rate.

In September 1993, the IAC-200 was deemed acceptable by SMU/RUB. GERESS is now considered to be the most sensitive seismological station in Central Europe.

TABLE 2. -- GERESS DEFICIENCY STATUS

DEFICIENCY	DESCRIPTION	STATUS 5/8/91
1	INTEGER SECOND TIME ERRORS	RESOLVED
2	TIME SET COMMAND FAILURE	RESOLVED
3	DRIFT COMPENSATION VALUES NOT SET	RESOLVED
4	RDAS INITIALIZATION FAILURES	RESOLVED
5	CALIBRATION COMMAND FILURE	RESOLVED
6	HIGH-FREQUENCY CHANNEL LAG TIME	RESOLVED
7	SINGLE CHANNEL DATA LOSS	UNRESOLVED
8	RDAS READY MESSAGE	RESOLVED
9	VAULT INTRUSION ALARM CAUSING RDAS CRASH	RESOLVED
10	DIGIBOARD FAILURES	RESOLVED
11	ADCCP PROTOCOL/REDUCE "SUPER" FRAME	RESOLVED
12	COMMUNICATION LINKS	UNRESOLVED
13	RDAS POWER ANALYSIS	UNRESOLVED
14	DC OFFSET	UNRESOLVED
15	SHI EXABYTE DRIVES	RESOLVED
16	GERESS DOCUMENTATION	IN PROCESS
17	"ICI" LOSES RDAS S/N'S AT RESTART	RESOLVED
18	HIGH-FREQUENCY 'E' CHANNEL NOISE	UNRESOLVED
19	HORIZONTAL CHANNEL POLARITIES	RESOLVED
20	METEOLROLOGICAL SYSTEM INOPERATIVE	RESOLVED

22	SPIKES IN BB AND GS CHANNEL SPECTRA	UNRESOLVED
23	RDAS RATE SET COMMAND ERROR MESSAGE	RESOLVED
24	IAC UNSOLICITED ERROR MESSAGES	UNRESOLVED
25	FIBER OPTIC REPEATERS NOT INSTALLED	RESOLVED
26	EXCESSIVE FRAME DROPS ON SITE D7	UNRESOLVED
27	IAC STATE-OF-HEALTH NOT DISPLAYED	RESOLVED
28	RDAS WILL NOT CALIBRATE BELOW 1 HZ	RESOLVED
29	IAC WILL NOT AUTOSTART	RESOLVED
30	"ICI" WILL NOT ACCEPT S/N "ALL"	RESOLVED

GERESS Dedication and Symposium

A Symposium on Regional Seismic Arrays and the official opening of GERESS was held from 22 through 24 June 1992 at the *Vier Jahreszeiten* (Four Seasons) Hotel in Waldkirchen and at the GERESS site. At registration on the 22nd, delegates were provided with material prepared by the SMU Staff: A three-ring binder entitled *GERESS Symposium* that contained the Agenda, Abstracts, and list of Participants, and a booklet entitled *German Experimental Seismic System: GERESS* that provided engineering, seismological, and instrumentation particulars.

Symposia sessions were held on June 23rd and the morning of the 24th at the hotel. They were followed the afternoon of the 24th by a tour of the array site and a ribbon-cutting dedication ceremony announcing the formal opening of GERESS. An evening barbecue at the site ended the Symposium.

The purpose of the Symposium was to address the present and future use of regional arrays in nuclear test-ban verification with emphasis on the use of the research facilities at RUB and NORESS associated with GERESS and their contribution to DARPA's experimental program in the development of regional arrays.

GERESS was designed and constructed through a cooperative program of *Joint Research in Seismology* between Ruhr-University Bochum (RUB) and Southern Methodist University (SMU) of Dallas under DARPA's sponsorship. Subcontractors included:

Southern Methodist University (SMU) of Dallas under DARPA's sponsorship. Subcontractors included:

1. Teledyne Geotech -- sensors and data-acquisition hardware,
2. Science Horizons -- communication-interface modules (CIM) and workstations for real-time monitoring and archiving,
3. MST -- A German engineering and management firm, and
4. Lahmyer -- The principal German contractor.

Array Processing Software

Background

Array-processing software was developed to beamsteer GERESS. The design objective of a seismic array is to maximize signals and minimize noise. Specifically, a seismic array is used to extract that part of the signal that doesn't occupy the same region of frequency-wavenumber-space as does the noise. Because the signals are coherent and the noise is [somewhat] random, the S/N ratio will be optimized when the signals are summed.

The apparent velocity of a seismic wave across an array is given by $V_A = V/\sin\theta$. As the wave propagates across an array, phase shifts exist between the seismometer outputs. The phase shift, β, relative to a reference point in the center of the array, P, for the nth seismometer is given by $\beta_n = 2\pi (d_r/\lambda) \cos(\theta - a_r)$ where d_r is the distance of the nth seismometer from P and a_r is the angle subtended by the nth seismometer. The process of delaying and summing the recorded waveforms to compensate for these phase shifts is called *beamforming*. And the combination of the shifted waveforms is called a *beam*. In practice when the direction of approach and velocity are unknown, delays can be computed for each sensor output for a number of beams, say every 30°, and several apparent velocities till the correlation statistic is maximized. The individual seismometer waveforms, the delay-and-summed waveform, the correlation statistic, and the azimuth can then be output for the optimum beam. Computational procedures and algorithms can be greatly simplified by "tuning" the array to a predetermined azimuth and a known velocity. This is the approach that will be followed in the development of the array-processing software for GERESS.

It is clear that new processing techniques will be required for a nine element array as compared to a large 25 element array such as GERESS. We are currently using GERESS data for this purpose. By choosing different elements of the array, say just the D-ring or some of the C and part of the D, we can simulate different array configurations. The following is a brief outline of one proposed processing technique and some preliminary results.

Azimuth estimates for regional events recorded at GERESS show standard deviations of the order of ± 15 degrees using RONAPP processing as part of the IMS. This scatter is surprisingly large and, in fact, is comparable to the azimuth scatter for a single 3- component station. An array with an aperture of 4 km should provide much more precise estimates of azimuth, perhaps with standard deviations of a few degrees. This level of precision will be required before calibration techniques can be used to determine azimuth bias related to horizontal refraction.

For a sparse array, say 9-elements, with an aperture similar to GERESS, beam forming or f-k methods such as those used in RONAPP can be expected to produce even more scatter in azimuth estimates. We have begun the development of array processing techniques similar to those described by Bernard Massinon in his description of a proposed array in France which he presented at the recent GERESS symposium in Bavaria. An outline of this procedure which is being applied to data from the D-ring at GERESS is given below.

GERESS Azimuth Calculations

Part I Δt calculations

1) Use RONAPP output to determine approximate azimuth and to identify the initial wave type (Pn, Pg, ?). The remainder of these procedures assumes we are operating on Pn arrivals, however, the same techniques will apply to Pg arrivals.

2) Using the D-ring elements obtain, by cross-correlations on cosine-

tapered Pn waveforms, a set of Δt's between all D-ring elements and a D-ring reference element accurate to the nearest sample point.

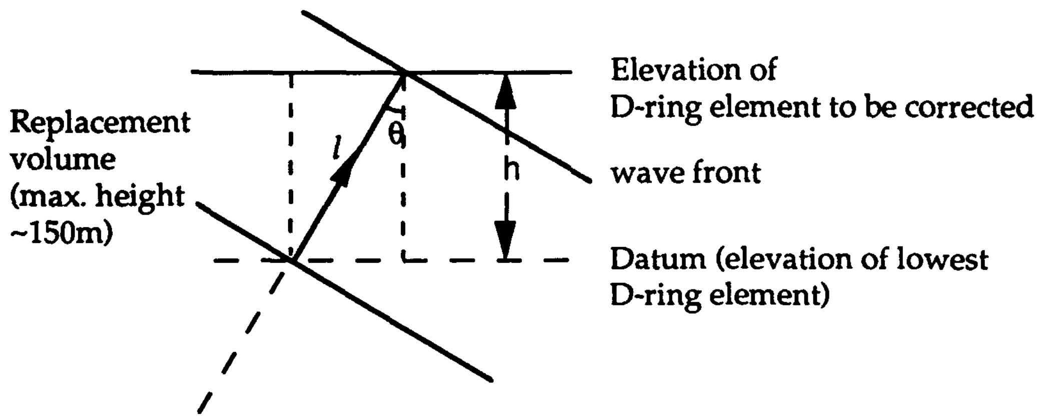
3) Compute cross-spectral functions for the Δt adjusted waveforms with Δt set to maximize the cross-correlation functions (x-corr.)

4) Calculate the unwound phase vs. frequency in the band 0.5 to 15.0 Hz.for each x-corr. function

5) Fit a least squares line constrained to go though 0 phase at 0 Hz. From the slope of the line obtain d Δt (vernier time shift).

6) Combine d Δt's with appropriate Δt's to obtain a table of time shifts (Δt) for Pn arrivals at D-ring elements relative to the time of arrival at the earliest element (reference element).

Part II Static corrections for D-ring (Assume locations and elevations of sensors are known without error)



Let the replacement wave speed be V. Then the horizontal phase velocity is

$$V_H = \frac{V}{\sin \theta}$$

The slant path (l) is

$$l = \frac{h}{\cos\theta} = h\left(1 - \frac{V^2}{V_H^2}\right)^{-1/2} \quad \text{thus}$$

$$l = h\, V_H \left(V_H^2 - V^2\right)^{-1/2} .$$

Allowing for the horizontal component of wave progression in the replacement volume, h tan q, the static correction is

$$\Delta ts = \frac{hV_H}{V(V_H^2 - V^2)^{1/2}} - \frac{hV}{V_H(V_H^2 - V^2)^{1/2}}$$

which reduces to

$$\Delta ts = \frac{h}{VV_H}(V_H^2 - V^2)^{1/2} .$$

For Pn arrivals $V_H = V_{Pn}$ and h is known for each element so that the set of Δt_S has the replacement velocity V as parameter to be determined.

Part III Azimuth determination

1) Start with the RONAPP azimuth as a trial azimuth. The trial azimuth must be consistent with the first D-ring element to record the Pn wave (reference element for Δt table).

2) Apply static corrections to the Δt table to obtain a table of Δt (values corrected to datum).

3) Using locations of D-ring element and geometrical relations set up equations of conditions (linear relations) of azimuth vs. Δt values.

4) Solve for " best" azimuth. Perhaps an L-l method should be used in the research mode at least until the "best" replacement velocity (V) is found. Then a least square (L-2) method might be more efficient in practice.

Part IV Determination of a "best" replacement velocity (V)

1) Determine azimuth as described in part III using a trial replacement velocity (V) based on Hans-Peter Harjes' average refraction velocity for the massif under GERESS.

2) Residuals from the fit in Step (1) can be linearly regressed against h. From the slope of the regression line corrections to V can be inferred.

3) V would be changed and Step (1) repeated.

4) Iteration should continue until a value of V is found which minimizes the residual in the azimuth - Δt fit perhaps using an L-1 norm.

5) Subsequently this replacement velocity would be used for all static corrections.

6) We should investigate whether there seems to be a reason to make V site dependent, but we hope that such a correction is not needed for the D-ring.

Initial results using cross-correlation techniques are very promising indicating that these techniques should be used in determining regional locations with a sparse array.

We will investigate the optimal spacing and processing for a sparse array by selecting elements from GERESS. For instance, a 1-3-5 array can be simulated using 1 A-ring, 3 C-ring and 5 D-ring elements, with various processing techniques being applied to the resulting data set. Preliminary results indicate that cross-correlation methods applied to data from a sparse array will yield substantially better estimates of azimuth for regional events than current IMS estimates using all elements of GERESS.

A number of questions need to be addressed regarding the cross-correlation method. What are the optimum frequency bands and time windows for the various wave types (Pn, Pg, Sn and Lg)? How will the processing handle distances near the Pn-Pg cross-over? What is the trade-off between aperture and signal correlation for a sparse array based on GERESS data? How can the correlation method best be implemented in a real-time processing system such as IMS? We plan to provide the answers to these kinds of questions via future programs.

We have proposed the construction of two experimental mini-arrays. One in Egypt approximately 100 km east of the city of Luxor (LUXESS) and one at the existing LTX station (TEXESS). We will address the question of optimal configuration of a nine element array as well as special processing techniques. We also plan to make TEXESS available for use as an open array as defined by the UN/CD GSE.

CHAPTER TWO

TEN CD SEISMOGRAPH STATIONS

The 10 Inteleseis I Systems provided by this task were needed to satisfy the commitments for the six US GSE Network Stations and CD Station commitments for DARPA's Cooperative Research Programs in China, Poland, Spain, and the USSR, in addition to those provided by Task 1 for the Lajitas CD Station and Task 2 for three additional CD Stations.

Teledyne Geotech was responsible for the following subtasks: (1) the manufacture of the 10 Inteleseis I Systems, (2) coordination of workstation integration, (3) RDAS-200 unit tests, (4) RDAS-200 and workstation integration, (5) support engineering and documentation, and (6) operation and maintenance manuals. The Sun-3 workstations were provided by Science Horizons as part of SMU's SeisMS.NOMAD System procurement.

The original quote was submitted to SMU by Teledyne Geotech in December 1988 for work beginning 1 January 1989, and a revised quote was submitted on 31 January 1989 for work beginning 1 February with a 31 May 1989 delivery date. As of 10 February, acquisition of selected equipment had begun as well as work on selected subassemblies. As of this date, workstations hadn't been ordered.

Prior to this task, three Inteleseis I Systems with RDAS-100's had been assembled and deployed at Lajitas, Albuquerque, and Weston Observatory for the Joint Verification Experiment (JVE) in the late Summer of 1988. After the JVE, the Inteleseis Stations at Albuquerque and Weston were returned to Teledyne Geotech to provide parts for Task 2.0 of Contract 89-C that called for the delivery to SMU of 3 CD Stations (Inteleseis I) having RDAS-200's. SMU, therefore, got credit for the RDAS-100's including associated electronic modules, thereby saving the project $30,000.

Hardware includes 10 RDAS-200's, 30 GS-13 short-period seismometers, 30 BB-13 broadband seismometers, 60 amplifiers, 3 PSAC laptop computers, cables, and cradles. The GS-13 seismometer is essentially identical to the standard S-13 with respect to the mechanical suspension, except for an improved magnet assembly, coil assembly, and calibration coil to provide increased sensitivity to earth motion.

Establish US GSE Network

Background

The initial planning meeting for the USGSE Network was held at Scripps/IGPP in La Jolla, CA, in February of 1989 where the design of the communication system was determined along with the deployment schedule. USGSE Deployment Plans were published and distributed by SMU to site contacts under a cover letter by Ann Kerr dated 18 May 1989. A second Network planning meeting was held at Scripps/IGPP from 31 May to 2 June 1989 to discuss GSETT-2 procedures and analysis requirements. Network information has been included in SMU-R-89-125, pages 5-10.

The four *NDC Centers* that controlled six CD Stations. These centers were SMU, Dallas, TX, controlling the Lajitas, TX, CD Station (LTX); Blacksburg, VA, controlling the Blacksburg CD Station (BLA); La Jolla, CA, controlling both the Pinyon Flat Observatory CD Station (PFO) at Piñon Flat, CA, and the Hawaii National Seismic CD Station (HVH) at Haleakala National Park on Maui, HI; and Pinedale, WY, controlling the Pinedale CD Station (PIN) and the North Pole, AK, CD Station (NPO).

CD Stations are described in GSE/US/52 and the *Sourcebook*. The *Sourcebook* provides a brief description of each site and the instrumentation. The fifth site is NDC Central located at the Center for Seismic Studies (CSS) in Arlington, VA. NDC Central is responsible for quality control of all station data, formatting of parameter files and waveform segments, and the distribution of data to IDC's. A Network Concentrator at Scripps/IGPP is dedicated to the continual archiving of all station data broadcast via satellite from each the six CD Stations. NDC Central can rapidly access the stored data at Scripps/IGPP either via INTERNET or via satellite communication link.

Site Descriptions and Installation

Site descriptions and installation are described in SMU-R-89-226, p. 79-82.

Operation -- GSETT-2

The first practical test of a global, data-collection-and-exchange system, GSETT-1, as discussed in SMU-R-91-252, Chapter Two, p. 25-27 was considered successful. However, certain limitations were noted for further research and development: (1) the monitoring performance was severely limited by outdated technology such as the earth-powered, analog WWSSN stations, (2) there was little participation from countries in the southern hemisphere and Africa, and (3) there was no provision for waveform data exchange and processing. GSETT-2 was undertaken to correct these limitations.

Phase 1

Phase 1 of GSETT-2 was the *start-up phase* in 1988-1989 to develop the CD Stations, develop Workstation hardware and software, deploy the US GSE Network, establish the NDC's and NDC Central, and install the Network Concentrator.

Phase 2

Phase 2 was a warm-up in January--March 1990 for Phase 3. The purpose of the warm-up was to gain experience with system, develop efficiency with specified procedures, and fine-tune to prepare for Phase 3. Data days were as follows;

Analysis

Tuesday	23 January	0000 -- 2400 UTC
Tuesday	30 January	0000 -- 2400 UTC
Tuesday	06 February	0000 -- 2400 UTC
Tuesday	13 February	0000 -- 2400 UTC
Tuesday	20 February	0000 -- 2400 UTC

Tuesday	27 February	0000 – 2400 UTC
Tuesday	06 March	0000 – 2400 UTC

Phase 3

Phase 3 was carried out in two parts. The first part was a preparatory phase that involved the exchange and processing of data for seven consecutive days, 26 November to 2 December 1990. The second phase involved the continuous full-scale testing over 42 consecutive days, 22 April to 2 June 1991. Results of Phase 2 and 3 analyses at LTX are presented in the K Contract Final Report, SMU-R-92-425.

Maui-to-Berkeley Relocation

The Maui (HVH) station proved to be noisy during Phase 2; therefore, a decision was made to relocate the station to Berkeley, California for Phases 3. In the band from 0 to 20 Hz, the noise power at Maui was about 75 dB greater than that at Lajitas.

Karl Thomason of SMU traveled to Maui to disassemble, pack, and ship the CD Station to Berkeley from 4 through 9 November 1990. He then traveled to Berkeley to receive and install the station. Paul Golden of SMU met him there and assisted in the station installation that was completed by 17 November.

A subcontract was awarded to Teledyne Geotech to provide special parts to adapt the Inteleseis I System to the site at the University of California at Berkeley. Equipment and supplies included shipping containers, 2 modems, cables, and the required manuals and documentation. The site was a shaft in the Berkeley Hills to the east of the campus where the original Berkeley seismograph station is located. The biggest problem encountered was the location of the clock antenna to assure adequate reception. This operation alone took a couple of days.

Establish Foreign Stations

Poland

Two CD Stations were installed in Poland by personnel from Teledyne Geotech. The Station installed at Ksiaz Seismological Observatory was designated KSP, and the other was designated SFP.

Pakistan

In 1991, a cooperative program was established between the Pakistan Atomic Energy Commission (PAEC) and DARPA to support the development of the Pakistan NDC in order for them to participate in GSETT-2. Chris Hayward of SMU traveled to Pakistan to assist in the installation from 11 to 28 May 1991. The system that was deployed as shown in the accompanying diagram, figure 9 of SMU-R-92-337, is similar in most respects to the Inteleseis System developed by Teledyne Geotech and Science Horizons for the GSE. Exceptions are the telemetry system based on INMARSAT technology and the borehole seismometer.

The Nilore (NIL) Station is located on the northern edge of the Punjabi plain, which consists of the valleys of the Indus River and its tributaries. Low mountain ranges leading into the Himalayas rise from the plain less than 10 km to the north of the site. The site is located on 100 meters of unconsolidated alluvium overlying sedimentary rocks of unknown age. Three GS-13 seismometers are located in an isolated building, and a Geotech 20171A borehole seismometer is located in an adjacent 200-ft borehole.

An RDAS that is collocated with the GS-13 seismometers digitizes and times the received signals. The digital data is then carried over a 300-meter cable to the NDC building. At the NDC, a CIM buffers the data for recording and analysis by a Sun-3 computer. The computer software is identical to that used at the US NDC stations. Installation of NIL was completed in time for the station to participate in the last three weeks of the Phase 3 test.

Communication Links for Network

Station Links

SMU-Lajitas Link

A 56 kbps duplex satellite link were established to transmit data from the short period and broadband channels at Lajitas to the prototype NDC at SMU in the Fall of 1988.

Links to NDC's

Satellite communication links were established from North Pole to Pinedale, and from Maui and Pinyon Flat to La Jolla.

Links from NDC's to the Central NDC

Seismic-data segments from the four NDC's mentioned above were transmitted to the NDC at CSS in Rosslyn, Virginia via phone lines or Internet.

Links to IGPP

Satellite communication links were established from the four NDC's to the network concentrator at IGPP at Scripps in La Jolla

Network Concentrator and Mass Store

Network Concentrator

The Network Concentrator was installed at Scripps/IGPP during the week of 10 September 1989. Civil work for satellite terminal equipment and ground antennas was completed by 15 October 1989.

The purpose of the Network Concentrator, Science Horizon Model SH-1369-226-R-1, was to (1) gather data from the 6 network stations, (2) maintain an on-line buffer of all formatted station data for a maximum time period of one day at data sample rates of 120 sps, and (3) construct standard CSS databases for archiving by CFS at SDSC.

Mass Store

The Mass Store at Scripps is a mechanical storage system utilizing magnetic-tape cassettes. It was designed to retain continuous data from each CD Station.

Network Maintenance

The network was maintained by SMU via subcontracts with Teledyne Geotech, Science Horizons, and GTE Spacenet.

NDC Workstations

Two Sun Microsystems Workstations were acquired for the NDC at CSS. They were shipped from SMU on 18 December 1989, and arrived at CSS on 20 December.

CHAPTER THREE

SUPPORT US PARTICIPATION IN GSE EXPERIMENT

Analyst Training

Nancy Cunningham of SMU conducted the first US GSE Analyst's School for CD Station Operators at SMU from 12 through 13 December 1989 for personnel from AFTAC, Lawrence-Livermore, Virginia Tech, and SMU. The purpose of the school was to train CD Station analysts for GSETT-2, Phase 2 beginning 23 January and continuing weekly through 6 March 1990. The agenda was as follows:

Tuesday 12 December 1989

9:00 till Noon	Overview
	SAVE
	VISTA
	Station Operation
1:00 till 5:00	Hands-on SAVE and VISTA

Wednesday 13 December 1989

9:00 till Noon	General Session
	Trouble Shooting
	Questions
	Continue Hands-on SAVE and VISTA

The US GSE Analyst's School was held at SMU from 19-21 March 1991 in response to a need to train new station personnel for GSETT-2, Phase 3, beginning 27 April 1991. This determination was made at the *Critique* that was held at Scripps/IGPP from 16 through 18 January 1991.

Critiques

A critique was held on 24-25 April 1990 at the Pinedale Seismic Research Facility (PSRF) near Boulder, Wyoming. PSRF is part of Detachment 489, A critique was held on 24-25 April 1990 at the Pinedale Seismic Research Facility (PSRF) near Boulder, Wyoming. PSRF is part of Detachment 489, which is operated by AFTAC. The critique was sponsored by DARPA to obtain feedback from participants and other experts in order to develop recommendations for improvements. Results of this critique were published in *Report on GSETT-2 Critique.* by Springer and Varnum in May 1991.

The GSETT-2 critique was held 16-18 January 1990 at the Institute of Geophysics and Planetary Physics, Scripps Institution of Oceanography, La-Jolla, California. The critique was sponsored by the Defense Advanced Research Projects Agency (DARPA) with the objectives of getting feedback from participants and other experts in order to develop recommendations for improvements. The final results of the critique reflected a common understanding of the system's operational status, the problems that remain together with recommended solutions, and specific action items in order to implement these solutions.

The GSETT-2 Full-Scale Test (Phase 3) took place between 22 April and 9 June 1991. Thirty participants were invited to attend a review meeting at Coolfont Conference Center 23-25 June to review the draft reports describing the results of US participation in GSETT-2, Phase 3, and to discuss highlights of the Test (see Romney, *et al.*, 1991).

GSETT-2 Workshop

The Geophysical Laboratory of SMU hosted a GSETT-2 Workshop from 3 through 5 December 1991. GSE delegates from 25 countries met on the University Campus. The US delegation was represented by Dr. Ralph Alewine who served a official host and conference convener. Excluding the hosts at SMU, there were 37 delegates from around the world.

The Workshop provided a forum for the detailed reports and review of GSETT-2. This review covered all aspects including signal detection, signal analysis, data transmission to NDC, and data transmission to the EIDC's for association with other seismic data and the compilation of the final event bulletin.

Paul Golden, Eugene Herrin, and Wilbur Rinehart of SMU presented a report entitled "The Use Of Station LTX Data In Preparing And Compiling The Final Event Bulletins."

The purpose of the Workshop was to draft a report on GSETT-2. Five study groups were charged with chapters as follows:

1. Seismograph Stations and Station Networks
   Convener: Petr Firbas, CSFR
2. National Data Centers
   Convener: Don Springer, USA
3. International Data Centers
   Convener: Urs Krandolfer, Switzerland
4. Communications Systems
   Convener: Svein Mykkeltveit, Norway
5. Seismological Evaluation
   Convener: Han-Peter Harjes, Germany

CHAPTER FOUR

OPERATE AND MAINTAIN SYSTEMS THROUGH 1992

Operation of Lajitas and Blacksburg CD Stations

Operation of the LTX station was contingent upon the continued arrangement with GTE Spacenet for the satellite-communication channel between Lajitas and Dallas. The station also required a maintenance contract. In addition, continued operation of the SMU NDC involved the maintenance of Workstation hardware and software by vendors.

The Blacksburg Station was operated by VPI on a subcontract basis to SMU; however, the arrangement was cancelled in 1991 at the request of DARPA.

Equipment Transfer

In order to provide the complete systems for GERESS and CD Stations as addressed in the Statement of Work, Appendix 1, a decision was made to transfer equipment from MDA972-88-K-0001 to MDA972-89-C-0054. This work is still in progress.

Rollup

Upon the completion of GSETT-2, Phase 3 in June 1991, the decision was made to deactivate the CD Network and satellite-communication links on 1 November 1991, except for the Lajitas-SMU link.

CHAPTER FIVE

CONCLUSIONS AND RECOMMENDATIONS

Highlights

A Memorandum of Understanding (MOU) between Ruhr-University Bochum (RUB) and Southern Methodist University (SMU) was executed in 1989 for a joint and cooperative program to install an experimental seismic array, the **GER**man **E**xperimental **S**eismic **S**ystem (GERESS), in the Federal Republic of Germany (FRG).

Provided FRG portable array to RUB for use in GERESS site noise survey.

Designed, tested, and installed GERESS in the crystalline rocks of the Bohemian Massif in Southeastern Germany near the Austrian and Czechoslovakian borders.

Designed and built standard CD Station for use during GSETT-2.

Installed, tested, and operated US GSE Network, consisting of 6 CD stations, during GSETT-2.

Installed, tested, and operated US GSE satellite communications network during GSETT-2.

Conducted training seminars for US GSE station operators and analysts.

Installed CD station in Pakistan, including INMARSET communications equipment, within weeks of request, enabling their participation in GSETT-2.

Trained Pakistani personnel on the use of CD station hardware and software for data acquisition and analysis during GSETT-2.

Provided two CD stations to Poland enabling their participation in GSETT-2.

Developed prototype US National Data Center (NDC) for use in GSETT-2.

Provided technical support to all US GSE station personnel including US NDC staff (Springer and Smith) during GSETT-2.

Operated and maintained SMU experimental seismic station, LTX, through 1992.

Conclusions

Although similar to NORESS and ARCESS, GERESS is an advancement in array technology because of it's greater sensitivity and dynamic range.

GERESS is the first array to feature fiber-optic cables for timing signals and inter-array communications.

Construction of GERESS involved extensive civil works, including 60 kilometers of trenches for cabling and excavation for underground vaults that often involved blasting.

Recommendations

Place seismometers and electronics in boreholes to greatly reduce construction costs for piers and vaults.

Use solar power whenever practical at each site rather than a central-power source to eliminate extensive cabling.

Use GPS receivers for time data at each seismometer site to replace central timing from the Hub.

Employ radio links from seismometer sites to Hub to eliminate cable links and associated construction costs.

Use modular equipment so host country can install array.

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APPENDIX 1. -- STATEMENT OF WORK

1. Complete and deploy the GERESS Seismic Array in southeast Germany (FRG), establish workstations which accept the array data at Bochum FRG and at NORSAR, and provide the interface to the Intelligent Array System at NORSAR.

2. Acquire commercial communication links as required for the GERESS Array.

3. Acquire 6 (six) new exportable CD Stations and provide assistance in installation of these Stations at 6 (six) foreign locations, to be designated by the COTR.

4. Provide 6 (six) domestic CD Stations (4 [four] new and 2 [two] upgraded from contract MDA972-88-K-0001) and establish the six-station U. S. GSE Network with capability to transmit data from each station to the archive facility at the University of California at San Diego.

5. Acquire commercial communication links to handle the data for the 6 (six) CD Stations located in the United States.

6. Provide operational maintenance for the equipment at each of the 6 (six) CS Stations located in the U. S.

7. Acquire 2 (two) workstations to be located at the National Data Center in Washington, DC to interface with the U. S. GSE Network. Provide maintenance for these 2 (two) workstations.

8. Operate the CD Stations at Lajitas, TX and Blacksburg, VA.

9. Support U. S. participation in the initial 1990 GSE experiment.

10. Transfer equipment from MDA972-88-K-0001 as necessary to combine with equipment acquired on this contract in order to provide the complete system described above. The details of this equipment transfer will be coordinated with the COTR.

APPENDIX 2. -- GERESS FACTS

Site Preparation Contractor:

Lahmyer International GmbH
Lyoner Strasse 22
P. O. Box 710651
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Mr. Hans-Walter Grau, Project Manager
Mr. Manfred Reutzel, Site Engineer

Consultant and Laison:

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(Management Strategie Technologie)
Blarerstraβe 56
D-7750 Konstanz 1

Dr. Peter Seidel, Geschaftsfuhrer (Managing Director)
Mr. Heinz Laue, Project Manager

Vault Manufacturer:

Bayricher Behaelter Bau
Nau GmbH
8052 Moosburg-Pfrommbach

Construction Data:

Vaults Installed = 26	
Vault Overall Height:	5 @ 3.9 meters
	2 @ 4.4 meters
	19 @ 4.9 meters
Vault Inside Diameter:	2.0 meters

Vault Excavations:	4.0x4.0x5.0 meters depth maximum (3.5 meters minimum) Estimated 1,928 m^3 material removed
Vault Slabs (Concrete):	Approx. 2.7 meters dia. x 0.3 meters min thickness. Pinned to bedrock in 4 places where practical.
Cable Trenches:	0.4 m wide x 1 m deep = 20,351 m 0.6 m wide x 1 m deep = 1,116 m Estimated 8,809 m^3 material removed
Conduit Installed:	110 mm dia = 21,871 m 50 mm dia = 21,871 m (multiple conduits per trench)
Fiber Optic Cable Installed:	59,089 m (4 fibers/cable)
DC Power Cable Installed:	15,618 m 1.5 mm (AWG 16) 7,498 m 2.5 mm (AWG 14) 12,824 m 4 mm (AWG 12) 11,346 m 6 mm (AWG 10) 25,803 m 10 mm (AWG 8)

Total	73,089 m

Construction Details:

All vault floors are a minimum of 3 m and a maximum of 5 m below grade level. The vault floor is a concrete pier, a minimum of 0.3 m thick, and pinned to bedrock using four 25 mm dia steel pins, where practical.

Fiber optic and D-C power cables are in buried conduit in a common trench. Trenches are approximately 1 m deep, with the fiber-optic cable conduits at the bottom of the trench. D-C power cables are above, and separated from the fiber-optic cables by approximately 0.3 m.

Functional Operation:

The GERESS array consists of 25 sites, one in the center of the array, with 24 sites arranged in concentric circles of approximately 250, 500, 1000, and 2000 m radius. A 26th site is collocated with vault C2 near the hub. Site seismometer instrumentation is as follows:

Site Nu	Single Vertical Short Period (GS-13)
Site A1	Three-Component Short Period (GS-13)
Site A2	Single Vertical Short Period (GS-13)
Site A3	Single Vertical Short Period (GS-13)
Site B1	Single Vertical Short Period (GS-13)
Site B2	Single Vertical Short Period (GS-13)
Site B3	Single Vertical Short Period (GS-13)
Site B4	Single Vertical Short Period (GS-13)
Site B5	Single Vertical Short Period (GS-13)
Site C1	Single Vertical Short Period (GS-13)
Site C2A	Three Component High Frequency (GS-13)
Site C2B	Single Vertical Short Period (GS-13) and Three-Component Broadband (BB-13)
Site C3	Single Vertical Short Period (GS-13)
Site C4	Single Vertical Short Period (GS-13)
Site C5	Single Vertical Short Period (GS-13)

Site C6	Single Vertical Short Period (GS-13)
Site C7	Single Vertical Short Period (GS-13)
Site D1	Three-Component Short Period (GS-13)
Site D2	Single Vertical Short Period (GS-13)
Site D3	Single Vertical Short Period (GS-13)
Site D4	Three-Component Short Period (GS-13)
Site D5	Single Vertical Short Period (GS-13)
Site D6	Single Vertical Short Period (GS-13)
Site D7	Three-Component Short Period (GS-13)
Site D8	Single Vertical Short Period (GS-13)
Site D9	Single Vertical Short Period (GS-13)

Data is acquired, processed, digitized, time tagged, and transmitted to the Teledyne Geotech Inteleseis Array Controller (IAC-200) at the Hub Facility using Geotech Remote Data Acquisition System (RDAS-200). Critical RDAS status functions are monitored and transmitted in a multiplexed format to the IAC with the seismic data. Each RDAS is configured via hardware and software for the particular sensor compliment at the site. Short-period sensor channels are sampled at 40 sps, high-frequency channels are sampled at 120 sps, and broadband channels are sampled at 10 sps.

At the Hub Facility, an IAC accepts data from all RDAS's in near real-time, and formats the data in "super frames" for retransmission to RUB and NORSAR via land line and/or satellite telemetry. A time-of-day clock (DCF-77) is included in the IAC for array synchronization and timer tagging. The IAC serves additionally as a monitor and maintenance tool for on-site maintenance personnel. A local operator can display any two operator-selectable data channels from the array in near real time. The display is capable of being "zoomed" in both time and amplitude domains. The IAC user interface allows operator command of all RDAS and sensor functions via the inter-array communications network. Locally acquired meteorological data is feed to the IAC and is transmitted to RUB and NORSAR along with the seismic data and status information. The same command capability afforded a local operator is available to an operator at the RUB workstation.

Array power is provided by two 1000 VA uninterruptable power system. All equipment at the Hub Facility operates directly from the output of these UPS's. A set of 48 and 72 VDC power supplies provide D-C power for transmission via hard-wire connections to each remote site. Site power (48 or 72 VDC) and power-cable sizing varies with the cable-route distance to each site, and the RDAS configuration at the site. Each site is powered by a dedicated Hub Facility power supply. The UPS system will power the complete array for a period greater than 15 minutes in the event of a primary-power-source failure.

Intra-array communications is via fiber-optic links. A synchronous set of fiber-optic modems transmits command and control information to each RDAS, and seismic data from the RDAS to the IAC. An asynchronous fiber-optic modem transmits a 1 pps clock signal to each RDAS for array synchronous. Each RDAS maintains an internal time-of-day clock (Epochal time), synchronized to this 1 pps signal, for time tagging. A fourth fiber to each site functions as a spare and/or voice communication link using fiber-optic talk sets. All sites having cable-route distances greater than 4 km utilize a fiber-optic repeater collocated with an intermediate RDAS/sensor complement.