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FINAL REPORT

SEISMIC INSTRUMENT DEVELOPMENT

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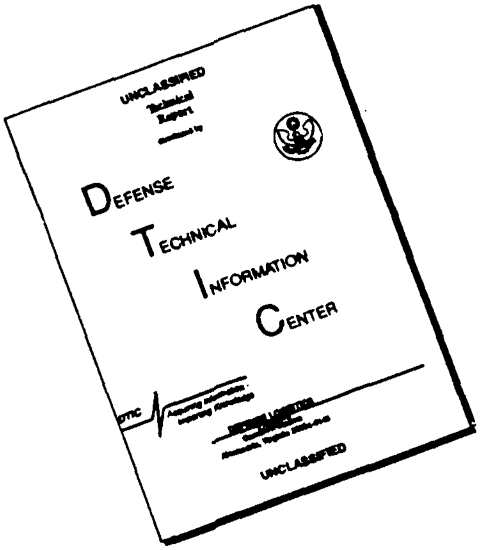

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1. OBJECTIVES OF WORK

The overall objective of Contract F08606-84-C-0023 has been to continue the design, development, test, and evaluation of improved seismic sensor systems. The Statement of Work delineated three separate ~~tasks~~ which contributed to the overall project objective. Each separate task and its associated specific objective is briefly described below.

1.1 STRAIN-INERTIAL SEISMOMETER (SIS) OBJECTIVES

Under the previous Contract F08606-80-C-0014, two prototype SISs were designed, fabricated, and subjected to initial test and evaluation at Geotech's Garland, Texas facility and at a remote test site near McKinney, Texas. The SIS was being developed in order to investigate the potential use of the combined outputs of collocated stain and inertial sensors to enhance signal-to-noise ratio. If the development is successful and if a practical SIS system can be implemented, then the instrument could be used in lieu of small arrays of inertial instruments to record high quality seismic data in seismically noisy areas.

1.2 MODEL 44000 SEISMOMETER OBJECTIVES

Under the previous Contract F086086-78-C-0034, two Model 44000 Seismometers (one engineering model and one prototype) had been designed, fabricated, and subjected to bench level and borehole testing at Geotech's Garland, Texas facility. The Model 44000 design objectives have been: meet or exceed the performance of the KS36000 Seismometer; not exceed the cost of the KS36000; design to install in a 4-inch diameter borehole up to 15 degrees off vertical; design to reduce complexity of installation, operation, and maintenance procedures; and take maximum advantage of design concepts already developed for the KS36000 system.

1.3 SPECIAL DATA COLLECTION SYSTEM (SDCS) OBJECTIVES

The objectives of this task were to store units of the SDCS. This portable seismic instrumentation was used during previous projects to collect data from unique natural or explosive sources. During the conduct of the current project, units of the SDCS were used to support instrument development or other data collection activities.

2. SCOPE OF WORK

A discussion of the general background and the scope of work for each major task is provided in the following paragraphs.

2.1 STRAIN-INERTIAL SEISMOMETER

Results of work under the previous Contract F08606-80-C-0014 were reported in Teledyne Geotech Technical Report No. 83-9, Development of the Model 52500 Strain-Inertial Seismometer System (Prototype). Results which were important drivers to Contract F08606-84-C-0023 are reviewed below.

2.1.1 Excessive Noise

The system noise level of the prototype SIS had to be substantially reduced before high quality seismic data could be collected and analyzed to exploit the noise reduction properties of linear combinations of collocated strain and inertial sensors. Results obtained from the initial field tests of the SIS indicated the excessive noise was due to capacitance bridge transducer imperfections with a helium backfill.

Under the current Contract, the strain transducer design was modified to incorporate KS36000 hard vacuum technology to eliminate the identified problems. Two instruments were reconfigured, and additional data were collected and analyzed to further evaluate instrument performance.

2.1.2 Ancillary Equipment and Facilities

Under the previous Contract, special boreholes for the Strain-Inertial Seismometer were successfully constructed at a site near McKinney, Texas and at a site near Lajitas, Texas. Two boreholes, separated approximately 5-feet at the surface, were constructed at the McKinney site for comparative testing of the SIS systems. Wellhead terminal equipment, installation equipment, and other support items were also available from the previous Contract.

2.2 MODEL 44000 SEISMOMETER

Results of work under the previous Contract F08606-78-C-0034 were reported in Teledyne Geotech Technical Report No. 84-3, Final Report on the Model 44000 Seismometer System Development. Results which were important drivers to Contract F08606-84-C-0023 are reviewed below.

2.2.1 Response-Linearity Limitation

The Model 44000 feedback loop design required modification to achieve a broadband response. It was essential that linear operation be extended from the existing 2.5 Hz cutoff to at least 4 Hz. The existing design used the capacitance bridge transducer for both forward sensing and electrostatic force feedback. The design was very efficient in form, fit, and function, but imposed a response-linearity limitation.

2.2.2 Design Change and Test Coordination

The engineering effort to develop the required design changes was accomplished in parallel with the Sandia National Laboratories program to test the existing prototype configuration. Incorporation of the design changes into the prototype hardware was phased in to minimize the impact to the test program. Bench level and field testing of the modified prototypes was conducted to assess the adequacy of the design changes.

2.3 SPECIAL DATA COLLECTION SYSTEM

This effort was a continuation of efforts initiated by the VELA program to record seismic data from underground nuclear explosions and other seismic events of special interest to DARPA and AFTAC. These data were used to evaluate the signal characteristics of seismic signals. No experiments had been identified that would require deployment of SDCS instrumentation, but this instrumentation was maintained in storage ready for deployment as required to support possible measurement programs.

The SDCS equipment was stored, and an inventory of the equipment was maintained, but no equipment maintenance was performed.

3. SUMMARY OF WORK

3.1 RESPONSIBILITIES

The three major tasks identified above were managed as three separate projects with each having a dedicated project engineer. W. G. Kikendall had program management responsibility for the overall Contract and project responsibility for the SDCS equipment.

M. E. Robinson*, Strain-Inertial Project Engineer under Contract F08606-C-0014, was unable to continue work under Contract F08606-C-0023. J. C. Moore, O. D. Starkey, A. O. Endress, and Dr. Todd Li continued the Strain-Inertial Seismometer Development.

K. R. Verges was Project Engineer for the 44000 Seismometer work under Contract F08606-C-0023 and was responsible for the strain-inertial data recording system.

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*After an extended illness, Mr. Martin E. Robinson took medical retirement on 5 May 1985, and died on 20 January 1986.

3.2 SUMMARY OF STRAIN-INERTIAL WORK

3.2.1 Vibrational Modes

Work began in August 1984 with a search for high-Q vibrational modes in the existing instruments. Information on such modes was important in making design changes. The lower frequency modes could limit the useful range of the SIS, and the higher-Q modes could, through mechanical distortion, produce in-band noise.

One system was observed while operating in a previous test configuration at the McKinney site. The strain rod had been disconnected from the strain transducer which let the transducer act as an inertial seismometer and track the inertial output. However, no modal vibrations were apparent on the unfiltered signals.

The other prototype system was observed in a laboratory test stand. The strain transducer was flushed to clear it of all silicone damping fluid used in previous testing. When the system was excited with random vibrations, low Q vibrational modes were identified at 44 Hz and 142 Hz. These modes were isolated to within the strain/centering capacitance bridge transducer assembly by disconnecting the strain rod.

In contrast with the KS36000, fewer modal frequencies were observed, and the Q's were much lower. It was concluded that modal vibrations were not a significant source of noise in the last configuration of the prototype systems.

3.2.2 Instrument Design Revisions

With the results discussed above and an abundance of information from previous work, the design concept for the revised instrument was developed to have the following improvements.

1. High Sensitivity Transducer, using plate configuration made possible by items 4 and 5 (below).

2. Stray Capacitance Reduced, Insulation Increased.

3. Better Transducer Thermal Isolation, Matching.

4. Spring Bias To Couple Transducer To Strain Rod.

5. Centering Capacitor Assembly Eliminated, Adjust Length Of Strain Rod.

6. Strain Rod Length Adjustment Motor Located Away From Strain Rod And Transducer.

7. Critical Transducer Electronic Components Located Inside Transducer.

8. Double Vacuum Transducer Assembly.

9. Helium Atmosphere Around Most Of Strain Rod.

10. Eliminated Weak-Rod/High-Stress Calibrator.

11. Shortened Package Length And Eliminated Stabilizer.

12. Inertial Seismometer And Strain Transducer Couple To Package Housing At The Same Point.

13. More Rigid Mounting For Inertial Seismometer.

14. Eliminate Manual First-Adjustment Of Strain Rod Length.

15. Stainless Steel Strain Rod.

Fabrication drawings were made and two sets of revised parts were fabricated. With parts from the two original models, two revised systems were assembled. The Installation-Controller was modified to provide operator controls for precision rod length adjustment. The strain and the inertial velocity responses were matched and extended to 10 Hz, (later changed to 20 Hz during data collection).

3.2.3 SIS Bench and Field Testing

The two revised systems were checked in the lab and then installed at the McKinney site for more rigorous testing. The installations and comparative testing were successfully completed and the systems were made ready for the data collection phase during March 1985.

Dynamic inertial noise was approximately -180 dB relative to 1 $(\text{meter/sec})^2$ per Hz. Dynamic strain noise was approximately -240 dB relative to 1 $(\text{meter/meter})^2$ per Hz. Dynamic noise measurements were limited by the preliminary test equipment, but the results justified advanced data collection and analysis. Please refer to SIS Volume, Part 1 for a description of the revised system and test results.

3.2.4 SIS Data Collection and Preliminary Analysis

A flexible, digital recording system was prepared and a set of 18300 Seismometers was located in a tank vault near the strain-inertial wellheads. Data were recorded on magnetic tapes and processed using the Geotech computer facility. Data collection and preliminary data analysis continued interactively for approximately three months during the summer of 1985.

Results were generally good. Coherence between strain and surface inertial was consistently better than that of the collocated strain and inertial. Please refer to SIS Volume, Part 2 for data descriptions and results of the preliminary analysis.

3.3 SUMMARY OF MODEL 44000 WORK

The following paragraphs, 3.3.1 through 3.3.5, summarize the work accomplished on and events relating to the Model 44000 Seismometer Development Program from August 1984 through May 1990. Please see 44K Volume, Part 1 of this report for a more comprehensive description of the Model 44000 Seismometer and 44K Volume, Part 4 for a discussion of final test results.

3.3.1 Electromagnetic Feedback Transducer

Please refer to Technical Report No. 84-3, Final Report on the Model 44000 Seismometer Development, for a discussion of limits imposed by the electrostatic feedback transducer. Also note that T.R. No. 84-3 is the final report for Contract F08606-78-C-0034, and not the final report for the Model 44000 Project.

An electromagnetic feedback modification to 44000-type sensor modules had been designed, implemented and, tested through other programs during 1983 and 1984. This modification was applicable to the Model 44000 Project with one exception. The coil form in the transducer would have to be changed from brass to a non-conductive material. The brass coil form provided optimum matching of temperature characteristics but at the expense of reduced suspension Q or increased thermodynamic fluctuation noise. For the Model 44000 Project, matching of temperature characteristics for a borehole environmental was secondary to noise requirements.

The Plastic polymer "Kel-F 81" was selected for the non-conductive coil form material, and modification of two vertical and two horizontal sensor modules was accomplished in the latter part of 1984.

Long term vacuum testing of "Kel-F 81" was also started in late 1984. This testing eventually demonstrated that "Kel-F 81" would not be satisfactory for the Model 44000. However, the excessive outgassing of "Kel-F 81" did not disturb task schedules except for some extra evacuation cycles at 6 to 9 month intervals.

An alternate coil-form material was identified and evaluated later in the project, but, due to task schedules, it was not incorporated into the sensor modules.

3.3.2 Modification and Test Coordination

The Field Test and Evaluation (FT&E) by Sandia National Laboratories called for dual vertical and dual horizontal system configurations. Modularity of the development systems was greatly improved to support multiple test configurations. Connectors were incorporated into the sensor elements and into the electronic elements of the engineering model system and the prototype system.

Two low-noise transistors used in the sensor module and an operational amplifier used in the sensor electronics had become obsolete. Candidate replacement devices were purchased, tested, and selected to insure supportable systems during the test phase.

Preparations were taken to enable the two systems to be field tested individually and concurrently by Sandia National Laboratories and the U.S. Geological Survey Albuquerque Laboratory.

3.3.3 Prototype Model versus Engineering Model

Various documents on the Model 44000 refer to the development seismometers as engineering model and/or prototype. Where both systems have been referred to as prototypes, it is in the sense that both signal subsystems were of the latest prototype level. It is worthwhile to further clarify this terminology and to discuss distinctive features and applications.

The 44000 Engineering Model (44000EM) system has a primitive configuration particularly well suited for testing. In 1984, the downhole package was in sore need of refurbishment and upgrade. Much of the refurbishment and upgrade was accomplished in the electromagnetic feedback modification wherein it was conditioned for use as the primary test system. The 44000EM had minimal control electronics in the downhole package, and used a high-speed communication or control link between the downhole package and the surface controller. It could easily accommodate dual horizontal or dual vertical sensor modules.

The "44000 Prototype" was the Model 52900 Borehole Seismometer System which consisted of the Model 44000 Borehole Seismometer and the Model 53380 Wellhead Terminal. The Prototype System provided both automatic and semi-automatic leveling-positioning of the sensor modules. Automatic leveling-positioning requires a 3-axis set of modules. The semi-automatic leveling-positioning was intended only for fine trimming by the operator. It could accommodate dual sensors, but awkwardly, due to the limited travel increments available to the operator. The Prototype

System was reconfigured to be more like the 44000EM configuration for testing.

The Prototype System was implemented with three downhole microprocessor subsystems for communications, leveling, and calibration, respectively. The microprocessor was the RCA (CMOS) CDP1802 and support for efficient software revision or development was not available.

Viewing the 44000EM and Prototype situation from the 1990 time frame, two points should be noted: a) provisions should always be available for dual vertical/horizontal testing, even in production systems; and b) configurations, both with and without downhole microprocessors, are still in use.

3.3.4 Borehole Test and Evaluation

The following table outlines the schedule of borehole test and evaluation. FACT or ASL indicates the test facility near Albuquerque, New Mexico. FACT is the Facility for Acceptance, Calibration, and Test operated by Sandia National Laboratories. ASL is the Albuquerque Seismological Laboratory of the U.S. Geological Survey.

System & Configuration	Garland Test	Albuquerque Test
System 1,Dual Verticals	1Dec-15Dec84	FACT 1 Mar-15Mar85
System 1,Dual Horizontals	15Jan-30Jan85	FACT 15Mar-30Mar85
System 1, 3 Component		FACT 1 Apr-30May85
System 2, 3 Component	1 Mar-15Mar85	ASL 1 Apr-30May85

System 1 was based on the former 44000 Engineering Model and System 2 was based on the former Prototype System. Except for the 3-component configuration of System 1, configurations were checked in a borehole at Garland and then relocated to a borehole at the indicated test facility.

The long-period (100 to 10 sec) background at the Garland borehole is not radically different from that at the Albuquerque test facilities. However, the 5 to 50 Hz cultural backgrounds differ by 2 to 3 orders of magnitude. The Garland borehole tests served to verify that the total integrated system was ready for operational testing at a quieter site.

These borehole tests showed that the 44000 Seismometer suffered from two major difficulties: 1) long-period horizontal noise; and 2) short-period vertical noise. Results of these borehole tests were presented at the November 1985 Assessment Review. The assessment committee recommended that a limited series of tests be undertaken to identify the source of the long-period horizontal noise.

Please refer to 44K Volume, Part 4 for further discussion of the borehole testing and test results.

3.3.5 Vault Testing

The source of excess long-period horizontal noise referred to above was judged not to be within the inertial suspension or system electronics. The most likely candidates were taken to be: a) the sensor module support system; and b) the module leveling mechanism. Based on these assumptions, a test plan was developed which would locate, by elimination, noise sources in the module support or leveling assemblies.

The test plan consisted of a 5-step set of vault based measurements which were started at the Sandia FACT underground vault by January 1986. The first three steps of these measurements were substantially completed at FACT before long-term schedule complications and delays were encountered. In 1987 the 44000 equipment at FACT was returned to Garland, Texas in order to complete the vault testing using Geotech's underground vault.

Step 3 of the vault test plan was repeated at the Geotech facility with outstanding results in March 1988. Results showed that excess long-period horizontal noise was due solely to the sensor module installation/mounting technique. Vault testing was concluded and results were reported in Technical Report No. 88-9, Test Report on the Model 44000 Seismometer System.

The contents of Technical Report No. 88-9 are included in 44K Volume, Part 3 of this report. Vault testing was not directed at the vertical excess noise, but test results of the dual vertical channels were also reported. Incoherent long-period noise was larger than expected and was possibly due to temperature variation in the vault. Please refer to 44K Volume, Part 3 for further discussion of the vault testing of the vertical sensor and vertical test results.

3.4 SUMMARY OF SDCS WORK

Not all work on the SDCS was routine equipment storage and inventory. In 1985, Contract F08606-84-C-0023 was amended to: a) descope storage Tasks 1.1.3, 2.3, and 3.3.1; b) transfer accountability of the SDCS equipment to Project T/5152; and c) increase the level of technical support for 44000 field test and evaluation.

The descoping and transfer were due to the identification of an experiment that called for the deployment of three systems which could reliably sense and digitally record seismic signals over a two year period.

3.4.1 Planning Support for SDCS Refurbishment

There had been no contract to maintain the SDCS equipment since 1980, and DCASMA Dallas, Texas had classified the majority of the equipment as not serviceable for field deployment. Refurbishment was required and the planning accomplished here was essential in selecting and utilizing SDCS equipment items.

Contract F08606-85-C-0033 was awarded to Teledyne Geotech for refurbishing SDCS equipment items and implementing the three systems for the identified experiment. After May 1985, SDCS Tasks were reported under Project T/5152, Contract F08606-85-C-0033.

3.4.2 Seismic Instrumentation Rental

Another event beyond normal equipment storage and inventory was the rental of SDCS long-period seismic instrumentation to Teledyne Geotech for research sponsored by the Gas Research Institute during the summer of 1985. Modification No. A00001 set reimbursement to Contract F08606-84-C-0023 at a rate of $2,169.60 for each month's use.

4. CONCLUSIONS AND RECOMMENDATIONS

4.1 STRAIN-INERTIAL SEISMOMETER

Analyses of strain-inertial data collected at McKinney, Texas during the summer of 1985 suggested the following conclusions.

1. In the regional seismic bandwidth (1 Hz to 20 Hz), there was a significant improvement in strain system noise levels over earlier systems and this made combinations of strain-inertial data in the regional bandwidth feasible.

2. The best configuration for a strain-inertial combination of sensors will depend upon the structure of noise at the site. If the noise is dominated by higher mode Rayleigh waves, the best configuration will require some vertical separation of the strain and inertial sensors. If the noise is dominated by fundamental mode Rayleigh waves, collocated sensors may be appropriate.

Please refer to SIS Volume, Part 2 for a more complete discussion of conclusions and recommendations. Further development of the strain-inertial technique should include a vertical borehole seismometer such as the Model 20171A or

23900 which can be relocated for optimum separation of strain and inertial sensors.

4.2 MODEL 44000 SEISMOMETER

The 44000 Development Program has had such scope, duration, cost, and results that we must attempt to make accurate, incisive conclusions of equitable weight. Development of the Model 44000 Seismometer began shortly after the first production of the Model 36000 Seismometer with a prime objective of reducing life cycle cost while maintaining or improving performance relative to the Model 36000.

One of the more important performance drivers is a long-period resolution of 10^{-22} g^2/Hz, $(10^{-20}$ $(m/sec^2)^2/Hz)$. This resolution was established in an era pioneered using 10 Kg, 20 second suspensions with velocity transducers, galvanometer-phototube amplifiers, and deep vaults or mines. This level of resolution has been the basis for the long-period borehole system itself, and it has been required of the Model 36000, the Model 44000, and the Model 54000.

The Model 54000 is a system which utilizes the leveling techniques of the 44000, the seismometer modules of the 36000, and other 44000 based features that improve life cycle cost. The Model 54000 has been included in the following comparison of life cycle cost elements.

4.2.1 Life Cycle Cost Elements

The elements of life cycle cost (LCC) assumed here are: a) design (and development); b) production (and validation); c) borehole construction (and logistics); d) installation (and logistics); and e) maintenance (and logistics).

The following table compares a relative weighing of life cycle cost elements for the 36000, 44000, and 54000 systems.

10 System Life Cycle Cost Comparison

LCC Element	36000	44000	54000
Design	6	10	3
Production	9	8	8
Borehole	8	3	5
Installation	5	2	3
Maintenance	5	3	3
Cumulative	33	26	22

4.2.1.1 Design LCC Elements

The 36000 design weight of 6 encompasses the new technology that was necessary in moving from large geometry of the Model 31300 Symmetrical Triaxial Seismometer to the small geometry of the KS Seismometer.

The 44000 design weight of 10 is due to the sensor module design effort in moving from the 36000 "package diameter, slant angle" of "5-inches, 5-degrees" to the 44000 "3.75-inches, 15-degrees".

The 54000 design weight of 3 is due to the utilization of 36000 and 44000 designs, and increasing package diameter from 5-inches to 5.375-inches. The 3/8-inch increase did not conflict with existing borehole accessories.

4.2.1.2 Production LCC Elements

Production through maintenance comparisons assume approximately 10 sets of seismometers and accessories. Production costs of borehole systems are high. The 36000 production weight of 9 is highest due to the risk and testing associated with the gas bearing leveling method.

Fabrication of the 44000 sensor modules and borehole accessories is lowest, but sensor assembly and test bring the overall production weight to about that of the 54000.

4.2.1.3 Borehole LCC Elements

The 36000 borehole weight is highest at 8 for 7-inch API casing with 3-degree slant.

The 44000 borehole weight is lowest at 3 for 4.5-inch casing with 15-degree slant.

The 54000 borehole weight is intermediate at 5 for 7-inch API casing with 10-degree slant. The 10-degree slant was made practical by 3/8-inch increase in diameter.

4.2.1.4 Installation LCC Elements

The 36000 installation weight is highest at 5 due to the following factors: a) installation requires a highly trained crew; b) peculiarities of the gas bearing leveling method; c) the gas bearing and sensors damage at 10g and 15g, respectively, and require special shipping provisions; and d) vertical sensors are preset for polar, temperate, or equatorial sites.

The 44000 installation weight is lowest at 2. It can withstand two to three times more impact than the 36000 and can be reliably leveled without extensive training. On-site adjustment of the vertical sensor has not been proven but the sensor element is modular and can be replaced with moderate facilities.

The 54000 installation weight is intermediate at about 3. The sensors damage at 15g and require special shipping provisions. Modular sensor elements can be replaced with moderate facilities. It can be reliably leveled without extensive training.

4.2.1.5 Maintenance LCC Elements

The 36000 maintenance weight is highest at 5 due to the following factors: a) the entire 36000 package must be reworked at the factory for sensor module or leveling repair; b) rework and system testing at the factory; and c) risk in shipping and handling.

The 44000 and 54000 maintenance weights are approximately the same at 3. Only the sensor element need be reworked at the factory. Rework cost for the 44000 sensor module is greater, while shipping cost for the 54000 element is greater.

4.2.1.6 LCC Weighing Summary

Although based on much experience, the above comparisons of LCC elements are somewhat subjective. The discussions are intended to aid readers in forming their own assessment. For example; supply, training, and other specialists may be uniquely aware of other cost factors in their area of expertise.

For the situation assumed above, there is nothing more to be gained from the 44000 Development. However, for a large number of systems or sites in remote areas where only small drill rigs are available or practical, the advantages of the 44000 are very important. The following table shows the LCC comparison extended for 50 systems.

50 System Life Cycle Cost Comparison

LCC Element	36000	44000	54000
Design	6	10	3
Production	45	40	40
Borehole	40	15	25
Installation	25	10	15
Maintenance	25	15	15
Cumulative	141	90	98

There is still opportunity to reduce production cost of the 44000. If this can be accomplished, then the advantages of the 44000 become even more dramatic. If short-period resolution can be maintained, then the associated cost of the companion borehole vertical can be avoided.

4.2.2 Short-Period, High-Frequency Capability

Since requirements were developed for the Model 44000 Development, there has been continued interest in higher frequency signals. Short-period and high frequency topics are discussed in the following.

4.2.2.1 Short-Period Vertical Noise

The 36000-03 and 36000-04 Seismometers were observed to have excessive mechanical noise in the vertical short-period band. Similar noise was observed in the older 36000-01, but at a lower level. Investigation of the phenomena led to the conclusion that the noise was assembly related creep magnified by the LaCoste-type suspension. The astatized suspension has not been used in the 44000 vertical to avoid the risk of excess noise in the teleseismic short-period band.

However, avoiding excess short-period noise is secondary to achieving long-period resolution, and, in support of the 44000 Project, Geotech designed an astatized suspension for the 44000. This design is described in Technical Note No. TN-79-4, The La Coste Suspension and Application To An Astatized, Borehole Configuration. This design remains a candidate if the 44000 Development is continued.

4.2.2.2 High-Frequency Considerations

Requirements for measurements higher than about 10 Hz differ in several ways from long-period requirements. With current technology, these differences will probably result in two different seismometers.

Resolution needed in the high-frequency band is 10^{-20} g^2/Hz, an order of magnitude higher than that needed for the long-period band. However, achieving this resolution to 50 Hz is difficult. Even the GS-13 (Model 18300 version with high energy transducer) cannot provide this resolution beyond approximately 20 Hz.

Geotech has recently completed lab testing of a small translational accelerometer design which qualifies it for 10^{-20} g^2/Hz to 50 Hz. This new design can fit into the space of the 44000 vertical, but not the horizontal space. However, its long-period resolution is also 10^{-20} g^2/Hz which may not warrant the cost of a long-period borehole installation.

Coupling becomes increasingly critical with frequency. Coupling requirements for a 50 Hz system may: a) prohibit the use of leveling mechanisms; b) require a strap-down configuration; and c) require coordinate transformation in a 15-degree borehole.

It is a mistake to assume that any feedback arrangement is unconditionally stable independent of its boundary conditions. This rule is particularly applicable in seismic instrumentation where boundary conditions can change with each installation. For boreholes and systems constructed of typical high-Q materials, a 50 Hz feedback seismometer may not be practical.

In view of the foregoing considerations, we do not recommend high-frequency capability for the Model 44000. Short-period capability should be maintained unless there is conflict with long-period requirements.

4.2.3 Horizontal Sensor Element

The final series of vault testing showed dramatic improvement in horizontal noise performance. Since the improvement followed specific efforts planned to reduce the noise, we believe that we have identified the most significant noise source on the 44000 Horizontal modules.

To take advantage of this information, we must change the design of the seismometer system. The upper clamping ring must be eliminated from the system. Furthermore, we must minimize all non-equilibrium forces on the modules. Electrical connections can be permitted to apply forces. We should consider different materials for the module support seat to avoid typically high coefficient of friction between like materials. Finally, we should test these changes in the vault environment where we have good baseline data from the tests to date.

4.2.4 Vertical Sensor

We have not performed a controlled test on the vertical module to determine the source of the short-period noise. To do so, we must disassemble subject modules and make internal changes. We may need to weld the spring terminations and/or change the spring material. Furthermore, the mass position adjustment mechanism may require modification. A piezoelectric stepper motor may provide adequate resolution in movement without the present mechanical parts.

In the long-period passband, the vertical module has historically performed adequately. The seat design improvements should further improve its operation. We feel confident that the vertical sensor can be made to perform at least as well as the Model 36000 vertical sensor at all frequencies.

4.2.5 Summary

Regardless of our confidence, after a dozen years and a half-dozen designers, one must again question the feasibility of putting long-period sensors in a 3.75-inch borehole package. The task has been very difficult with our technology, but we have not encountered an impassable physical barrier.

Improved technology for long-period sensors may be available in the future, but at present the 44000 designs are the only designs capable of 10^{-22} g^2/Hz in a 3.75-inch borehole package at 15-degrees.

The long-period capability of our new 50 Hz accelerometer will be investigated. Initial requirements are based on the broad-band/high-frequency application, and we do not yet know the practical limitations for long-period. It is the first step in using new techniques for a small sensor geometry.

The life cycle cost discussions indicate that completion of the 44000 Development would give significant benefits in a major procurement. We recommend the completion of sensor development using existing equipment. After sensor performance is established, the overall system should then be upgraded to encompass modern devices, techniques and practices.

5. EQUIPMENT LISTS

5.1 STRAIN-INERTIAL

Strain-Inertial equipment items were transferred to Dr. John Ferguson, University of Texas at Dallas, Contract F19678-87-K-0029 on 06 February 1990.

5.2 44000 SEISMOMETER

(Equipment list on following page.)

5.3 SDCS EQUIPMENT

As discussed in 3.4.1, SDCS equipment items were transferred to Project T/5152, Contract F08606-85-C-0033 as of May 1985.

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                                                    T E L E D Y N E   G E O T E C H
GPRPT1                                   GOVERNMENT CONTRACT PROPERTIES SORTED BY CONTRACT, DESCRIPTION
                       RUN DATE   5/21/90                       RUN TIME   7:22                       PAGE   1

                                                                                 - - - ACQUISITION - --          PRO  COND    UNIT          TOTAL
L #  CONTR DESCRIPTION              SEQ NO MANUFACTURER  MODEL       SERIAL      GOVT ID     REFERENCE TYPE GOV YR FSC  LOC CTY  CD     COST           COST  QUAN


  1  40023 -SEISMOMETER MN SP V/H   30930 GEOTECH        18300       8           121450000230 C-40023-01  I    F  65       1737 0              306            306   1
  2  40023 -SHORT PERIOD FILTER     44283 GEOTECH        43050                               C-0014-07   W    F  83       SMU  0            3,000          3,000   1
  3  40023 CAN. TRANSDUCER          42698 UNK            N4          NONE        NO TAG      C-40023-01  D    F  71       WHSE 0              200            200   1
  4  40023 FILE MAP 5 DRAWER        41898 HAMILTON       755A6       NONE         00880000001 C-0023-04   D    P  69       1737 0              146            146   1
  5  40023 HOLELOCK INST. TOOL      44131 GEOTECH        51096       N/A         0034-0002   C-0034-02   W    P  82       BLD3 0            4,800          4,800   1
  6  40023 HOLELOCK-44000           44130 GEOTECH        51108       N/A                     C-0034-02   W    P  82       LOTA 0            1,200          1,200   1
  7  40023 KS PART SEIS             44293 GEOTECH                    N/A                     C-0014-07   W    P  83       LAB3 0            1,850          3,700   2
  8  40023 MACHINE VIBRTN TESING    19640 LAB CORP       RVH30-300   426025      46990024    C-0023-03   D    F  65 6635  ETL3 S            5,068          5,068   1
  9  40023 MICRO MONITOR            43700 RCA            CD185030    2042        0034-0000001 C-0034-02  R    P  80       LAB3 0            2,250          2,250   1
 10  40023 SEIS MODULE-HORIZONTAL   44133 GEOTECH        51141       N/A                     C-0034-02   W    P  82       LAB3 0            5,000          5,000   1
 11  40023 SEIS MODULE-VERTICAL     44134 GEOTECH        51139       N/A                     C-0034-02   W    P  82       LAB3 0            6,000          6,000   1
 12  40023 SEISMOMETER-PROTOTYPE    44123 GEOTECH        44000       N/A         0034-0006   C-0034-02   W    P  82       BLD3 0           30,000         30,000   1
 13  40023 SET TEST CONTROLLER      42793 GEOTECH        37960       X001        0008-0000005 C-40023-01 W    F  74 6635  LAB3 S            5,000          5,000   1
 14  40023 SHORT PERIOD FILTER      44282 GEOTECH        43050                               C-0014-07   W    P  83       LAB3 0            3,000          3,000   1
 15  40023 STABILIZER LEVER-7-5/8   44138 GEOTECH        38135       SET OF 3    0034-0009   C-0034-02   W    P  82       LAB3 0            1,000          1,000   1
 16  40023 STABLIZER 44000          44129 GEOTECH        51133       N/A         0034-0007   C-0034-02   W    P  82       BLD3 0            1,300          1,300   1
 17  40023 STRAIN RELIEF 44000      44128 GEOTECH        51114       N/A         0034-0010   C-0034-02   W    P  82       BLD3 0            1,300          1,300   1
 18  40023 TOOL HOLELOCK INSTAL     42794 GEOTECH        37319       X0001       0008-0000006 C-40023-01 W    F  74       WHSE 0            3,000          3,000   1
 19  40023 TOOLING SPEC CASING      44292 GEOTECH                                            C-0014-07   W    P  83 3456  WHSE T            1,500          1,500   1
 20  40023 WINCH (WHITE)            42278 GOI            SKM305      12          999990000962 C-40023-01 D    F  70       LOT  0            3,150          3,150   1
 21  40023 WINCH DEEP WELL (RUST)   39270 GO PERFORATOR  18211-1     NONE         95210000054 C-40023-01 D    F  64       LOT  0            1,591          1,591   1
 22  40023 WINCH PORTABLE           42391 GEOTECH                    NONE        999990001017 C-40023-01 Z    F  70       HCK  0              100            100   1

     TOTALS FOR CONTRACT          DIPEC       MILITARY     SPECIAL TEST      TOOLING           OTHER          TOTAL
                    COST              0              0           10,068        1,500          72,843         84,411
                   ITEMS              0              0                2            1              20             23
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PART 1

ASSESSMENT INFORMATION SET

DESCRIPTION OF STRAIN-INERTIAL SEISMOMETER SYSTEM

TABLE OF CONTENTS

Page

PART 1 - DESCRIPTION OF STRAIN-INERTIAL SEISMOMETER SYSTEM

LIST OF ILLUSTRATIONS

LIST OF ILLUSTRATIONS

1. PHYSICAL DESCRIPTION

The basic feature of the Model 52500 Strain-Inertial Seismometer, distinguishing it from previous designs, is the degree of collocation of strain and inertial sensors. The strain rod, strain transducer and inertial seismometer are located within a vertical span of approximately 1.5 meters.

1.1 STRAIN-INERTIAL BOREHOLE AND CASING

Since the strain displacement resolution of 0.2 picometer per root Hz can be violated by a variety of structural and supporting creep noise mechanisms, the initial instrument support has been made an integral part of the borehole casing. The special casing section shown in figure 1.1-1 contains the upper and lower supports for the seismometer.

The special casing section is made of stainless-steel tubing to avoid corrosion noise sources. Wall thickness of the tubing was selected to approximate the rigidity of rock formations at Garland and McKinney. Special cementing procedures are required with the thin-wall closed tubing section. At a depth of forty meters, cementing pressure developed in the annulus can crush the special casing section. Two boreholes at the Garland plant and one at the McKinney site were damaged in developing a safe cementing procedure. Three operable strain-inertial boreholes have been constucted to date; two at the McKinney site and one at the Lajitas site.

1.2 STRAIN-INERTIAL SEISMOMETER

The strain-inertial boreholes discussed above, most handling equipment, wellhead equipment, and two prototype strain-inertial seismometers were designed, fabricated and tested under the original development contract F08606-80-C-0014. Although several reductions in noise were accomplished, excess noise in the strain seismometer prohibited any significant data analysis. Assessment of noise mechanisms in the initial design were made, and basic changes to the strain instrument were recommended. Subsequently,

FIGURE 1.1-1. INSTRUMENT CASING SECTION

the strain-inertial development has been continued under contract F08606-84-C-0023.

Figure 1.2-1 shows the first prototype strain-inertial seismometer supported in a test stand with upper cover removed. Figure 1.2-2 shows the modified or current prototype strain-inertial seismometer. Figure 1.2-3 is a drawing of the current instrument showing principal dimensions and weights. Unless stated otherwise, all further references to a strain-interial (S-I) seismometer will mean the seismometer as modified during 1984-1985 under contract F08606-84-C-0023.

1.3 WELLHEAD EQUIPMENT

The wellhead terminal for the strain-inertial system is a version of the 43330 assembly used in the 43300 Multichannel Sensor System. The formal wellhead terminal is pictured in figure 1.3-1. Two of these assemblies were fabricated under the original contract and used without shelter during testing at the McKinney site where they were damaged by lightning. In order to shelter the wellhead equipment in the recording trailer at the McKinney site, the equipment has been mounted in the dual-system equipment rack shown in figure 1.3-2. Figure 1.3-2 also shows the controller used in installing and calibrating the strain-inertial seismometers.

1.4 HANDLING EQUIPMENT

The tilt mast, wellhead packoffs, and borehole cables were fabricated during the original contract. The winch used previously is beyond service, and several revisions have been made in order to use a small electric winch. Figures 1.4-1 and 1.4-2 show setups for erecting and lowering the mast, respectively. An adapter plate allows the small electric winch (GO-LO) to be readily mounted or dismounted on the rear bumper of a pickup truck. Approximately 180 feet of 1/4-inch wire rope is initially loaded on the winch spool. The small erection mast is mounted on the tilt mast and the wire rope is routed through the yoke of the erection mast, over the sheave and secured

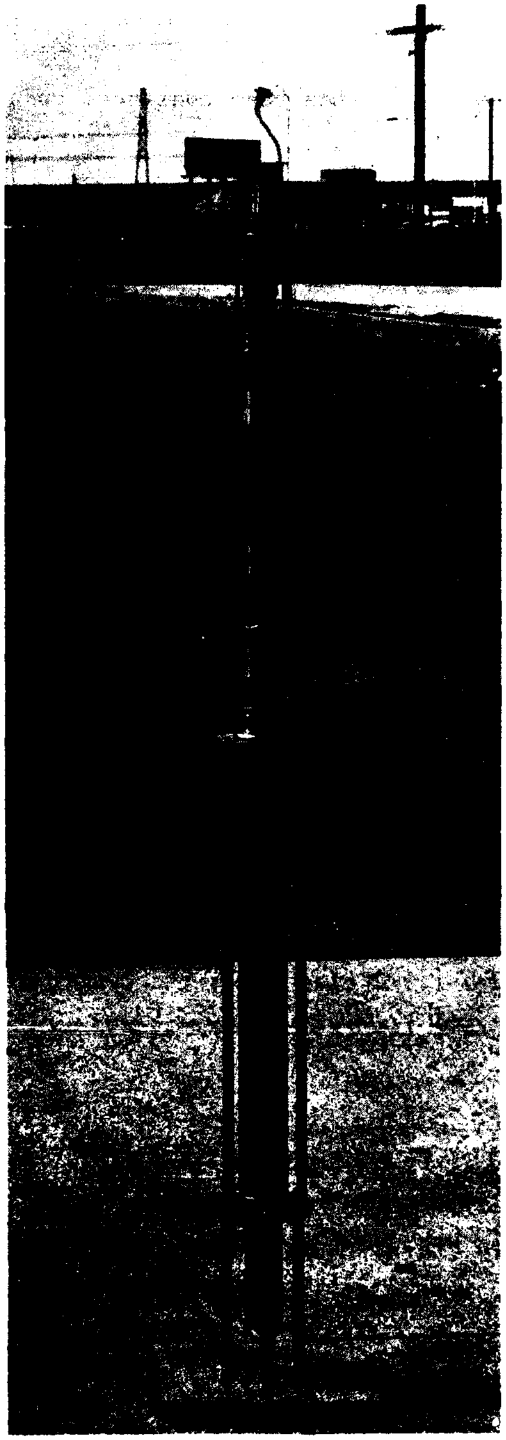


FIGURE 1.2-1. FIRST PROTOTYPE S-I SEISMOMETER (WITH OUTER CASES REMOVED)

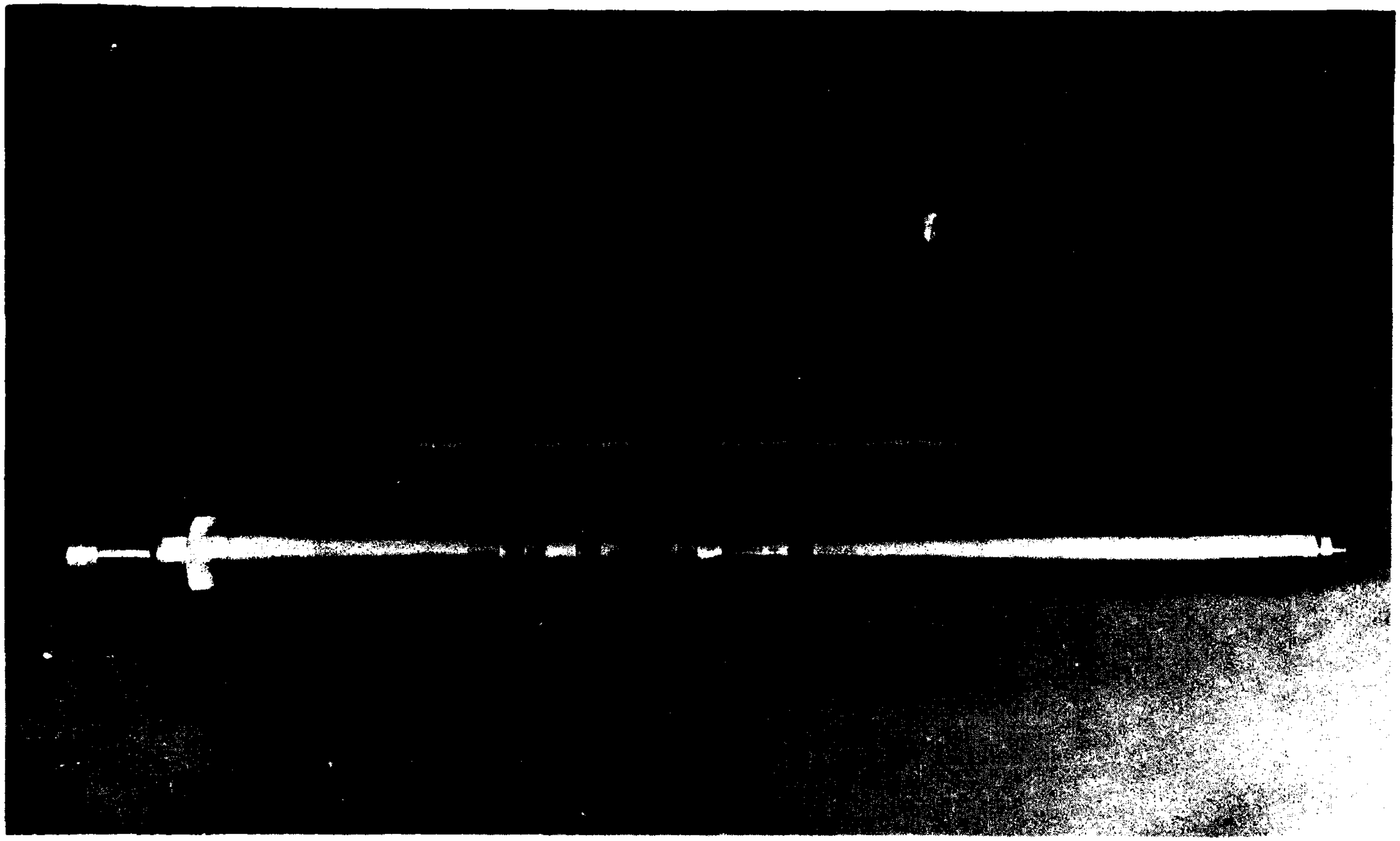
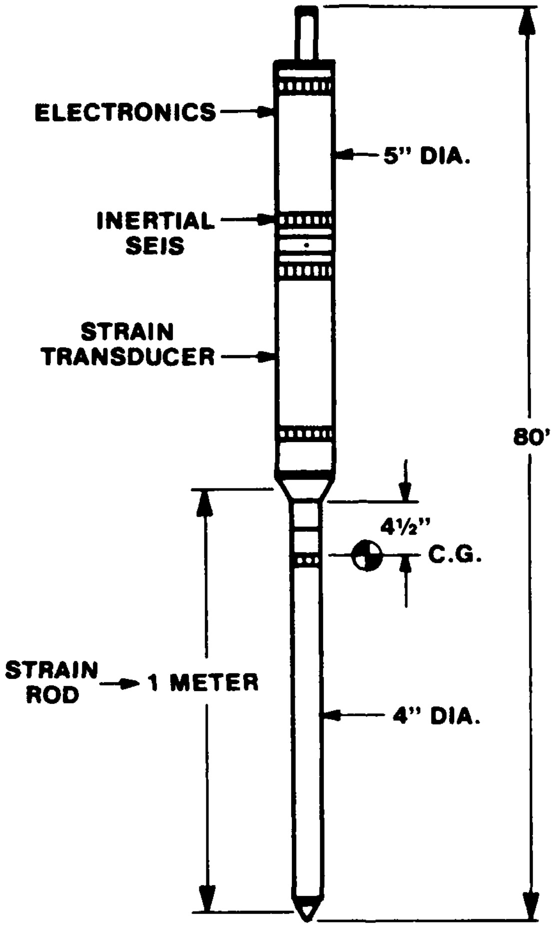


FIGURE 1.2-2. PHOTO OF STRAIN-INERTIAL SEISMOMETER



LOAD ON TOP SEAT = 116 LBS

LOAD ON BOT. SEAT = 76 LBS

TOTAL SEIS ST. = 192 LBS

FIGURE 1.2-3. STRAIN-INERTIAL SEISMOMETER

G 15779

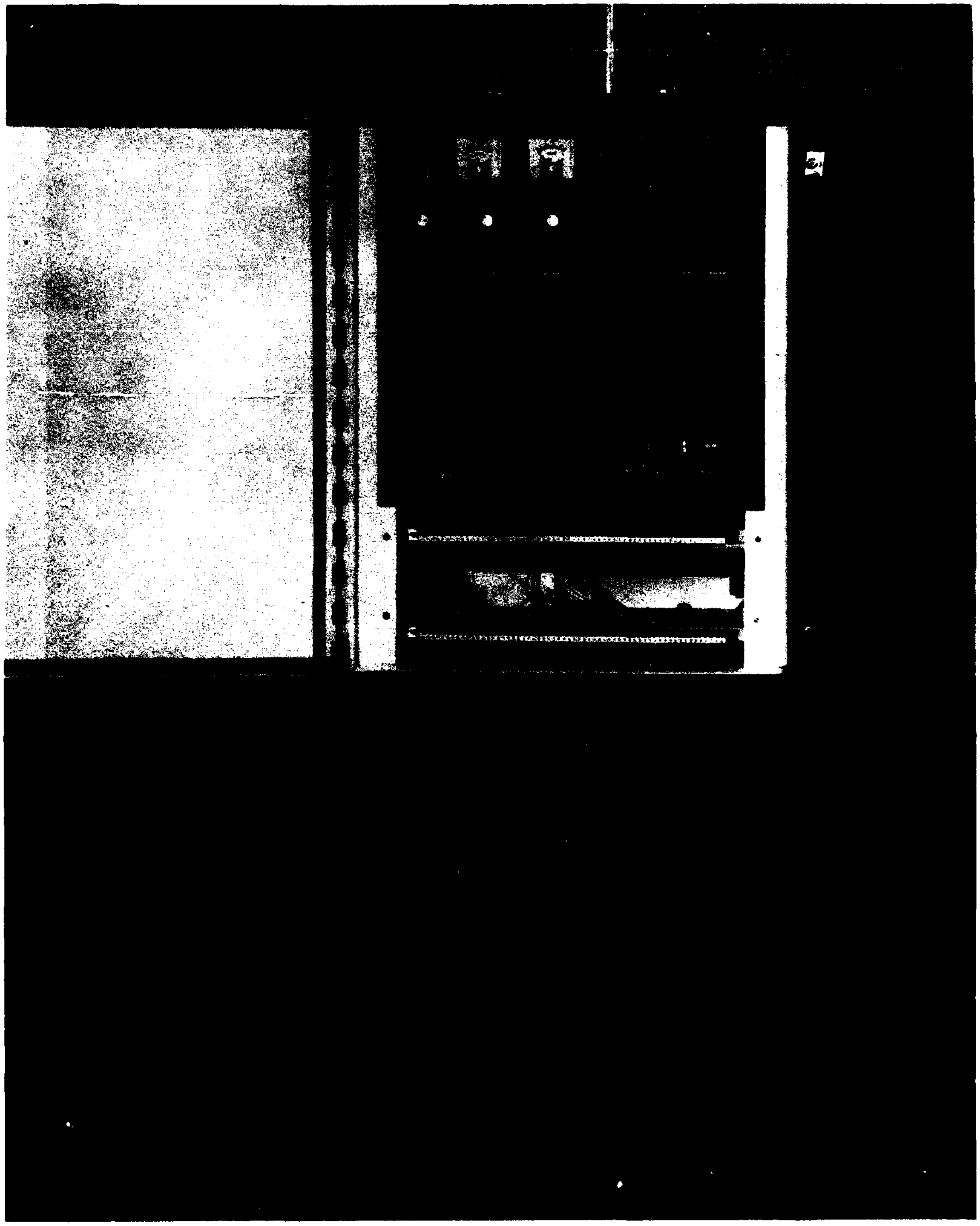


FIGURE 1.3-1. WELLHEAD TERMINAL

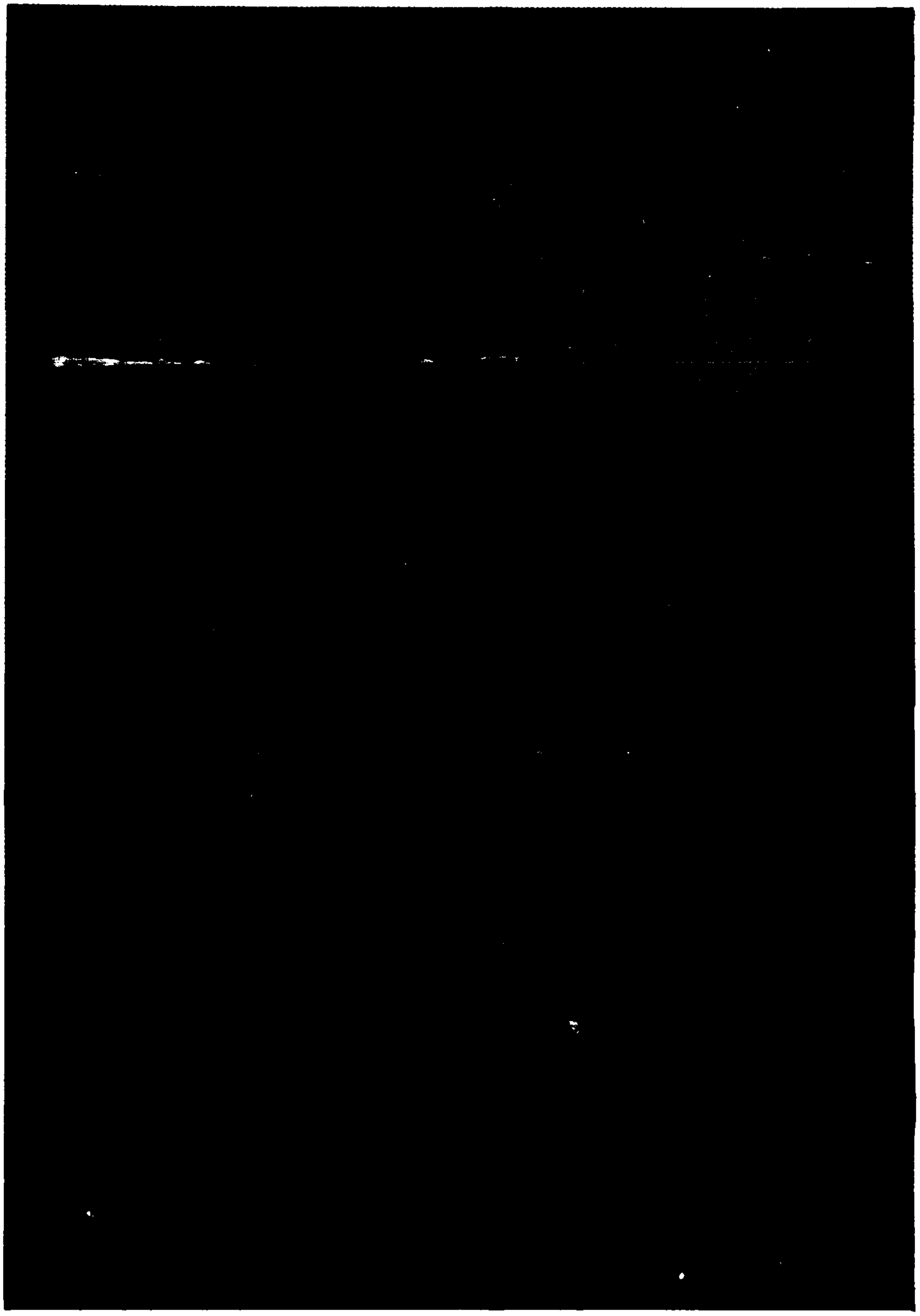


FIGURE 1.3-2. DUAL-SYSTEM WELLHEAD EQUIPMENT RACK

STAND CLEAR!

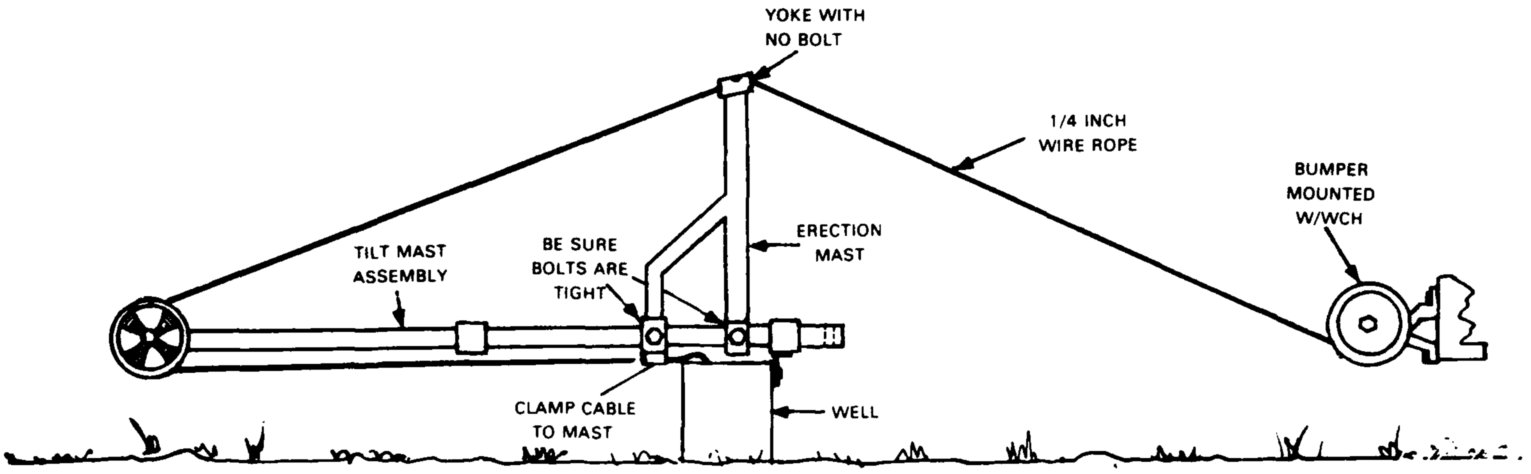


FIGURE 1.4-1. SETUP FOR ERECTING MAST

G 16063

STAND CLEAR!

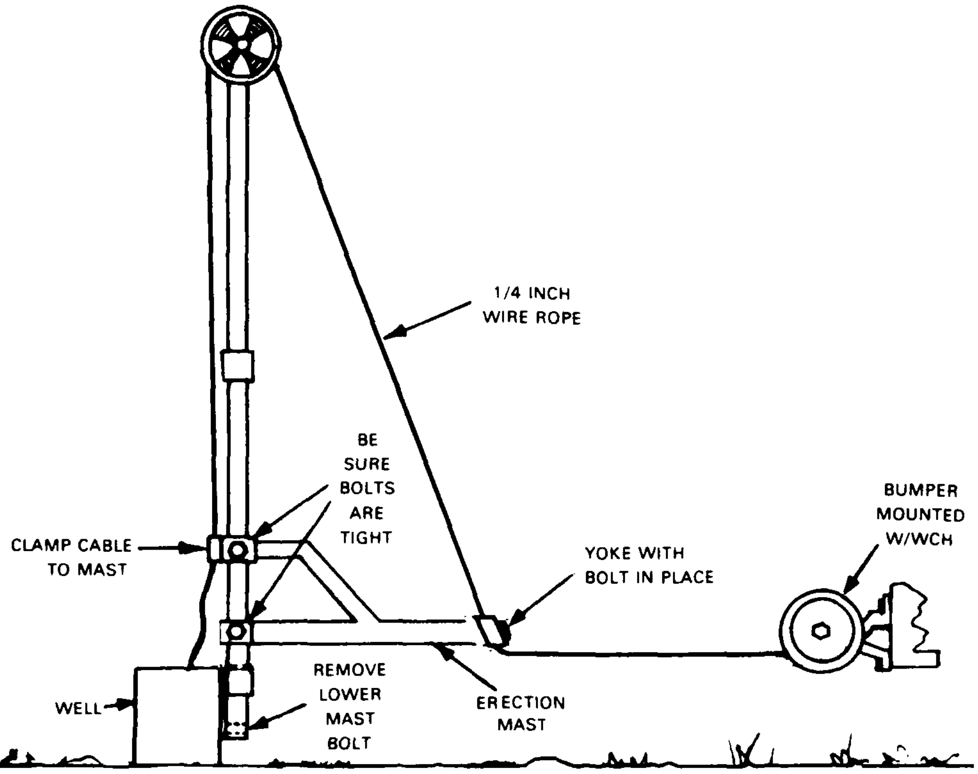


FIGURE 1.4-2. SETUP FOR LOWERING MAST

in the rope clamp on the underside of the erection mast brace. The winch can then be used to erect the tilt mast. After the tilt mast is erected, the wire rope is connected to the cable strain relief of the borehole instrument string and used as the load-bearing element during installation in the 40-meter (131 ft.) S-I borehole. The borehole signal cable is clamped to the wire rope at approximately thirty-foot intervals. After installation, the wire rope is secured as before, but with the rope restrained in the yoke of the erection mast. The winch is then used to lower the tilt mast.

1.5 STABILIZER

The original S-I design is used a special non-centralizing stabilizer at the top of the instrument package. The vertical alignment of the S-I package must be established by the upper and lower seats. Therefore, if a stabilizer is used, then it must not defeat the alignment established by the two seats and, hence, the non-centralizing stabilizer. The weight of the current design has been distributed as indicated in figure 1.2-3 so that no stabilizer is needed. A lightweight bail is used at the top of the instrument package. A chain connects the bail to the *bottom* of the cable strain relief.

2. FUNCTIONAL DESCRIPTION

Figure 2-1 shows a mechanical schematic of the strain-inertial seismometer. The strain rod (A) rests on the lower seat formed by the intersection of the conical end with the lower three balls (B). Housing (C) rests on the upper seat formed by the intersection of the conical section with the upper three balls (D). The strain transducer (E) consists of a balanced variable capacitor with the outer plates rigidly coupled to the housing (C), and the inner plate rigidly coupled to the strain rod (A) through the rod length adjustment mechanism. The inertial seismometer (F) is rigidly coupled to the conical section resting on the upper seat. An electronic subassembly and a motor to actuate the rod length adjustment are located in the top section of the housing. Positive signal polarities correspond to compression between the upper and lower seats for the strain and upward motion of the upper seat for the inertial.

2.1 STRAIN SUBSYSTEM

Figure 2.1-1 diagrams the strain signal channel. The fundamental strain sensing element is the one-meter strain interval formed by the upper and lower seats of the borehole casing section. The strain rod functions as a pushrod supported by the lower seat and transmitting motion of the lower seat to the strain transducer. The strain transducer, supported by the upper seat, responds to the differential displacement between the top of the rod and the upper seat.

For example, if a wave is propagating along the axis of the borehole, then the wavelength (λ), frequency (ω) and velocity (v) are related by $v = (\omega) \cdot (\lambda)$.

Maximum deflection between the upper and lower seats occurs when one seat is in peak compression and the other is in peak rarefaction; i.e., when the wavelength is twice the strain interval, or $\lambda = 2$ meters. Taking 4000 meter/sec as a typical velocity for the McKinney site, the frequency

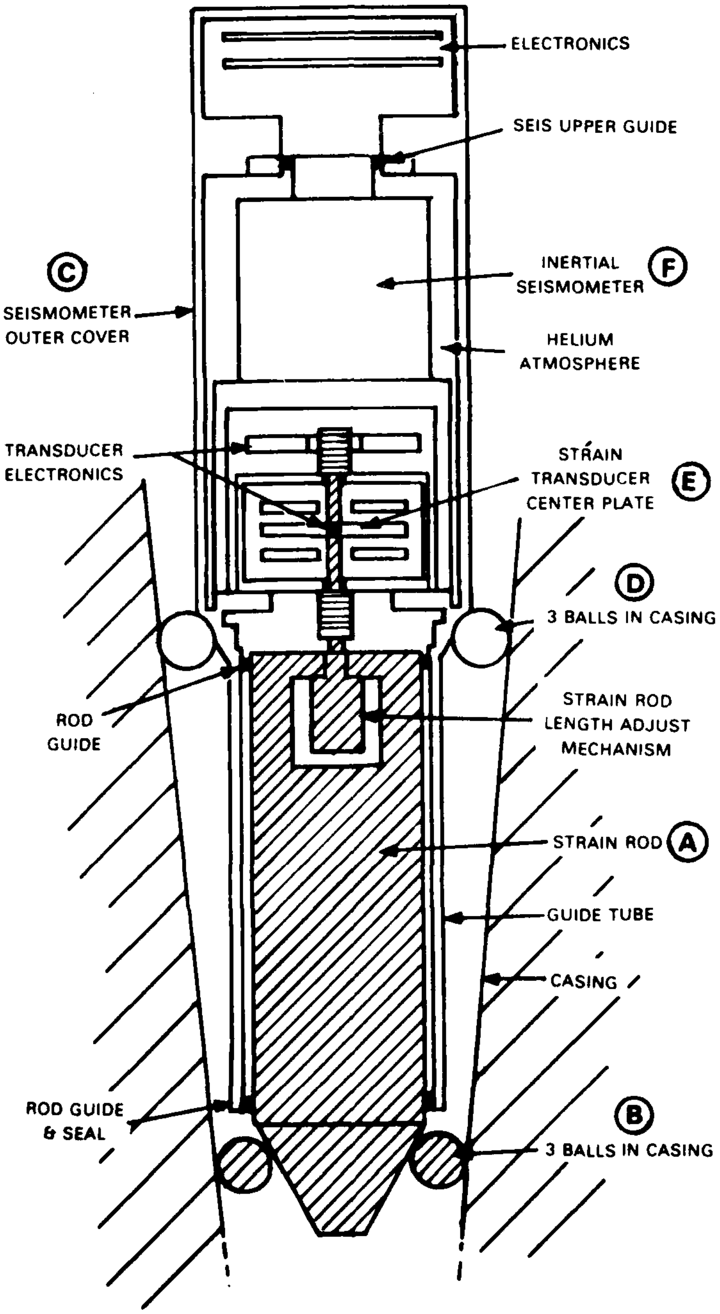


FIGURE 2-1. STRAIN TRANSDUCER SECTIONAL VIEW

G 16062

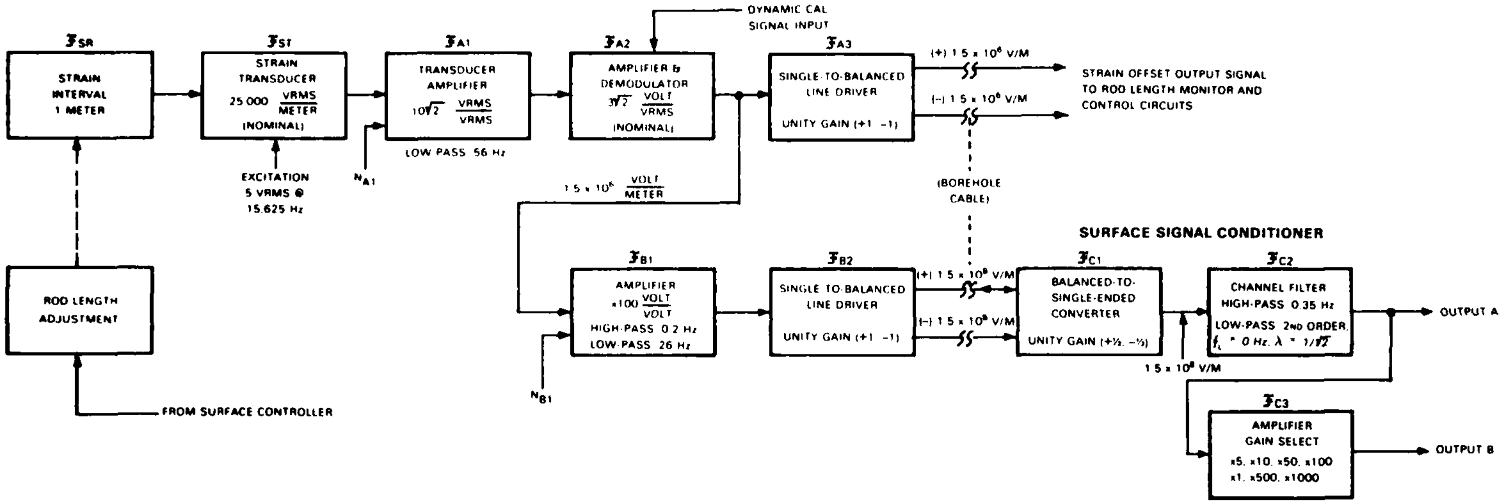


FIGURE 2.1-1. STRAIN SIGNAL CHANNEL DIAGRAM

corresponding to maximum strain is 2000 radian/sec or 318 Hz. Note that strain sensitivity ($\delta \ell/\ell$) and particle motion (y) are related by

$$\delta \ell = 2y \text{ and } \ell = \lambda/2 \text{ and } \lambda = v/\omega \text{ so that}$$

$$\delta \ell/\ell = 4\omega y/v \text{ or } \frac{(\delta \ell/\ell)}{\omega y} = \frac{4}{v} \left\{\frac{m/m}{m/s}\right\}.$$

Therefore, in 4000 m/sec media, the strain sensitivity is 0.001 m/m per m/sec.

The above relation depends on the media, direction of propagation, and wave type, and is, therefore, not a universal expression for sensitivity. However, it illustrates the velocity-strain relation, and it has been used in selecting strain-inertial response shaping and calibration functions.

The strain transducer is a balanced-capacitance bridge modulator excited with positive and negative phases of a 15,625 Hz carrier. Differential displacement of the upper seat and the top of the strain rod produces an amplitude-modulated signal at a nominal sensitivity of 25,000 Vrms per meter. The transducer amplifier, located in the outer vacuum compartment of the strain transducer, amplifies the signal by a factor of 14.14 Vrms per Vrms, (23.0 dB).

The amplifier-demodulator, located in the lower bay of the electronic subassembly, amplifies and demodulates the signal with a nominal gain of 4.24 volts per Vrms. The gain is trimmed to develop a sensitivity of 1.5 million volts per m/m. The stage has a first-order low-pass filter at 56 Hz. This dc-coupled signal is: a) output to the surface through a unity gain, single-to-balanced line driver; and b) applied to an ac-coupled amplifier. (The dynamic or electronic calibration signal is also applied to a point in the amplifier-demodulator circuit and will be discussed in another section.)

The dc-coupled channel is the strain offset output which is used during installation to adjust the strain rod to its operating length. The strain offset output is also used for motor calibration of the strain instrument. In future applications, the channel may also be used for long-period measurements.

The ac-coupled channel sensitivity is increased to 150 million volts per meter by the amplifier and output to the surface through a unity gain single-to-balanced line driver. The amplifier is a low-noise carrier-type with an overall gain factor of 100 (40 dB), a first-order high-pass corner at 0.2 Hz and a first-order low-pass corner at 26 Hz.

The surface signal conditioner provides a balanced-to-single-ended converter input stage, a first-order high-pass filter, a second-order low-pass filter, a unity gain output A, and a gain-selectable output B. The high-pass corner has been set at 0.35 Hz and the low-pass corner has been set at 10 Hz (0.7 damping), for initial testing and calibration. However, it is anticipated that the channel filtering will be changed during the data collection and analysis phase. Figure 2.1-2 summarizes the transfer functions of the strain subsystem.

2.1.1 Strain Rod Length Adjustment

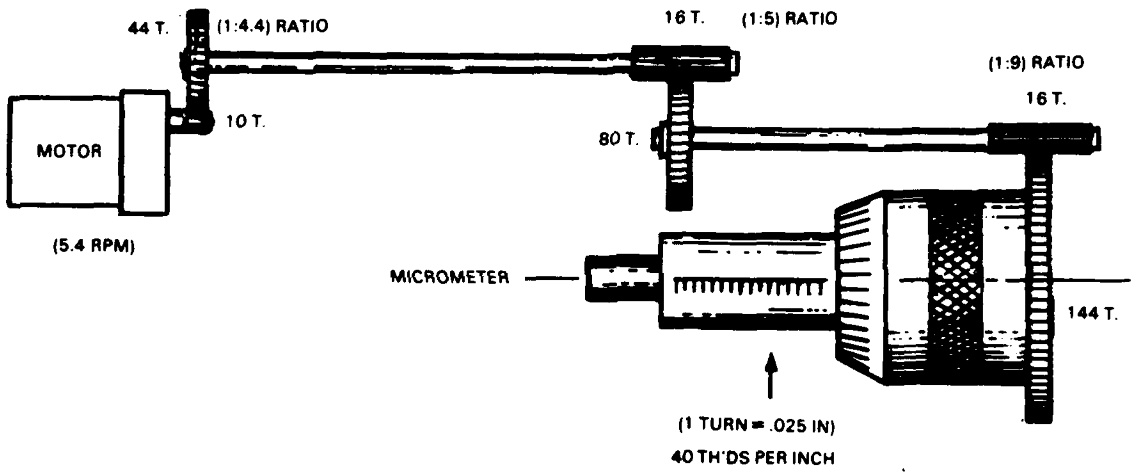
The top end of the strain rod includes a precision micrometer with a drive gear. The micrometer is driven through a gear shaft by a motor located near the top of the package to keep motor heat from disturbing the operation. The motor is controlled from the surface to drive the micrometer and adjust the rod length. The timing motor and motor drive circuits used in the original design have been maintained in the current design. Figure 2.1.1-1 diagrams the drive train and the rates involved.

The prototype controller has been modified to provide a variety of timed motor drive sequences. Figure 2.1.1-2 lists the programmed runs that are available. The motor can be driven to increase or decrease the rod length

	Displacement	Velocity
$\mathcal{F}_{SR}$ (Strain Rod/Interval)	$\frac{\partial y}{\partial z} \cdot (\delta z = 1\text{m})$	$\frac{4}{v} \quad \frac{m/m}{m/s}$ *
$\mathcal{F}_{ST}$ (Strain Transducer)		$(+)\ 25{,}000\ \frac{\text{Vrms}}{\text{meter}}$
$\mathcal{F}_{A1}$ (Transducer Amplifier)		$(-)\ 10\sqrt{2}\ \frac{\text{Vrms}}{\text{Vrms}}$
$\mathcal{F}_{A2}$ (Amplifier-Demodulator)		$\left[\frac{(-)\ 3\sqrt{2}\ \frac{\text{volt}}{\text{Vrms}}}{1+j(f/56)\text{Hz}}\right]$
$\mathcal{F}_{B1}$ (High-Pass Amplifier)	$\left(-100\ \frac{\text{volt}}{\text{volt}}\right) \left[\frac{j(f/0.2\ \text{Hz})}{1+j(f/0.2\ \text{Hz})}\right] \left[\frac{1}{1+j(f/26\text{Hz})}\right]$	
$\mathcal{F}_{B2} \cdot \mathcal{F}_{C1}$ (Line Driver-BSC)		$(-)\ 1\ \frac{\text{volt}}{\text{volt}}$
$\mathcal{F}_{C2}$ (Surface Filter)	$\left[\frac{j(f/0.35)}{1+j(f/0.35)}\right] \left[\frac{-1}{1 - (f/10\ \text{Hz})^2 + j\sqrt{2}\ (f/10\ \text{Hz})}\right]$	
$\mathcal{F}_{C3}$ (B-Out Gain Selection)	$(+)\ 5,\ 10,\ 50,\ 100,\ 1,\ 500,\ 1000\ \frac{\text{volt}}{\text{volt}}$ (selectable)	

* Increase in rod length or earth compression taken as positive polarity. An oversight in the number of inversions in the modified surface signal conditioner has resulted in negative voltage at output A and B for earth compression on strain and earth-up on inertial.

FIGURE 2.1-2. STRAIN TRANSFER FUNCTIONS



$5.4 \text{ RPM} \times \frac{1}{4.4} \times \frac{1}{5} \times \frac{1}{9} = .0272727$ MICROMETER RPM

$\times$ .025/REV. = .0006818 INCHES PER MIN.

WITH 5.4 RPM MOTOR, RATE IS .0006818 IN/MIN.

FIGURE 2.1.1-1. STRAIN/INERTIAL GEAR SYSTEM

G 16061

Control Setting					Cycles	Offset					
Rng	D	C	B	A	@ 60 Hz	S.E. Volts		Travel		Run Time	
0	0	0	0	0	---	---		---		---	
0	0	0	0	1	---	---		---		---	
0	0	0	1	0	1	7.22	mV	4.81	nm	16.7	ms
0	0	0	1	1	2	14.4	mV	9.62	nm	33.3	ms
0	0	1	0	0	4	28.8	mV	19.2	nm	66.7	ms
0	0	1	0	1	8	57.7	mV	38.4	nm	133.3	ms
0	0	1	1	0	16	115.5	mV	77.0	nm	266.7	ms
0	0	1	1	1	32	230.9	mV	154.9	nm	533.3	ms
0	1	0	0	0	64	461.8	mV	307.9	nm	1.070	sec
0	1	0	0	1	128	923.6	mV	615.7	nm	2.133	sec
0	1	0	1	0	256	1.847	V	1.231	m	4.267	sec
0	1	0	1	1	512	3.694	V	2.463	m	8.533	sec
0	1	1	0	0	1024	7.389	V	4.926	m	17.07	sec
0	1	1	0	1	2048	14.78	V	9.852	m	34.13	sec
0	1	1	1	0	4096	29.56	V	19.70	m	68.27	sec
0	1	1	1	1	8192	3	ppFS	39.41	m	136.5	sec
1	0	0	0	0	64	461.8	mV	307.9	m	1.070	sec
1	0	0	0	1	128	923.6	mV	615.7	m	2.133	sec
1	0	0	1	0	256	1.847	V	1.231	m	4.267	sec
1	0	0	1	1	512	3.694	V	2.463	m	8.533	sec
1	0	1	0	0	1024	7.389	V	4.926	m	17.07	sec
1	0	1	0	1	2048	14.78	V	9.852	m	34.13	sec
1	0	1	1	0	4096	1.5	ppFS	19.70	m	1.14	min
1	0	1	1	1	8192	3	ppFS	39.41	m	2.28	min
1	1	0	0	0	16384	6	ppFS	78.81	m	4.55	min
1	1	0	0	1	32768	12	ppFS	157.6	m	9.10	min
1	1	0	1	0	65536	24	ppFS	315.3	m	18.20	min
1	1	0	1	1	131072	48	ppFS	630.5	m	36.41	min
								0.25	inch		
1	1	1	0	0	262144	96	ppFS	1.261	mm	1.214	hour
								0.050	inch		
1	1	1	0	1	524288	192	ppFS	2.522	mm	2.427	hour
								0.099	inch		
1	1	1	1	0	1048576	394	ppFS	5.044	mm	4.855	hour
								0.199	inch		
1	1	1	1	1	2097152	988	ppFS	10.09	mm	9.709	hour
								0.397	inch		

"ppFS" indicates peak-to-peak full-scale voltage range.

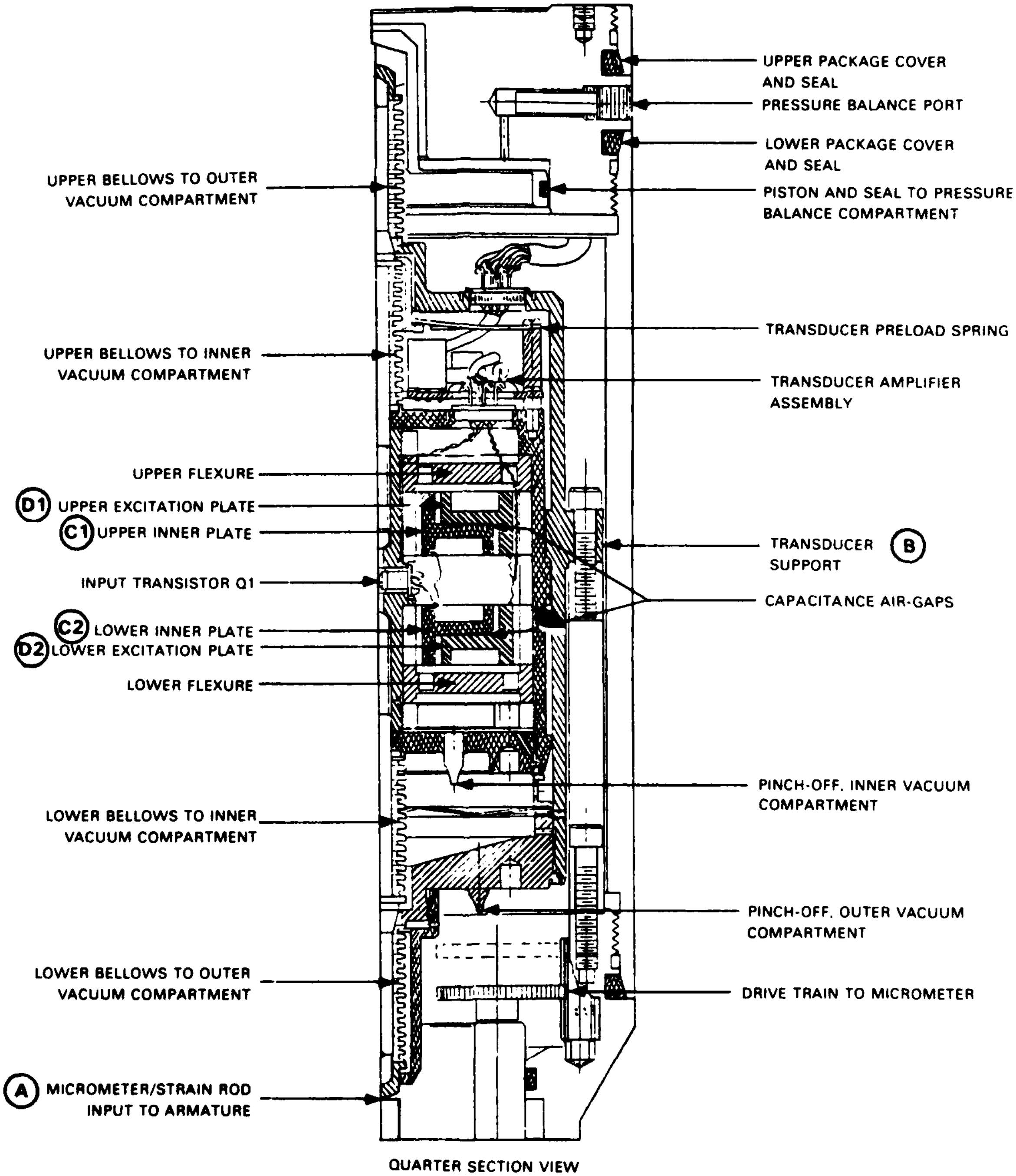
FIGURE 2.1.1-2. CONTROLLER MOTOR DRIVE SEQUENCES from 4.81 nanometers to 10.09 millimeters. The controller also provides a comparator which the operator can select to monitor the strain offset output and automatically stop the drive sequence when the output is zeroed.

During handling and transit, the strain rod is set to near-minimum length to ensure that the massive strain rod cannot damage the strain transducer. For operating lengths in the McKinney boreholes, this requires negative runs of 9.709 and 2.427 hours to retract the micrometer for handling and transit.

2.1.2 Strain Transducer

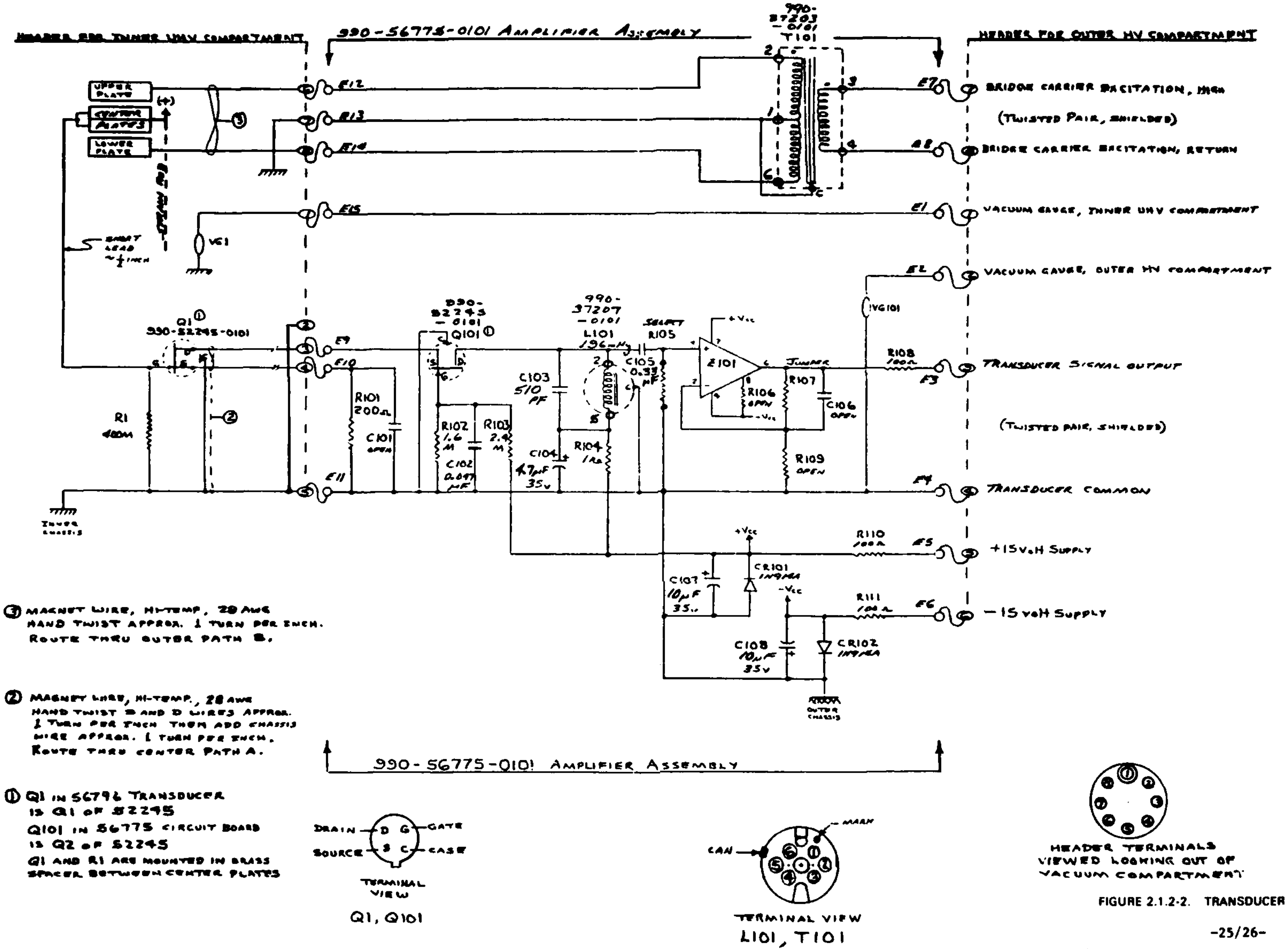
Figure 2.1.2-1 shows a sectional view of the strain transducer. Note the area (A) where the micrometer point contacts the armature, and the area (B) where the transducer is supported. These are the differential inputs to the strain transducer. Plates (C1) and (C2) are rigidly connected to input (A) while plates (D1) and (D2) are rigidly connected to input (B). All four cylindrical plates are electrically insulated from structural ground by a quartz-brass fabrication technique. Plate (D1) is driven by the positively phased 15,615 Hz excitation signal and plate (D2) is driven by the negatively phased excitation signal. Both plates (C1) and (C2) are connected to the input of the first amplifier stage mounted between (C1) and (C2). The output of the first amplifier stage is routed through the center of the armature to the header of the ultra-high vacuum compartment. The balance of the transducer amplifier is located on the circuit board in the outer high-vacuum compartment. The schematic of the transducer and transducer amplifier is shown in figure 2.1.2-2.

The inner compartment is first assembled, evacuated for two weeks at 95°C, pinched-off from the evacuation system, and tested. The inner compartment is then assembled into the outer compartment which is then evacuated for two weeks at 95°C as before.



G 16065

FIGURE 2.1.2-1. STRAIN TRANSDUCER SECTIONAL VIEW



③ MAGNET WIRE, HI-TEMP, 28 AWG
HAND TWIST APPROX. 1 TURN PER INCH.
ROUTE THRU OUTER PATH B.

② MAGNET WIRE, HI-TEMP., 28 AWG
HAND TWIST S AND D WIRES APPROX.
1 TURN PER INCH THEN ADD CHASSIS
WIRE APPROX. 1 TURN PER INCH.
ROUTE THRU CENTER PATH A.

① Q1 IN 56796 TRANSDUCER
IS Q1 OF 52245
Q101 IN 56775 CIRCUIT BOARD
IS Q2 OF 52245
Q1 AND R1 ARE MOUNTED IN BRASS
SPACER BETWEEN CENTER PLATES

FIGURE 2.1.2-2. TRANSDUCER SCHEMATIC G 18080

Note that the mechanical input (A) to the armature is carried through bellows at each end of the transducer. The S-I housing has a port which allows air pressure in the borehole to act on the upper end of the armature to neutralize bouyant force on the strain rod.

2.1.3 Strain Noise Model

There are numerous potential sources of noise within the strain signal channel. However, successful implementation will allow the strain channel noise to be modeled with two dominant sources as indicated in figure 2.1-1. Noise N_{A1} is the component associated with the input of the transducer amplifier, and noise N_{B1} is the component associated with the input of the x100 amplifier stage.

Noise model functions are summarized in figure 2.1.3-1.

The transducer amplifier noise N_{A1} can be estimated by

$$N_{A1} = E_{Q1} + \left(\frac{4kT}{R1} + I_{Q1} \right) \left[\frac{(R1)^2}{1 + (\omega_c R1C_s)^2} \right]$$

where: E_{Q1} is the noise voltage of input FET Q1, 1×10^{-17} $(\text{volt})^2/\text{Hz}$;

k is Boltzman's constant, 1.38×10^{-23} Joule/°K;

T is absolute temperature, 300°K;

I_{Q1} is the noise current of input FET Q1, 1×10^{-30} $(\text{amp})^2/\text{Hz}$;

R1 is the input resistance, 5×10^{8} ohm;

C_s is the capacitance bridge output capacitance, 250×10^{-12} farad; and

$\omega c = 2\pi fc$ and fc is the excitation frequency, 15,625 Hz.

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Since the output of the capacitance bridge is an amplitude modulated signal, the information band has been translated to a band about the excitation or carrier frequency. Therefore, the N_{A1} expression is evaluated at 15,615 Hz. The $R1C_s$ time constant has been made large so that the R1 and I_{Q1} contribution are attenuated to well below E_{Q1} within the translated information band. The estimate for N_{A1} is

$$N_{A1} = 1 \times 10^{-17} \frac{V^2}{Hz} + \left[\left(3.3 \times 10^{-29} + 1 \times 10^{-29}\right) \frac{A^2}{Hz}\right] \left[\frac{2.5 \times 10^{17} \ \Omega^2}{1 \times 1.51 \times 10^8}\right]$$

$$N_{A1} = 1 \times 10^{-17} \frac{V^2}{Hz} + 7.14 \times 10^{-20} \frac{V^2}{Hz} \doteq 1 \times 10^{-17} \ V^2/Hz.$$

The N_{B1} noise component is significant in that:

a. Strain channel noise should be that established by N_{A1};

b. Dc gain between the N_{A1} and N_{B1} input points is limited by the minimum repeatable increment of the rod length adjustment mechanism; and

c. High-pass gain is needed to ensure that channel resolution is not degraded in transmission to the surface equipment.

The above factors were considered in setting the strain offset output sensitivity at 1.5×10^6 volt/meter, the strain short-period (SP) output sensitivity at 1.5×10^8 volt/meter, and the rod length adjustments in figure 2.1.1-2.

Noise component N_{B1} consists of both a noise voltage (E_n) and a noise current (I_n), and can be estimated at the SP output by

$$E_{out} = \frac{(A)^2\ (E_s)\ (\omega C\overline{R})^2}{1 + (\omega C\overline{R})^2} + \frac{I_n\ (R^2)\left(\frac{A}{1-A}\right)^2}{1 + (\omega C\overline{R})^2} + (E_n)\ \left(\frac{A}{1-A}\right)^2 \left[\frac{1 + (\omega CR)^2}{1 + (\omega C\overline{R})^2}\right]$$

Where:

A is the base gain of the B1 stage, -100 volt/volt;

C is the high-pass capacitor, 80×10^{-6} farad;

R is the stage feedback resistor, 1×10^{6} ohm;

ω is 2π f and f is frequency in Hz;

$\overline{R} = R/1-A = R/101;$

$E_n = 4 \times 10^{-16}\ (\text{volt})^2/\text{Hz}$

$I_n = 1 \times 10^{-28}\ (1 + 10/f)\ (\text{amp})^2/\text{Hz}$

E_s is an input voltage supplied to the B1 stage in $(\text{volt})^2/\text{Hz}$; and

E_{out} is the output of the B1 stage in $(\text{volt})^2/\text{Hz}$.

Substituting values,

$$E_{out} = E_s\ (1 \times 10^4) \left[\frac{(f/0.2009)^2}{1 + (f/0.2009)^2}\right] + \left[\frac{9.80 \times 10^{-17}\ (1 + 10/f)}{1 + (f/0.2009)^2}\right] +$$

$$(3.92 \times 10^{-16}) \left[\frac{1 + (f/0.00199)^2}{1 + (f/0.2009)^2}\right].$$

Letting $E_s = N_{A1}\,\mathcal{F}_{A1}\,\mathcal{F}^*_{A1}\,\mathcal{F}_{A2}\,\mathcal{F}^*_{A2} = (1 \times 10^{-17})\,(60)^2 = 3.6 \times 10^{-14}\ \mathrm{V^2/Hz}$,

and evaluating E_{out} at $f = 0.005$ Hz, 0.2 Hz, 1 Hz, and 10 Hz, then

$$\begin{array}{lcccccccc}
 & & \underline{N_{A1}\ \mathrm{TERM}} & & \underline{I_N\ \mathrm{TERM}} & & \underline{E_N\ \mathrm{TERM}} & & \\
E_{out}\Big|_{0.005} & = & 2.2 \times 10^{-13} & + & 2.0 \times 10^{-13} & + & 2.9 \times 10^{-15} & = & 4.2 \times 10^{-13}\ \mathrm{V^2/Hz} \\
E_{out}\Big|_{0.2} & = & 1.8 \times 10^{-10} & + & 5.0 \times 10^{-15} & + & 2.0 \times 10^{-12} & = & 1.8 \times 10^{-10}\ \mathrm{V^2/Hz} \\
E_{out}\Big|_{1\ \mathrm{Hz}} & = & 3.5 \times 10^{-10} & + & 4.1 \times 10^{-17} & + & 3.8 \times 10^{-12} & = & 3.5 \times 10^{-10}\ \mathrm{V^2/Hz} \\
E_{out}\Big|_{10\ \mathrm{Hz}} & = & 3.6 \times 10^{-10} & + & 7.8 \times 10^{-20} & + & 4.0 \times 10^{-12} & = & 3.6 \times 10^{-10}\ \mathrm{V^2/Hz}
\end{array}$$

Note that the N_{B1} terms should not limit channel noise in the long-period band (0.01 to 0.1 Hz) nor in the short-period band (0.2 to 10 Hz). Since the N_{A1} component is dominant and uniform at $1 \times 10^{-17}\ \mathrm{V^2/Hz}$, the equivalent strain input noise (S_n) can be estimated by

$$S_n = \frac{1 \times 10^{-17}\ \mathrm{V^2/Hz}}{(25{,}000\ \mathrm{V/m})^2\ (1\ \mathrm{m})^2} = 1.6 \times 10^{-26}\ \frac{(\mathrm{m/m})^2}{\mathrm{Hz}}\ ;$$

where the strain transducer sensitivity is 25,000 volt/meter.

2.2 INERTIAL SUBSYSTEM

The original strain-inertial design planned to use the vertical VKS seismometer module and electronics. It was necessary to change this plan since the unresolved noise of the vertical KS suspension was prohibitive to the objectives of the strain-inertial development. The S750 Seismometer was then selected for the inertial subsystem, and it has been maintained in the current design. However, a change of inertial sensors will be needed pending analysis of strain-inertial data and evaluation of the strain-inertial technique.

The S750 Seismometer has marginal-to-excessive noise for teleseismic monitoring at frequencies below about 1 Hz. Therefore, if the strain-inertial technique is to be used for lower frequencies, then the vertical element of the Model 44000 should be used. If the strain-inertial technique is applied above 1 Hz, and the S750 proves to be satisfactory for the application, then the S750 should be upgraded to the S750A to improve repeatability. It should be noted that incorporating the S750A changes the internal amplifier of the S750, while incorporating the vertical element of the Model 44000 is a significant effort.

2.2.1 S750 Seismometer Module

The basic design of the S750 was derived from the Geotech S500 design which uses piezoelectric or ferroelectric transducers to convert the mass-frame displacement of an inertial suspension into an electrical signal. The fundamental response of the unit is uniform with respect to input acceleration, but with a first-order, high-pass (6 dB/octave) at 0.01 Hz. Figure 2.2.1-1 shows a block diagram of the S750 seismometer module.

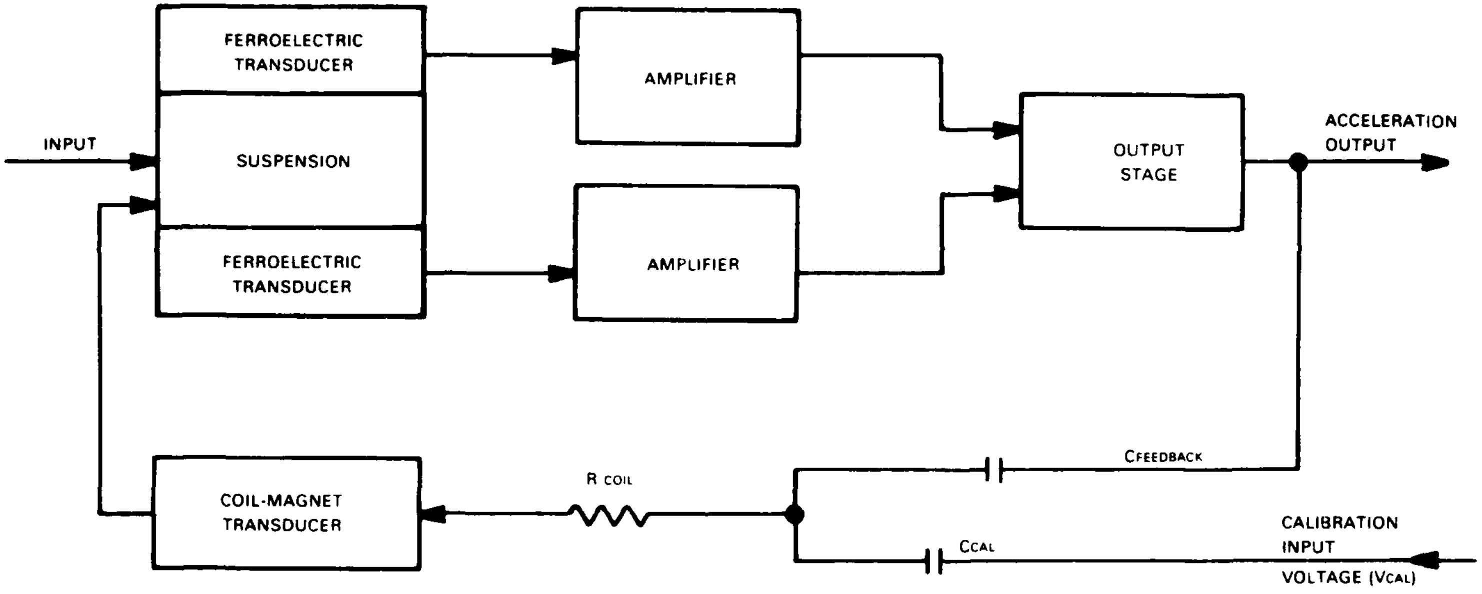

FIGURE 2.2.1-1. BLOCK DIAGRAM, S750 SEISMOMETER MODULE, 990-52100-0102

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INERTIAL SUSPENSION

Relative to the S500, the S750 suspension has been made much softer for greater sensitivity and equipped with travel limits; however, the S750 can still be operated either horizontal or vertical without mechanical adjustment. Nominal parameters for the S750 suspension are listed below.

Mass	2 kilograms
Natural frequency	54 Hz
(Spring rate	230,000 newton/meter)
Internal damping	<5% of critical
Travel limits	±0.001 inch (25 microns)

FERROELECTRIC TRANSDUCERS

Piezoelectric ceramics bonded to constraining flexures at each end of the mass, convert flexure stain into an electrical analog. Operating as a voltage generator, each transducer produces 265,000 volts per meter in series with a source capacitance of 0.032 microfarad. This source capacitance in conjunction with the 500-megohm input resistance of the amplifier form the 0.01 Hz high-pass circuit.

AMPLIFIERS

Low-noise, high-input resistance circuits amplify the voltage produced by each transducer. Resolution is limited at the low end of the passband by the Johnson noise current of the 500-megohm input resistor, and is limited at the high end by the voltage noise of the amplifier circuit. The two amplified signals are summed in the output stage to produce the (Acceleration Output) signal.

COIL-MAGNET TRANSDUCER

The coil-magnet transducer (6 newton/amp) has a low-impedance winding, (80 ohm, 6 millihenry) to form a current summing node for both feedback and calibration signals. The feedback capacitor provides a coil current proportional to the time derivative of the output to damp the suspension. The calibration capacitor is selected for the individual motor constant of the transducer, to provide a uniform equivalent velocity drive of $8\pi \cdot (\text{Vcal})/10$ microns per second.

FREQUENCY RESPONSE

The frequency response for the S750 seismometer module is shown in Figure 2.2.1-2 in terms of volts per unit acceleration (meter/second^2).

The high-frequency corner of the response is modified by a resistive feedback component so that the second-order corner (12 dB/octave) for the closed-loop circuit occurs at approximately 90 Hz rather than at the 54 Hz suspension natural frequency.

RESOLUTION

Figure 2.2.1-3 shows the noise of the S750 seismometer module referred to equivalent input acceleration power spectral density in dB relative to 1 (meter/second^2)^2 per Hz. Columns A, V, and D in Figure 11 list equivalent noise as follows.

Column A	(meter/second^2)^2 per Hz
Column V	(meter/second)^2 per Hz
Column D	(meter)^2 per Hz

FREQUENCY (HERTZ)	ACCELERATION RESPONSE		VELOCITY VOLT/(M/S)	DISPLACEMENT VOLT/(M)
	VOLT/(M/S^2)	PHASE		
0.015625	80.60	+ 67.3 °	5.60	0.388
0.03125	96.89	+ 33.0 °	19.02	3.735
0.06250	97.87	+ 17.4 °	38.43	15.09
0.1250	98.00	+ 8.71°	76.97	60.45
0.250	98.03	+ 4.16°	153.98	241.88
0.500	98.04	+ 1.65°	307.99	976.6
1.000	98.04	- 0.04°	616.0	3870
2.000	98.04	- 1.75°	1232	1.548×10^4
4.000	98.07	- 4.35°	2465	6.190×10^4
8.000	98.16	- 9.13°	4934	2.480×10^5
16.00	98.53	- 18.6 °	9905	9.958×10^5
32.00	99.58	- 38.8 °	2.001×10^4	4.026×10^6
64.00	91.08	- 88.4 °	3.662×10^4	1.473×10^7
90.51	60.30	-129.2 °	3.429×10^4	1.950×10^7
128.0	27.82	-170.8 °	2.238×10^4	1.800×10^7

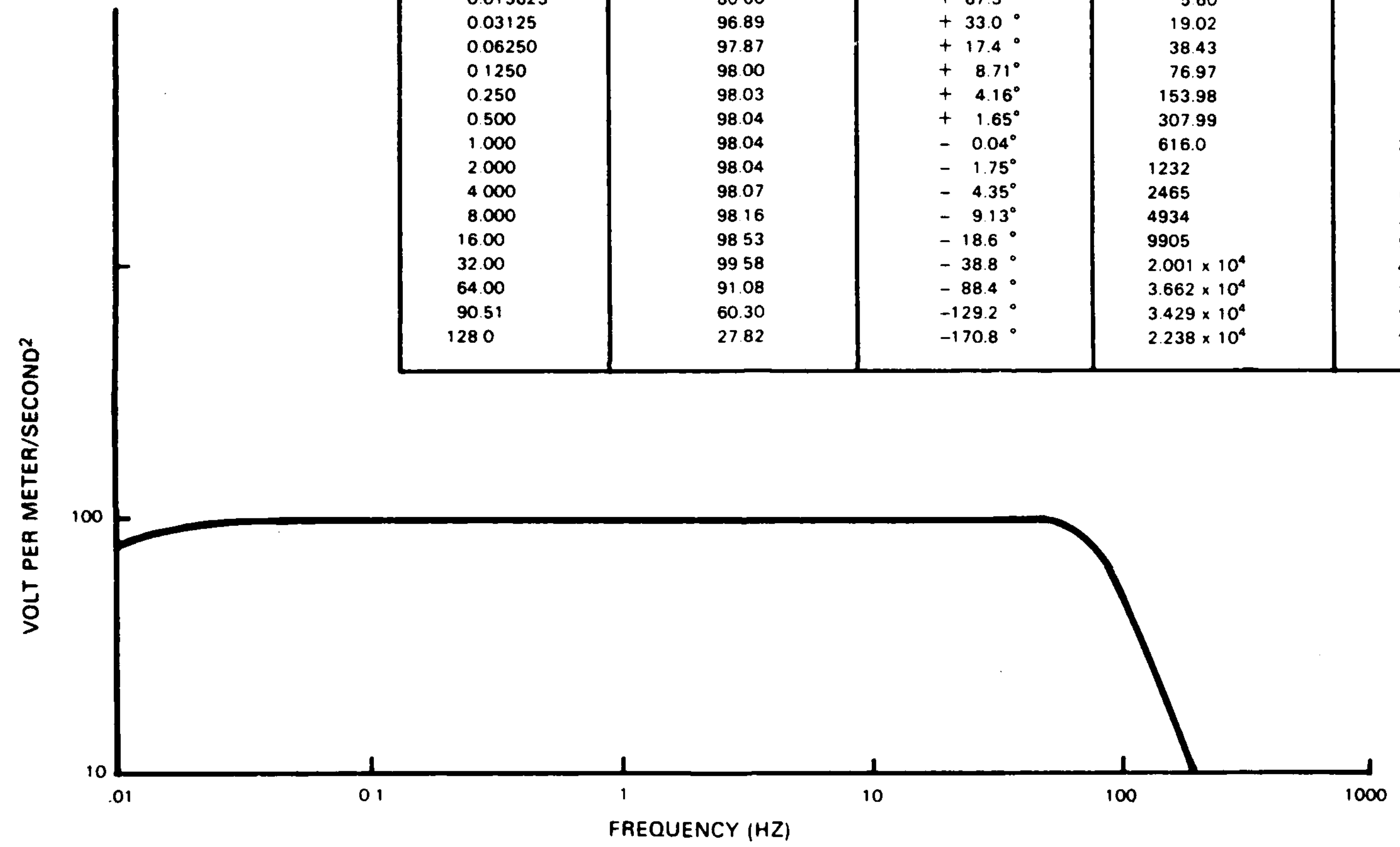

FIGURE 2.2.1-2. FREQUENCY RESPONSE, S750 SEISMOMETER MODULE

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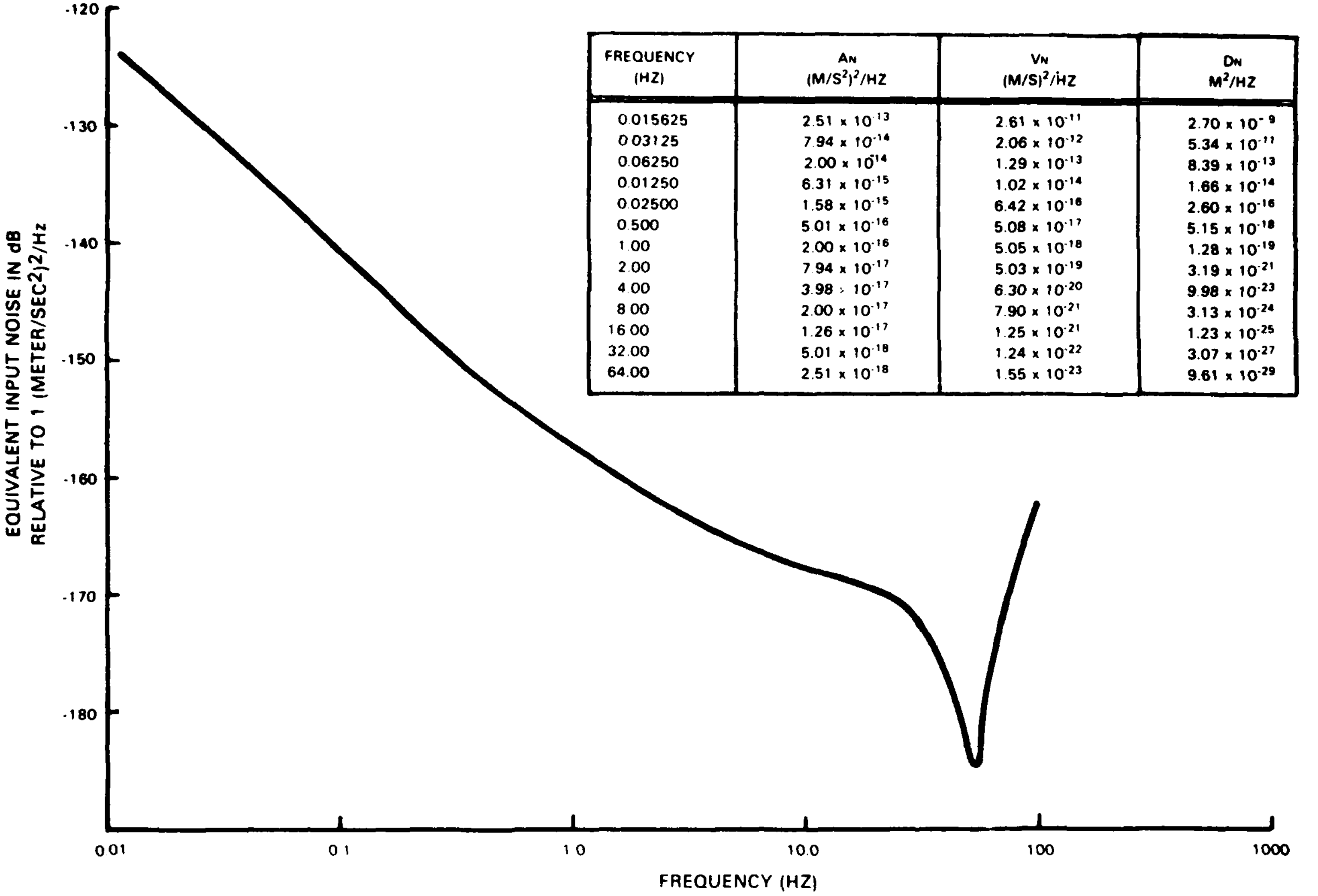

FREQUENCY (HZ)	A_N $(M/S^2)^2/HZ$	V_N $(M/S)^2/HZ$	D_N M^2/HZ
0.015625	2.51×10^{-13}	2.61×10^{-11}	2.70×10^{-9}
0.03125	7.94×10^{-14}	2.06×10^{-12}	5.34×10^{-11}
0.06250	2.00×10^{-14}	1.29×10^{-13}	8.39×10^{-13}
0.01250	6.31×10^{-15}	1.02×10^{-14}	1.66×10^{-14}
0.02500	1.58×10^{-15}	6.42×10^{-16}	2.60×10^{-16}
0.500	5.01×10^{-16}	5.08×10^{-17}	5.15×10^{-18}
1.00	2.00×10^{-16}	5.05×10^{-18}	1.28×10^{-19}
2.00	7.94×10^{-17}	5.03×10^{-19}	3.19×10^{-21}
4.00	3.98×10^{-17}	6.30×10^{-20}	9.98×10^{-23}
8.00	2.00×10^{-17}	7.90×10^{-21}	3.13×10^{-24}
16.00	1.26×10^{-17}	1.25×10^{-21}	1.23×10^{-25}
32.00	5.01×10^{-18}	1.24×10^{-22}	3.07×10^{-27}
64.00	2.51×10^{-18}	1.55×10^{-23}	9.61×10^{-29}

FIGURE 2.2.1-3. NOISE LEVEL S750 SEISMOMETER

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2.2.2 Inertial Signal Channel

The inertial signal channel is diagrammed in figure 2.2.2-1. The acceleration output of the S750 is applied to the bandpass filter located on the Interface Assembly, 990-53918-0101. The bandpass filter has a center frequency of 0.2 Hz with a 0.79 damping ratio. This circuit is also referred to as the velocity shaper since it results in a response that is uniform in velocity from 0.2 to 90 Hz. The gain of the velocity shaper produces a sensitivity of 15,000 volts per meter/second.

The output of the velocity shaper is applied to the single-to-balanced line driver for transmission to the surface signal conditioner. The input stage of the surface signal conditioner is a balanced-to-single-ended converter which develops a single-ended sensitivity of 15,000 volts per meter/second.

The channel filter for the inertial channel is the same as that for the strain channel. Initially, the channel filter has a first-order high-pass filter at 0.35 Hz and a second-order low-pass filter at 10 Hz with 0.707 damping ratio. Output A has fixed midband sensitivity of 15,000 volts per m/s and output B provides selectable gains. Figure 2.2.2-2 summarizes the transfer functions of the inertial signal channel.

2.3 CALIBRATION

The original design used a coil-magnet transducer acting on a weakened section at the lower end of the strain rod to produce a variable strain in the rod. The weakened rod section was considered a potential source of creep noise and eliminated in the current design. The current design incorporates a rod length adjustment mechanism, and this same mechanism is also used for calibration.

Calibration by rod length adjustment, while accurate, is limited to dc-type calibration and must be supplemented with a provision for broadband calibration. This has been accomplished by scaling and injecting the calibration signal in the output stage of the amplifier and demodulator section of the strain amplifier.

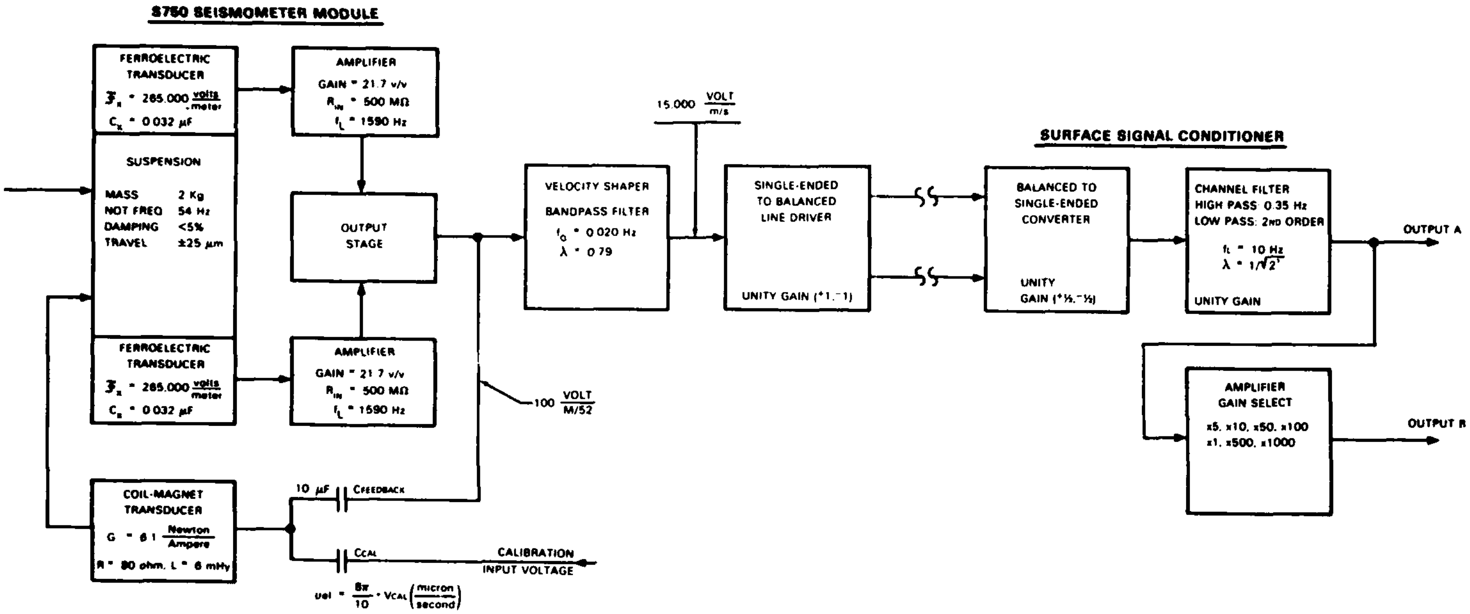

FIGURE 2.2.2-1. INERTIAL SIGNAL CHANNEL DIAGRAM

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$\mathscr{F}_{S2}$
(S750 Seismometer)

$$\frac{(-)(4.60)\left[\frac{jf/0.01}{1+jf/0.01}\right]\left[1+\frac{20.5}{1+jf/1592}\right]}{1-\left(\frac{f}{54}\right)^2+j\left(\frac{f}{54}\right)\left\{0.05+(4.60)\left[\frac{jf/0.01}{1+jf/0.01}\right]\left[1+\frac{20.5}{1+jf/1592}\right]\left[\frac{1.916\times 10^{-4}}{1+jf/198.9}\right]\right\}}\quad\frac{\text{volts}}{\text{m/sec}^2}$$

$\mathscr{F}_{VS}$
(Velocity Shaper)

$$\frac{(-)jf(606.1)}{1-f^2\,(24.983)+jf\,(7.931)}\quad\frac{\text{volt}}{\text{volt}}$$

$\mathscr{F}_{B2}\cdot\mathscr{F}_{C1}$
(Line Driver - BSC)

$$1\ \frac{\text{volt}}{\text{volt}}$$

$\mathscr{F}_{C2}$
(Surface Filter)

$$\left[\frac{j(f/0.35)}{1+j(f/0.35)}\right]\left[\frac{-1}{1-(f/10)^2+j\,(f/10)\sqrt{2}}\right]$$

$\mathscr{F}_{C3}$
(B-Out Gain Selection)

$$(+)\ 5,\ 10,\ 50,\ 100,\ 1,\ 500,\ 1000\ \frac{\text{volt}}{\text{volt}}\quad\text{(selectable)}$$

FIGURE 2.2.2-2. INERTIAL TRANSFER FUNCTIONS

The S750 Seismometer had an established velocity calibration function of (8.) Vcal/10 microns/sec per volt, and the broadband calibration for the strain channel has been similarly scaled. As discussed in section 2.1, the velocity transfer function of the strain channel involves propagation velocity, and scaling since the broadband calibration signal has been based on a velocity of 4,000 meters per second along the axis of the instrument.

For example, consider a calibration of ±10 volts applied to both strain and inertial channels. For the inertial channel, the calibration voltage is coupled through a capacitor to coil-magnet transducer to produce a mass-frame displacement equal to that which would be produced by an earth velocity of ±8. or ±25.13 micron/second. A sensitivity of 15,000 volts per meter/second or 0.015 volt per micron/second will output a voltage of ±0.377 volt.

For the strain channels, the calibration signal is scaled to an equivalent input of ±8. micron/second. Since the response of the one-meter strain interval for a 4,000 meter/second is 0.001 m/m per m/s, the equivalent input strain is ±8. nanometer/meter. A sensitivity of 1,500 volts per m/s or 1,500,000 volts per m/m will produce a voltage of ±0.377 volt on the strain offset channel. Accordingly, the strain SP channel at a sensitivity of 150,000 volts per m/s or 150,000,000 volts per m/m will develop an output of ±3.77 volts.

Calibration controls have been revised so that the inertial channel can be calibrated singly, or both strain and inertial channels can be calibrated simultaneously. Calibration polarities have been arranged so that positive voltage corresponds to a positive input, i.e., earth-compression for the strain and earth-up for the inertial.

2.3.1 Strain Offset Calibration

The strain offset or motor calibration should be performed as part of the installation procedure and at monthly to annual intervals as a data base is developed. It is essential for the strain offset output to be in a linear operating range (-10 to +10 volts) for SP output data to be valid. Likewise, the motor calibration is the only provision for determining the sensitivity of the strain offset channel.

A typical motor calibration would be as follows. The controller is connected to the wellhead terminal connector, and a dc voltmeter is connected to monitor strain offset output. The controller is then operated to drive the rod positively until the output is at +10 volts or greater. The rod is then driven negatively to approximately +5 volts and drive stopped. The controller is then set to run for 17.07 seconds to produce rod length change of 4.926 microns. The exact output is measured and recorded immediately before and after the 17.07-second run. The negative drive is then continued until the output is at -10 volts or more negative. The rod is then driven positively to approximately -5 volts and stopped. The controller is then set for the 17.07-second run in the positive direction. The exact output is measured and recorded immediately before and after the 17.07-second run. The change in output offset is then averaged and divided by 4.926 micron to calculate sensitivity. After the motor calibration is complete, drive the rod for zero output.

3. TEST AND CALIBRATION RESULTS

Two modified strain-inertial prototype systems have been fabricated, assembled and bench tested. Both systems have been installed in the strain-inertial boreholes at the McKinney site and operationally tested immediately after installation. In the following, section 3.1 reviews the bench testing and section 3.2 reviews the operational testing.

3.1 REVIEW OF BENCH TESTING

Bench testing activity has been concentrated on the following items:

1. Strain transducer
2. Rod-length adjustment mechanism
3. Borehole electronics
4. Wellhead electronics
5. Controller

3.1.1 Strain Transducer

Strain transducer testing has been coordinated with the assembly procedure for these doubly evacuated transducers. Both inner units were first assembled without the internal Q1 transistor. This allowed mechanical dimensions to be checked and transducer capacitances to be measured. The two prototypes were very similar having an average effective plate spacing of 0.3724 mm (0.01466 in.), and an average output capacitance of 250 pF. The inner units were then fully assembled, sealed, electrically checked and evacuated for two weeks at 95°C (203°F).

After evacuated bakeout and pinch-off, the inner units were checked electrically, assembled into the outer unit with the transducer amplifier, and tested for gain, noise and maximum output. The transducers were then sealed, evacuated for two weeks at 95°C, pinched-off and retested for gain, noise and maximum output. At this point, the strain transducers were ready for the next level of assembly.

3.1.2 Rod-Length Adjustment Mechanism

Pinion gear stock used in earlier, similar mechanisms could not be purchased for prototype fabrication, and a more course stock was selected. The drive train made with the course stock was checked for uniform drive characteristics and found inadequate. A sufficient amount of the original gear stock was located in-plant to remake the drive trains for both prototypes. Drive trains made with the finer gear stock were satisfactory, and the rod-length adjustment mechanism allowed the strain transducer to be centered to better than 10 nanometers.

3.1.3 Borehole Electronics

The electronic subassembly developed in the original design has been modified and used in the current design. Wiring changes were required, and the current wiring diagram for the strain-inertial seismometer is shown in 990-52557-2102.

Changes in calibration circuits and motor-drive circuits were made to the 53918 interface assembly. The current interface assembly is diagrammed in 990-53918-21M1.

The 53921 strain amplifier has been revised and is diagrammed in 990-53921-21M1.

Both electronic subassemblies were bench tested to verify design revisions and to ensure that all lightning-damaged and degraded parts had been eliminated. Modifications to the wiring and interface assembly were checked out without complication, but complications were encountered in noise testing the strain amplifier.

As discussed in section 2.1.3, the noise of the strain channel should be established by the noise of Q1 in the strain transducer, and gain through the strain offset channel must be held to a value satisfactory for rod-length adjustment and motor calibration. With this objective, the Z2 operational amplifier in the demodulator section of the strain amplifier was changed from the obsolete HA2-2700 selected device to a lower noise OP22 device. It was found that, while the OP22 has superior noise characteristics in "normal" operation, its noise increased by more than 6 dB (to near that of the original device) in the Z2 function.

Consequently, the strain-channel noise is not clearly dominated by the Q1 noise. Spectral measurements showed that the Z2 noise contribution is approximately equal to the Q1 noise contribution when observed at the channel output. Other revisions were made with only minor improvements. When a better replacement for the Z2 demodulator device is determined, channel noise can be improved by approximately 2 dB.

Bench test noise for both strain-inertial prototype systems (A and B) are shown in figure 3.1.3-1 where channel noise has been expressed in equivalent input strain power spectral density.

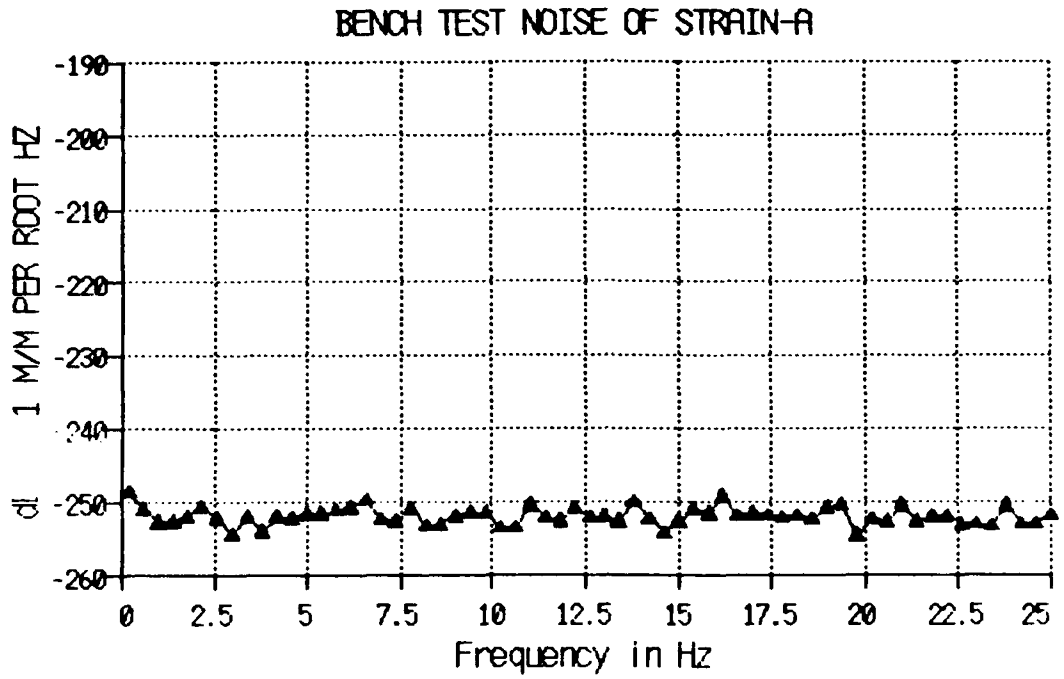
3.1.4 Wellhead Electronics

Wellhead equipment from both wellhead terminals were thoroughly cleaned and mounted in a small equipment rack for the dual-system testing at McKinney.

Two filters, one power regulator and one dc-to-dc converter/regulator had been damaged by lightning. The filters, or surface signal conditioner, were modified to eliminate gain trims and broaden channel response for both strain and inertial channels. Strain and inertial signal conditioners were made identical as indicated earlier in figures 2.1-1 and 2.2.2-1.

3.1.5 Test Set/Controller

The original strain-inertial test set or controller was modified to include provisions for rod-length adjustments as shown on sheet 2 of 990-53796-2102. Originally, the borehole electronics interface assembly had a 240 Hz clock which was divided to 60 Hz and used to drive the timing motor for offset adjustment. In order to use the current rod-length adjustment for



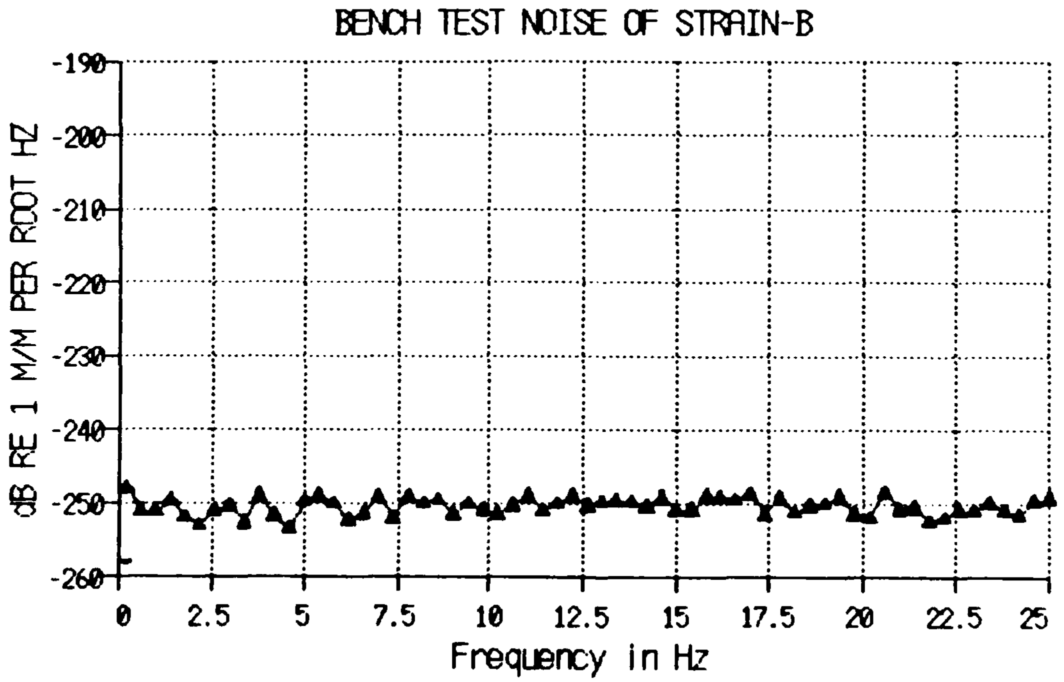


FIGURE 3.1.3-1

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calibration, the 240 Hz clock was brought to the surface where the adjustment could be accurately controlled with minimum change to borehole and wellhead assemblies. The controller has been satisfactory in bench testing and in operation, but the design is not recommended for production.

3.2 OPERATIONAL TESTING

The two strain-inertial seismometers were installed in the adjacent strain-inertial boreholes at the McKinney site on 13 March 1985. Initial rod-length adjustments were completed on 17 March 1985, and full calibrations of strain and inertial subsystems were performed on the same day.

Seismometer A was installed in the north borehole, and seismometer B was installed in the south borehole. The boreholes are separated approximately six feet at the surface. The recording (10-foot) trailer was set up approximately fifty feet east of the boreholes near the ac power service. After connections were made to the wellhead equipment in the trailer, the strain rods were adjusted sequentially with each requiring approximately thirteen hours of continuous running. The controller counter and auto-stop features worked satisfactorily, and both strain offset channels were readily adjusted to within a few millivolts of zero. Strain offset drifts were not accurately monitored after the initial thirteen hours of adjustment, but it is estimated that, without interim corrections, total drift would not exceed 10 volts (0.007 mm or 0.0003 in.) and would stabilize within forty-eight hours.

3.2.1 Strain Calibration

Calibration began immediately after initial rod-length adjustment of system B. Motor calibration of the strain offset channels were performed first using two 17.07-second (4.926 micron) drive sequences. The sensitivity for Strain-A was measured as 1.477 volt/micron and Strain-B sensitivity was measured as 1.490 volt/micron. These values are within two percent of ideal, and most of this error is attributed to the relatively noisy conditions during the bench-test gain setting.

The Hewlett-Packard Model 3582A was then used to measure and compute the broadband transfer function amplitude and phase of the SP strain channels. The B output of the surface signal conditioner was used with x5 gain, (750,000,000 volts per m/m nominal).

Figures 3.2.1-1a and -1b show the transfer function amplitude of Strain-A and Strain-B, respectively. The data have been corrected for motor calibration values and expressed in decibels (dB) relative to 1 volt per meter/meter. Figures 3.2.1-2a and -2b show the transfer function phase of Strain-A and Strain-B, respectively.

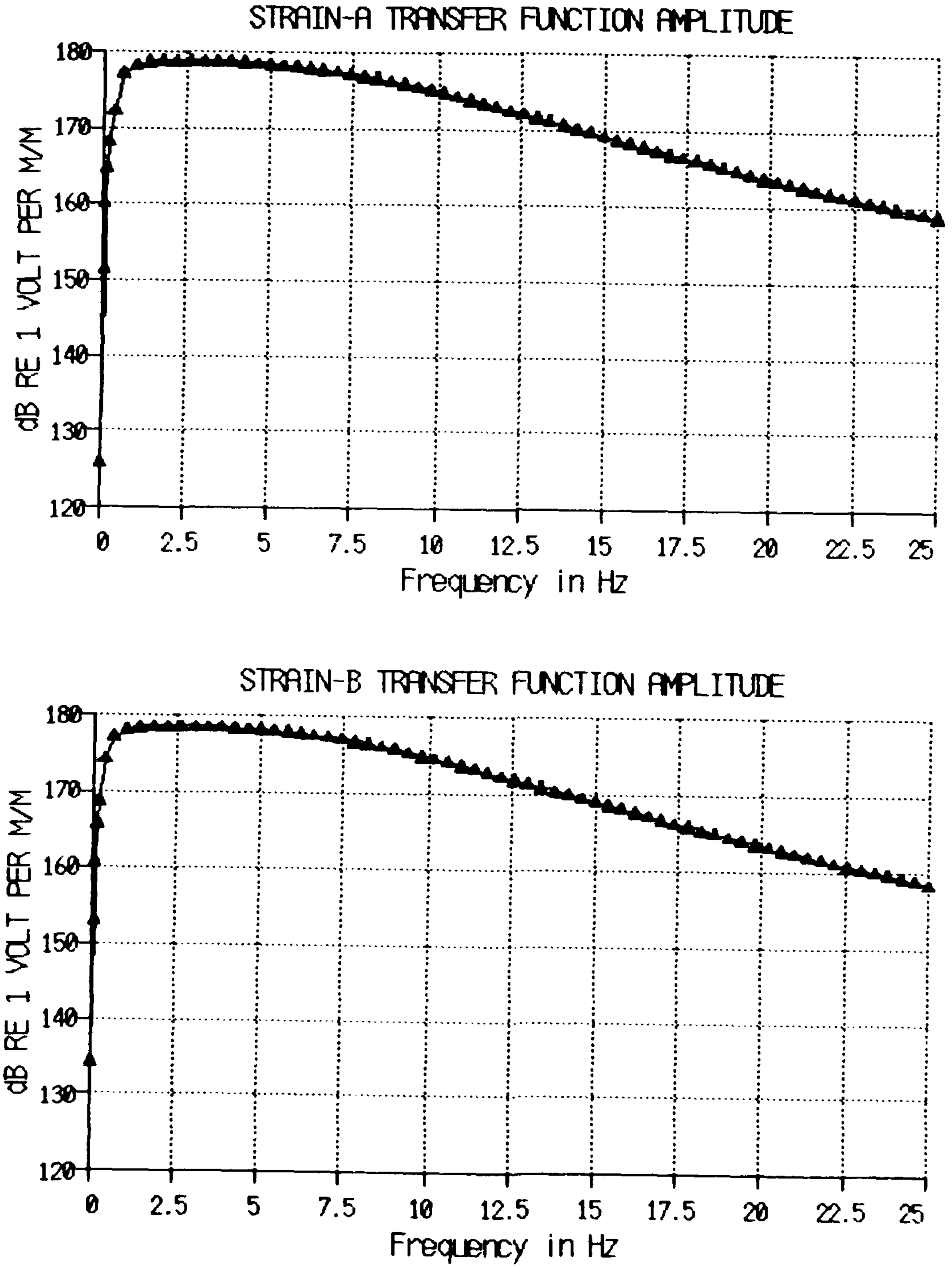
3.2.2 Inertial Calibration

The Hewlett-Packard Model 3582A was also used to measure and compute the broadband transfer function amplitude and phase of the inertial channels. The B output of the surface signal conditioner was used with x50 gain, (750,000 volts per m/sec nominal).

Figures 3.2.2-1a and -1b show the transfer function amplitude of Inertial-A and Inertial-B, respectively. The data have been and expressed in decibels (dB) relative to 1 volt per meter/second. Figures 3.2.2-2a and -2b show the transfer function phase of Inertial-A and Inertial-B, respectively.

3.2.3 Comparative Test Data

The Model 3582A Dual-Channel Spectrum Analyzer, in conjunction with an H-P 85 Microcomputer, was then used to estimate the dynamic operating noise of dual-inertial and dual-strain channels. Figure 3.2.3-1a shows the average background spectrum of the inertial sample. The data have been corrected for system response and expressed in dB relative to 1 meter/second per root Hz. Figure 3.2.3-1b shows the coherence (squared) between the two inertial channels.


STRAIN-A TRANSFER FUNCTION AMPLITUDE

STRAIN-B TRANSFER FUNCTION AMPLITUDE

FIGURE 3.2.1-1

G 16067

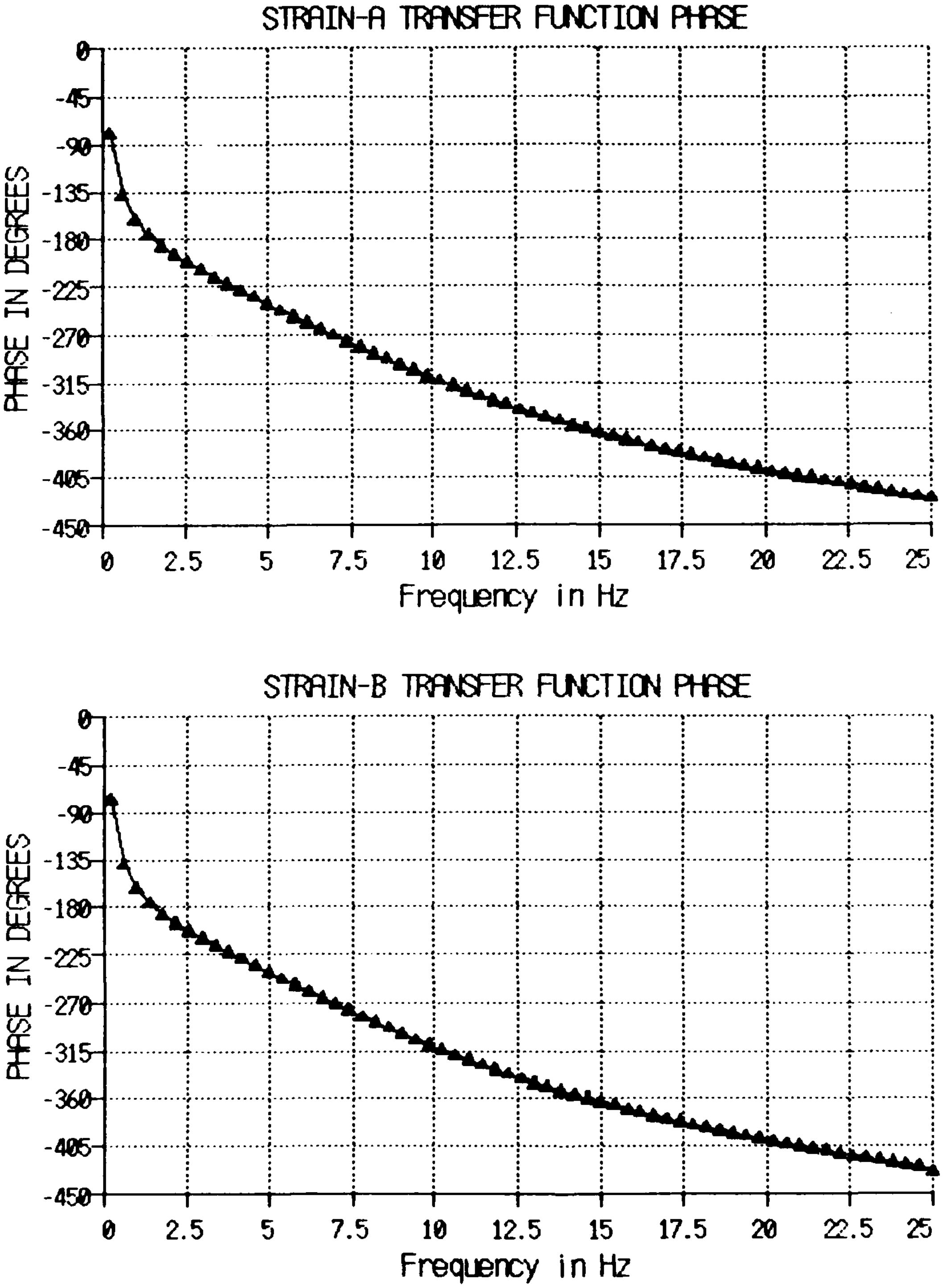


FIGURE 3.2.1-2

G 16068

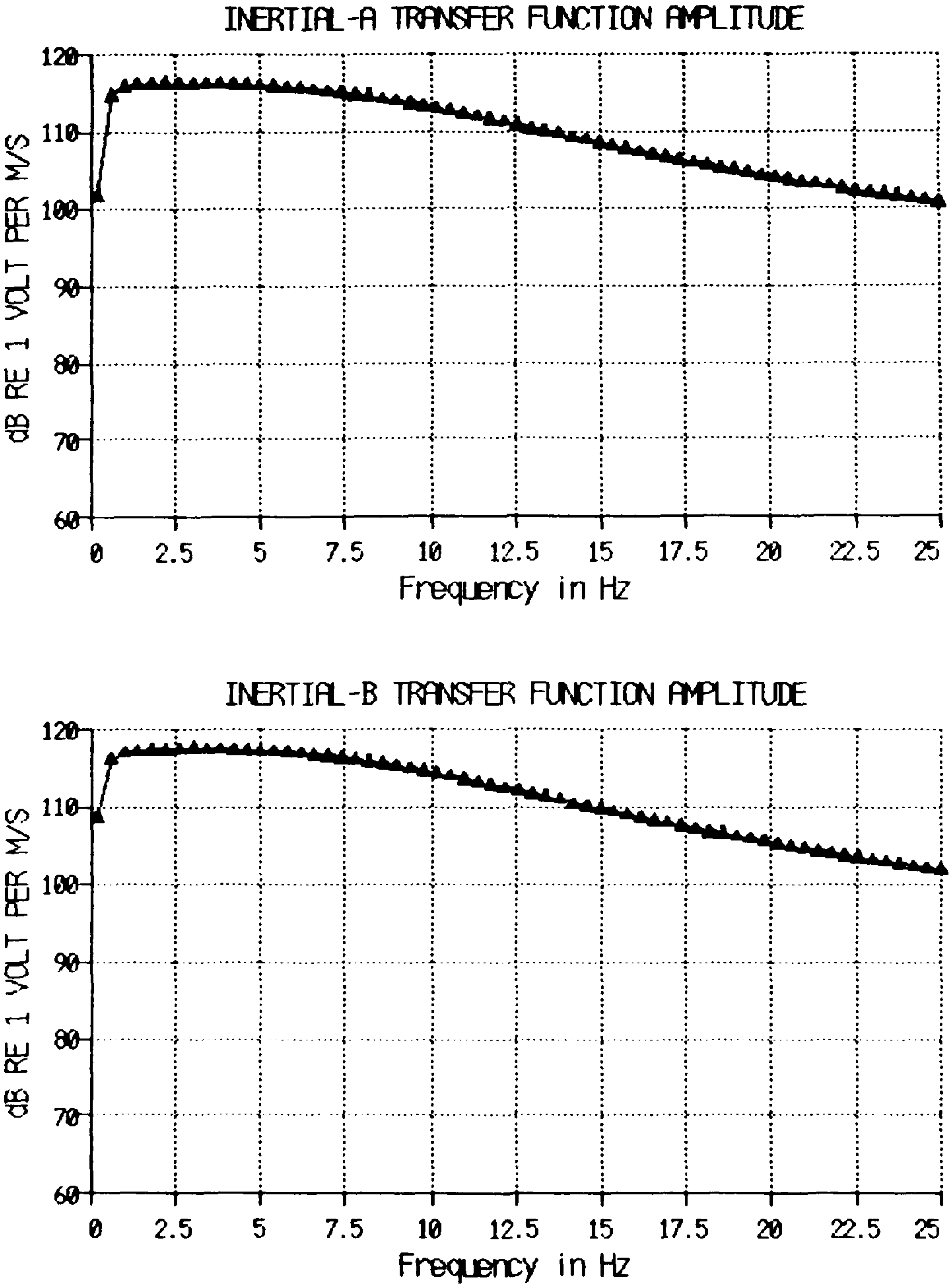
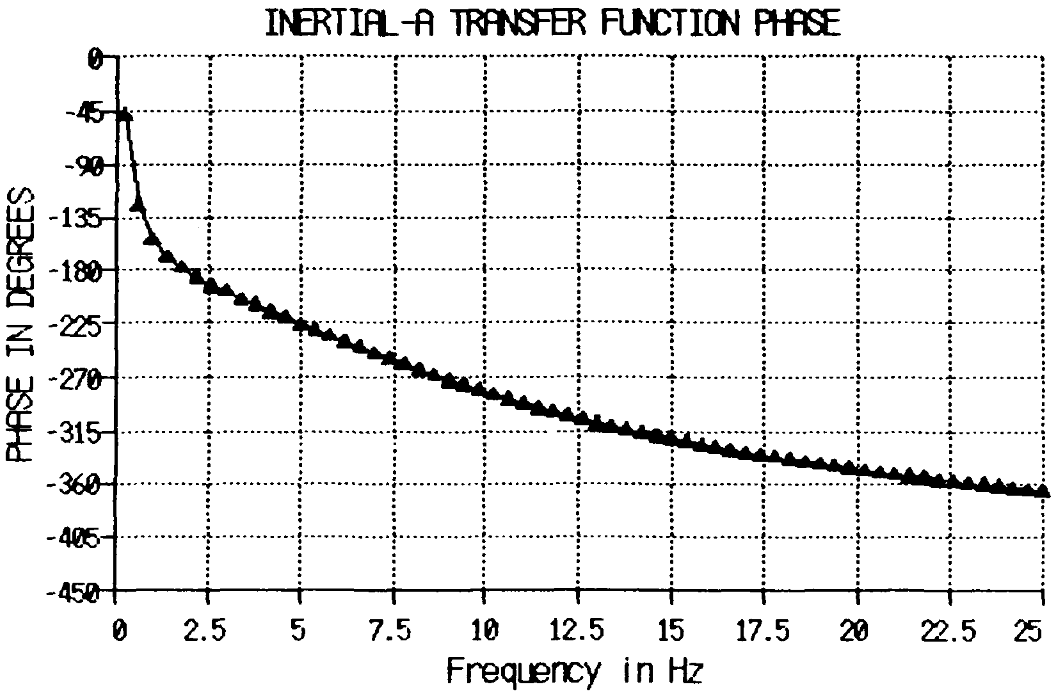
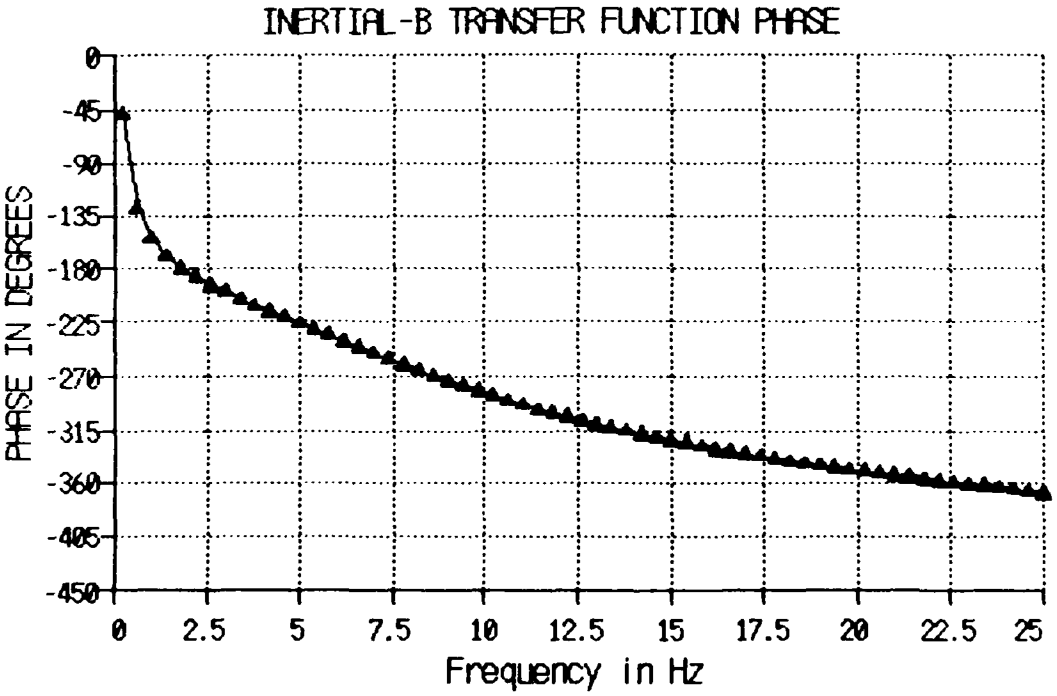


FIGURE 3.2.2-1

G 16069



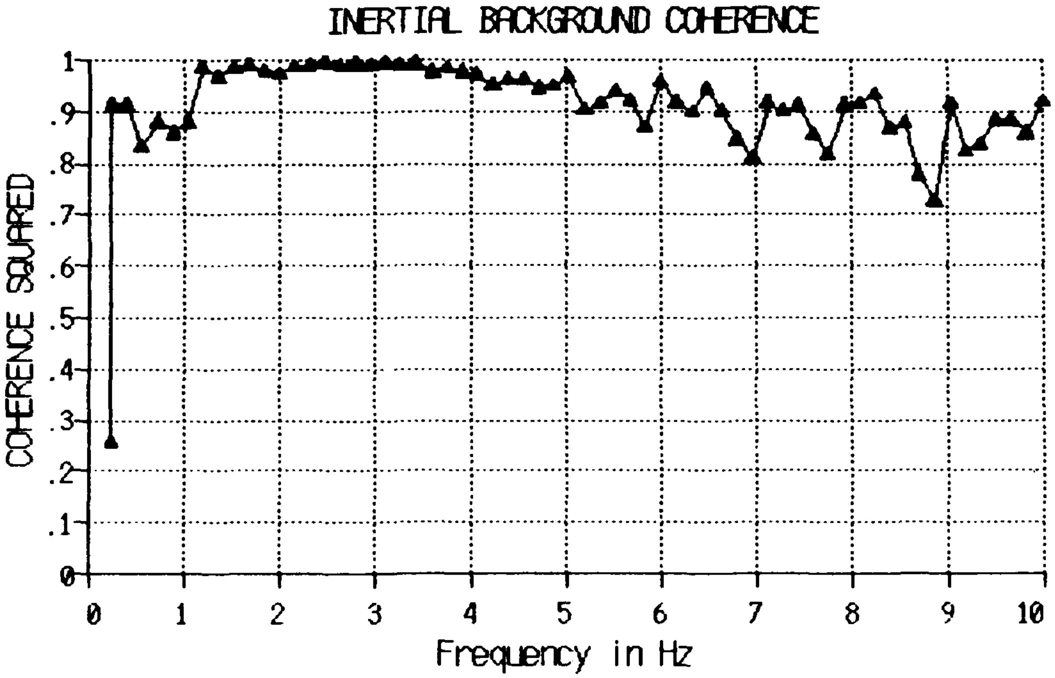
INERTIAL-A TRANSFER FUNCTION PHASE



INERTIAL-B TRANSFER FUNCTION PHASE

FIGURE 3.2.2-2

G 18070



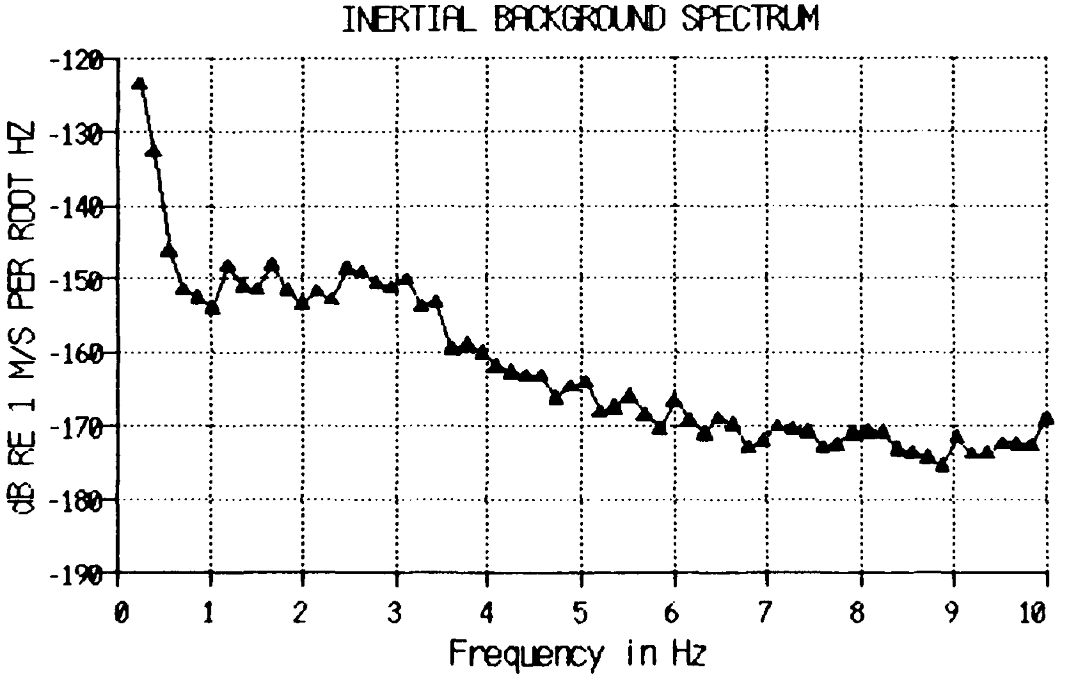


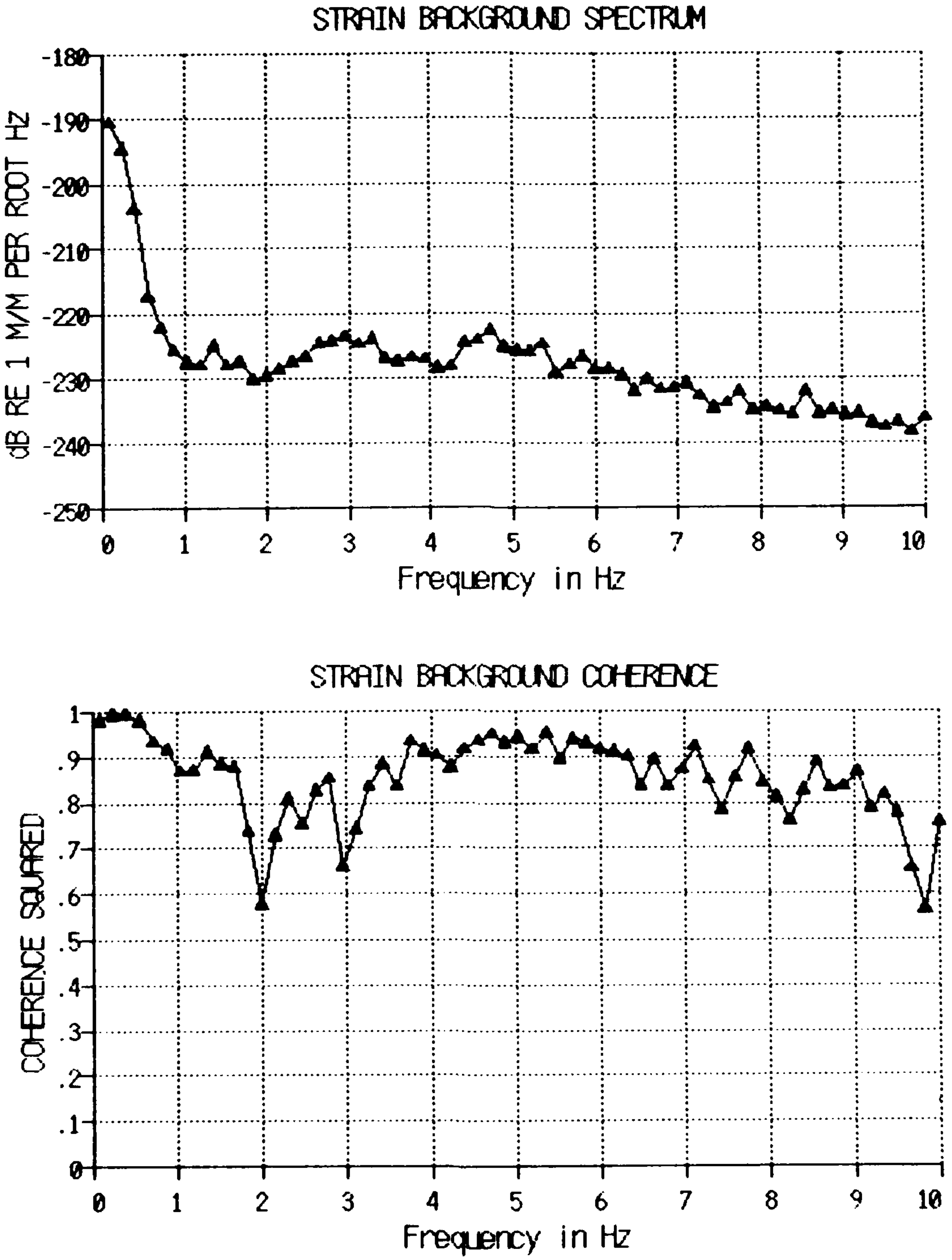
FIGURE 3.2.3-1

G 16071

Figure 3.2.3-2a shows the average background spectrum of the strain sample. The data have been corrected for system response and expressed in dB relative to 1 meter/meter per root Hz. Figure 3.2.3-2b shows the coherence (squared) between the two strain channels

Figures 3.2.3-3a and -3b show the incoherent noise estimates for the strain and inertial channel pairs, respectively. The data have been corrected for system response and expressed in terms of earth input. The -3 dB factor for individual channel estimates has not been applied.

Although the above noise estimates are limited by the preliminary acquisition system, the results justified advanced data collection and analysis. Part 2 of the Assessment Information Set has been reserved for the results of the Strain-Inertial Data Collection and Analysis Task of Contract F08606-84-C-0023.


STRAIN BACKGROUND SPECTRUM

STRAIN BACKGROUND COHERENCE

FIGURE 3.2.3-2

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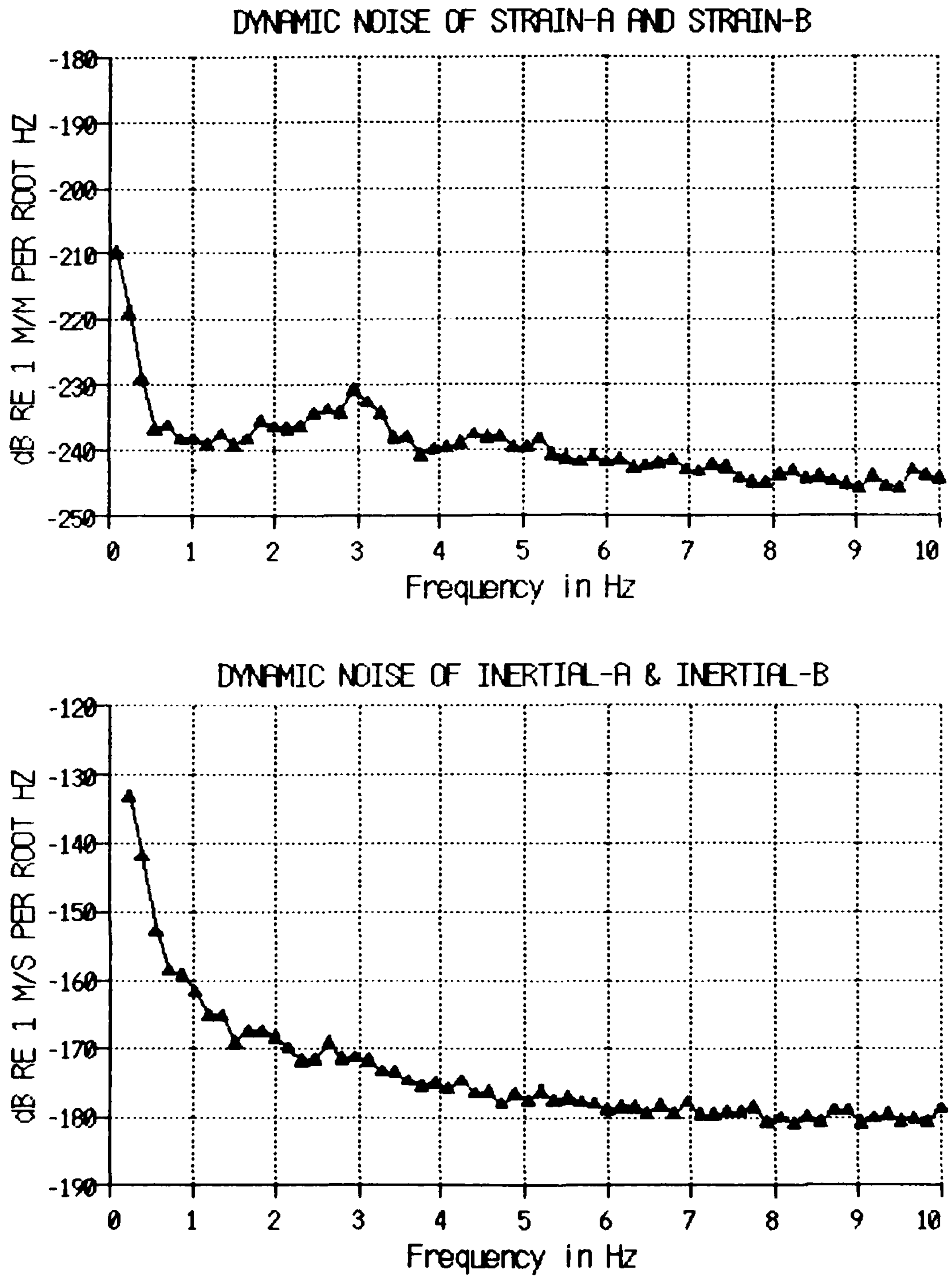

FIGURE 3.2.3-3

G 16073

PART 2

ASSESSMENT INFORMATION PACKAGE

DATA COLLECTION AND ANALYSIS
FOR THE
MODEL 52500 STRAIN-INERTIAL SEISMOMETER SYSTEM (PROTOTYPE)

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ILLUSTRATIONS

ILLUSTRATIONS (Continued)

ILLUSTRATIONS (Continued)

ILLUSTRATIONS (Continued)

ILLUSTRATIONS (Continued)

DATA COLLECTION AND ANALYSIS

1. INTRODUCTION

Field tests were conducted at McKinney, Texas to evaluate the performance of the prototype strain-inertial seismometer system, Model 52500. Two prototype sensors, referred to as sensor A and sensor B, were installed at the Southern Methodist University seismological site (MCK). The two boreholes are 1.83 m (6 ft.) apart and 40 m deep. Preliminary analyses of the data were performed to evaluate the potential usefulness of strain-inertial combinations to improve signal-to-noise ratios in the regional bandwidth.

2. USE OF STRAIN-INERTIAL COMBINATIONS TO ENHANCE SNR'S

The concept of using strain seismometers to enhance signal-to-noise ratios (SNR's) on inertial seismometers has been described by previous authors (Romney, 1964; Shopland and Kirklin, 1969; Shopland and Kirklin, 1970; Sorrells and Starkey, 1980). One measure of the potential reduction in inertial noise power through the use of prediction-error filtering, in which the strain data are used to predict the inertial noise, is the squared coherence between the strain and inertial noise. Neglecting the effects of signal distortion, Sorrells and Starkey (1980) show that the SNR enhancement capabilities of a vertically oriented strain-inertial system is given by

$$I = \frac{1}{1 - \gamma^2_{ei}} \qquad (1)$$

where I is the maximum potential improvement in SNR due to prediction-error filtering, and γ^2_{ei} is the squared coherence between the strain and inertial channels. Thus, for a strain-inertial noise coherence of 0.75, the potential improvement in SNR after prediction-error filtering is a factor of 4 in power, or 6 dB maximum potential reduction in noise power. For example, the coherence for strain-inertial system A is shown in figure 1a using 16-bit data collected on June 26, 1985 at McKinney, Texas. The peak value of the coherence is about 0.53 at 6 Hz. The corresponding maximum potential improvement in SNR due to prediction-error filtering is shown in figure 1b with a peak value of about 3 dB at 6 Hz. The actual improvement in SNR will depend on the amount of signal distortion caused by the filtering process. Distortion for P-wave signals with near-vertical angles of incidence should be less than about 5 dB.

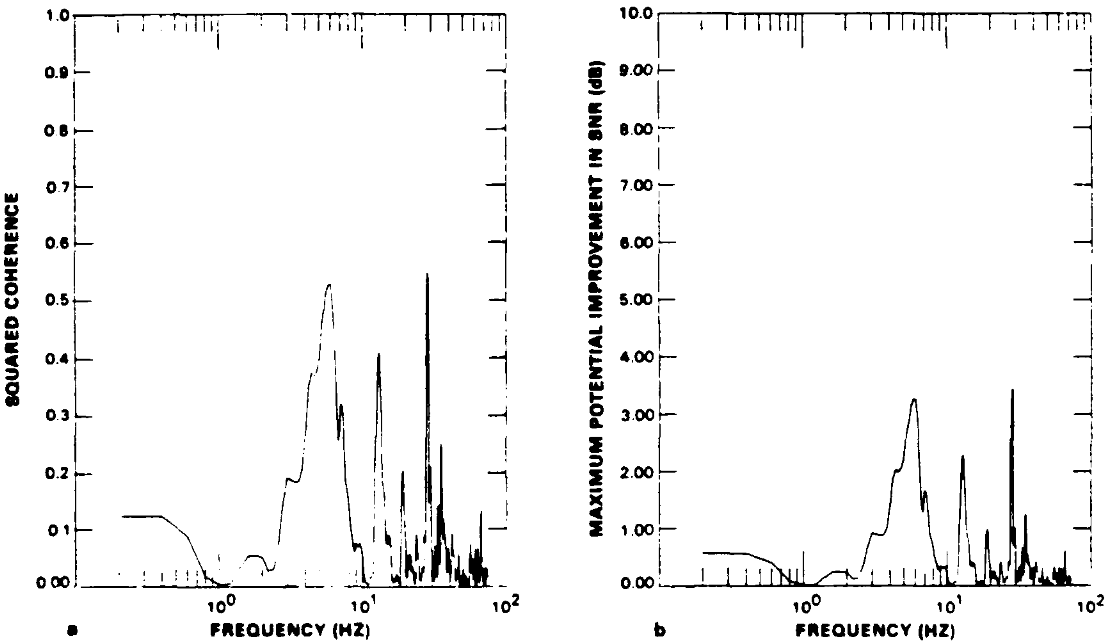

FIGURE 1. STRAIN-INERTIAL NOISE COHERENCE ON JUNE 26, 1985 AT 13:10:38 85 CENTRAL DAYLIGHT SAVINGS TIME. THE DATA IS 16-BIT DATA SAMPLED AT 150 SAMPLES PER SECOND. COHERENCE ESTIMATES WERE OBTAINED BY BLOCK AVERAGING 20 WINDOWS OF 750 SAMPLES (5 SECONDS), OVERLAPPED BY 50%. A TOTAL OF 52.5 SECONDS OF DATA. EACH BLOCK WAS MULTIPLIED BY A COSINE WINDOW FUNCTION IN TIME. THE AVERAGE WIND SPEED WAS 14.3 MILES PER HOUR (6.4 METERS PER SECOND)

(a) SQUARED COHERENCE BETWEEN THE STRAIN AND INERTIAL SENSORS AT 40 METERS

(b) THE MAXIMUM POTENTIAL IMPROVEMENT IN SIGNAL-TO-NOISE RATIO FROM PREDICTION-ERROR FILTERING, USING THE STRAIN-DATA TO PREDICT THE INERTIAL NOISE (EQUATION 1).

G 16222

3. FIELD TESTING OF THE PROTOTYPE STRAIN-INERTIAL SYSTEM

Field tests were conducted at McKinney, Texas to evaluate the performance of the prototype strain-inertial seismometer system, Model 52500. Two prototype sensors, referred to as sensor A and sensor B, were installed at the Southern Methodist University seismological site in March, 1985. The approximate location of the site is 33°15'N latitude and 96°39'W longitude. The two boreholes are 1.83 m (6 ft.) apart and 40 m deep. Preliminary analyses of the data were performed to evaluate the potential usefulness of strain-inertial combinations to improve signal-to-noise ratios in the regional bandwidth.

Data were collected during the time period from April 24, 1985 through May 24, 1985 using an FM analog tape recorder (Honeywell Model 101) and then digitizing the analog data with a 12-bit digitizer. The surface short-period filter (Model 43050) was configured to have a 10 Hz low-pass corner. Beginning June 12, 1985, the data were collected using a digital data collection system designed under the SDCS refurbishment contract. Both 12-bit and 16-bit data were collected using this system. The Model 43050 short-period filter was modified to have a 20 Hz low-pass corner. On July 15, 1985, a surface vault was installed and cementing of the two boreholes was completed to the surface. Following this, the channel B strain sensor was inoperative. A three-axis set of Model 18300 (S-13) short-period seismometers were installed in the surface vault. Data from the A strain-inertial seismometer and the surface sensors were collected on August 1, 1985 and August 28, 1985.

Previous versions of the strain seismometer suffered from excessive system noise (Teledyne Geotech, 1984). An estimate of the self-noise power of the system can be obtained from the power spectra of two side-by-side systems, P_{ss} and their coherence (Stearns, 1979)

$$P_{nn} = P_{ss} \, (1 - \hat{\gamma}^2_{ss}) \tag{2}$$

where P_{nn} is the noise power of system and $\hat{\gamma}^2_{ss}$ is the coherence between the two systems. Thus, an examination of the coherence between strain-A and strain-B will provide an indication of the self-noise of the strain system. Figure 2 shows a comparison of strain-A and strain-B coherence estimates obtained at McKinney from data collected on October 27, 1982 (Teledyne Geotech, 1984) and from the newer system on June 26, 1985. There is a significant improvement in coherence in the new system such that the coherence is greater than 0.75 throughout the 1 Hz to 10 Hz band and is as high as 0.98 at about 5.5 Hz. Note that the decrease in coherence at frequencies above 10 Hz may be due in part to the 20 Hz low-pass filter that is in the surface short-period filter Model 43050. This conclusion arises from the observation that the coherence above 10 Hz increased after the short-period filter was modified to change the low-pass corner frequency from 10 Hz to 20 Hz. Average background spectra obtained during March, 1985 are shown in Figure 3. Note that the dynamic noise measurements for the strain sensor pair is relatively higher than for the inertial sensor pair. This is particularly true

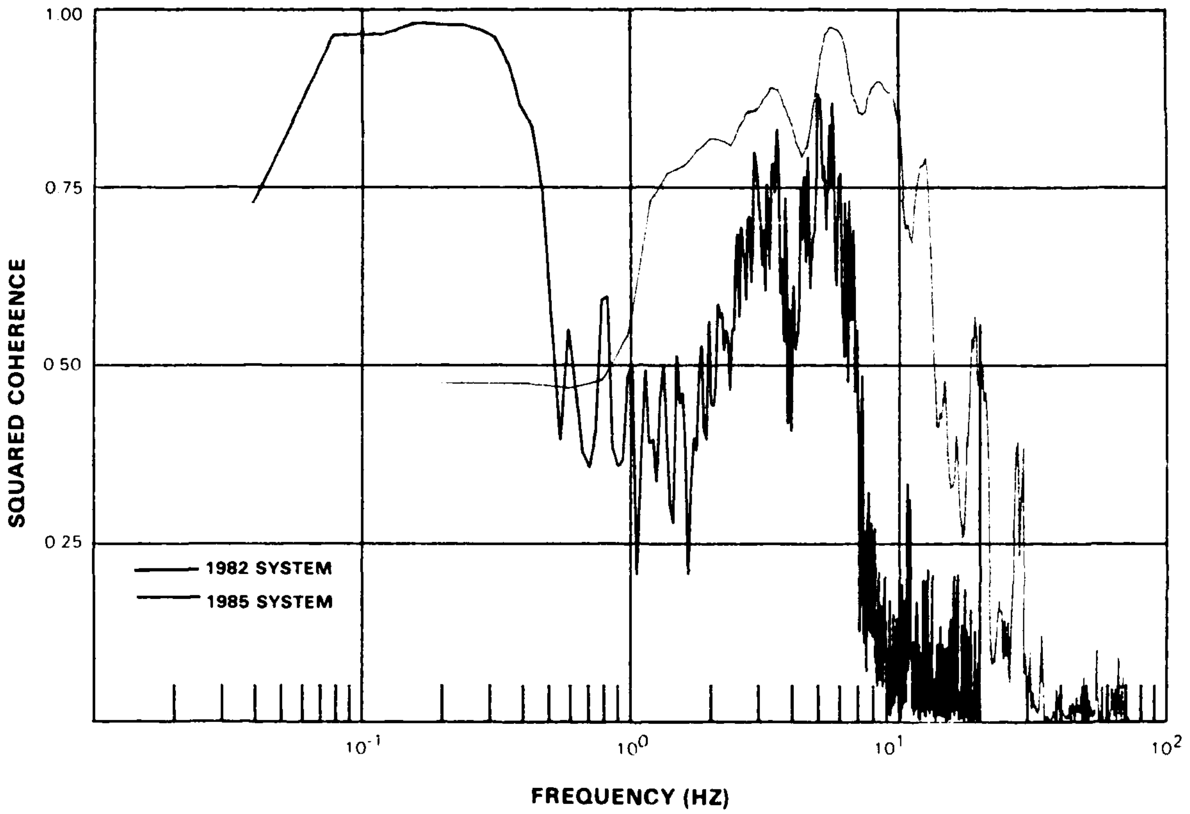

FIGURE 2. COMPARISON OF NOISE BETWEEN STRAIN-A AND STRAIN-B FROM THE 1982 SYSTEM AND THE 1985 SYSTEM. DATA FROM THE 1982 SYSTEM WAS COLLECTED ON OCTOBER 27, 1982 SAMPLED AT 40 SAMPLES PER SECOND. THE COHERENCE WAS ESTIMATED BY AVERAGING 22 BLOCKS OF 1024 SAMPLES. DATA FROM THE 1985 SYSTEM WAS COLLECTED ON JUNE 26, 1985 SAMPLED AT 150 SAMPLES PER SECOND. THE COHERENCE WAS ESTIMATED BY AVERAGING 20 BLOCKS OF 750 SAMPLES WHERE BLOCKS WERE OVERLAPPING BY 50% AND WINDOWED WITH A HANNING WINDOW (50% COSINE TAPER). NOTE THAT THE 1985 SYSTEM EXHIBITS A SUBSTANTIAL IMPROVEMENT IN COHERENCE IN THE 1 TO 20 HZ BAND OVER THE 1982 SYSTEM.

G14650A

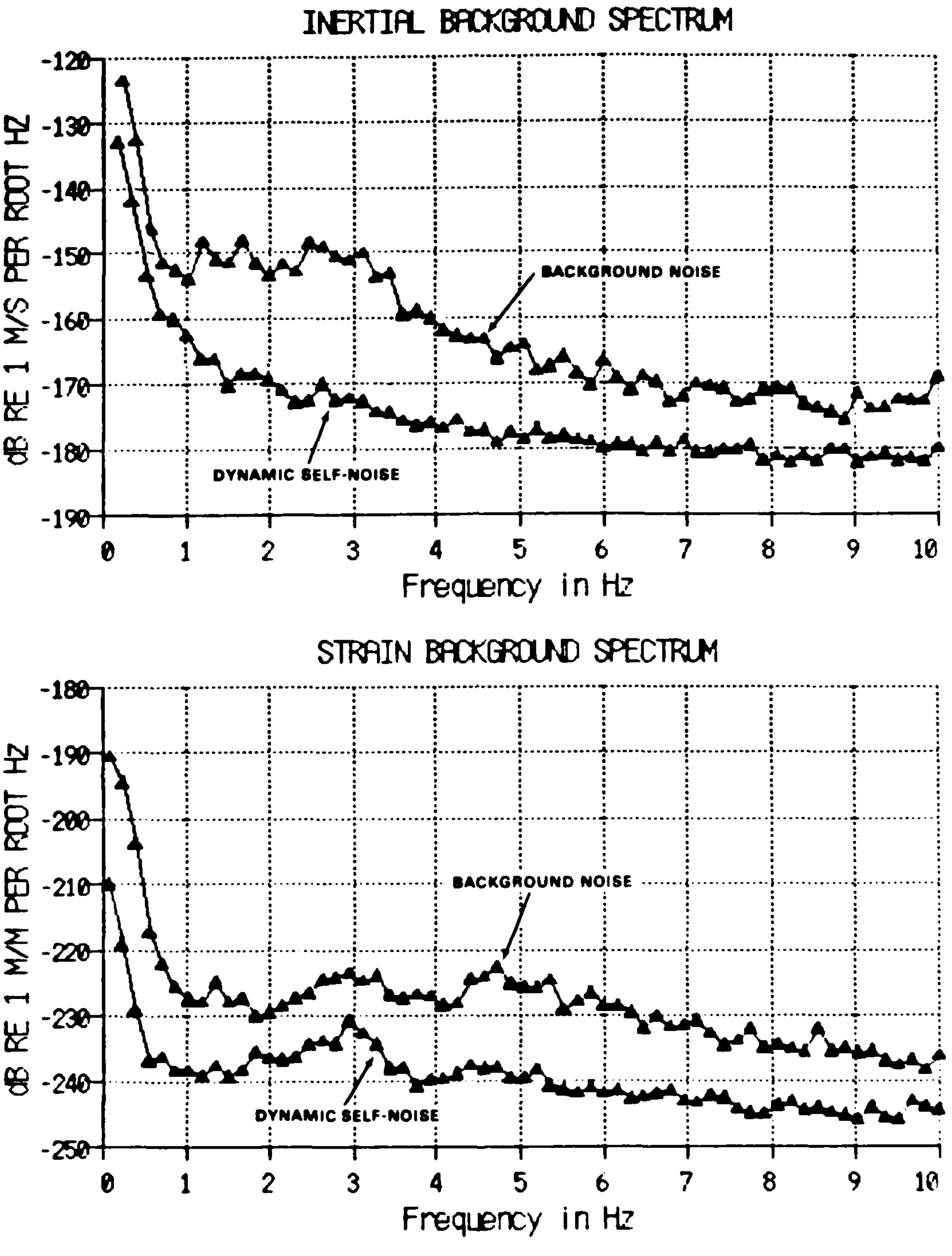

FIGURE 3 AVERAGE BACKGROUND SPECTRA FOR THE PROTOTYPE STRAIN-INERTIAL SEISMOMETERS AT McKINNEY, TEXAS OBTAINED IN MARCH, 1985. THE AVERAGE SPECTRA WERE OBTAINED WITH A HEWLETT-PACKARD MODEL 3582A DUAL-CHANNEL SPECTRUM ANALYZER IN CONJUNCTION WITH AN H-P85 MICROCOMPUTER. THE DYNAMIC OPERATING NOISE OF THE DUAL-INERTIAL AND DUAL-STRAIN CHANNELS WERE OBTAINED FROM EQUATION 2. THE DATA HAVE BEEN CORRECTED FOR SYSTEM RESPONSE.

(a) INERTIAL BACKGROUND SPECTRUM AND DYNAMIC NOISE OF INERTIAL-A AND INERTIAL-B
(b) STRAIN BACKGROUND SPECTRUM AND DYNAMIC NOISE OF STRAIN-A AND STRAIN-B

G 16236

in the 1 to 3 Hz band which is dominated by cultural noise on the inertial sensors (Ferguson and Li, 1981). The reason for this discrepancy in relative dynamic self-noise is not known but may be caused by strain installation noise. Two possibilities are the incomplete cementing of the boreholes or buoyancy effects in the air column of the boreholes.

The performance of a strain-inertial system is dependent not only on the system and installation noise, but also on the composition and state of organization of the earth noise. In the regional bandwidth (0.5 Hz to 20 Hz) the noise may consist of several components including wind-generated noise, culturally-generated noise, and oceanically-generated noise. The potential effectiveness of the strain-inertial system will depend on which of these noise components are dominant at a given site, or during a given time period (Sorrells and Starkey, 1980). The noise reduction potential at McKinney is suggested from analysis of a series of noise samples collected on August 1, 1985, which includes inertial data from the surface vault as well as borehole strain-inertial data. Six samples of noise data were chosen, beginning at about 1:26 p.m. Central Daylight Savings Time, and spaced arbitrarily one hour apart. Seven channels of 12-bit data were collected at 100 samples per second. The channels were strain-A, inertial-A, inertial-B, vertical, north, and east inertial components from the surface vault, and wind speed. Coherence estimates for the six noise samples are shown in figures 4 through 9 for strain-A versus inertial-A and the vertical component of the inertial sensor in the surface vault. The wind speed during each time period is also shown. The following conclusions can be drawn from these figures:

1. In the frequency band from 1 Hz to 2 Hz, the coherences between both of the strain-inertial pairs are about the same. The peak coherences range from about 0.3 to 0.6 and do not appear to be directly correlated to the wind speed.

2. In the frequency band from about 3 Hz to 20 Hz, the strain versus surface-inertial coherence is consistently greater than the strain versus downhole-inertial coherence. The peak of the strain-downhole inertial coherences range from about 0.5 to 0.7, while the peak of the strain-surface inertial coherences range from about 0.8 to 0.9. The bandwidth of high coherence is also larger for the strain-surface inertial pair than for the strain-downhole inertial pair. The bandwidth limit at 20 Hz may be due in part to the 20 Hz high-cut filter in the system. The coherence levels appear to be roughly inversely correlated to wind speed; the periods with high coherence roughly correspond to the periods with low wind speed.

These results can be interpreted in light of what is known about the ambient noise at McKinney. The lithology and a velocity model for McKinney from Ferguson and Li (1981) are shown in figure 10. The theoretical phase velocity curves for the fundamental and first three higher Rayleigh modes are shown in figure 11, and the corresponding group velocity curves are shown in figure 12. A comparison of phase velocity measurements and the theoretical Rayleigh mode dispersion curves suggest that the noise at McKinney is dominated by higher mode Rayleigh waves rather than fundamental mode Rayleigh waves in the

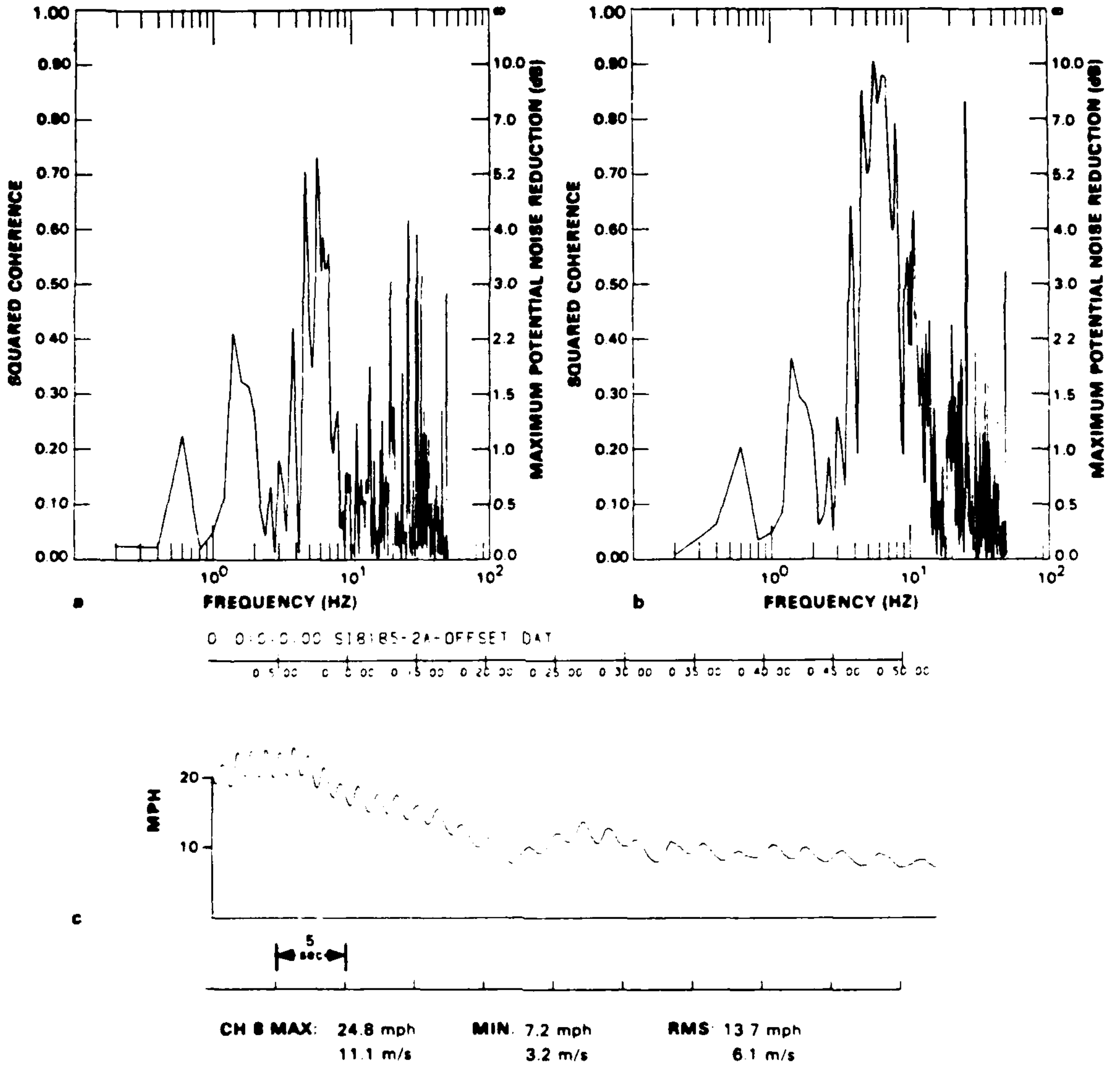

FIGURE 4 COHERENCES BETWEEN THE STRAIN AND INERTIAL SENSORS OR EQUIVALENTLY, THE MAXIMUM POTENTIAL NOISE REDUCTION FROM PREDICTION-ERROR FILTERING (EQUATION 2) FOR NOISE AT MCKINNEY TEXAS ON AUGUST 1 1985 THE 12-BIT DIGITAL DATA WAS SAMPLED AT 100 SAMPLES PER SECOND COHERENCE ESTIMATES WERE OBTAINED BY AVERAGING 20 BLOCKS OF 500 SAMPLES (5 SECONDS) OVERLAPPED BY 250 SAMPLES (2.5 SECONDS) FOR A TOTAL OF 52.5 SECONDS EACH 5 SECOND BLOCK WAS WINDOWED WITH A COSINE FUNCTION THE START TIME OF THE NOISE SAMPLE WAS 13:26:02 CENTRAL DAYLIGHT SAVINGS TIME

(a) SQUARED COHERENCE BETWEEN THE STRAIN SENSOR AT 40 m AND THE INERTIAL SENSOR AT 40 m

(b) SQUARED COHERENCE BETWEEN THE STRAIN SENSOR AT 40 m AND THE INERTIAL SENSOR IN THE SURFACE VAULT

(c) WIND SPEED FOR THIS TIME PERIOD NOTE THAT 1 MILE PER HOUR IS EQUAL TO 0.447 METERS PER SECOND

G 16223

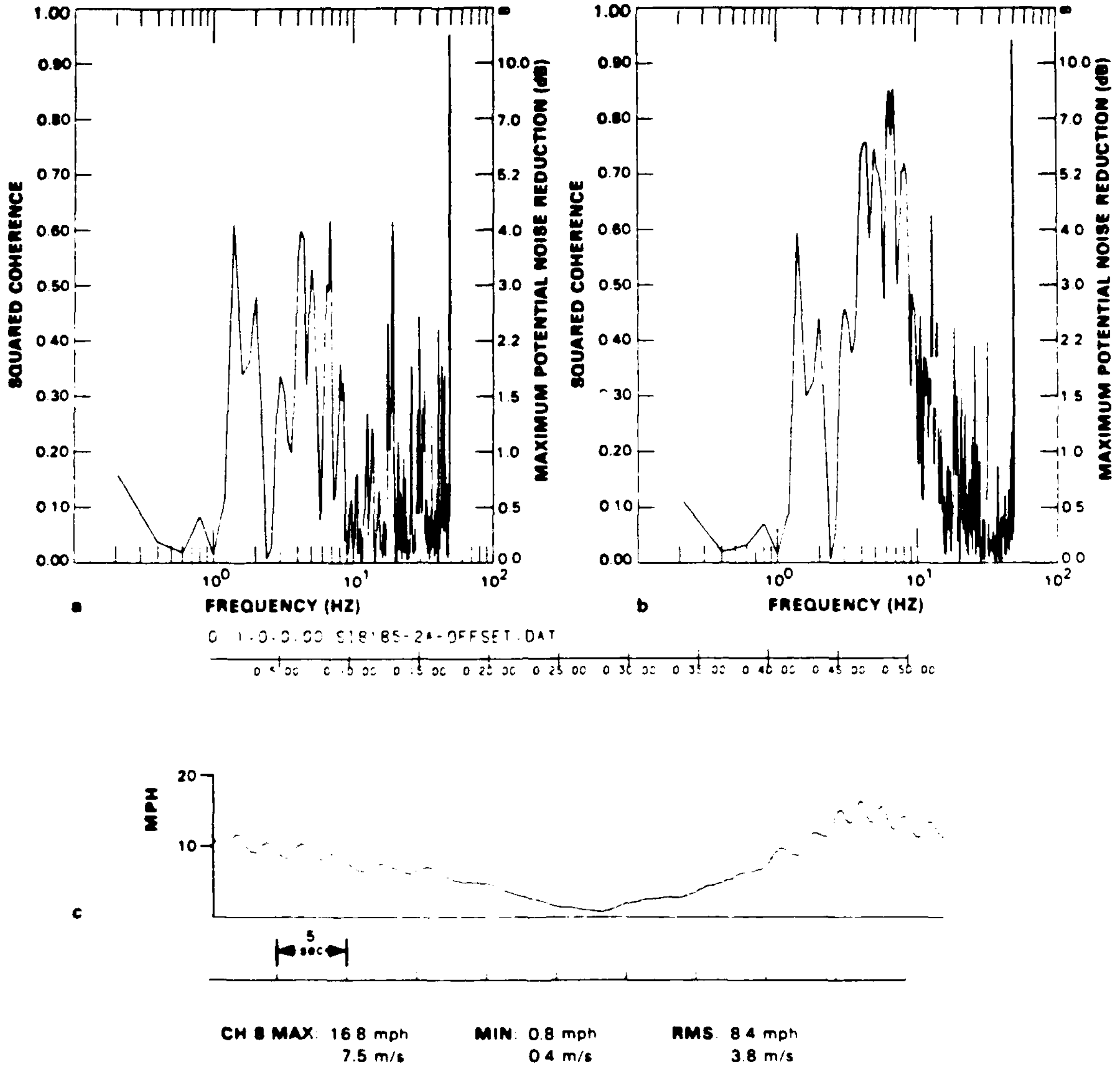

FIGURE 5 COHERENCES BETWEEN THE STRAIN AND INERTIAL SENSORS, OR EQUIVALENTLY THE MAXIMUM POTENTIAL NOISE REDUCTION FROM PREDICTION-ERROR FILTERING (EQUATION 2) FOR NOISE AT MCKINNEY, TEXAS ON AUGUST 1 1985 THE 12-BIT DIGITAL DATA WAS SAMPLED AT 100 SAMPLES PER SECOND COHERENCE ESTIMATES WERE OBTAINED BY AVERAGING 20 BLOCKS OF 500 SAMPLES (5 SECONDS) OVERLAPPED BY 250 SAMPLES (2 5 SECONDS) FOR A TOTAL OF 52 5 SECONDS EACH 5 SECOND BLOCK WAS WINDOWED WITH A COSINE FUNCTION THE START TIME OF THE NOISE SAMPLE WAS 14.26:02 CENTRAL DAYLIGHT SAVINGS TIME

(a) SQUARED COHERENCE BETWEEN THE STRAIN SENSOR AT 40 m AND THE INERTIAL SENSOR AT 40 m

(b) SQUARED COHERENCE BETWEEN THE STRAIN SENSOR AT 40 m AND THE INERTIAL SENSOR IN THE SURFACE VAULT

(c) WIND SPEED FOR THIS TIME PERIOD NOTE THAT 1 MILE PER HOUR IS EQUAL TO 0 447 METERS PER SECOND

G 16224

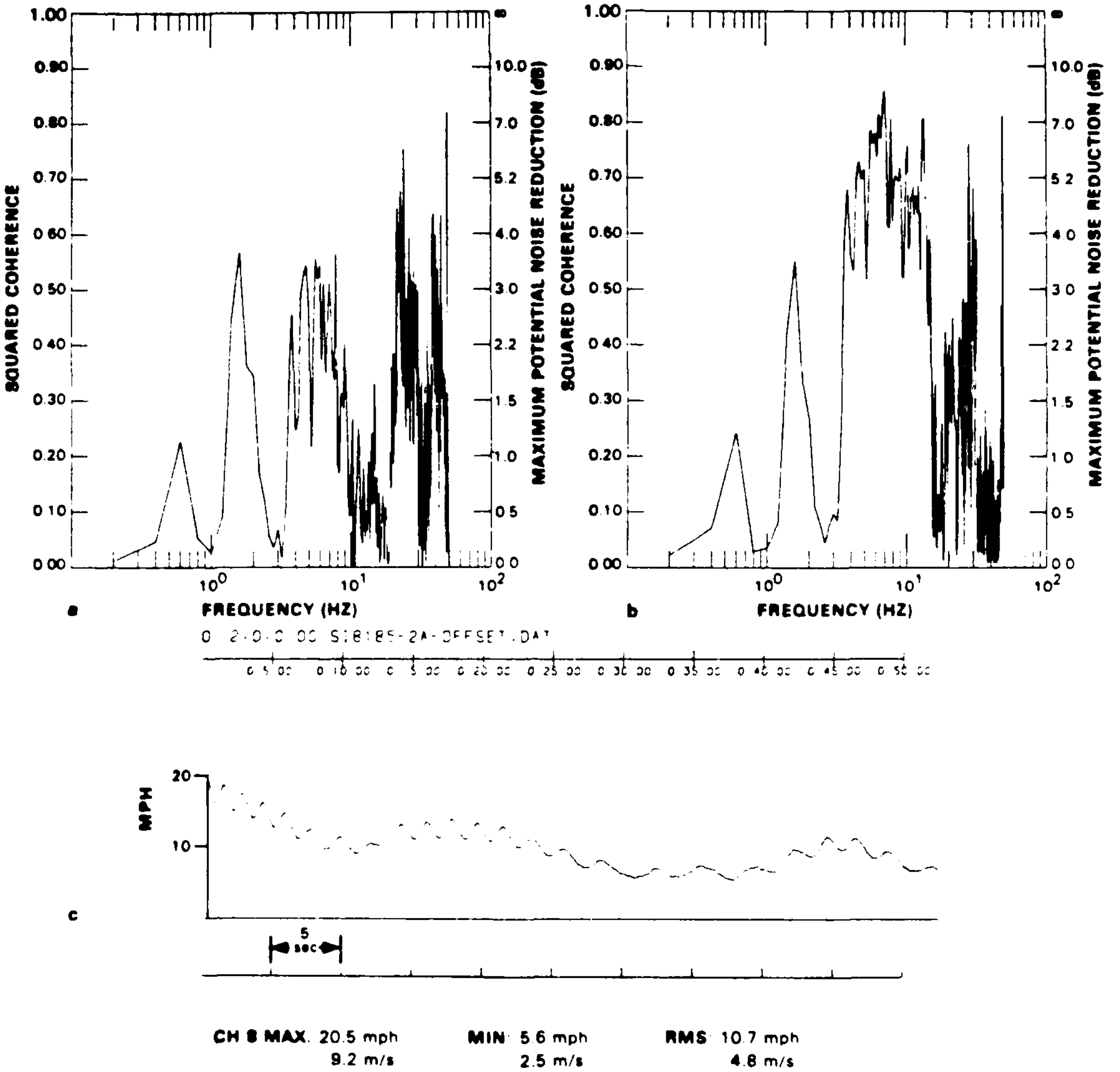

FIGURE 6 COHERENCES BETWEEN THE STRAIN AND INERTIAL SENSORS OR EQUIVALENTLY THE MAXIMUM POTENTIAL NOISE REDUCTION FROM PREDICTION-ERROR FILTERING (EQUATION 2). FOR NOISE AT MCKINNEY TEXAS ON AUGUST 1 1985 THE 12-BIT DIGITAL DATA WAS SAMPLED AT 100 SAMPLES PER SECOND COHERENCE ESTIMATES WERE OBTAINED BY AVERAGING 20 BLOCKS OF 500 SAMPLES (5 SECONDS) OVERLAPPED BY 250 SAMPLES (2 5 SECONDS) FOR A TOTAL OF 52 5 SECONDS EACH 5 SECOND BLOCK WAS WINDOWED WITH A COSINE FUNCTION THE START TIME OF THE NOISE SAMPLE WAS 15:26:02 CENTRAL DAYLIGHT SAVINGS TIME

(a) SQUARED COHERENCE BETWEEN THE STRAIN SENSOR AT 40 m AND THE INERTIAL SENSOR AT 40 m

(b) SQUARED COHERENCE BETWEEN THE STRAIN SENSOR AT 40 m AND THE INERTIAL SENSOR IN THE SURFACE VAULT

(c) WIND SPEED FOR THIS TIME PERIOD NOTE THAT 1 MILE PER HOUR IS EQUAL TO 0 447 METERS PER SECOND

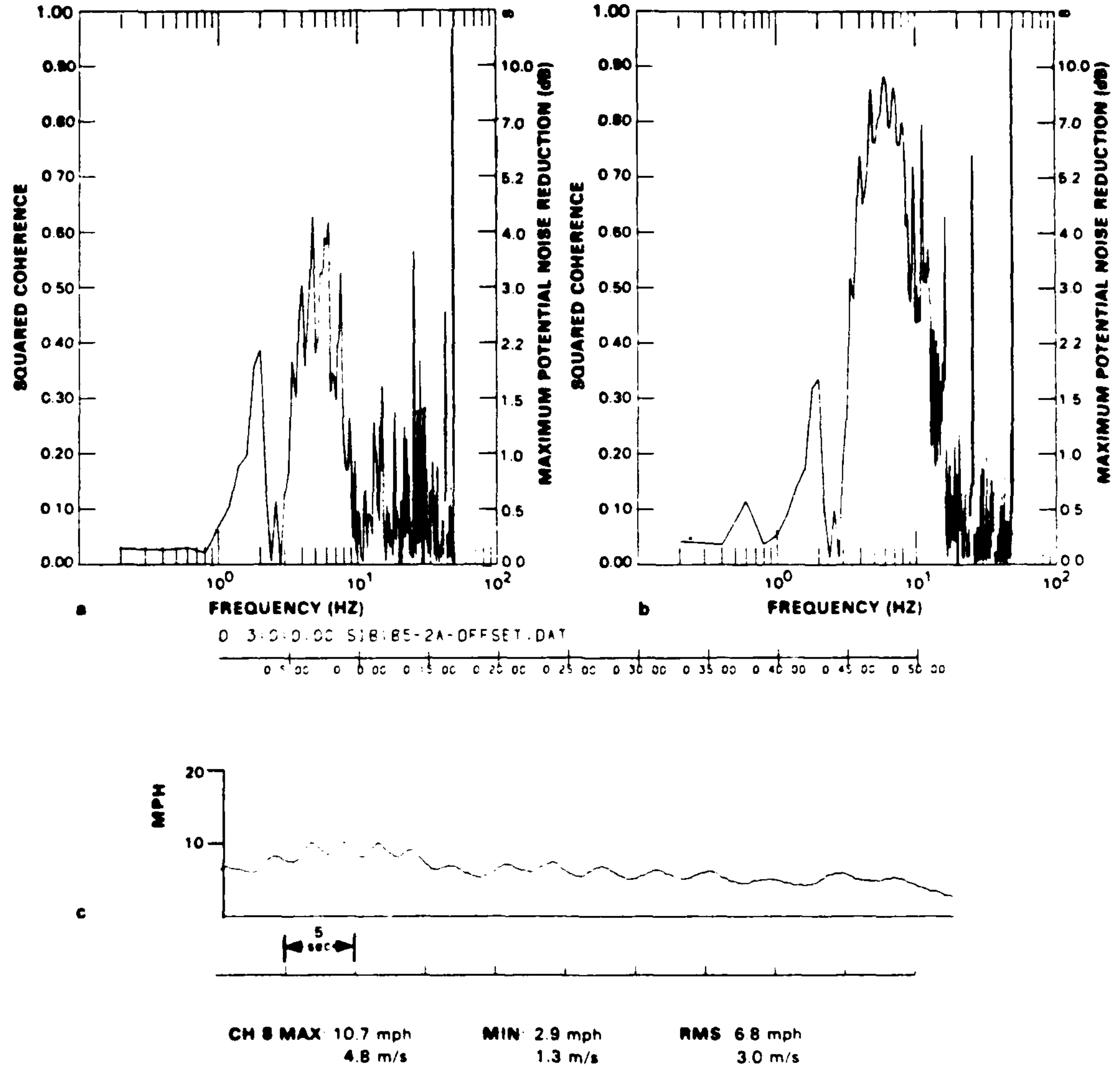

FIGURE 7 COHERENCES BETWEEN THE STRAIN AND INERTIAL SENSORS, OR EQUIVALENTLY, THE MAXIMUM POTENTIAL NOISE REDUCTION FROM PREDICTION-ERROR FILTERING (EQUATION 2), FOR NOISE AT MCKINNEY, TEXAS ON AUGUST 1 1985. THE 12-BIT DIGITAL DATA WAS SAMPLED AT 100 SAMPLES PER SECOND. COHERENCE ESTIMATES WERE OBTAINED BY AVERAGING 20 BLOCKS OF 500 SAMPLES (5 SECONDS), OVERLAPPED BY 250 SAMPLES (2.5 SECONDS), FOR A TOTAL OF 52.5 SECONDS. EACH 5 SECOND BLOCK WAS WINDOWED WITH A COSINE FUNCTION. THE START TIME OF THE NOISE SAMPLE WAS 16:26:02 CENTRAL DAYLIGHT SAVINGS TIME

(a) SQUARED COHERENCE BETWEEN THE STRAIN SENSOR AT 40 m AND THE INERTIAL SENSOR AT 40 m

(b) SQUARED COHERENCE BETWEEN THE STRAIN SENSOR AT 40 m AND THE INERTIAL SENSOR IN THE SURFACE VAULT

(c) WIND SPEED FOR THIS TIME PERIOD. NOTE THAT 1 MILE PER HOUR IS EQUAL TO 0.447 METERS PER SECOND

G 16226

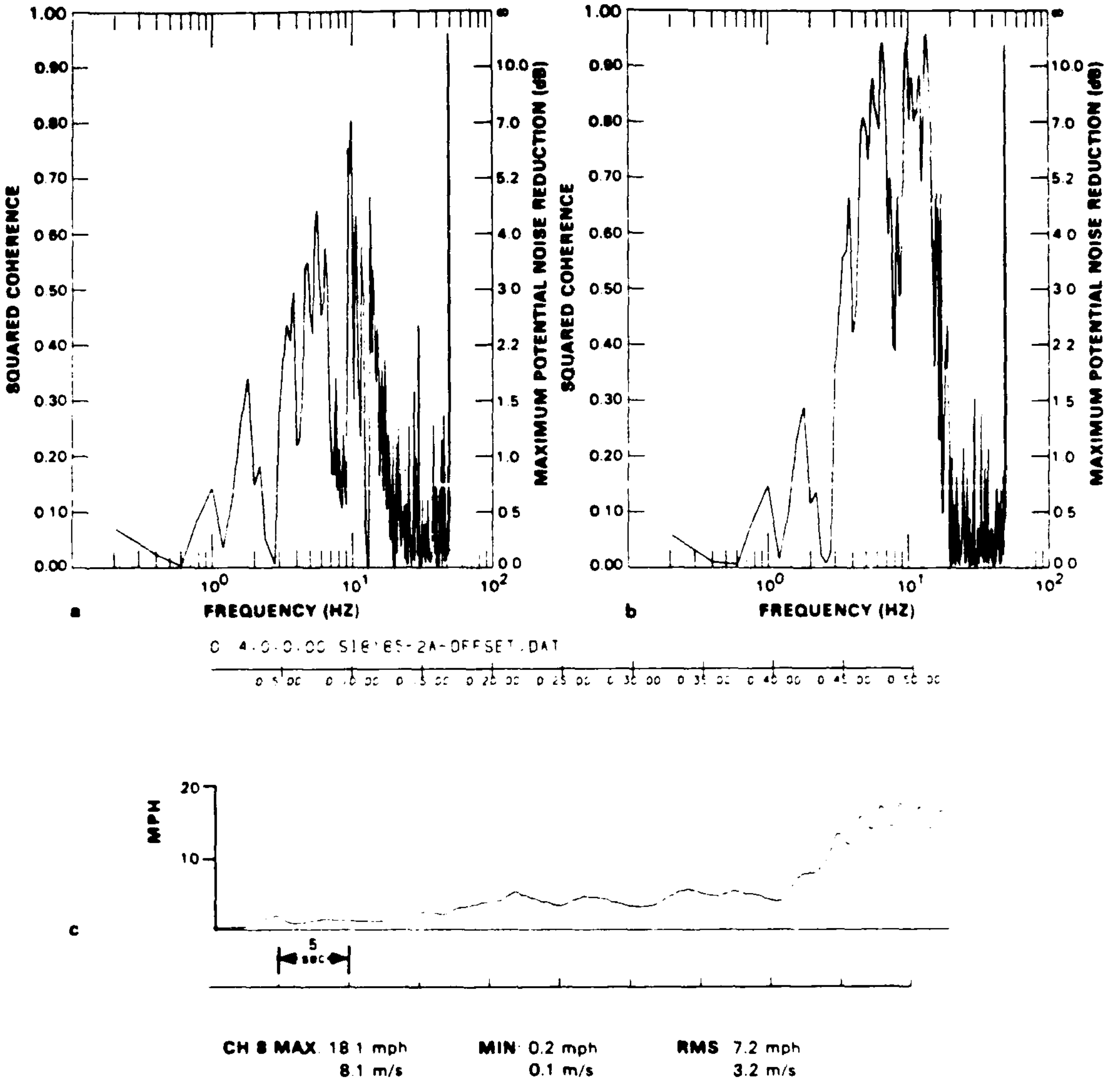

FIGURE 8 COHERENCES BETWEEN THE STRAIN AND INERTIAL SENSORS, OR EQUIVALENTLY, THE MAXIMUM POTENTIAL NOISE REDUCTION FROM PREDICTION-ERROR FILTERING (EQUATION 2). FOR NOISE AT MCKINNEY, TEXAS ON AUGUST 1 1985. THE 12-BIT DIGITAL DATA WAS SAMPLED AT 100 SAMPLES PER SECOND. COHERENCE ESTIMATES WERE OBTAINED BY AVERAGING 20 BLOCKS OF 500 SAMPLES (5 SECONDS), OVERLAPPED BY 250 SAMPLES (2.5 SECONDS), FOR A TOTAL OF 52.5 SECONDS. EACH 5 SECOND BLOCK WAS WINDOWED WITH A COSINE FUNCTION. THE START TIME OF THE NOISE SAMPLE WAS 17:26:02 CENTRAL DAYLIGHT SAVINGS TIME

(a) SQUARED COHERENCE BETWEEN THE STRAIN SENSOR AT 40 m AND THE INERTIAL SENSOR AT 40 m

(b) SQUARED COHERENCE BETWEEN THE STRAIN SENSOR AT 40 m AND THE INERTIAL SENSOR IN THE SURFACE VAULT

(c) WIND SPEED FOR THIS TIME PERIOD. NOTE THAT 1 MILE PER HOUR IS EQUAL TO 0.447 METERS PER SECOND

G 16227

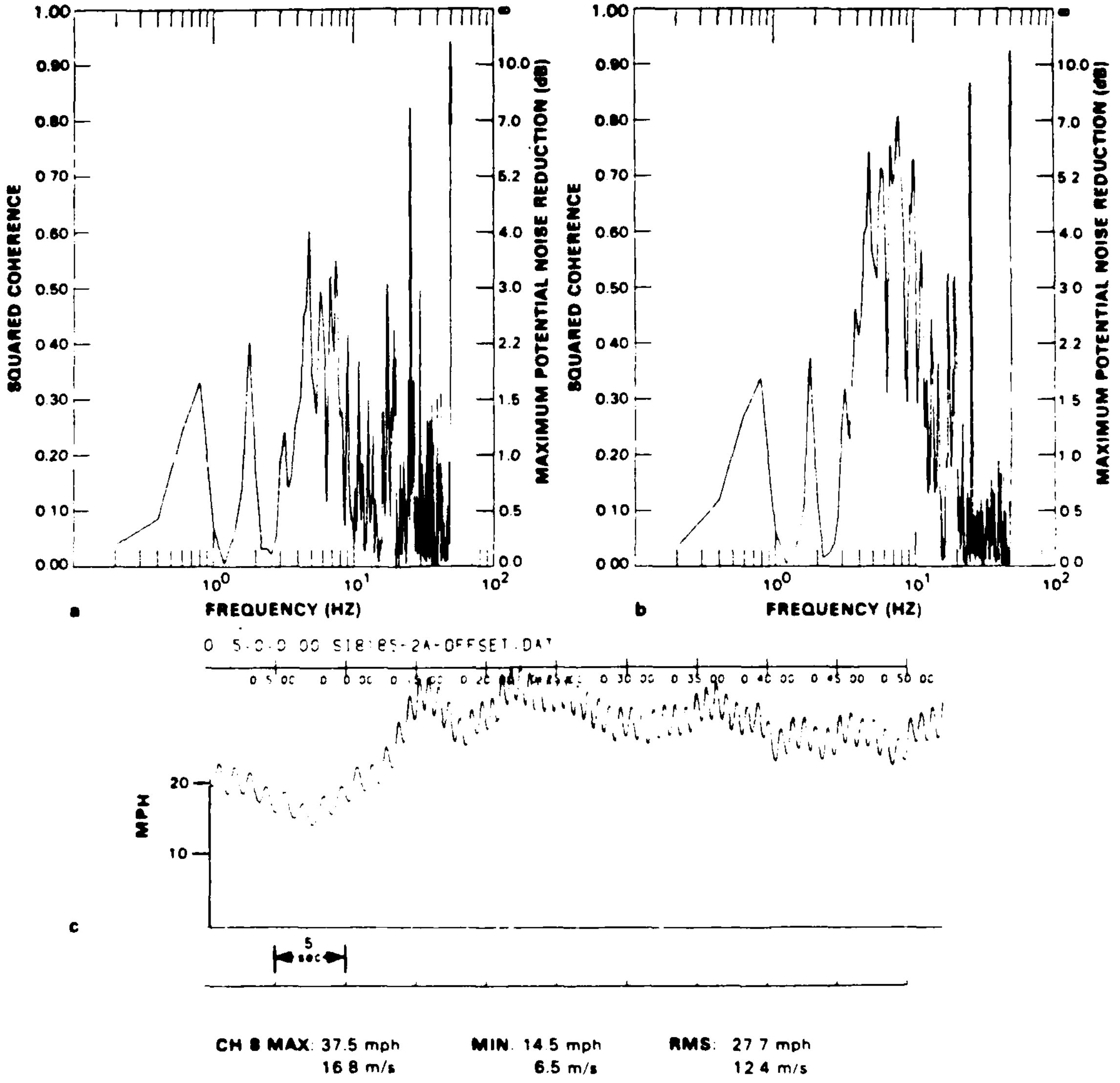

FIGURE 9. COHERENCES BETWEEN THE STRAIN AND INERTIAL SENSORS, OR EQUIVALENTLY THE MAXIMUM POTENTIAL NOISE REDUCTION FROM PREDICTION-ERROR FILTERING (EQUATION 2), FOR NOISE AT MCKINNEY, TEXAS ON AUGUST 1 1985. THE 12-BIT DIGITAL DATA WAS SAMPLED AT 100 SAMPLES PER SECOND. COHERENCE ESTIMATES WERE OBTAINED BY AVERAGING 20 BLOCKS OF 500 SAMPLES (5 SECONDS), OVERLAPPED BY 250 SAMPLES (2 5 SECONDS) FOR A TOTAL OF 52 5 SECONDS. EACH 5 SECOND BLOCK WAS WINDOWED WITH A COSINE FUNCTION. THE START TIME OF THE NOISE SAMPLE WAS 18.26:02 CENTRAL DAYLIGHT SAVINGS TIME

(a) SQUARED COHERENCE BETWEEN THE STRAIN SENSOR AT 40 m AND THE INERTIAL SENSOR AT 40 m

(b) SQUARED COHERENCE BETWEEN THE STRAIN SENSOR AT 40 m AND THE INERTIAL SENSOR IN THE SURFACE VAULT

(c) WIND SPEED FOR THIS TIME PERIOD. NOTE THAT 1 MILE PER HOUR IS EQUAL TO 0 447 METERS PER SECOND

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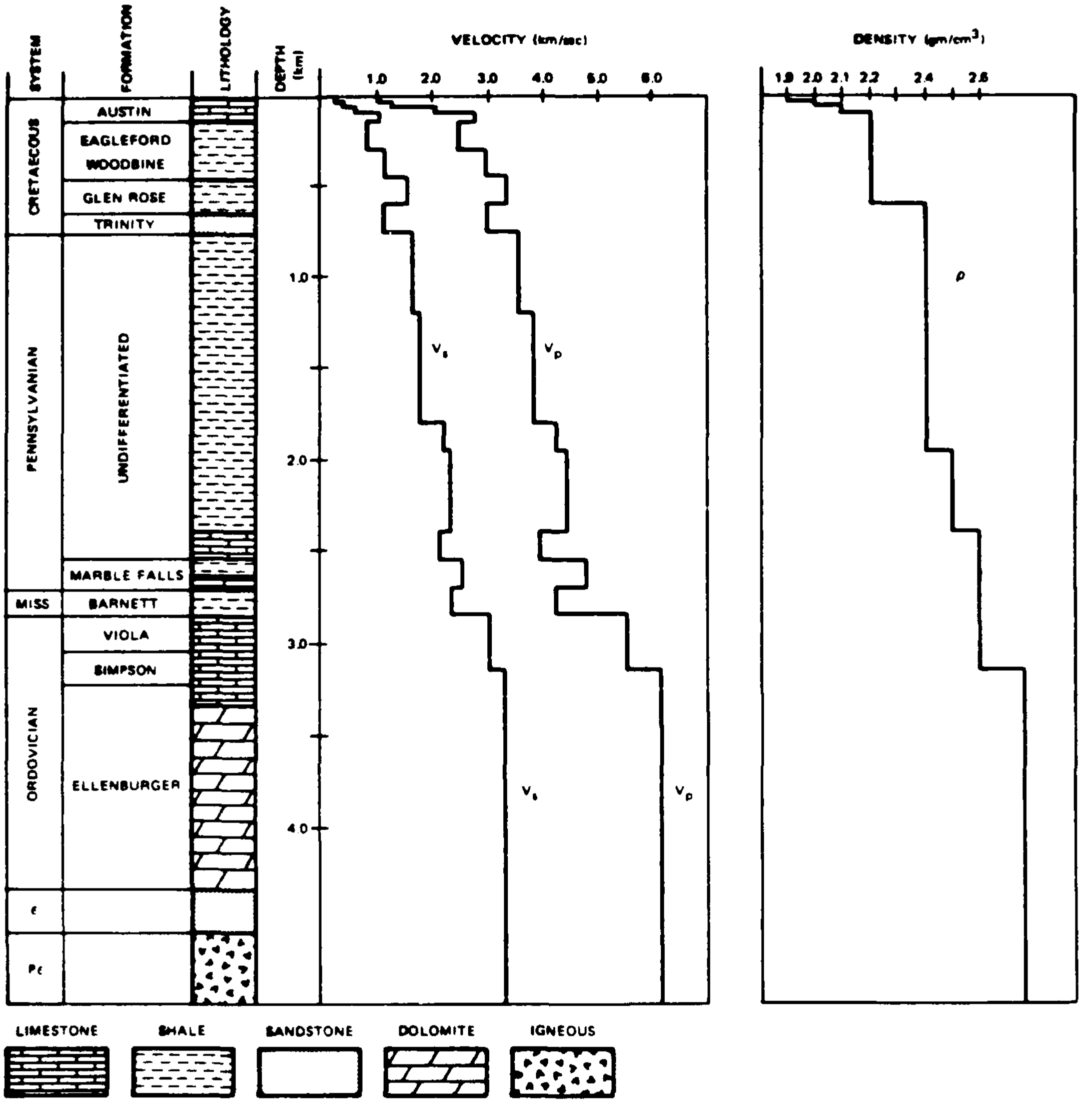

FIGURE 10. DALLAS/COLLIN COUNTY VELOCITY-DENSITY MODEL WITH THE CORRESPONDING LITHOLOGY (AFTER FERGUSON AND LI,

G 11753

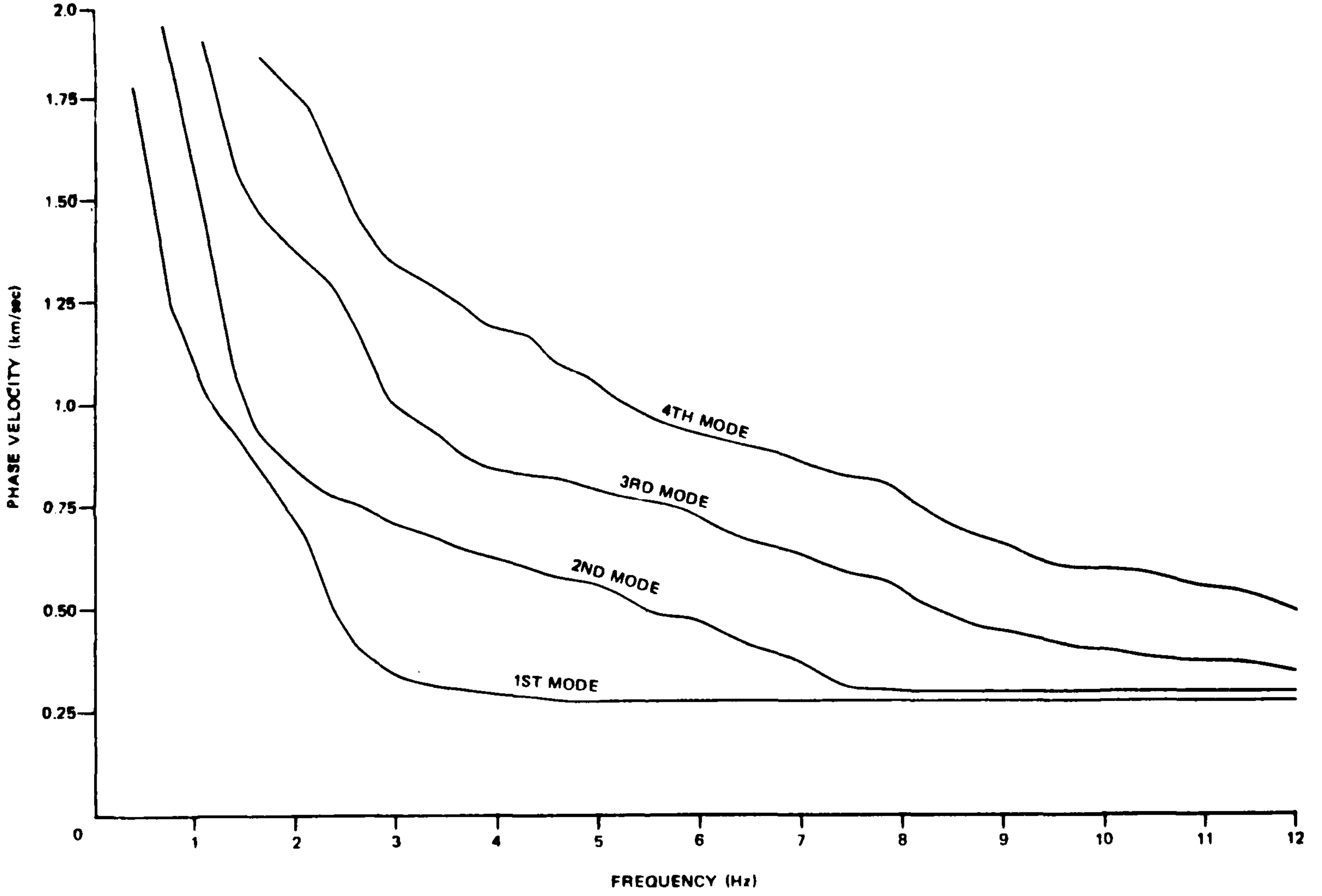

FIGURE 11. THEROETICAL RAYLEIGH WAVE PHASE VELOCITY DISPERSION CURVES FOR THE DALLAS/COLLIN COUNTY VELOCITY MODEL (AFTER FERGUSON AND LI, 1981)

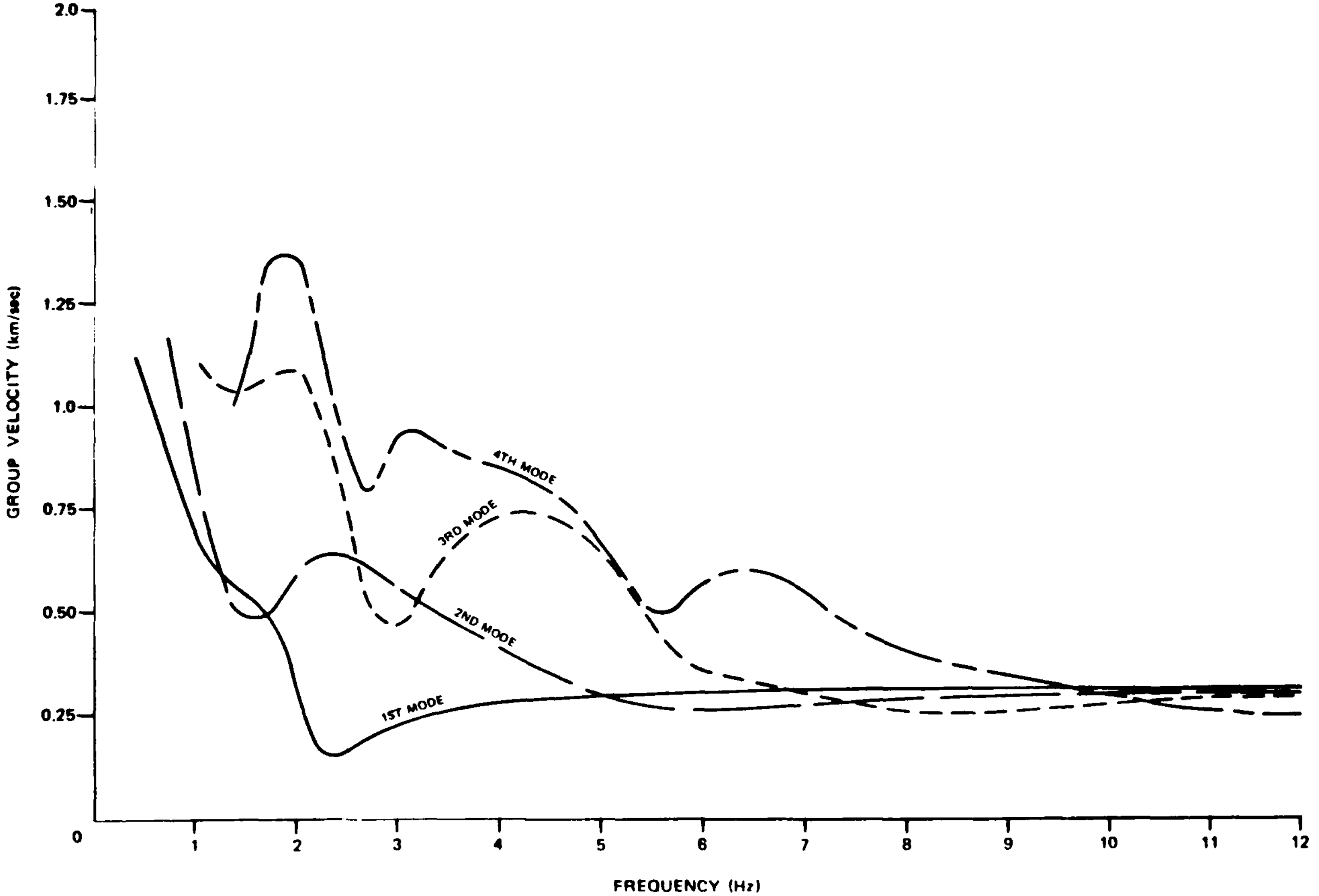

FIGURE 12. THEORETICAL RAYLEIGH WAVE GROUP VELOCITY DISPERSION CURVES FOR THE DALLAS/COLLIN COUNTY VELOCITY MODEL (AFTER FERGUSON AND LI, 1981)

G 11756

frequency band above 3 Hz (figure 13). The theoretical vertical displacement functions for the first four modes at McKinney are shown in figure 14 for 3 Hz, in figure 15 for 5 Hz, and in figure 16 for 10 Hz. The approximate shapes of the vertical strain for the corresponding modes are also sketched in these figures, based on an eyeball vertical derivative of the vertical displacement functions. Note that, for the higher modes, the vertical strain at depth tends to peak where there is a node in the vertical displacement function. Thus, when the noise consists of higher mode Rayleigh waves, a vertical separation between strain and inertial sensors will probably be required to obtain maximum strain-inertial coherence. If the noise is dominated by fundamental mode Rayleigh waves, which may be the case in the 1 Hz to 2 Hz band at McKinney, either separated or collocated strain-inertial sensors may be adequate.

An indication of the potential noise reduction capabilities of strain-inertial combinations is shown in figure 17. This figure shows the spectrum of noise from the vertical-component inertial sensor in the surface vault during a low-wind time period (< 5 mph). In addition to the raw data, figure 17 also shows the spectra of the noise after filtering to take advantage of the strain-inertial combination. The three filtering techniques used were (1) forward-in-time adaptive prediction-error filtering (Griffiths et al., 1977) in which the strain is used as predictor of the inertial noise, (2) two-channel pure-state polarization filtering (Samson and Olson, 1981) which suppresses incoherent noise between the strain and inertial sensors, and (3) pure-state polarization filtering followed by prediction-error filtering. The noise reduction provided by the prediction-error filtering alone is what would be expected from the coherence estimates. Very little noise reduction occurs at 3 Hz, but nearly 10 dB noise reduction occurs in the 5 Hz to 6 Hz band, where the coherence approaches 0.9. The pure-state filter produces 10 dB of noise reduction throughout most of the band out to 20 Hz, except near 10 Hz. When the prediction-error filter is applied to the pure-state filtered data, an additional 3 to 10 dB of noise reduction is achieved in the 3 Hz to 10 Hz band. Above 20 Hz, which is the high-cut filter corner, none of the filtering techniques suppress what is probably system noise.

An example of the application of these filtering techniques to a signal is given in figure 18 which shows the time series of a high-frequency signal of unknown origin. The high-frequency arrival is followed by lower frequency surface wave arrivals that are clipped. The relatively low coherence between the strain and inertial sensors during this time period suggests that only a few decibels of noise reduction will be achieved by prediction-error filtering. Note that the Rayleigh waves associated with the signal have been significantly reduced although the signal is clipped. The pure-state filtered output was produced by using a 4-channel estimate of the polarization state to design the filter. The four channels were the vertical, north, and east components of the inertial instruments in the surface vault and the strain-A sensor. The resulting filtered output shows significant improvement in signal-to-noise ratio for the high-frequency signal, and this is consistent with the observation that the strain noise and the inertial noise are largely incoherent. The combination of pure-state filtering followed by prediction-error filtering with the pure-state filtered output provides the best overall improvement in signal-to-noise ratio. These results are encouraging and suggest that further study of strain-inertial processing techniques should prove fruitful.

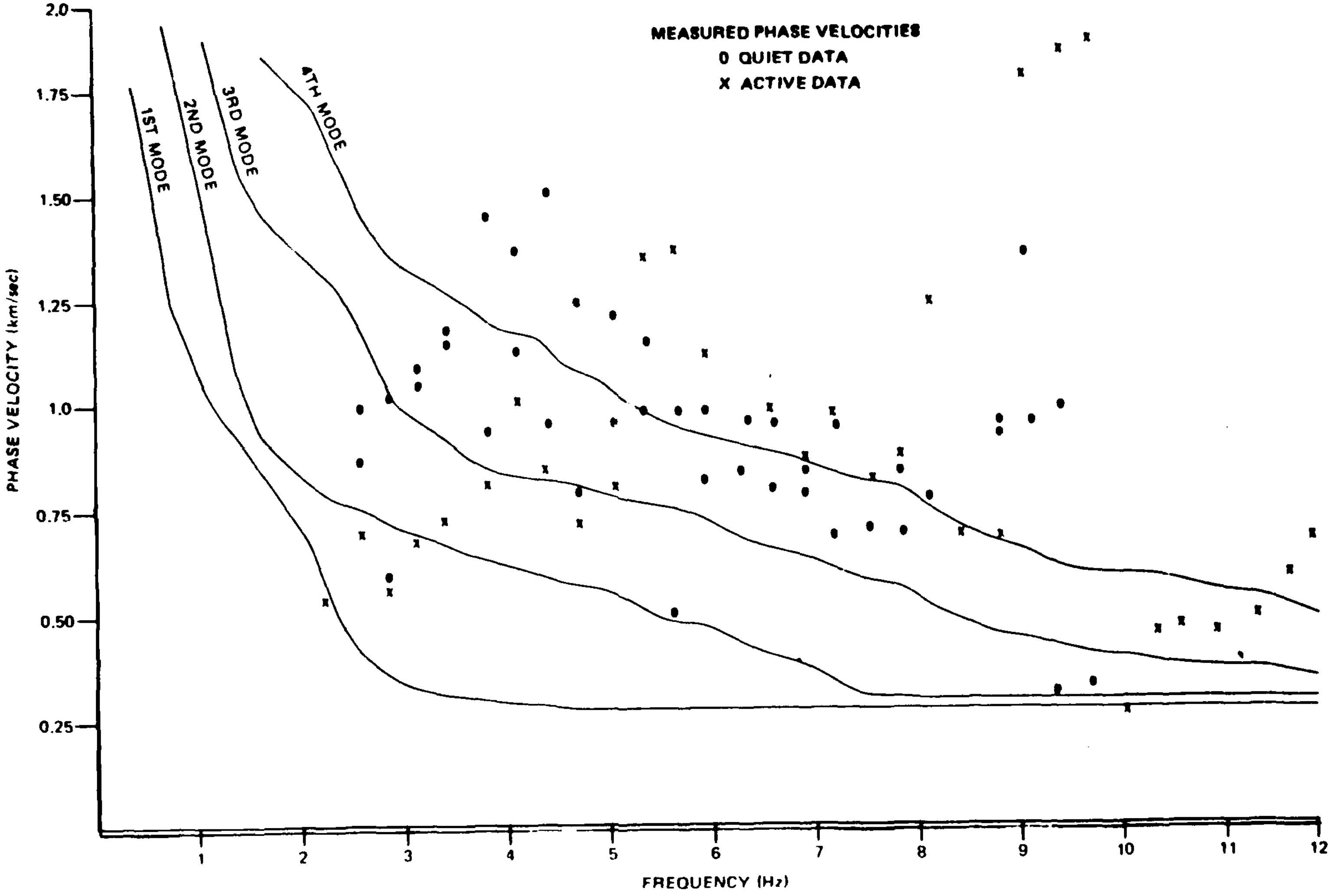

FIGURE 13 COMPARISON OF THEORETICAL AND OBSERVED PHASE VELOCITIES AT McKINNEY, TEXAS (AFTER FERGUSON AND LI, 1981)

G 11785

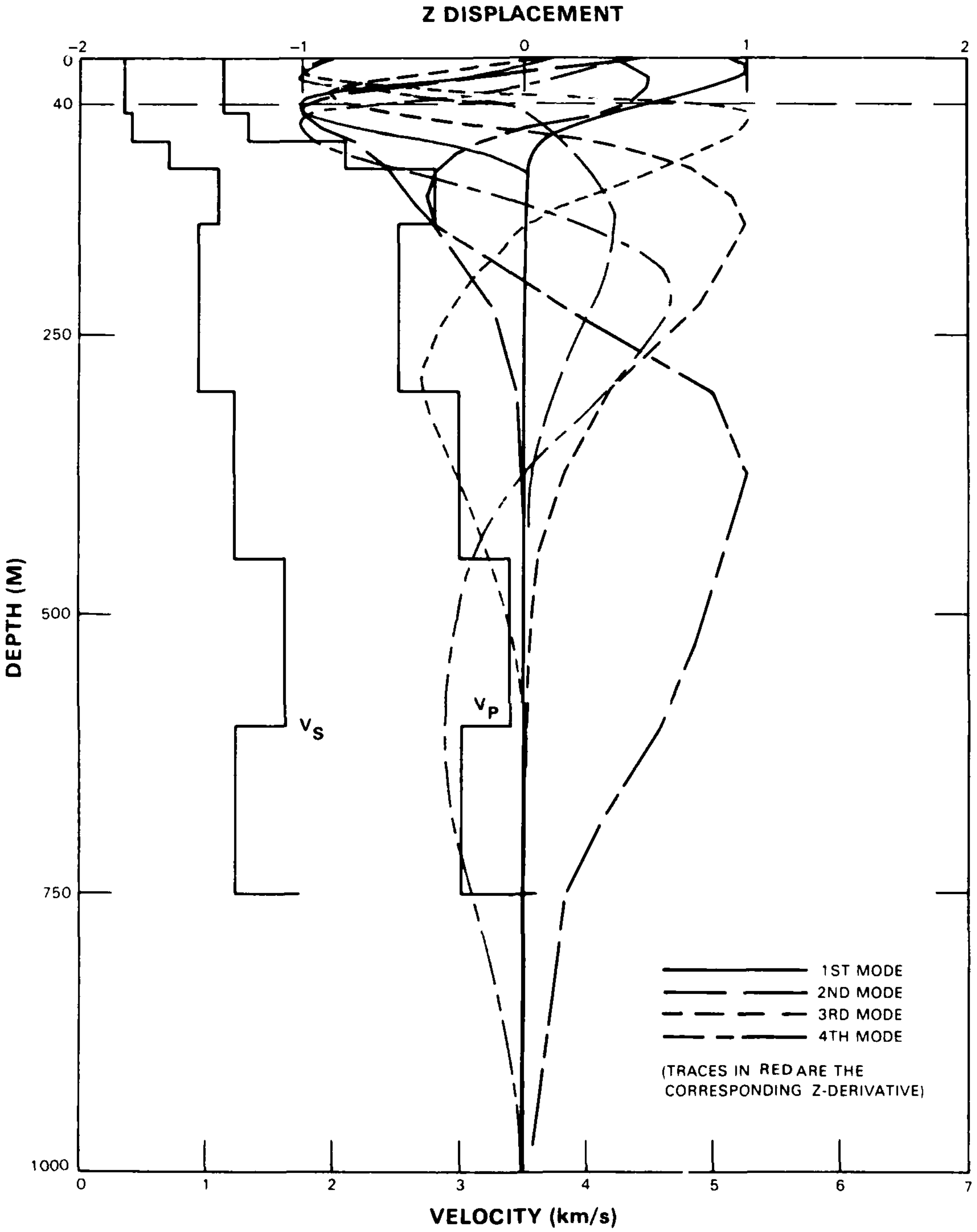

FIGURE 14. VERTICAL DISPLACEMENT EIGENFUNCTIONS (IN BLACK) OF THE RAYLEIGH MODES, NORMALIZED TO THE PEAK DISPLACEMENT, FOR THE DALLAS/COLLIN COUNTY VELOCITY MODEL, AT 3 HZ. THE TRACES IN RED ARE SKETCHES OF THE VERTICAL DERIVATIVE OF THE RAYLEIGH DISPLACEMENT EIGENFUNCTIONS.

G 11757A

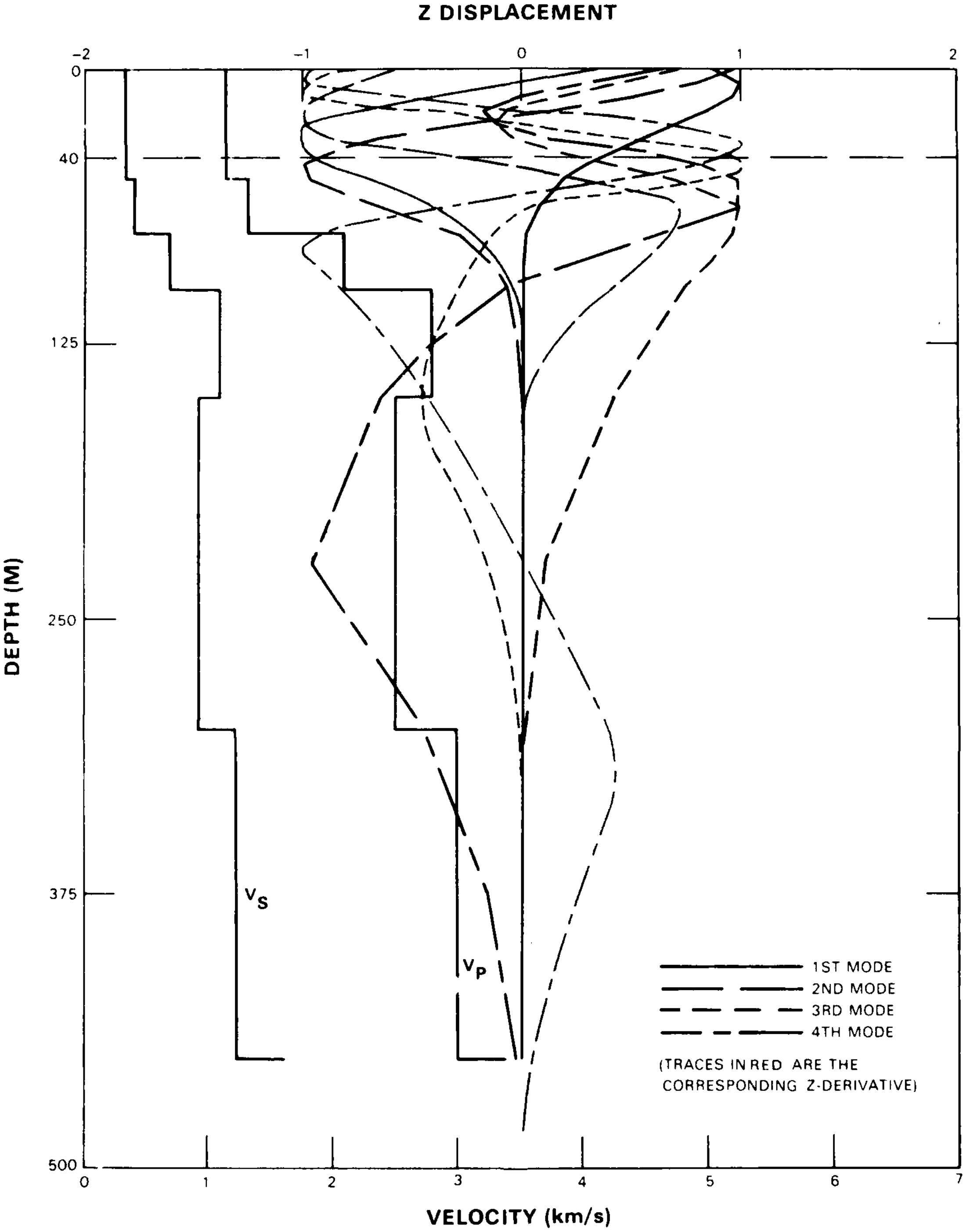

FIGURE 15. VERTICAL DISPLACEMENT EIGENFUNCTIONS (IN BLACK) OF THE RAYLEIGH MODES, NORMALIZED TO THE PEAK DISPLACEMENT, FOR THE DALLAS/COLLIN COUNTY VELOCITY MODEL, AT 5 HZ. THE TRACES IN RED ARE SKETCHES OF THE VERTICAL DERIVATIVE OF THE RAYLEIGH DISPLACEMENT EIGENFUNCTIONS.

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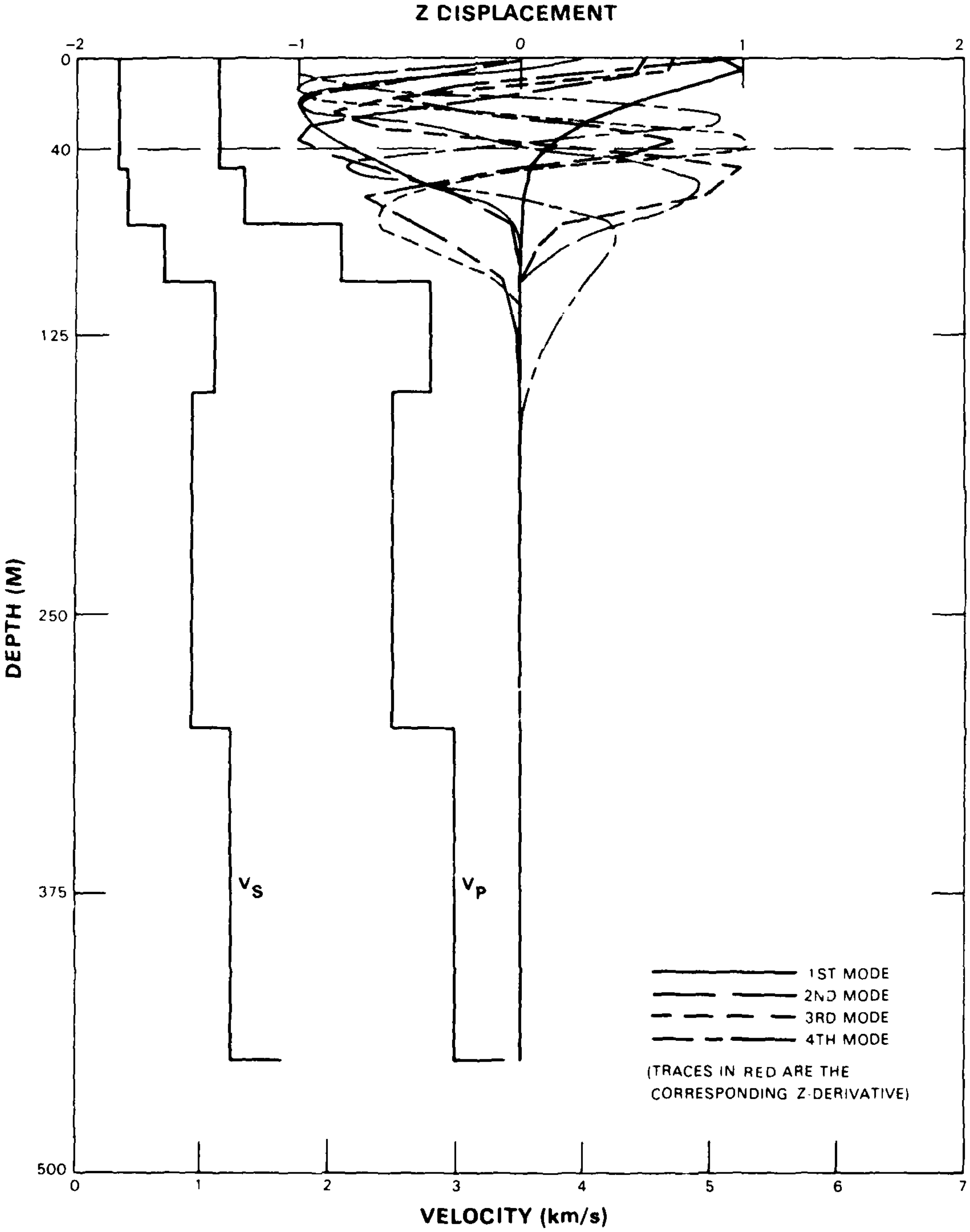

FIGURE 16. VERTICAL DISPLACEMENT EIGENFUNCTIONS (IN BLACK) OF THE RAYLEIGH MODES, NORMALIZED TO THE PEAK DISPLACEMENT, FOR THE DALLAS/COLLIN COUNTY VELOCITY MODEL, AT 10 HZ. THE TRACES IN RED ARE SKETCHES OF THE VERTICAL DERIVATIVE OF THE RAYLEIGH DISPLACEMENT EIGENFUNCTIONS.

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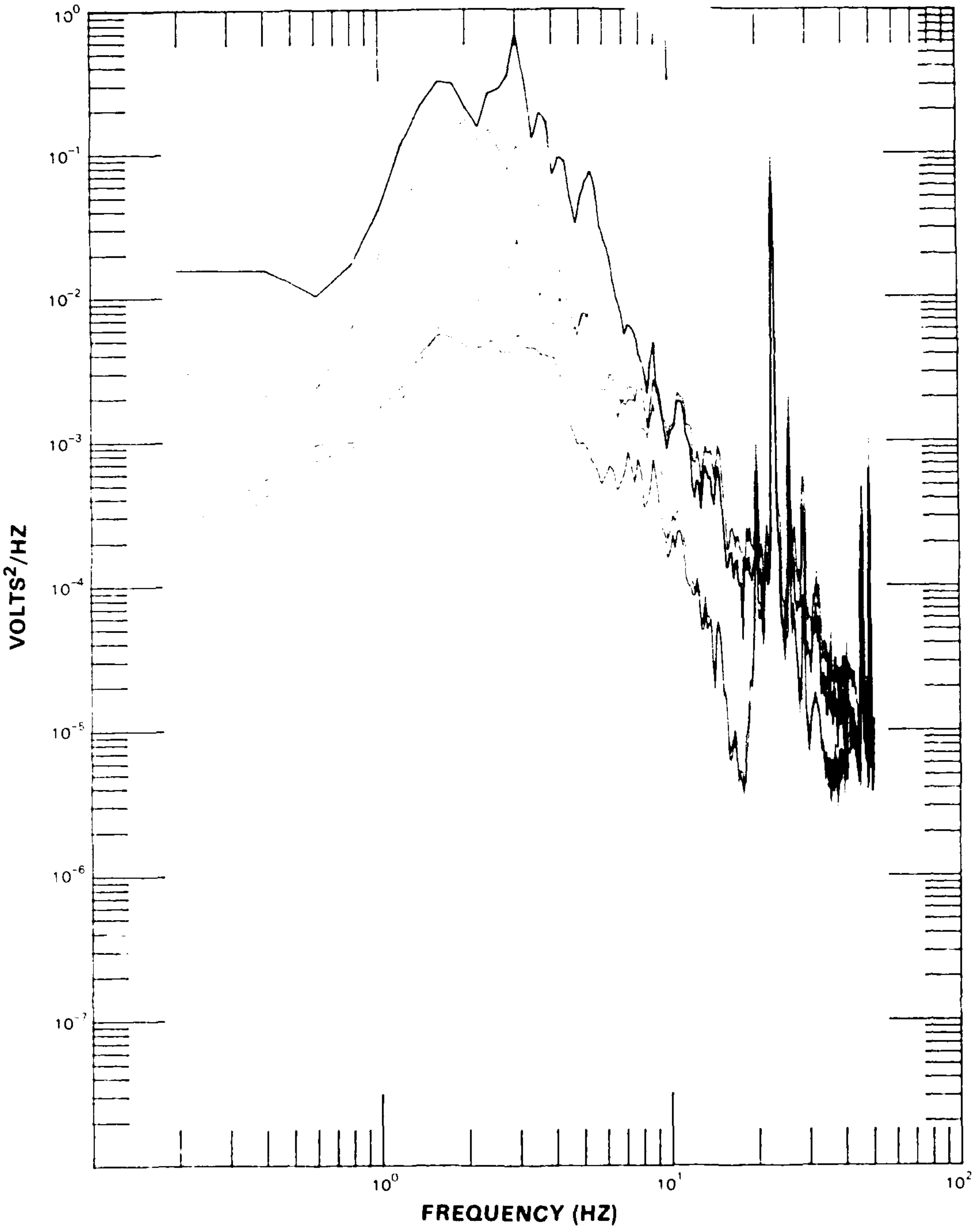

FIGURE 17. POWER SPECTRAL DENSITY OF VERTICAL-COMPONENT INERTIAL NOISE IN THE SURFACE VAULT AT McKINNEY, TEXAS, ON AUGUST 1, 1985, BEFORE AND AFTER FILTERING. THE 12-BIT DATA WERE SAMPLED AT 100 SAMPLES PER SECOND. THE NOISE SAMPLE CONSISTS OF 52.5 SECONDS OF DATA BEGINNING AT 13:44:07 CENTRAL DAYLIGHT SAVINGS TIME DURING A LOW-WIND TIME PERIOD. THE SPECTRAL ESTIMATES WERE OBTAINED BY BLOCK AVERAGING 20 WINDOWS OF 500 SAMPLES (5 SECONDS), OVERLAPPED BY 50%, EACH WINDOW MULTIPLIED BY A COSINE WINDOW IN THE TIME DOMAIN. THE SPECTRA ARE NOT CORRECTED FOR INSTRUMENT RESPONSE.

BLACK – RAW DATA

RED – DATA AFTER PREDICTION-ERROR FILTERING, USING THE STRAIN AT 40M TO PREDICT THE NOISE ON THE INERTIAL IN THE SURFACE VAULT. (OPERATOR LENGTH = 500 SAMPLES, CONVERGENCE FACTOR = 0.65).

BLUE – DATA AFTER PURE-STATE FILTERING WITH THE STRAIN AT 40 M AND THE VERTICAL-COMPONENT SURFACE INERTIAL. THE OPERATOR LENGTH WAS 100 SAMPLES, WITH 50 SAMPLE UPDATE. SPECTRAL SMOOTHING OF 7 FREQUENCY POINTS AND A FILTER POWER OF 3 WERE USED.

GREEN – DATA AFTER PREDICTION-ERROR FILTERING, USING THE PURE-STATE FILTERED STRAIN TO PREDICT THE PURE-STATE FILTERED SURFACE INERTIAL. (OPERATOR LENGTH = 500 SAMPLES, CONVERGENCE FACTOR = 0.65).

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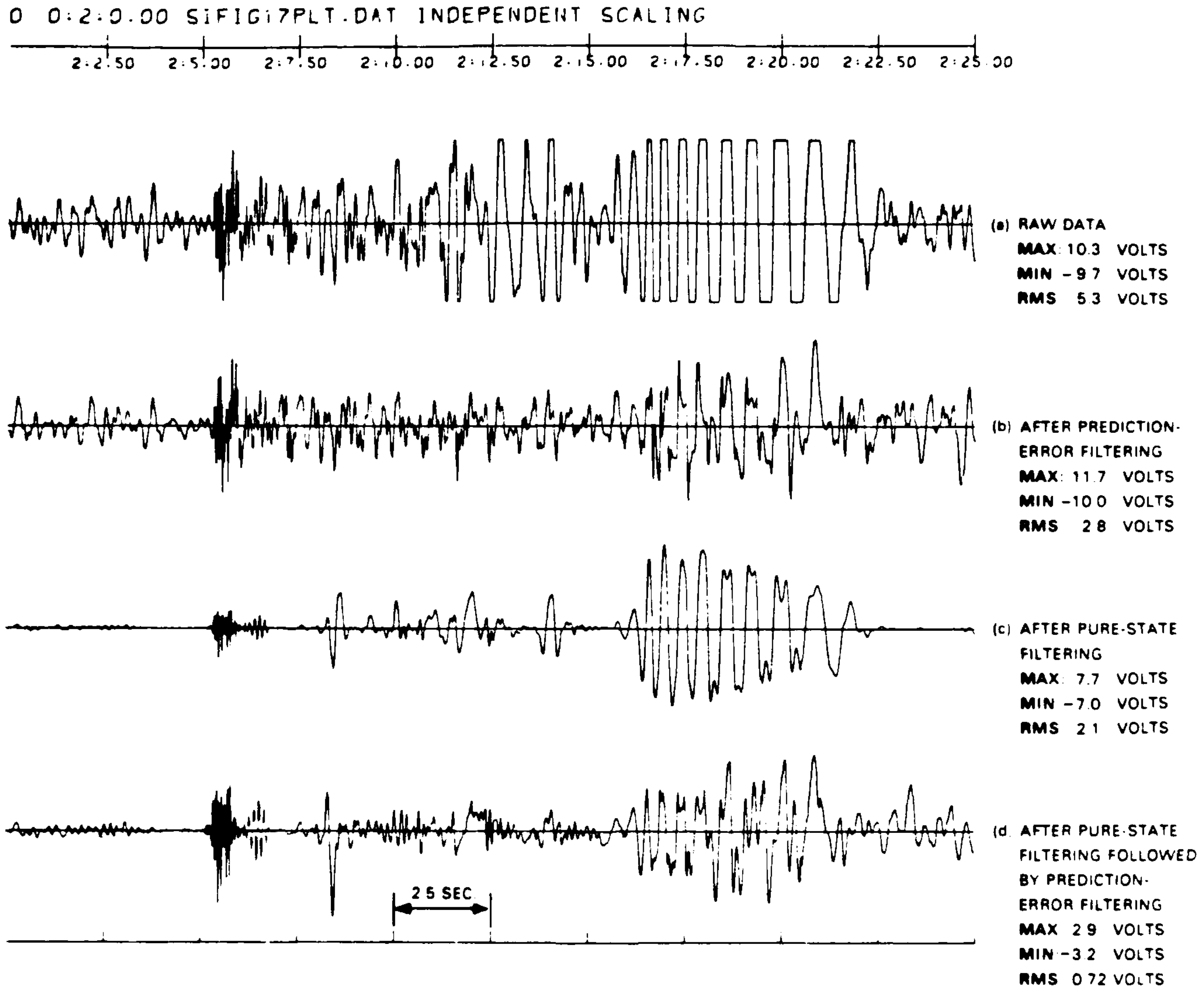

FIGURE 18 TIME SERIES OF A HIGH-FREQUENCY SIGNAL RECORDED AT McKINNEY, TEXAS, ON AUGUST 28, 1985, ON THE VERTICAL-COMPONENT INERTIAL SENSOR IN THE SURFACE VAULT. THE SIGNAL OCCURS AT ABOUT 10:27:42 CENTRAL DAYLIGHT SAVINGS TIME. THE 12-BIT DATA WERE SAMPLED AT 50 SAMPLES PER SECOND

(a) RAW TIME SERIES. NOTE CLIPPING AFTER ABOUT 2:11.0

(b) TIME SERIES AFTER ADAPTIVE PREDICTION-ERROR FILTERING, USING THE STRAIN DATA TO PREDICT THE INERTIAL DATA. THE OPERATOR LENGTH WAS 500 SAMPLES (10 SECONDS), AND THE CONVERGENCE FACTOR WAS 0.65. FILTERING WAS INITIATED ABOUT 125 SECONDS PRIOR TO THE START OF THE HIGH-FREQUENCY SIGNAL

(c) TIME SERIES AFTER PURE-STATE POLARIZATION FILTERING BASED ON THE VERTICAL, NORTH, AND EAST INERTIAL COMPONENTS IN THE SURFACE VAULT AND THE STRAIN SENSOR. THE OPERATOR LENGTH WAS 50 SAMPLES (1 SECOND) UPDATED EVERY 25 SAMPLES AND WINDOWED WITH A COSINE FUNCTION. THE SPECTRAL ESTIMATES WERE SMOOTHED WITH A 7-POINT AVERAGE IN THE FREQUENCY DOMAIN AND A FILTER POWER OF 3 WAS USED.

(d) TIME SERIES AFTER ADAPTIVE PREDICTION-ERROR FILTERING USING THE PURE-STATE FILTERED STRAIN DATA TO PREDICT THE PURE-STATE FILTERED INERTIAL DATA. THE SAME FILTER PARAMETERS USED IN (b) AND (c) WERE USED HERE

EACH TRACE IS SCALED INDEPENDENTLY. NOTE THE INCREASE IN SIGNAL-TO-NOISE RATIO FOR THE HIGH-FREQUENCY SIGNAL AND THE RELATIVE SUPPRESSION OF THE SURFACE WAVES

G 16233

4. CONCLUSIONS

The analyses of the most recent strain-inertial data from McKinney, Texas suggest the following conclusions:

1. In the regional seismic bandwidth (1 Hz to 20 Hz), there is a significant improvement in strain system noise levels over earlier systems, and this makes combinations of strain-inertial data in the regional bandwidth feasible.

2. In the 1 Hz to 2 Hz band, the coherence between the strain and inertial sensors ranges to peak values of between 0.3 to 0.6. This implies that a maximum improvement in SNR of about 4 dB can be achieved at McKinney from prediction-error filtering with the strain-inertial combination in the 1-2 Hz band.

3. In the 3 Hz to 20 Hz band, the coherence between the strain and the surface inertial is consistently greater than the coherence between the strain and the downhole inertial. The peak coherences between the strain and surface inertial range from 0.8 to 0.9 in the 3-20 Hz band. This implies that up to 10 dB of improvement in SNR may be possible from prediction-error filtering with the strain-inertial combination in the 3-20 Hz band at McKinney.

4. The strain-inertial coherences of noise at McKinney, Texas are consistent with earlier studies of noise at McKinney, which suggest that the noise is dominated by higher mode Rayleigh waves for frequencies above 3 Hz. In the 1 to 2 Hz band, the fundamental mode may dominate.

5. The best configuration for a strain-inertial combination of sensors will depend upon the structure of the noise at the site. If the noise is dominated by higher mode Rayleigh waves, the best configuration will require some vertical separation of the strain and inertial sensors. If the noise is dominated by fundamental mode Rayleigh waves, collocated sensors may be appropriate. At frequencies near 1-2 Hz, the noise consists of fundamental mode Rayleigh waves at Garland, Texas and Houlton, Maine (Shopland and Kirklin, 1970), but is dominated by higher mode Rayleigh waves at the Wichita Mountains Observatory (Shopland and Kirklin, 1970) and at the Eniwetok Atoll (The Geotechnical Corporation, 1964). At frequencies above 2 Hz, higher mode Rayleigh wave noise may become dominant as at McKinney, Texas. At Norway, the noise appears to consist of both Rayleigh wave noise below 1 Hz and mantle P-wave noise in the 1.5-4 Hz band (Mykkeltveit et al., 1981). Significant SNR enhancement should be possible in the presence of mantle P-wave noise (Sorrells and Starkey, 1980).

6. Wind-generated noise will tend to degrade the observed strain-inertial coherences, so investigations of techniques appropriate for suppression of wind noise in the regional bandwidth should be continued.

7. The best noise suppression appears to come from a combination of strain-inertial data to suppress both predictable surface-wave noise (prediction-error filtering, e.g., Griffiths et al., 1977) and incoherent noise (pure-state polarization filtering, e.g., Samson and Olson, 1981). The appropriate processing technique will be dependent on the structure of the noise at a given time and location. In order to take full advantage of the strain-inertial combination, evaluation of the processing techniques appropriate for various noise types is needed. An auto-regressive (AR) noise model is often assumed, and many appropriate deconvolution algorithms are available (Burg, 1975; Griffiths et al., 1977; Jurkevics and Wiggins, 1984). In some cases, a more general mixed autoregressive-moving average (ARMA) noise model may be more appropriate, but more difficult to model. A promising ARMA estimation technique has been described by Gray and Woodward (1985) which is a modification of the Tsay and Tiao (1984) technique for ARMA parameter estimation, but uses the Burg (1975) algorithm to estimate the AR parameters.

5. REFERENCES

Burg, J. P., (1975), Maximum entropy spectral analysis, Ph.D. Dissertation, Stanford University, Stanford, California.

Ferguson, J., and T. Li, (1981), McKinney noise study, Technical Report No. 81-3, Teledyne Geotech, Garland, Texas, 60 p.

The Geotechnical Corporation, (1964), Spectral analysis of seismic noise at the Eniwetok E-1 well, Parry Island, Eniwetok Atoll, Marshall Islands, Pacific Ocean, Technical Report No. 64-17, The Geotechnical Corporation, Garland, Texas, 17 p.

Gray, H. L., and W. A. Woodward, (1985), Improved ARMA spectral estimation, preprint, submitted to J. Amer. Statist. Assoc.

Griffiths, L. J., F. R. Smolka, and L. D. Trembly, (1977), Adapative deconvolution: A new technique for processing time-varying seismic data, Geophysics, 42 (4), 742-759.

Jurkevics, A., and R. Wiggins, (1984), A critique of seismic deconvolution methods, Geophysics, 49, (12), 2109-2116.

Mykkeltveit, S., E. S. Husebye, H. Bungum, and K. Astebol, (1981), NORESS data analysis, in Semiannual Technical Summary, 1 October 1980 - 31 March 1981, edited by A. K. Nilsen, pp. 31-39, NORSAR Scientific Report No. 2-80/81.

Romney, C., (1964), Combinations of strain and pendulum seismographs for increasing the detectability of P, Bull. Seism. Soc. Am., 54 (6B), 2165-2174.

Samson, J. C., and J. V. Olson, (1981), Data-adaptive polarization filters for multichannel geophysical data, Geophysics, 46 (10), 1423-1431.

Shopland, R. C., and R. H. Kirklin, (1969), Application of strain seismographs to the discrimination of seismic waves, Bull. Seism. Soc. Am., 59 (2), 673-689.

Shopland, R. C., and R. H. Kirklin, (1970), Application of a vertical strain seismograph to the enhancement of P waves, Bull. Seism. Soc. Am., 60 (1), 105-124.

Sorrells, G. G., and O. D. Starkey, (1980), An assessment of the use of strain and inertial seismographs to enhance seismic signal to noise ratios, Technical Report No. 80-6, Teledyne Geotech, Garland, Texas, 54 p., 5 app.

Stearns, S. D, (1979), Applications of the Coherence Function in Comparing Seismometers, SAND79-1633, Sandia Laboratories, Albuquerque, New Mexico, 33 p.

5. REFERENCES (Continued)

Teledyne Geotech, (1984), Development of the model 52500 strain-inertial seismometer system (prototype), Technical Report No. 83-9, Teledyne Geotech, Garland, Texas.

Tsay, R. S., and G. C. Tiao, (1984), Consistent estimates of autoregressive parameters and extended sample autocorrelation functions for stationary and non-stationary ARMA models, J. Amer. Statist. Assoc., 79, 84-96.

PART 3

ASSESSMENT INFORMATION PACKAGE

PRIME ITEM DEVELOPMENT SPECIFICATION

FOR THE

MODEL 52500 STRAIN-INERTIAL SEISMOMETER SYSTEM (PROTOTYPE)

TYPE BI

PRIME ITEM DEVELOPMENT SPECIFICATION
FOR THE
MODEL 52500 STRAIN-INERTIAL SEISMOMETER SYSTEM (PROTOTYPE)
TYPE B1

AUTHENTICATED BY ______________________ APPROVED BY ______________________
(PROCURING ACTIVITY) (CONTRACTOR)

DATE ______________________ DATE ______________________

CONTENTS

CONTENTS (Continued)

ILLUSTRATIONS

1. Scope

1.1 This specification establishes the performance, design, development and test requirements for the Model 52500, Strain-Inertial Seismometer System Prime Item.

2. Applicable documents

2.1 Government documents. The following documents of the issue in effect on the date of invitation for bids or request for proposal form a part of the specification to the extent specified herein.

Document	Description
MIL-STD-454F	Standard General Requirements for Electronic Equipment
MIL-STD-883B	Test Methods and Procedures for Microelectronics
MIL-STD-1472A	Human Engineering Design Criteria
MIL-HDBK-217B	Military Standardization Handbook, Reliability Prediction of Electronic Equipment
MIL-STD-14768B	Prefered Items List, Electronic and Electromechanical
MIL-STD-19500F	General Specification for Semiconductor Devices

2.2 Non-government documents. The following documents form a part of the specification to the extent specified herein. Unless otherwise indicated, the issue in effect on date of invitation for bids or request for proposal shall apply.

2.2.1 Specifications

	Description	Part Number
a.	Enclosure	NEMA-Type 12
b.	Cable	USS-12J465B/Vector 746NT
c.	Cable strain relief	Crousie-Hinds-Type CBG
d.	Edge board connector	Viking-2VH22/1AB8
e.	Process control procedure	Geotech 40000-9700

2.2.2 Drawings

Description	Part Number
Winch	Geotech 38760-0102
Tilt Mast	Geotech 43296-0101
Lightning Protection Panel	Geotech 43298-0101
Lightning Protection Card	Geotech 43431-0101
Transient Voltage Protection Card	Geotech 43442-0101
Wellhead Terminal Basket	Geotech 43395-0101
Cal Buffer Amplifier	Geotech 43020-0101
Buffer Amplifier	Geotech 43030-0101
Maintenance Test Set	Geotech 51110-0101
CRS Filter Basket	Geotech 43405-0101
Vertical Seismometer Element	Geotech 35120-6101

3. Requirements. The Model 52500, Strain-Inertial Seismometer System shall contain the hardware required to sense both the vertical differential displacement (strain) and the vertical input acceleration components of earth motion in a vertically oriented cased borehole. The data outputs will be electrical analogs of the seismic input of displacement and differential displacement over a section of the borehole.

3.1 Strain-inertial seismometer system definition. The Model 52500, Strain-Inertial Seismometer System, shall be a high-quality sensing and signal conditioning system designed for installation and operation in a near-vertical cased borehole located near manned facilities or in remote unmanned areas. To meet the requirement for remote operation, the system shall have low power drain, have high reliability, and be capable of being remotely calibrated and monitored. System output interfaces shall be designed to be compatible with analog data acquisition systems such as the Model 43300 Multichannel Sensor System and digital data acquisition systems such as the Digital Data Collection System (DDCS) and the B Station Processor presently employed in the B technique network by AFTAC. The system shall be comprised of six major components as follows:

a. The cased borehole,

b. Borehole casing-to-instrument support,

c. The strain-inertial seismometer,

d. The wellhead terminal,

e. The Central Recording Station (CRS) response shaping filter basket (for use in remote installations only),

f. Installation and handling equipment.

The cased borehole, the borehole casing and instrument support, the strain-inertial seismometer, the wellhead terminal, and the installation and handling equipment with the exception of a cable winch and tilt mast assembly must be developed. Maximum use shall be made of existing designs in the Model 43300 Multichannel Sensor System wellhead terminal during this development.

3.1.1 Item diagrams. Figure 1 is a functional block diagram of the system. Figure 2 is a functional block diagram of the strain-inertial seismometer, and figures 3 and 4 are functional block diagrams of the wellhead terminal in a local and remote configuration, respectively. Figure 5 is a functional diagram of the installation and handling equipment used on the system. The cased borehole shown in figure 1 supplies the noise isolation and stable operating environment for the sensor systems. The borehole support provides a method of coupling the strain instrument to two points in the cased borehole which are spaced approximately one meter apart. It also couples the vertical short-period seismometer to the borehole casing. The strain-inertial seismometer shown in figure 2 shall provide signals which are the electrical analogs of the earth's displacement at one point in the borehole and the differential displacement between this point and another point on the order of a meter below the first point. The output signals from these two sensors shall then be conditioned and transmitted uphole to be further conditioned for use in user-supplied processes or processors to enhance the detection of body waves. The borehole seismometer system also conditions all of the power required by the sensors and their associated circuitry and provides the functions to lock or unlock the sensor transducers and to calibrate each of the sensors using calibration signals transmitted from the top of the borehole. The wellhead terminal shown in figure 3 (local configuration), and in figure 4 (remote configuration), shall provide for the preconditioning of the input power required to operate the electronics in the borehole and in the wellhead terminal itself. It shall also provide the monitor and control functions to lock/unlock the sensor transducers and to monitor their position relative to their electrical and mechanical zero. It shall also provide for calibration of strain transducer and isolate the calibration circuit to the short-period seismometer so that the circuit remains shorted and less vulnerable to extraneous noise except during calibration periods. Part of its function shall be to start calibrations on a positive going zero crossing of the input sine wave calibration signal. In the local configuration shown in figure 3, the wellhead terminal shall contain signal conditioning circuits

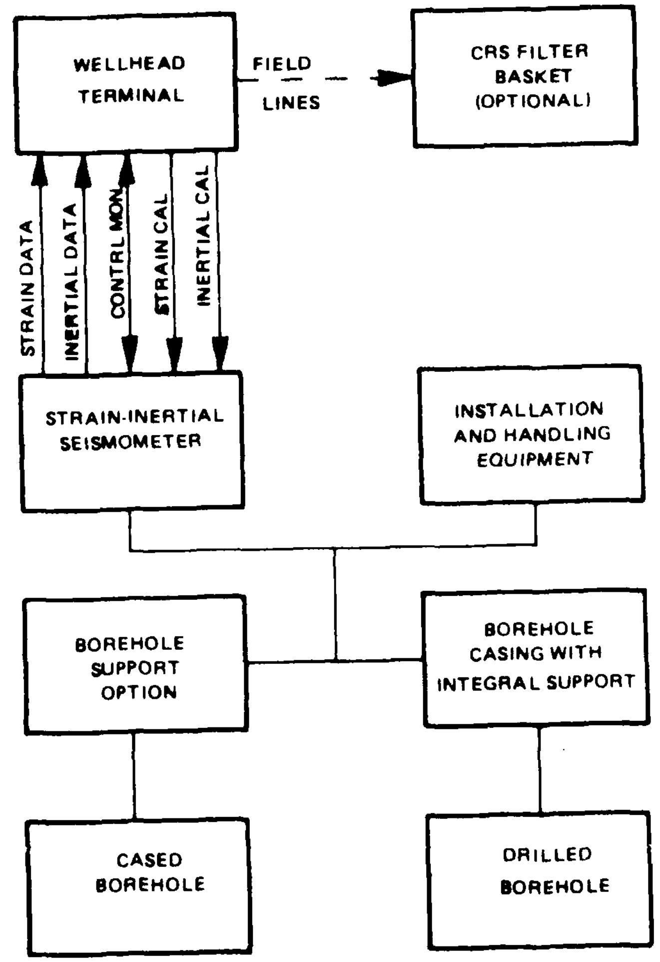

FIGURE 1. MODEL 52500 SYSTEM FUNCTIONAL DIAGRAM

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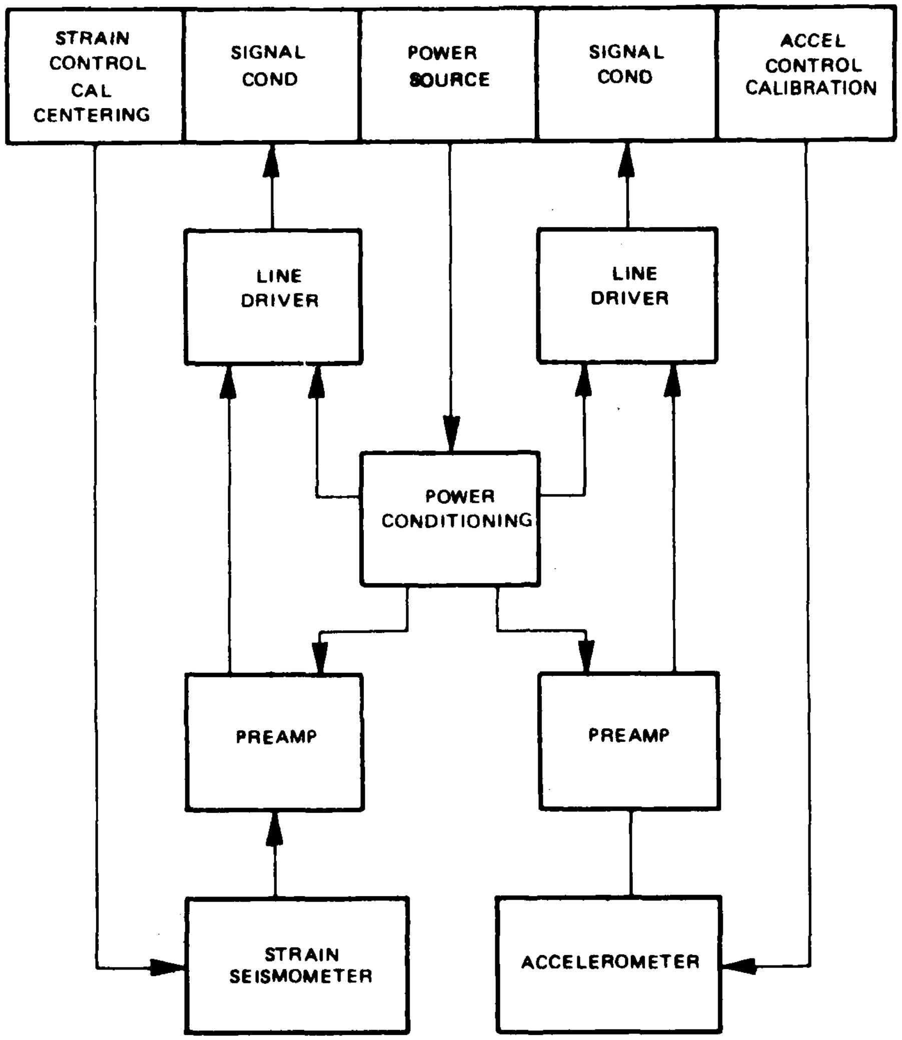

FIGURE 2. STRAIN-INERTIAL SEISMOMETER, FUNCTIONAL DIAGRAM

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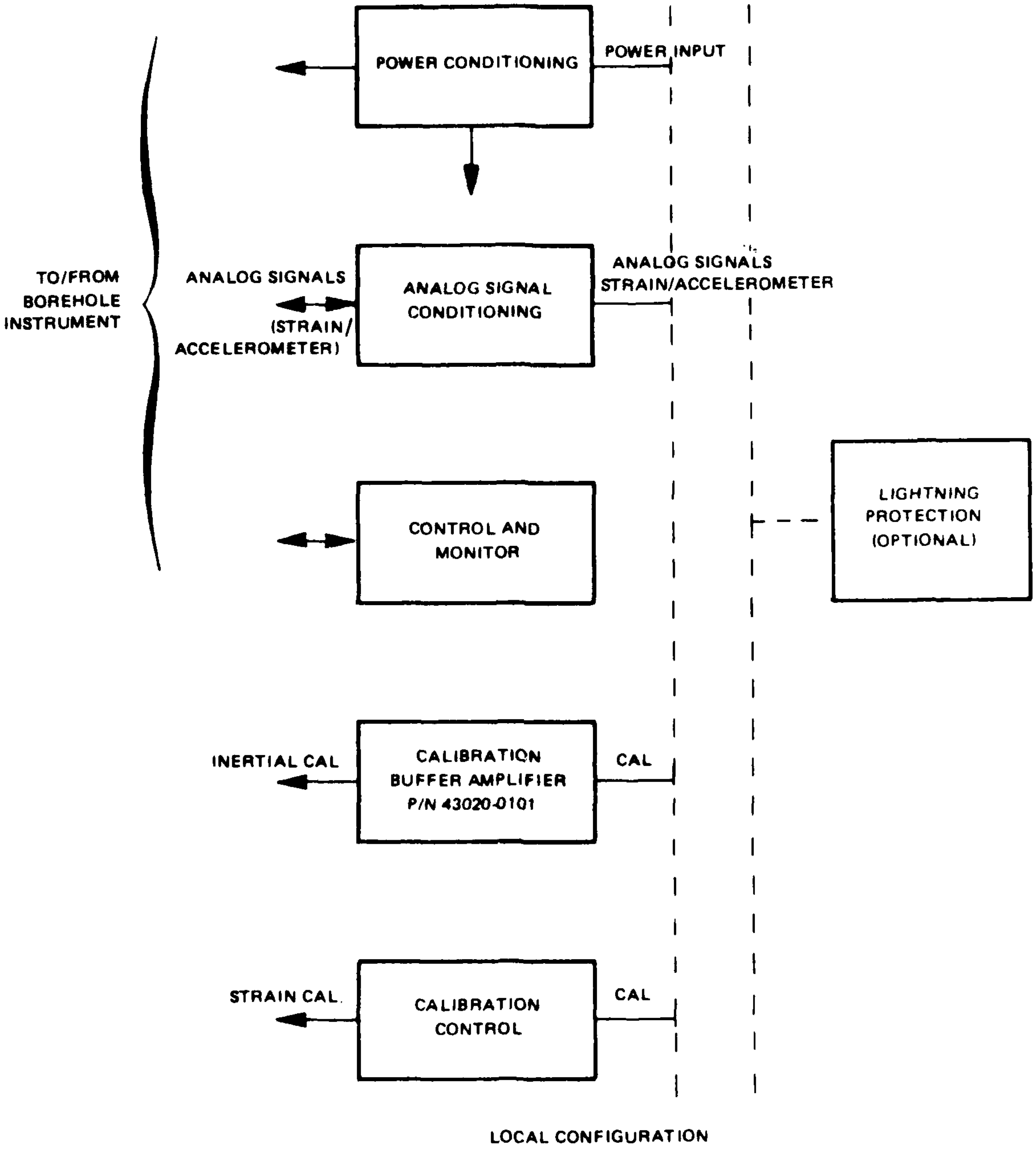

FIGURE 3. WELLHEAD TERMINAL FUNCTIONAL DIAGRAM, LOCAL CONFIGURATION

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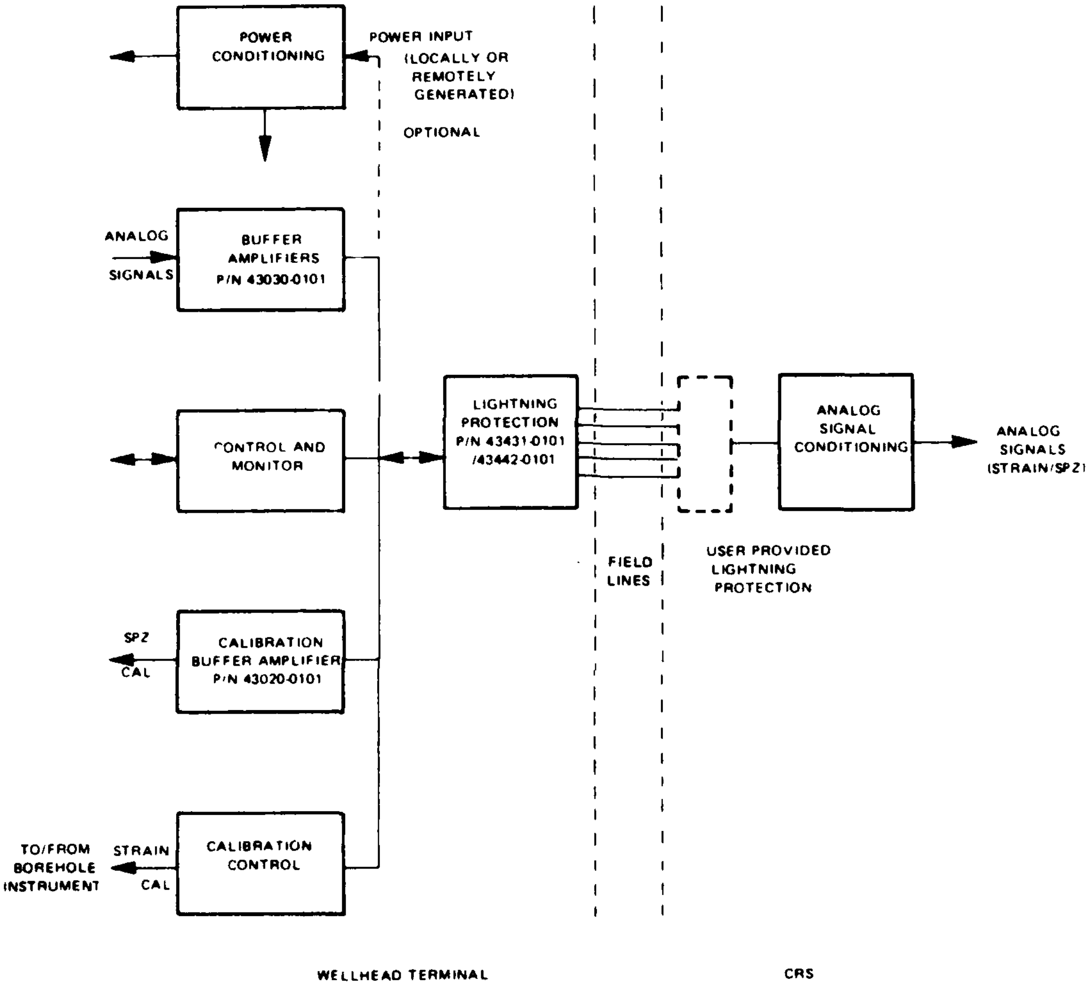

FIGURE 4. WELLHEAD TERMINAL FUNCTIONAL DIAGRAM, REMOTE CONFIGURATION

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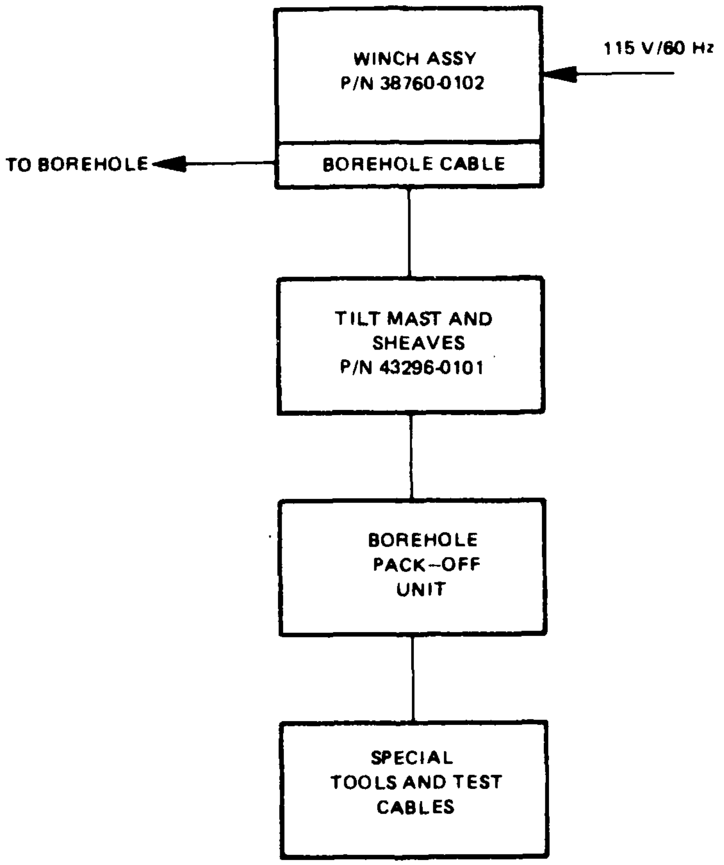

FIGURE 5. INSTALLATION AND HANDLING EQUIPMENT, FUNCTIONAL DIAGRAM

G 11347

to shape and match the response of the two channels of data input by the two borehole sensors. The output of the signal conditioner is input to user-supplied signal processors. The wellhead terminal shall also provide for the optional installation of lightning protection cards for power input and calibration lines in the event these inputs are not generated at the same locality as the user's signal processor. In the remote configuration shown in figure 4, the wellhead terminal shall provide all of the functions of the local configuration unit except signal conditioning of the sensor output signals. Instead of signal conditioners, it shall provide buffer amplifiers for isolation and the power required to drive field lines with the analog signals from the two borehole sensors. Lightning protection cards shall be supplied in the wellhead terminal for all field lines in this configuration, and the analog signal conditioning electronics shall be located in the CRS. Lightning protection at the CRS termination of the field lines shall be provided by the user. The analog output of the signal conditioner is input to user-supplied signal processors. Figure 5 is a functional diagram of the installation and handling equipment. An electric slow-speed winch shall provide the method to lower the instrument into the borehole. A borehole cable wound on its drum shall provide for both the load-bearing requirements of the instrument, and all of the electrical conductors required to interconnect the borehole seismometer system and the wellhead terminal. A tilt mast and sheaves is also part of this major component of the system. The mast assembly shall attach to the borehole collar and provide the clearance required above the borehole surface collar to install the instrument. A borehole pack-off unit which seals the borehole after the instrument is installed shall provide a sealed entry for the borehole cable. Special tools and test cables shall be provided to prepare the borehole seismometer for installation in the field. The test cables are those required for the initial tests of the system before the borehole cable is disconnected from the winch and terminated at the wellhead terminal.

3.1.2 Interface definition. The Model 52500 Strain-Inertial Seismometer System shall have external interfaces to a drilled borehole. External interfaces to the output data circuits shall be compatible with analog data acquisition systems such as the Model 43300 Multichannel Sensor System and digital data acquisition systems such as the GSS employed by the AFTAC "B" technique. Other external interfaces shall be with the power circuits and calibrator circuits. Internal interfaces shall be provided between the major components within the system. The system interfaces are illustrated in figure 6.

3.1.2.1 Borehole interface. The borehole interface shall provide for the installation of the borehole support subsystem. The borehole support subsystem will be initially constructed as an integral part of the bottom section of the borehole casing before the casing is set and cemented in a drilled borehole. After performance characteristics have been established, then the borehole support subsystem may be constructed to be installed in an existing cased and cemented borehole by using a special tool designed for that purpose. The borehole support shall be rigidly coupled to the borehole casing.

3.1.2.2 Borehole support interface. The borehole support interface shall couple the seismometer to the cased borehole at two points spaced approximately one meter apart and shall center the seismometer in the casing.

3.1.2.3 Borehole seismometer/cable interface. The borehole seismometer to borehole cable interface shall provide all electrical and load-bearing connections between the seismometer and the surface. This cable shall have the basic construction features of logging cables employed in the oil and gas industry, and maximum use will be made of existing designs which are now in use in borehole instrument systems. The seismometer/cable interface shall provide a sealed coupling for the electrical connections at the seismometer interface.

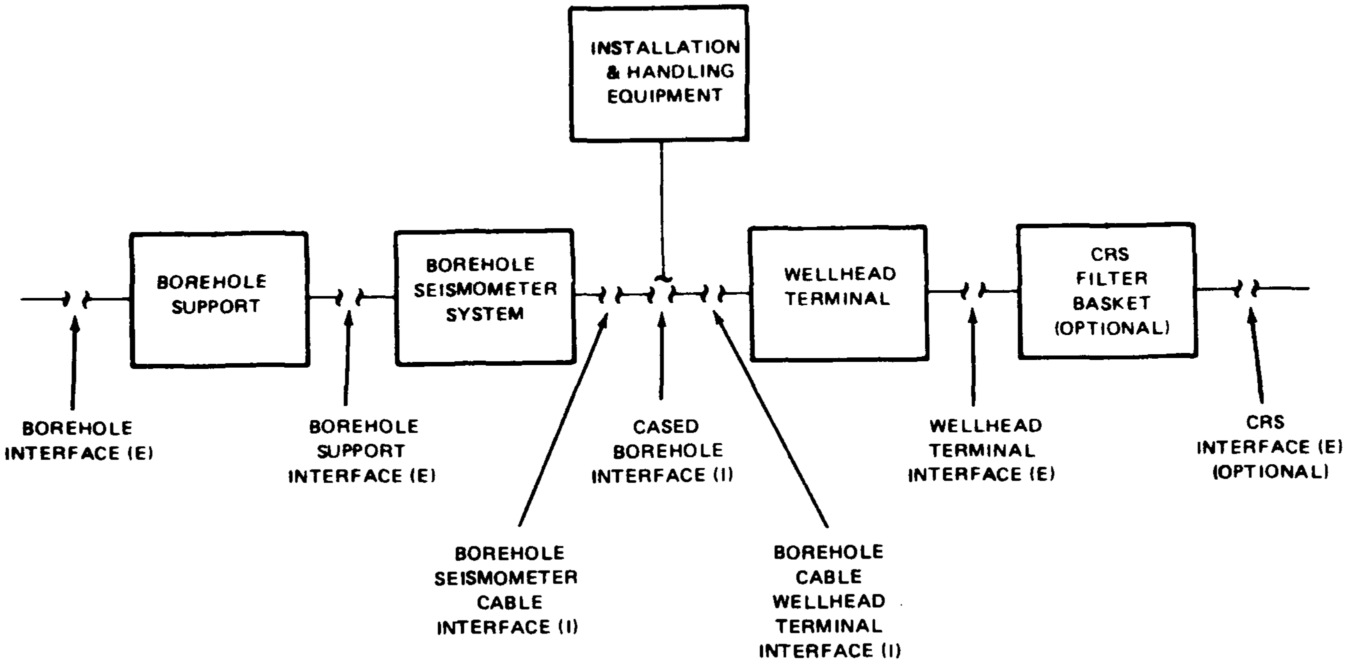

FIGURE 6. MODEL 52500 SEISMOMETER SYSTEM INTERFACES

G 11348

3.1.2.4 Cased borehole interface. The cased borehole shall interface with the installation and handling equipment. The borehole packoff unit shall adapt to or replace the top collar on the borehole casing. The tilt mast and sheave assembly shall be a Geotech P/N 43296-0101 or equivalent. The winch shall be Geotech Model 38760-0102, slow-speed electric winch, or equivalent. Power for the winch shall be user-supplied and shall consist of 115 V/60 Hz power mains or a portable generating unit with a capacity of 2500 watts. A grounding lug sized to retain a number 4 AWG copper ground wire shall be attached to the packoff/top collar of the borehole.

3.1.2.5 Borehole cable/wellhead terminal interface. The borehole cable shall terminate on a Buchannan terminal strip near the bottom of the wellhead terminal. Cable entry to the wellhead terminal shall be through a Crouse-Hinds type CBG strain-relief on the bottom of the wellhead terminal. The cable armour shall be terminated at a ground bus in the wellhead terminal along with a #4 AWG or larger insulated and stranded copper ground wire which shall be laid along side the borehole cable and terminated at the ground lug provided on the wellhead terminal. Termination of the borehole cable shall be made within 300 feet of the borehole.

3.1.2.6 Wellhead terminal interface. The wellhead terminal shall be mounted in an enclosure which protects it from the direct effects of the weather such as wind and precipitation. No environmental control for temperature or humidity shall be required. Cable entry for all input and output signal, power, and control cables will be made through Crouse-Hinds type CBG strain-reliefs at the bottom of the wellhead terminal. All cables (except field lines), entering the wellhead terminal shall terminate on a Buchannan terminal strip near the bottom of the wellhead terminal. Field lines, when used in the optional remote configuration, shall terminate on a barrier terminal strip, Geotech P/N 43298-0101, located above the Buchannan terminal strip. Lightning Protection Cards, Type 43431-0101, shall be mounted on this same barrier strip to terminate the field line conductor pairs for output data circuits and Transient Voltage Protection Cards, Type 43442-0101, shall be mounted on this barrier strip to terminate the input power line. All lightning and transient protector cards shall have their ground connections terminated on the ground bus near the bottom of the wellhead. Input voltage level to operate the wellhead terminal shall be 22 to 28 volts dc.

3.1.2.7 CRS interface (optional). The CRS filter basket shall mount in a standard 19-inch wide instrument rack. It requires 5-1/4 inches of panel space and a clearance of 12 inches behind the front panel. All input and output data cable terminations shall be made on a barrier strip on the rear lightning protection circuits. The CRS filter basket shall be a Geotech Part Number 43405-0101 or equivalent, and the signal conditioning filters shall be designed to interface with this unit. Provisions are made on the filter basket to input 115/60 Hz power to one slot of the filter basket to provide for an optional user-furnished ac power supply. The design of this power supply is not a part of this development: Input voltage level to operate the CRS filter basket shall be ±22 to ±28 Vdc.

3.1.3 Major components list. The following is a list of the major components of the system and their development status.

Description	Qty	Development Status
Cased borehole with integral seismometer support	1	Drilling specifications and cementing technique developed to prototype level.
Instrument support for existing borehole	1	To be developed.
Strain-inertial seismometer	1	Developed to prototype level.
Wellhead terminal	1	Developed to prototype level.

Major Components List (Continued)

Description	Qty	Development Status
CRS filter basket P/N 43405-0101 (optional)	1	Production documentation complete.
Installation and handling equipment	1 set	Developed to prototype level.
Winch, P/N 38760-0102		Production documentation complete.
Tilt mast, P/N 43296-0101		Production documentation complete.

3.1.4 Government-furnished property list. The Model 52500, Strain-Inertial Seismometer System, shall not require the incorporation of government-furnished property to meet functional objectives.

3.1.5 Government-loaned property list. The loan of government property shall not be required to complete the system development.

3.2 Characteristics

3.2.1 Performance. The strain-inertial seismometer system shall combine a strain seismometer and an inertial seismometer to sense earth motion imparted to the borehole casing instrument support. The strain seismometer shall sense the linear differential displacement between the upper and lower seats of the borehole casing instrument support. The inertial seismometer shall be aligned with the sensitive axis of the strain seismometer and shall sense acceleration at the upper seat of the instrument support. The strain and inertial seismometer shall produce electrical analogs of their inputs. These electrical analog signals shall be amplified, conditioned and transmitted via the borehole cable to the wellhead terminal where additional response shaping or conditioning will be performed depending on whether the installation is located adjacent to the user-supplied signal processing system (local configuration) or whether the installation is located some distance (miles) from the user-supplied signal processing system (remote configuration). In the local configuration, final response shaping of the signal from the two sensors will be performed in the wellhead terminal, and the signals output to user-supplied analog recording systems or to digital data acquisitions systems such as the GSS Field Data Acquisition Subsystem. The wellhead terminal shall also provide the power conditioning, control functions, and monitor functions required to install and operate the borehole seismometer. In the remote configuration, the wellhead terminal shall provide all of the functions required in the local configuration except that the response shaping of the signals shall be performed by filters installed in a basket at the CRS, and the wellhead terminal shall provide the signal conditioning and lightning protection circuitry required to drive user-supplied field lines between the seismometer installation and the CRS. All of the major components in the system which are required during normal operation (signal channels, calibration circuits, and power conditioning circuits) shall be designed to have a mean time between failure of 10,000 hours or more and a useful life of 10 years. The following paragraphs discuss the detailed performance characteristics of the borehole seismometer and the wellhead terminal.

3.2.1.1 Borehole seismometer. The strain-inertial seismometer shall sense earth strain over a one-meter interval of a cased borehole at a depth of 40 meters (minimum). The inertial seismometer shall be located adjacent to and just above the strain seismometer. Both the strain and inertial seismometers shall employ a capacitance bridge type of transducer, and both instruments shall provide a primary output signal for use in data processing and a secondary output for use as a monitor of the relative position of the capacitance transducers in relation to their electrical zero position. The initial design for the inertial seismometer shall employ the Model 52100-0102 (S750) Seismometer.

The design of the strain seismometer shall make maximum use of the technology employed in the Model 36000 and Model 44000 Seismometers to sense the strain signal. It shall be possible to calibrate both instruments from the surface.

3.2.1.2 Wellhead terminal. The wellhead terminal shall provide for the control and monitoring functions required to install the borehole seismometer and make it operational. If control and monitor functions are contained in a detachable control and monitor unit, then the wellhead terminal shall interface the unit to the system. It shall accept 2-wire 22-28 Vdc power, condition it for use by the rest of the system and provide barrier strips to terminate all interconnection between the borehole instrument and the user-supplied signal processing equipment. In the local configuration, it shall contain a basket for electronic printed circuit boards that contain the response shaping filters for the sensor data circuits. The filter basket shall be a Geotech P/N 43395-0101, or equivalent, and one of the ten slots for printed circuit cards shall contain a ±24 Vdc to ±15 Vdc converter regulator, Geotech P/N 39541-0101, or equivalent, which shall supply the power required for the response shaping filters in the local configuration or the buffered line driving amplifiers in the remote configuration. The wellhead terminal shall also provide a Lightning Protection Panel Assembly, P/N 43298-0101, capable of mounting protection cards for eight pairs of conductors. In the remote configuration, the calibration circuit for the short-period vertical seismometer shall be isolated by a Calibration Buffer Amplifier, P/N 43020-0101, which shall mount in the wellhead terminal basket. In this configuration, output signal circuits shall also be isolated from the borehole seismometer by Buffer Amplifiers, P/N 43030-0101.

3.2.2 Physical characteristics. The Model 52500, Strain-Inertial Seismometer System, shall be configured in three basic packages, the borehole seismometer, the wellhead terminal, and the installation and handling equipment. The system shall have no material or characteristics that present a hazard to personnel. Installation and handling equipment shall be developed, and procedures shall be documented to assure safe handling during system installations. These packages shall have the following physical characteristics.

3.2.2.1 Borehole seismometer. The borehole seismometer package shall be no more than 2.4 m (8 ft.) in length and 15.25 cm (6 in.) in diameter. It shall weigh no more than 100 Kg (220 pounds) when assembled for borehole installation and no more than 200 Kg (440 pounds) when packed for shipment. A reuseable shipping crate shall be provided which shall be designed to withstand a shock up to 50 g's in any direction without damage to the instrumentation.

3.2.2.2 Wellhead terminal. The wellhead terminal shall consist of a weathertight NEMA-Type 12 steel enclosure which shall be used to house all of the other electronic equipment required near the wellhead on the surface. Entry of all cables shall be made through Crouse-Hinds Type CBG cable strain reliefs of appropriate size mounted in the bottom of the enclosure. All power lines input to or output from the enclosure will be protected by circuit breakers or fuses. The wellhead terminal basket assembly shall employ a 22-pin, edge card connector, Viking P/N 2VH22/1AB8 for all printed circuit boards. The wellhead terminal shall weigh no more than 45.4 Kg (100 pounds) when assembled and no more than 90 Kg (200 pounds) when packed for shipment. The wellhead terminal shall be packed in a disposable crate using good commercial practices for overseas shipment.

3.2.2.3 Installation and handling equipment. The installation and handling equipment shall consist of an instrument support designed for use in an integrally cased borehole and the coupling to standard API casing, a borehole cable which is compatible for use with a winch, P/N 38760-0102, a Tilt Mast Assembly, P/N 43296-0101, and all other special tools developed to assemble and install the borehole instrument in the field. The instrument support shall be shipped in a disposable crate, and the cable shall be shipped on a disposable reel. When the instrument support for an existing casing and the associated installation tool are developed, then the instrument support installation tool shall have a reusable crate.

3.2.3 Reliability. From an operational standpoint, the system consists of only two major equipment groups: the seismometer subassembly and the wellhead terminal. The seismometer subassembly will be operated under nearly ideal environmental conditions in an inert atmosphere and at constant temperature. The wellhead terminal will be operated in an environment described by MIL-HDBK-217B as equivalent to ground-fixed conditions. The signal channels, calibration circuits, and power conditioning circuits used in the system shall be designed to have an MTBF of 10,000 hours which, because of the operating environment described above, shall be apportioned by allowing 30 failures per million hours in the seismometer subsystem and 70 failures per million hours in the wellhead terminal. Computations of the reliability of the system to be developed shall be made per MIL-HDBK-217B to verify that this reliability has been achieved. Based on the experienced reliability of the Model 36000 siesmometer after over 1000 instrument-months of operation, the actual operational reliability should be approximately 10 times that predicted using the methods of MIL-HDBK-217B.

3.2.4 Maintainability. The system shall be designed to be modular in construction to the extent consistent with performance requirements. System maintenance shall be accomplished at three levels. (1) Field maintenance shall be limited to the replacement of the complete borehole instrument or functional modules in the wellhead terminal. (2) Depot-level maintenance shall include fault isolation, repair, and test to the component level of all modules except the loop boards, carrier source boards, and the sensor modules. (3) Loop boards, carrier source boards, and the sensor modules shall be returned to the manufacturer for repair. Field maintenance shall require the skill of AF level 5 technicians. Depot-level maintenance shall require the skill of AF level 7 technicians.

3.2.4.1 Requirements for preventive maintenance. The system shall be designed for unmanned remote operation, and no preventive maintenance shall be required.

3.2.4.2 System repair requirements. The system, with its associated handling equipment, shall be designed so that the borehole instrument can be replaced in no more than 24 hours after personnel and equipment are at the borehole site. It shall be possible to test the vertical short-period sensor module and the response-shaping filter amplifiers and isolate a fault to the component level at the depot.

3.2.5 Environmental conditions

3.2.5.1 Operating environment. The borehole strain-inertial seismometer shall be designed to operate in a dry, shallow borehole cased with 7-inch, 20-pound per foot casing. The borehole shall not have convecting air and shall be sealed to the direct effects of atmospheric pressure changes. The borehole shall be tilted not more than 4° from the local gravity vector. The wellhead terminal shall operate over a temperature range of -40°C to +60°C in a relative humidity of 0-95% without condensation.

3.2.5.2 Storage and shipping environment. The system, when packed, shall be capable of storage or shipment without damage within a temperature range of -60°C to +60°C, a relative humidity range of 0 to 95%, an altitude range of 0 to 50,000 feet and a vibration range of 0.04 inches peak-to-peak up to 50 Hz. The packing case for the seismometer shall be designed so that a shock of 50 g's to the packing case shall not be transmitted as more than 10 g's to the instrument.

3.2.6 Transportability. The system shall be packaged for shipment by commercial air carrier using standard commercial practices. The total system may be air lifted by helicopter to remote locations.

3.3 Design and construction. The electronic equipment used in the Model 52500 system shall conform in general design to the requirements of Teledyne Geotech specifications for Design and Test of Electronic Equipment (Process Control Procedure), drawing number 40000-97-00. All active components shall be hermetically sealed. Components selected for use in the system shall be available from at least two independent sources when consistent with performance requirements. Mechanical designs shall be developed to the extent possible to be compatible with standard shop practices.

3.3.1 Materials, processes and parts. System design requires careful selection and use of materials to maximize the stability of the mechanical system; however, no strategic or highly specialized materials shall be required in the design of the system. Active and passive electronic components shall be selected and/or screened as necessary to ensure essential operating characteristics consistent with performance requirements. All specifications or procedures required to select or screen these components shall be developed and documented.

3.3.2 Electromagnetic radiation. Standard commercial practice for preventing electromagnetic interference shall be employed in the design of the Model 52500 system.

3.3.3 Nameplates and product marking. All equipment shall be identified in accordance with requirement 67 of MIL-STD-454F.

3.3.4 Workmanship. The Model 52500 shall be manufactured and assembled in accordance with requirement 9 of MIL-STD-454F.

3.3.5 Interchangeability. Provisions for interchangeability of items in accordance with requirement 7 of MIL-STD-454F shall be followed to the maximum practical extent.

3.3.6 Safety. All equipment developed for the Model 52500 system shall be designed to meet requirement 1 of MIL-STD-454F.

3.3.7 Human performance and engineering. The design and packaging of a system for use in a borehole imposes constraints on the ability to provide an instrument with easy access to sensor modules and parts. The design concept is that the system shall operate for long periods of time without personnel/equipment interactions other than routine system calibration. To the extent possible, engineering design principles will be in accordance with MIL-STD-1472A to minimize demands on human skill, training, and manpower.

3.4 Documentation. All documentation for the Model 52500 system shall be in accordance with the Contract Data Requirements List (CDRL).

3.5 Logistics

3.5.1 Maintenance

3.5.1.1 Maintenance concept. The maintenance concept for the Model 52500 system is that restoration of a failed borehole instrument in the field will be accomplished by replacement of the instrument and by replacement of failed modules in the wellhead terminal. Wellhead terminal modules will be spared in the field, and complete borehole instrument packages will be spared only at the depot.

3.5.1.2 Field-level maintenance. Since the borehole seismometer will not be disassembled in the field, field-level maintenance shall include:

a. Incoming inspection to verify proper operation of the seismometer prior to installation;

b. Installation and removal of the seismometer in the borehole;

c. Verification of proper operation of the seismometer after installation by the use of the controls and monitors provided in the wellhead terminal and by calibrations;

d. Fault isolation and repair to the module or board level of the electronics contained in the wellhead terminal.

3.5.1.3 Depot-level maintenance. Depot-level maintenance shall include:

a. Disassembly/assembly of the seismometer;

b. Fault isolation and repair to the component level of any printed circuit board or module in the seismometer except the loop boards and carrier source boards;

c. Fault isolation and repair to the board level in the low-noise analog section of the seismometer electronics (e.g., loop boards and carrier source boards);

d. Fault isolation and repair to the sensor module level of the mechanical subassemblies;

e. Fault isolation and repair to the component level of any printed circuit board or module in the wellhead terminal;

f. Verification of depot and factory repairs and of the borehole seismometer prior to shipment.

3.5.1.4 Factory maintenance. Factory maintenance shall include:

a. Fault isolation and repair to the component level of the low-noise analog loop boards and carrier source boards;

b. Fault isolation and repair to the component or piece part level of the individual sensor modules.

3.5.1.5 Use of multipurpose test equipment. To the maximum extent possible, the Model 52500 system shall be designed to permit maintenance as defined for field-level maintenance by the use of standard 1155 TCHOS tools and test equipment such as multimeters, general-purpose oscilloscopes, and low-frequency oscillators.

3.5.1.6 Use of programmable automatic test equipment (PATE). To the maximum practical extent, the Model 52500 seismometer system shall be designed to be maintained at the depot level by use of PATE. To ensure that components and subassemblies of the system are compatible with PATE, it is important that the physical characteristics, analog and digital input and output connections, and electrical specifications of these units follow the guidelines listed below. However, any components that exceed these guidelines shall be identified and the guideline exceptions described.

a. Analog boards shall be testable through the use of 36 input test signals and 36 output test signals;

b. Power requirements of the boards shall not exceed 4 amps up to 10 Vdc, 2 amps up to 24 Vdc, and 0.5 amps up to 50 Vdc;

c. Digital boards shall meet the following characteristics:
(1) 216 I/O pins, exclusive of power and grounds, maximum;
(2) Logic levels ±15 volts dc maximum.

3.5.1.7 Maintenance and repair cycles. No preventive maintenance shall be required for the Model 52500 seismometer system.

3.5.2 Supply. The design of the Model 52500 seismometer system will introduce new and unique items into the supply system. With the exception of the buffer amplifiers, calibration buffer amplifiers, the basket assemblies used in the wellhead terminal and at the CRS, the lightning protection cards, and the common electronic components used, the uniqueness of the design and the small quantities used will preclude it from being an off-the-shelf item for resupply from manufacturers. Lead times of one year or more should be considered for resupply and the depot-level spares will, of necessity, be greater than the equipment reliability would indicate.

3.5.3 Facilities and facilities equipment

3.5.3.1 Facilities

3.5.3.1.1 Field facilities. Facilities required to support the system at a field site are:

a. A borehole cased with 7-inch API casing coupled to the integral instrument support (pending development of the separate instrument support and installation tool);

b. A small structure or shelter to protect the wellhead terminal from the direct effects of wind and precipitation during maintenance. No other environmental control shall be required.

3.5.3.1.2 Depot facilities. Facilities required at the depot to support the system are:

a. A borehole cased with 7-inch API casing coupled to the integral instrument support (pending development of the separate instrument support and installation tool).

3.5.3.2 Equipment

3.5.3.2.1 Field equipment. Equipment items required to support the system in the field are listed below:

Item	Teledyne Geotech Part Number
Tilt Mast Assembly	43296-0101
Winch	38760-0102
Borehole and integral support	Prototype borehole construction specifications 990-53379-9901
Instrument casing section	990-53468-0101
Separate instrument support and installation tool (for installations in existing cemented casing)	To be developed.

3.5.3.2.2 Depot equipment. Equipment items required to support the system at the depot are listed below:

Item	Teledyne Geotech Part Number
Tilt Mast Assembly	43296-0101
Winch	38760-0101
Maintenance Test Set	51110-0101

3.6 Personnel and training

3.6.1 Personnel. The Model 52500 system shall not require the performance of routine operating procedures other than calibration; therefore, an increase in the staff of the operating facility will not be required. Installation and maintenance of the system in the field will require trained personnel with a minimum technical capability comparable to that of an Air Force level-5 technician. Maintenance of the seismometer and its subassemblies at the depot will require trained personnel with a minimum technical capability comparable to that of an Air Force level-7 technician possessing basic knowledge in digital electronic circuits. Initially, from four (4) to six (6) qualified personnel will require specialized installation and maintenance training to assure the availability of competent personnel for these functions. Subsequent maintenance support of the systems will normally require the availability of two (2) or three (3) trained technicians.

3.6.2 Training. Installation, operation, and maintenance training shall be conducted at the manufacturer's facility at the time of delivery of the first production systems for up to eight (8) Air Force students. A minimum of eighty (80) and a maximum of one hundred twenty (120) hours of formal classroom and "hands on" instruction and training shall be provided for each student. The training course shall familiarize the students with the theory of operation of the system and provide a practical demonstration of installation and maintenance procedures and techniques. Safety precautions to be observed in handling the instrumentation and in working with field lines which can produce hazardous shocks shall be stressed.

3.7 Major component characteristics. The performance and physical characteristics of the major components are listed below. Characteristics that relate directly to data quality (i.e., operating background noise levels and dynamic range) can only be measured and are meaningful only for a system that is installed and operational at its field location. These type of characteristics have not been included in this list.

3.7.1 Cased borehole

Depth	40 meters (131 ft) minimum
Casing diameter	7-inch o.d. 20 pounds/foot, API
Slant angle	$\leq$ 4 degrees

3.7.2 Instrument support	Integral part of borehole casing
Distance between supports	1 meter

3.7.3 Strain-inertial seismometer

a. Noise Power (referred to input)	
Strain	4×10^{-26} $(m/m)^2/Hz$
Inertial	4×10^{-20} $(m/s)^2/Hz$
b. Primary Output (each line of balanced output)	
Strain	1.5×10^{8} volt/(m/m) 0.2 to 10 Hz
Inertial	1.5×10^{4} volt/(m/s) 0.2 to 10 Hz
c. Secondary Output (each line of balanced output)	
Strain	1.5×10^{6} volt/(m/m) d.c. to 10 Hz

d. Output (each line of balanced output)	
Strain	±10 V minimum with 10 kohm load
Inertial	±10 V minimum with 10 kohm Load
e. Dynamic Range (strain and inertial outputs)	120 dB
f. Calibration Type	
Strain	Electromechanical and electronic
Inertial	Electromagnetic
g. Calibrator Motor Constant	
Strain	
Electromechanical	289 nanometer per second (rod length adjustment rate)
Electronic	$\frac{8\pi}{10}$ $\frac{\text{nanometer/meter}}{\text{volt}}$ (equivalent input strain)
Inertial	$\frac{8\pi}{10}$ $\frac{\text{micron/sec}}{\text{volt}}$ (equivalent input velocity)
h. Power Requirement	
Installation	±22-28 Vdc, 1 amp max.
Operation	±22-28 Vdc, 100 mA max.
i. Physical Characteristics	
Diameter	≤ 15.25 cm (6 inches)
Length	≤ 2.4 m (8 feet)
Weight	≤ 100 kg (220 pounds)

3.7.4 Wellhead terminal

a. Input Data Circuits (local configuration)

Number	
Strain	2 (transducer centering, data)
Inertial	1 (data)
Type	Balanced
Impedance	20 kilohm (min) each line to common
Signal Range	±10 volts (min) each line to common
Common Mode	±10 volts (min)
Common Mode Rejection Ratio	74 dB (min)

b. Output Circuits (local configuration)

Number	
Strain	1
Inertial	1
Type	Single-ended
Impedance	Less than 10 ohms, 0-200 Hz
Signal Level	Up to ±10 volts (min), ±1 mA (min)
Distortion	Less than 100 ppm to 1/2 full scale

c. Input Data Circuits (remote configuration)

Number	
Strain	2 (transducer centering, data)
Inertial	1 (data)
Type	Balanced
Impedance	Greater than 1 Megohm each line to common
Signal Range	±10 volts (min) each line to common

d. Output Data Circuits (remote configuration)

Number	2 (strain and inertial)
Type	Balanced
Impedance	10 ohms (approx), either line to common
Signal Range	±10 volts (min) each line to common with 10 kohm load

e. Input Calibration Circuits

Strain	Calibration buffer amplifier, P/N 43020-0101
Inertial	Calibration buffer amplifier, P/N 43020-0101

f. Power Circuits	
Input	22 to 28 volts dc, 1.5 amp maximum
Output	±22 to ±28 volts dc, 1 amp maximum
g. Control Monitor Circuits	
Strain	Lock/unlock and center transducer Monitor sensor position
h. Part Number	990-43330-0102

3.7.5 <u>CRS filter basket</u> (remote configuration)

a. Input	
Number	Up to 9
Type	Differential
b. Input Impedance	20 kilohm (min) each line to common
c. Input Signal (each line to common)	±10 volts minimum
d. Common Mode	±10 volts minimum
e. Common Mode Rejection Ratio	74 dB minimum
f. Output	
Number	Up to 9
g. Output Impedance	Less than 10 ohms 0 to 200 Hz
h. Output Signal Level	±10 volts minimum ± 1 mA minimum

i. Distortion	Less than 100 ppm to 1/2 full scale
j. Physical Characteristics	5¼ in. H x 19 in. W x 12 in. deep
k. Power Requirements	±24 volts dc, ±125 MA maximum
l. Part Number	43405-0101

3.7.6 Installation and handling equipment

3.7.6.1 Winch

a. Size	30½ in. W x 52-5/16 in. L x 31 in. H
b. Drum Size	18 in. diam. spool x 17-7/8 in. Wide x 30 in. diam. flanges
c. Weight	
Operational (w/o cable)	630 pounds
Shipping	750 pounds
d. Power Requirements	115 V/60 Hz, 2500 watts

3.7.6.2 Tilt mast assembly

a. Height (top of borehole collar to bottom of top sheave)	14 feet
b. Weight	250 pounds

3.7.6.3 Installation tool, instrument support (optional)

a. Type	Dc motor driven
b. Drive	Reversible
c. Power Requirements	115 Vac, 60 Hz, 2.5 amp

3.8 Precedence. If a conflict occurs in any of the documents referenced in section 2 or in the detailed requirements of this specification, the requirements of this specification shall be considered superceding requirements.

4. Quality assurance provisions

4.1 General. The Model 52500 system shall be tested and evaluated to verify its compliance with the requirements of this specification. Testing and verification shall include part, component, subassembly and system-level testing. Because of the extremely low noise levels, small relative displacements, and high sensitivity to environmental changes, testing below the system level will necessarily be limited to functional verification tests. Final verification shall be determined by assembling the system, installing it in a borehole and conducting detailed system-level tests and analysis. A test program shall be developed that shall include plans for measuring those parameters that can be measured at the part and subassembly level and for rejecting nonconforming parts as early in the assembly process as possible. The plan shall also include detailed instructions for final system test as required to demonstrate conformance to all system requirements defined in section 3. The test plan and procedure for final system test shall require approval from the government before the tests are accomplished.

4.1.1 Responsibility for tests. Tests conducted in accordance with the approved test plan shall be the responsibility of the contractor. Detailed system tests for final verification of conformance to the requirements shall be conducted at a seismically noisy site and at a seismically quiet site to demonstrate the amount of improvement in signal-to-noise ratio that can be gained by employing this system.

4.1.2 Special tests and examinations. A number of special tests and examinations shall be conducted on selected parts to meet the critical performance standards for low noise and stability. The capacitors used in the bridge circuits and other critical circuits shall be selected for low leakage, and close tolerances on temperature coefficients and capacitance value. Operational amplifiers and field effect transistors shall be tested and classified in accordance with their measured parameters. The sealed and evacuated inertial seismometer shall be tested for losses in the suspension mechanical Q by observing the ring down of the mass after a step in displacement and calculating the internal damping losses by the log-decrement method.

4.2 Quality conformance inspections

4.2.1 Reliability testing. The quality provisions do not include detailed plans for reliability testing. System design effort, parts selection, and manufacturing and test methods that are developed for the Model 52500 system shall rely on the experience derived from the development of previous seismograph systems similar to the Model 52500. Estimates of failure rates shall be verified at the completion of the prototype development using the Parts Count Reliability Prediction method specified in MIL-HDBK-217B.

4.2.2 Test levels

4.2.2.1 Part and subassembly testing. The purpose of this level of testing shall be to assure that the critical parameters of all parts and subassemblies used in the system will meet the requirements. The major areas of testing shall be:

a. Testing of purchased parts for critical parameters such as leakage, noise, open and closed circuit resistance;

b. Testing of subassemblies such as printed circuit boards and electronic modules for satisfactory operation over the required temperature range;

c. Testing of sensor modules for mechanical losses in their suspensions and the integrity of their seals;

d. Testing of electronic circuits for noise, linearity, and frequency response;

e. Testing of the response and resolution of the strain transducer centering system, if used, to determine that it meets the requirements.

4.2.2.2 System functional tests. The purpose of the system functional tests shall be to determine that all system elements are functioning properly. These tests shall determine the following:

a. That all circuits are properly connected;

b. That all power and control circuits function properly;

c. That the mass lock/unlock system and the transducer centering system respond properly to commands;

d. That the inertial seismometer suspension is floating free.

4.2.2.3 Preliminary system performance tests. These tests will give the first indication of system performance relative to the requirements. Two systems shall be operated simultaneously in adjacent boreholes for the purpose of making comparative measurements. The following features shall be evaluated during this phase of the test program:

a. Evaluate the installation procedures;

b. Test and evaluate sensor unlock/lock and centering procedures;

c. Measure system linearity using the two-frequency method;

d. Measure system response for each data channel;

e. Measure and compare spectra and coherence between like data channels in separate boreholes;

f. Based on coherence and spectral plots, estimate the system noise level of each data channel. Because of high ambient seismic noise levels, it will probably not be possible to verify that system noise levels meet the requirements;

g. Prepare a report that summarizes system performance relative to the requirements and submit this report to the government with recommendations for subsequent program activities.

4.2.2.4 Final system performance tests. Tests conducted at this level will be performed in two adjacent boreholes installed at a known quiet location. These tests shall be the same as those conducted during the preliminary system performance test; however, the quiet location should allow precise measurements to be made and compared to the following critical requirements:

a. Linearity;

b. Frequency response;

c. System noise levels;

d. System dynamic range.

5. Preparation for delivery. Packing of the Model 52500 seismometer system shall be in accordance with good commercial practice and the requirements specified in paragraphs 3.2.2 and 3.2.6. The instrumentation packaging design shall incorporate the design concepts developed for similar seismograph systems. Drawing set 36000-0103 shall be used as a guide. All containers shall be clearly marked "Fragile" or other special handling instructions, as required.

6. Notes. This section is not applicable to this specification.

MODEL 44000 SEISMOMETER

DEVELOPMENT ASSESSMENT

FEBRUARY 19, 1985
PROGRAM MANAGER: WILLIAM G. KIKENDALL
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TELEDYNE GEOTECH
GARLAND, TEXAS

112.105

1.0 DESIGN GOALS

- 1.1 SEISMIC PERFORMANCE
- 1.2 IMPROVEMENTS OVER MODEL 36000
- 1.3 CONFIGURATION ISSUES

2.0 SYSTEM BLOCK DIAGRAMS

- 2.1 OVERALL
- 2.2 BOREHOLE PACKAGE
- 2.3 WELLHEAD AND COMMUNICATION

3.0 CRITICAL PERFORMANCE ITEMS

- 3.1 LINEARITY AND RESPONSE
- 3.2 MODULE SUSPENSION LOSSES

4.0 DESIGN CRITERIA

- 4.1 ELECTROMAGNETIC FEEDBACK
- 4.2 COILFORM MATERIAL
- 4.3 SUBASSEMBLY MODULARITY

5.0 DATA

- 5.1 MODULES
- 5.2 BENCH TESTS
- 5.3 BOREHOLE

6.0 CONCLUSIONS

1·1 SEISMIC PERFORMANCE

1·1·1 3 ORTHOGONAL AXES, Z, N, E

1·1·2 SENSITIVITY

FLAT ACCELERATION 0-4 HZ

0·7 OF CRITICAL DAMPING

2·0 x 10^4 V/M/S^2 OUTPUT

1·1·3 NOISE

INPUT REFERENCED NOISE

2·0 x 10^{-20} M/S^2 / HZ MAX

FROM 0·4 TO 4·0 HZ

1·1·4 LINEARITY

BETTER THAN ONE PART IN 10^3

1·2 IMPROVEMENTS OVER 36000

1·2·1 OUTSIDE DIAMETER 3·75 INCHES

1·2·2 PRECISION LEVELING FOR ±15° TILTS

1·2·3 MORE RUGGED MODULES

1·2·4 HIGHER TRANSDUCER SENSITIVITY

10^5 V/M vs. 2500 V/M

1·2·5 FEEDBACK TRANSDUCER INTERNAL TO PROOF MASS

1.3 CONFIGURATION ISSUES

- 1.3.1 COMMUNICATIONS
    - 1.3.1.1 UPHOLE - DOWNHOLE
    - 1.3.1.2 SITE - CENTRAL TERMINAL
- 1.3.2 FLEXIBILITY
    - 1.3.2.1 DOWNHOLE FUNCTIONS
    - 1.3.2.2 REMOTE FUNCTIONS
- 1.3.3 ACCESSORIES
    - 1.3.3.1 WELLHEAD
    - 1.3.3.2 INSTALLATION/MAINTENANCE
    - 1.3.3.3 CABLE
- 1.3.4 RELIABILITY AND COST

	MINIMUM DOWNHOLE	INTERMEDIATE DOWNHOLE	MAXIMUM DOWNHOLE
CABLE REQUIREMENTS	36 CONDUCTOR	12 CONDUCTOR	12 CONDUCTOR
MECHANICAL (SENSOR) STACK	ALL HAVE 3 SENSOR MODULES, 3 LEVELER ASSEMBLIES AND 3 MOTOR DRIVER BOARDS		
ELECTRONIC STACK:			
REGULATED POWER	YES	YES	YES
DC-DC CONVERTER	NO	NO	YES
LOOP BOARDS	3 EA.	3 EA.	3 EA.
CARRIER SOURCE	1 EA.	1 EA.	1 EA.
COM. CONTROLLER	NO	YES	YES
LEVEL CONTROLLER	NO	NO	YES
CALIBRATOR	NO	NO	YES
ELECTRONIC STACK LENGTH	32"	42"	71.5"
AUTO LEVELING	ALL INTELLIGENCE UPHOLE	ALL INTELLIGENCE UPHOLE/DOWNHOLE	ALL INTELLIGENCE DOWNHOLE
CALIBRATION:	SIGNAL/CONTROL UPHOLE	SIGNAL/CONTROL UPHOLE	SIGNAL/CONTROL DOWNHOL
KEY POINTS:	NEEDS SOPHISTICATED WELLHEAD CONTROL FOR INSTALLATION. NEEDS SOPHISTICATED WELLHEAD FOR REMOTE CAL, LEVEL, STATUS	LESS WELLHEAD CONTROL FOR INSTALLATION. NEEDS SOME WELLHEAD FOR REMOTE CAL, LEVEL, STATUS	ALMOST NO WELLHEAD NEEDED. STAND-ALONE SYSTEM FOR REMOTE OPERATION

CONFIGURATION TRADEOFFS

2.1 OVERALL SYSTEM FUNCTION

2.1.1 DATA

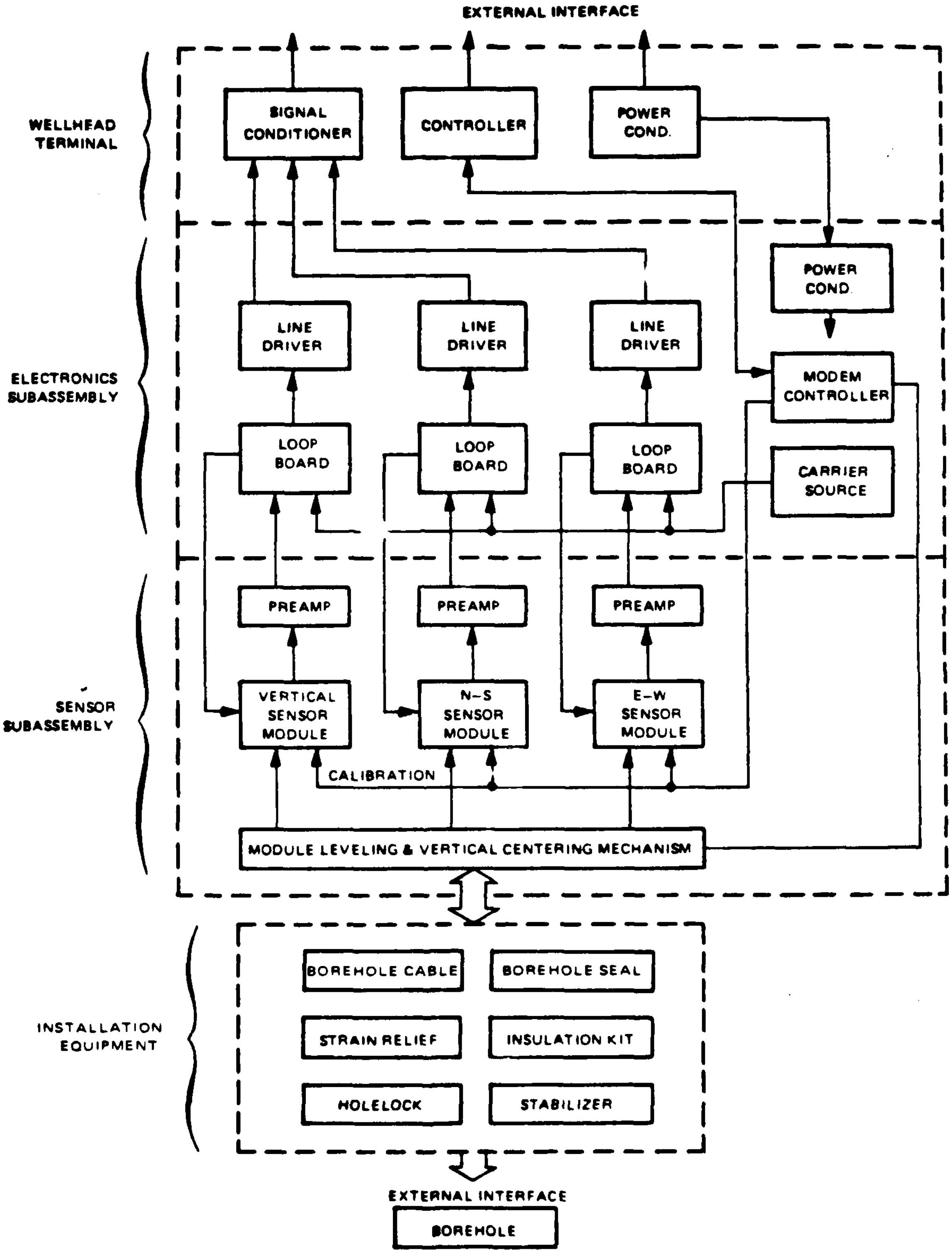
- 3 ORTHOGONAL AXES
- BROADBAND ACCELERATION
- SIGNAL CONDITIONING LP, SP

2.1.2 CONTROL

- PRECISION LEVELING, MASS POSITION ADJ.
- CALIBRATION
- STATUS

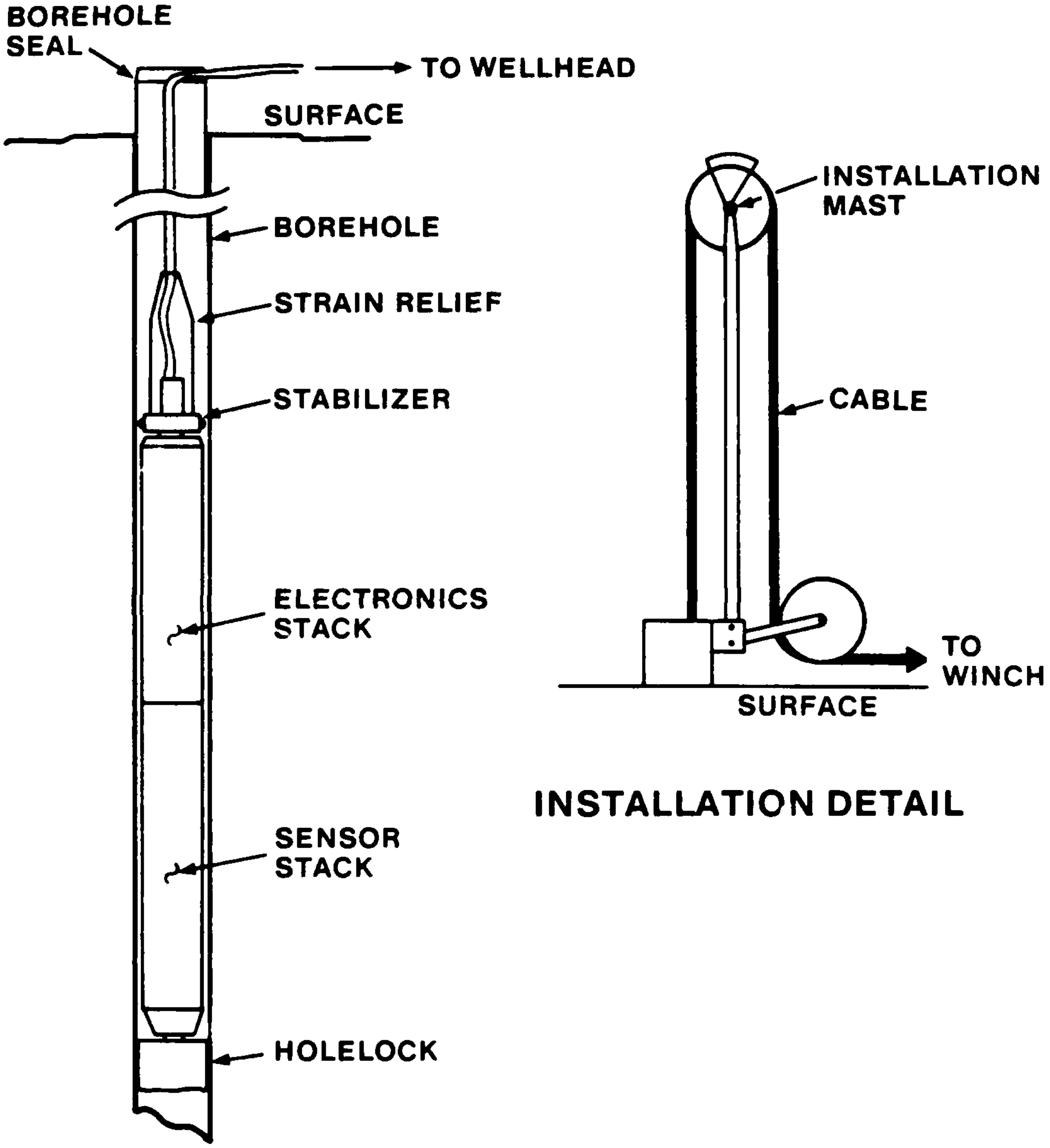
2.1.3 INTERFACE

- HOLELOCK
- STABILIZER/STRAIN RELIEF
- CABLE
- BOREHOLE SEAL



MODEL 52900 SYSTEM, FUNCTIONAL DIAGRAM

G 10747A



INSTALLATION DETAIL

52900 BOREHOLE SEISMOMETER

2.2 BOREHOLE PACKAGE

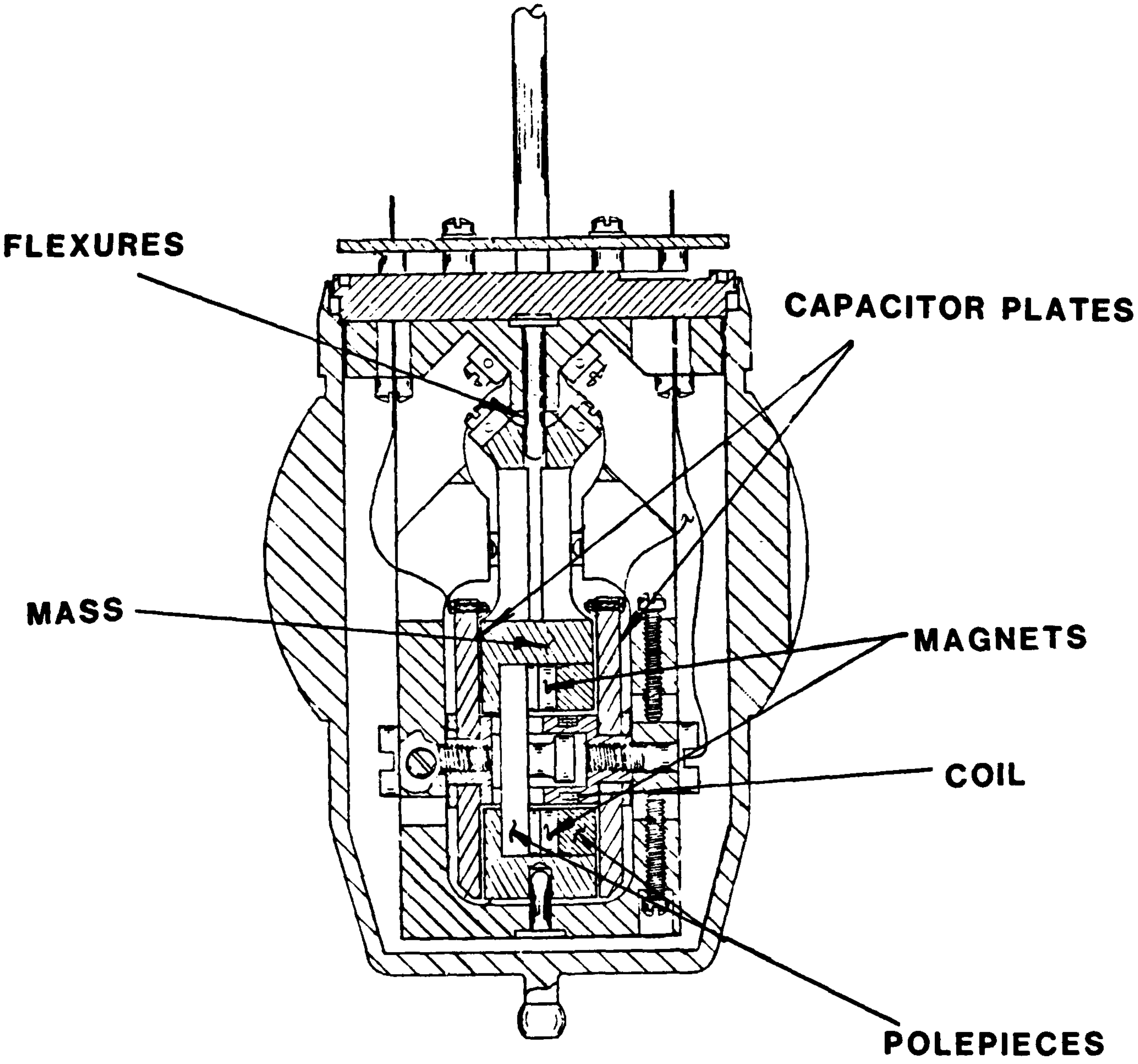
2.2.1 SYSTEM 1 (ENGINEERING MODEL)

- REGULATED POWER SUPPLY
- 3 SENSORS, LEVELERS, LOOP BOARDS
- CARRIER SOURCE
- COMMUNICATIONS MODEM
- 12 - CONDUCTOR ARMORED CABLE

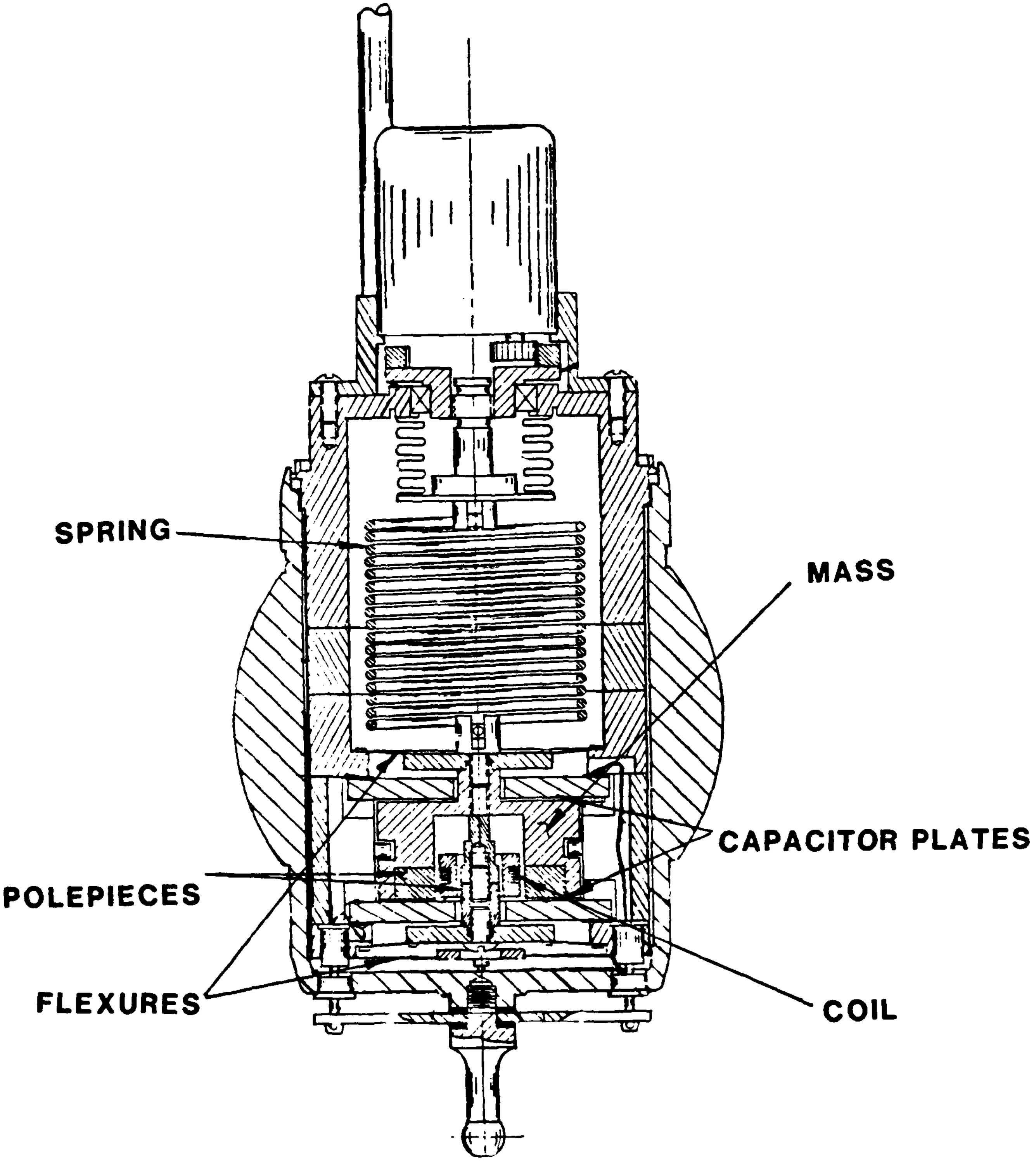
2.2.2 SYSTEM 2 (PROTOTYPE)

ALL OF THE ABOVE, WITH

- AUTOMATIC LEVELING DOWNHOLE
- CALIBRATOR DOWNHOLE

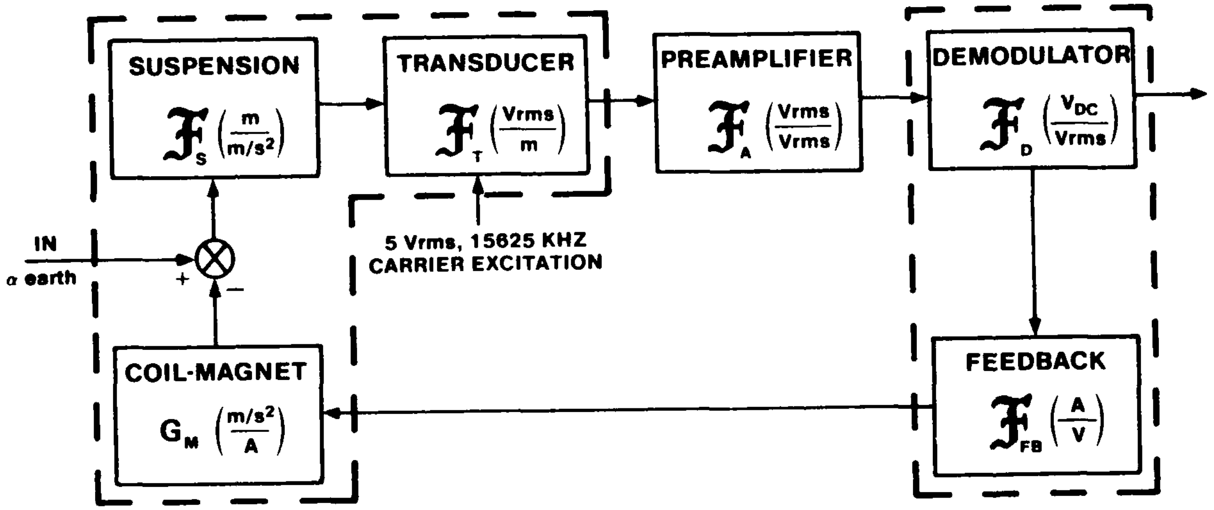


44000 HORIZONTAL MODULE CROSS-SECTION



44000 VERTICAL MODULE CROSS-SECTION

	MODULE	PREAMP LOOP BD	
HORIZONTAL:	990-55935-0101	990-56011-0101	990-56509-0101
VERTICAL:	990-55968-0101	990-56032-0101	



TYPICAL PARAMETERS:

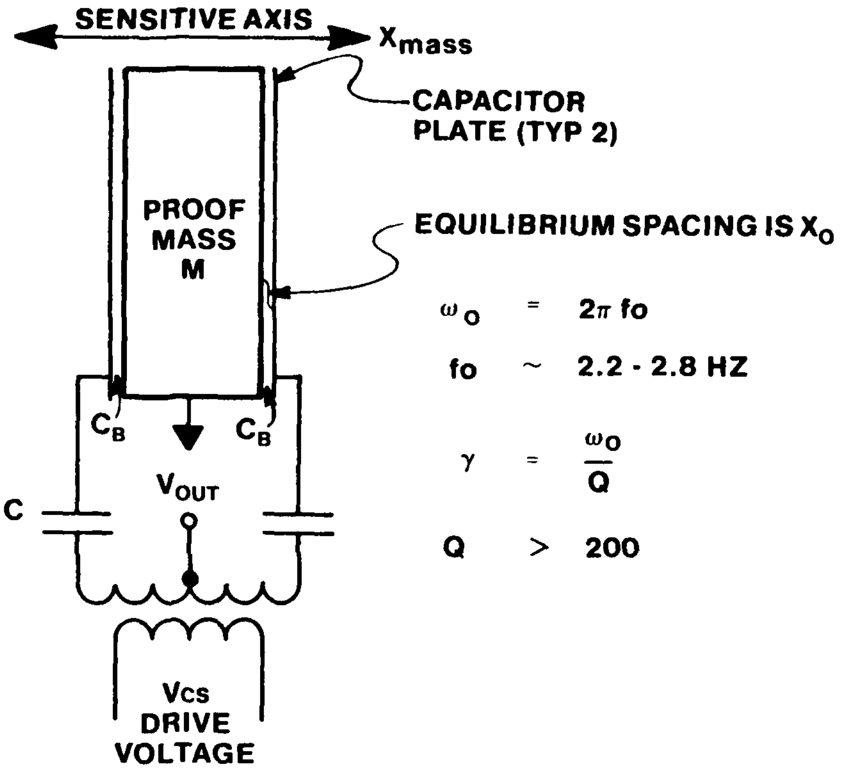
SUSPENSION:	fo	~	2.2 HZ, Q > 200
TRANSDUCER:	$\mathfrak{F}_T$	~	10^5 Vrms / meter
PREAMPLIFIER:	$\mathfrak{F}_A$	=	14.0 Vrms / Vrms
DEMODULATOR:	$\mathfrak{F}_D$	=	4 - 10 V_{DC} / Vrms
FEEDBACK: COIL-MAGNET:	G_M	=	7 - 12 m/s^2 / A

G 15777

MODULE TRANSFER FUNCTIONS

SUSPENSION PROVIDES RESTORING, FORCE, DAMPING

ELECTROMAGNETIC TRANSDUCER IS INTERNAL TO MASS, WITH MOTOR CONSTANT G_M



$\omega_O = 2\pi f_O$

$f_O \sim 2.2 - 2.8$ HZ

$\gamma = \frac{\omega_O}{Q}$

$Q > 200$

$$\mathfrak{F}_S = \frac{X_{mass}}{\alpha_{earth}} = \frac{1}{S^2 + \gamma S + \omega_O^2}\left(\frac{m}{m/s^2}\right)$$

$$\mathfrak{F}_T = \frac{V_{OUT}}{X_{mass}} = \frac{1}{1 + \frac{C_A^O}{C}} \times \frac{V_{CS}}{2X_O} \doteq \frac{V_{CS}}{2X_O}\left(\frac{V_{rms}}{m}\right)$$

$$G_M = G_M\left(\frac{m/s^2}{A}\right)$$

G 15774

PREAMPLIFIER:

PHYSICALLY ATTACHED TO MODULE, PROVIDES GAIN TO AMPLITUDE- MODULATED DATA

$$\mathfrak{F}_A = 14.0 \frac{\text{Vrms}}{\text{Vrms}}$$

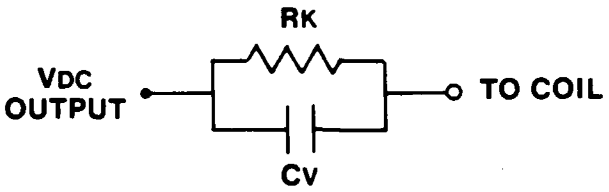
DEMODULATOR:

PART OF LOOP BOARD. RECTIFIES AM DATA TO GIVE "DC" OUTPUT. SELECTABLE

$$\mathfrak{F}_D = \mathfrak{F}_D \frac{V_{DC}}{\text{Vrms}}$$

FEEDBACK:

PART OF LOOP BOARD. PROVIDES ACTIVE DAMPING (via C_V) AND "SPRING" FORCE (via R_K).



$$\mathfrak{F}_{FB} = \frac{1}{R_K}(1 + S\, C_V R_K) \frac{\text{Amps}}{\text{Volt}}$$

ELECTRONIC TRANSFER FUNCTIONS

$$\mathfrak{F} = \frac{V_{OUT}}{\alpha\ \mathrm{earth}} = \frac{\mathfrak{F}_T\ \mathfrak{F}_A\ \mathfrak{F}_D}{\frac{1}{\mathfrak{F}_S} + \mathfrak{F}_T\ \mathfrak{F}_A\ \mathfrak{F}_D\ \mathfrak{F}_{FB}\ G_M}$$

$$\mathfrak{F} = \frac{\mathfrak{F}_F}{S^2 + S[\gamma + G_M\ C_V\ \mathfrak{F}_F] + [W_o^2 + \frac{G_M}{R_K}\mathfrak{F}_F]}$$

where $\mathfrak{F}_F = \mathfrak{F}_T\ \mathfrak{F}_A\ \mathfrak{F}_D$

DESIRED RESPONSE:

GAIN: IN $\frac{\mathrm{Volts}}{\mathrm{m/s^2}}$

CORNER FREQUENCY: $W_C = 2\pi fc$

DAMping: γ_C

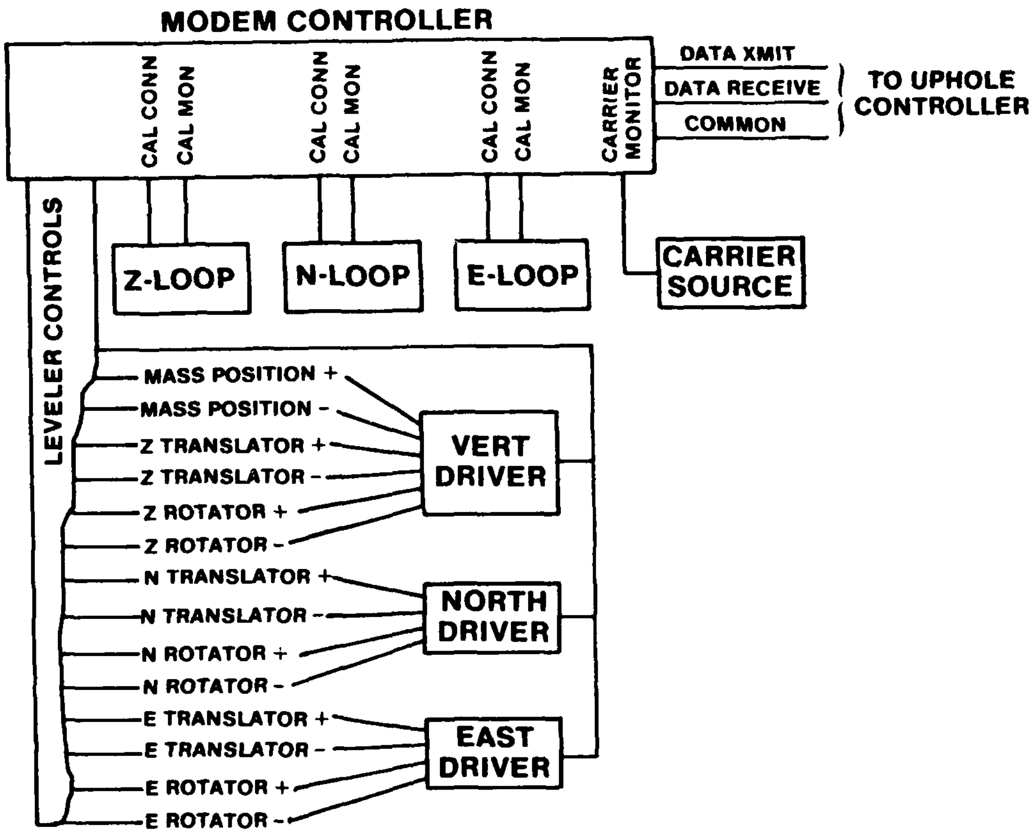
$$\mathrm{GAIN} = \frac{\mathfrak{F}_F}{W_C^2}$$

$$W_C^2 = W_0^2 + \frac{G_M}{R_K}\mathfrak{F}_F$$

$$\gamma_C = \gamma + G_M C_V \mathfrak{F}_F$$

LOOP RESPONSE

G 15770



DOWNHOLE CONTROL DETAIL

G 15776

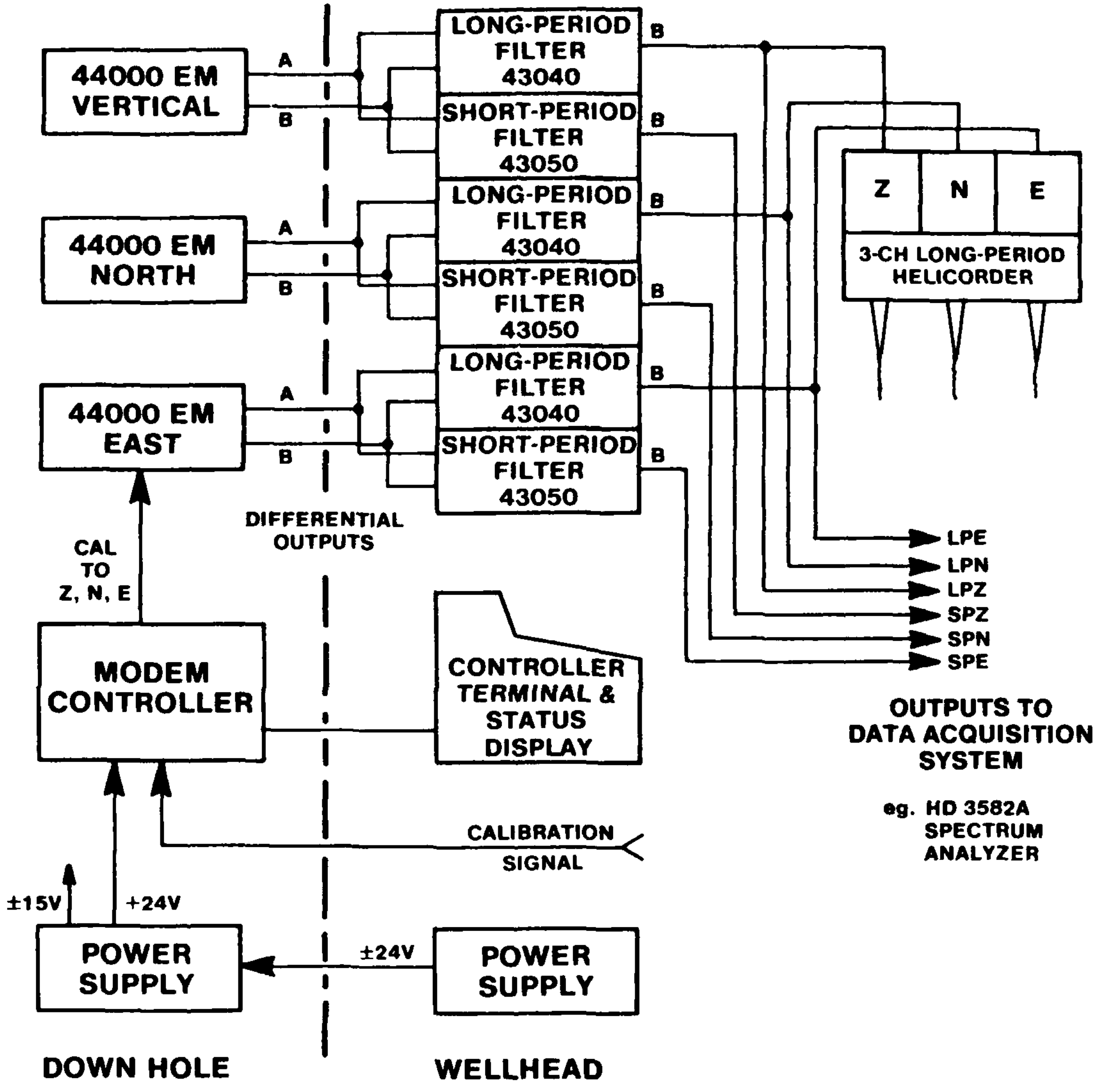
2.3 WELLHEAD AND COMMUNICATION

2.3.1 SYSTEM 1

- 3LP, SP FILTERS
- HELICORDER FOR LP (OPTIONAL)
- CALIBRATION SOURCE
- DATA ACQUISITION SYSTEM (OPTIONAL)
  (TYPE H/P 3582A)
- LEVELER CONTROLLER (CAN BE PORTABLE)
- POWER SUPPLY

2.3.2 SYSTEM 2

- 3 LP, SP FILTERS
- CONTROL AND DISPLAY ASSEMBLY, (CAN BE PORTABLE)
- POWER AND MONITOR ASSEMBLY



WELLHEAD FUNCTIONAL BLOCK DIAGRAM

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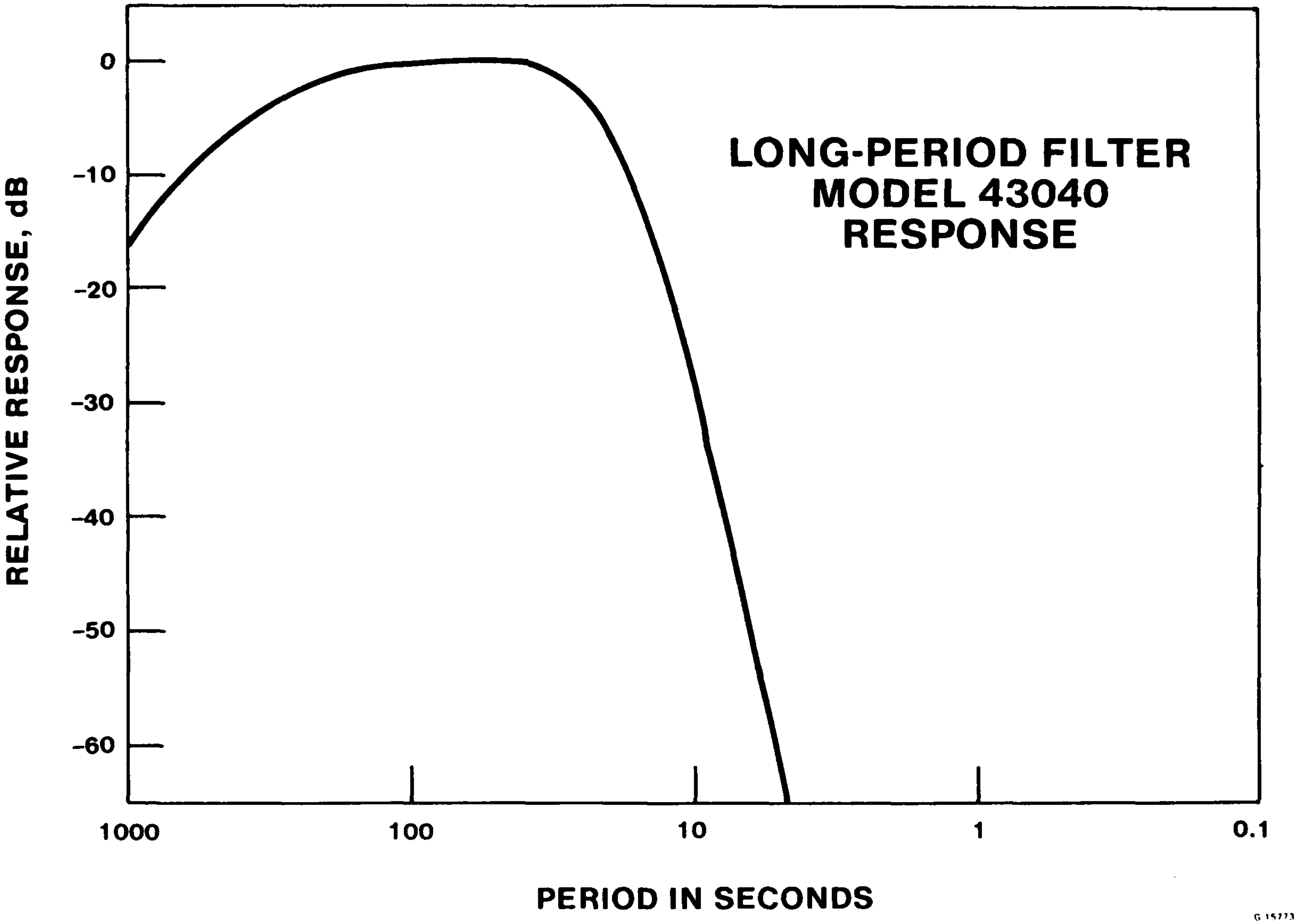


LONG-PERIOD FILTER
MODEL 43040
RESPONSE

2.3.3 COMMUNICATION

ADVANCES AND STANDARIZATION IN COMMUNICATION AND SUPPORT EQUIPMENT POINT TO A NEED TO MAKE THE 44000 BOREHOLE SEISMOMETER COMPATIBLE.

QUESTIONS:

- COMMUNICATIONS FORMAT (IF RS232, WHAT VERSION?)
- REMOTE TERMINAL CAPABILITY
- REMOTE FUNCTION NEEDED
    - CALIBRATION
    - LEVELING
    - STATUS

BASED UPON SUPPORT EQUIPMENT USED AND FUNCTIONS DESIRED, THE BOREHOLE SEISMOMETER AND WELLHEAD COMPONENTS CAN BE IDENTIFIED.

3.0 CRITICAL PERFORMANCE ITEMS

3.1 LINEARITY AND RESPONSE

3.1.1 LINEARITY

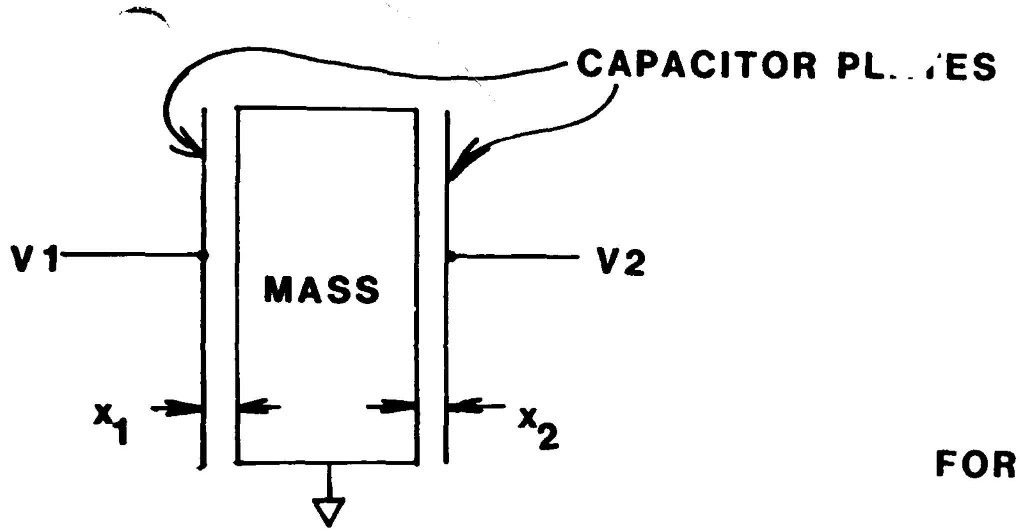
3.1.1.1 FEEDBACK TRANSDUCER

A COIL MAGNET (MOVING MAGNET) TRANSDUCER INTERNAL TO THE PROOF MAGS ACTING ALONG THE CENTER OF GRAVITY HAS BEEN ADDED. CRITICAL PERFORMANCE REQUIREMENTS ARE:

- IMPROVED LINEARITY OVER ELECTROSTATIC TRANSDUCER
- $G > .12$ N/A
- NO SPURIOUS MODE EXCITATION

3.1.1.2 MODULE TEST

DUE TO SMALL MASS MOTION AND SMALL SPACING OF MOVING PARTS, ALL MODULE TEST MUST BE DONE AFTER EVACUATED BAKEOUT.

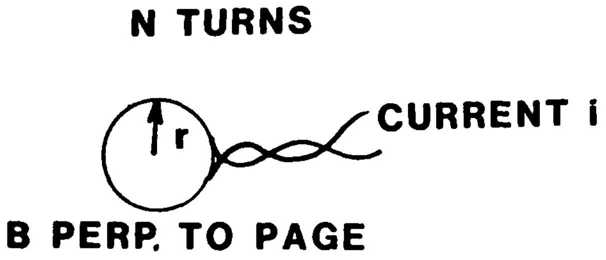


ENERGY STORED:

$$\phi = \frac{1}{2} C V_i^2 = \frac{1}{2} \frac{\epsilon_o A V_i^2}{x_i}$$

FOR CONSTANT VOLTAGE;

$$F_i = \left. \frac{\partial \phi}{\partial x_i} \right|_{V_i} = -\frac{1}{2} \epsilon_o A \frac{V_i^2}{x_i^2}$$



FOR A COIL IN A FIELD B:

$$F = ilB \qquad l = 2\pi r N$$

ELECTROSTATIC VS ELECTROMAGNETIC FORCE

3.2 MODULE SUSPENSION LOSSES

DAMPING LOSSES MUST BE MINIMIZED IN ORDER TO REDUCE MASS THERMAL MOTION NOISE.

THE FIGURE-OF-MERIT IN THIS CASE IS THE SUSPENSION "Q".

TO MEET SPECIFICATION OF ACCELERATION NOISE

$$2 \times 10^{-20} \ (M/S^2)^2 \ / \ HZ$$

$$Q > 100$$

IT IS BEST TO EXCEED THIS VALUE OF Q BY AS MUCH AS POSSIBLE SO CONTRIBUTION OF OTHER NOISE SOURCES DOES NOT EXCEED PERFORMANCE SPECIFICATION.

SUSPENSION WITH DAMPING FORCE:

$$F = -r\dot{x}$$

NOISE FORCE SPECTRUM:

$$F_n^2 = 4kTr = \frac{4kTM\omega_0}{Q}$$

ACCELERATION SPECTRUM:

$$a_n^2 = \frac{4KT\omega_0}{M\,Q}$$

44000 ESTIMATE :

$$a_n^2 = \frac{4\left(1.38\times10^{-23}\ \frac{\mathrm{Kg\,m^2}}{\mathrm{s^2\,{}^\circ K}}\right)(300^\circ\mathrm{K})(2\pi)(2.5\ \tfrac{1}{s})}{Q \times 0.2\,\mathrm{kg}}$$

$$= \frac{1.3\times10^{-18}}{Q}\ \frac{(m/s^2)^2}{Hz}$$

NOISE SPECIFICATION:

$$a_n^2 < 2\times10^{-20}\ \frac{(m/s^2)^2}{Hz} \qquad Q > 65$$

SUSPENSION DISSIPATION NOISE

4.0 DESIGN CRITERIA

4.1 ELECTROMAGNETIC FEEDBACK

4.1.1 LINEARITY

- ° INTRINSICALLY LINEAR TRANSDUCER

4.1.2 SPURIOUS MODES

- ° FORCE ACTS ALONG C. G.

4.1.3 GEOMETRY

- ° MUST FIT EXISTING MODULES
- ° RETROFIT OF OLD MODULES DESIRABLE

4.1.4 LOOP BOARD DESIGN

- • NO HIGH VOLTAGE NEEDED
- ° LOW-NOISE COMPONENTS

4.1.5 PREAMPLIFIER DESIGN

- • NO BIAS RESISTORS
- ° PARTS AVAILABILITY

4.2 COILFORM MATERIAL

4.2.1 EDDY CURRENT DAMPING

METALLIC OBJECTS MOVING IN A MAGNETIC FIELD FOLLOW LENZ'S LAW. CURRENTS PRODUCED OPPOSE MOTION AND CAUSE DAMPING.

4.2.2 OUTGASSING

PLASTICS OFTEN CONTAIN VOLATILE COMPONENTS THAT EVAPORATE SLOWLY UNDER VACUUM. GASEOUS PRODUCTS SO EVOLVED CAN CAUSE EXCESS VISCOUS DAMPING IN MODULE.

4.2.3 OUTGASSING TEST

4.2.3.1 PRESSURE VS. TIME

PER MAJOR CHENEY'S SUGGESTION, A KNOWN SURFACE AREA IN A KNOWN VOLUME IS BEING TESTED.

4.2.3.2 Q VS. TIME

MODULE Q IS MONITORED AS A FUNCTION OF TIME.

4.3 SUBASSEMBLY MODULARITY

4.3.1 TEST DESIRED

- DUAL HORIZONTAL
- DUAL VERTICAL

4.3.2 MAINTENANCE

- TROUBLESHOOTING
- REPAIR/REPLACEMENT

4.3.3 FLEXIBILITY

- CONFIGURATION CHANGE
- UPGRADE

4.3.4 FIELD TESTS

- FEW TOOLS NEEDED
- RAPID TURNAROUND

5.0 DATA

5.1 MODULES

5.1.1 RING - DOWN

WITH LOOP OPEN, MASS IS DISTURBED FROM EQUILIBRIUM AND POSITION MEASURED AS A FUNCTION OF TIME.

RESULTS:

NATURAL FREQUENCY - FO

SUSPENSION LOSSES - Q

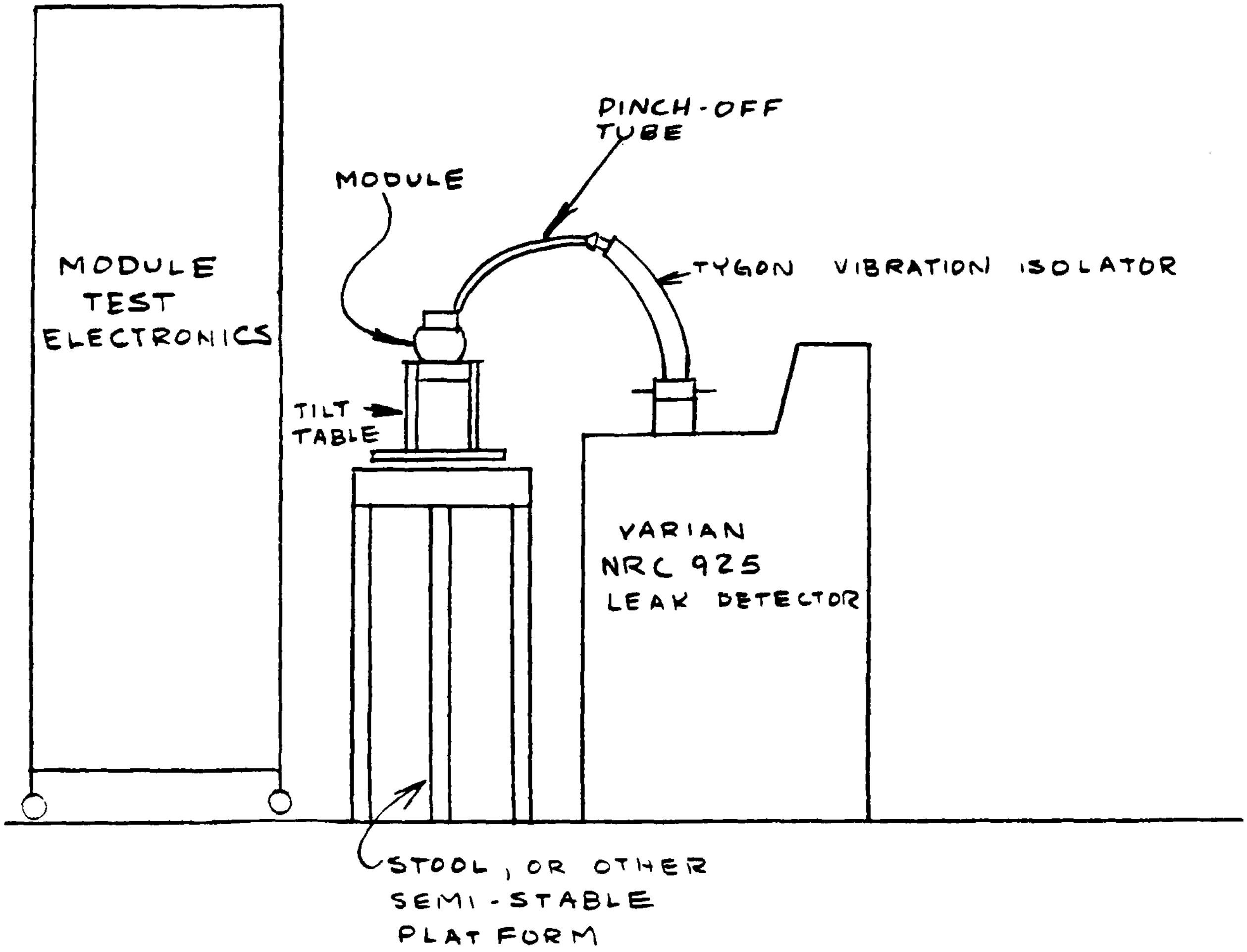
5.1.2 HORIZONTAL TILT

SEISMOMETER IS TILTED A KNOWN AMOUNT. COIL CURRENT TO RETURN MASS TO EQUILIBRIUM POSITION IS MEASURED.

RESULTS:

MOTOR CONSTANT - G_M

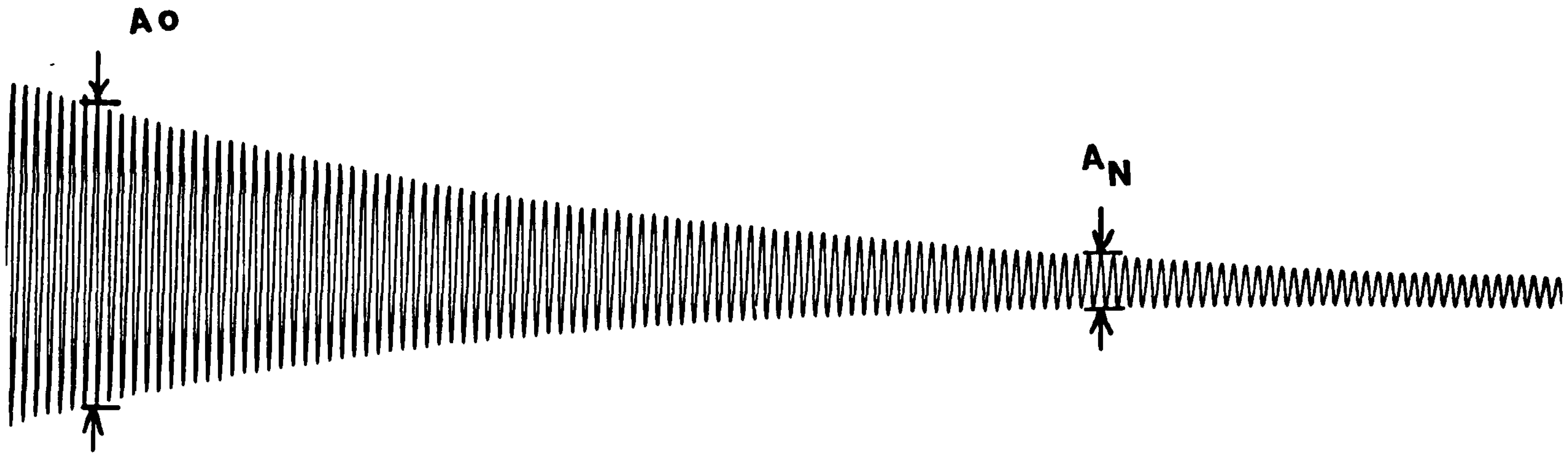
FIGURE 1: INTERIM TEST SETUP



TEST SETUP

1) ELECTRONICS AND SEIS MUST BE BROUGHT INTO APPLIED TECH LAB
2) NO QUANTITATIVE DATA WILL BE TAKEN, SO ANY SMALL TILT TABLE IS SUITABLE
3) SEAL MODULE IN CAN WITH O-RING AND EVACUATE MODULE TO < 5 TORR
4) MAKE SURE O-RING SEAL DOES NOT LEAK
5) LEVEL MODULE BY FLOATING MASS (OBSERVE PREAMPLIFIER OUTPUT)
6) ATTENUATE C.S. VOLTAGE SUFFICIENTLY TO OBSERVE RING DOWN IN THE NOISY ENVIRONMENT

SIZE A	CODE IDENT NO. 99019	DWG. NO. 990-	
SCALE		REV.	SHEET 4 of



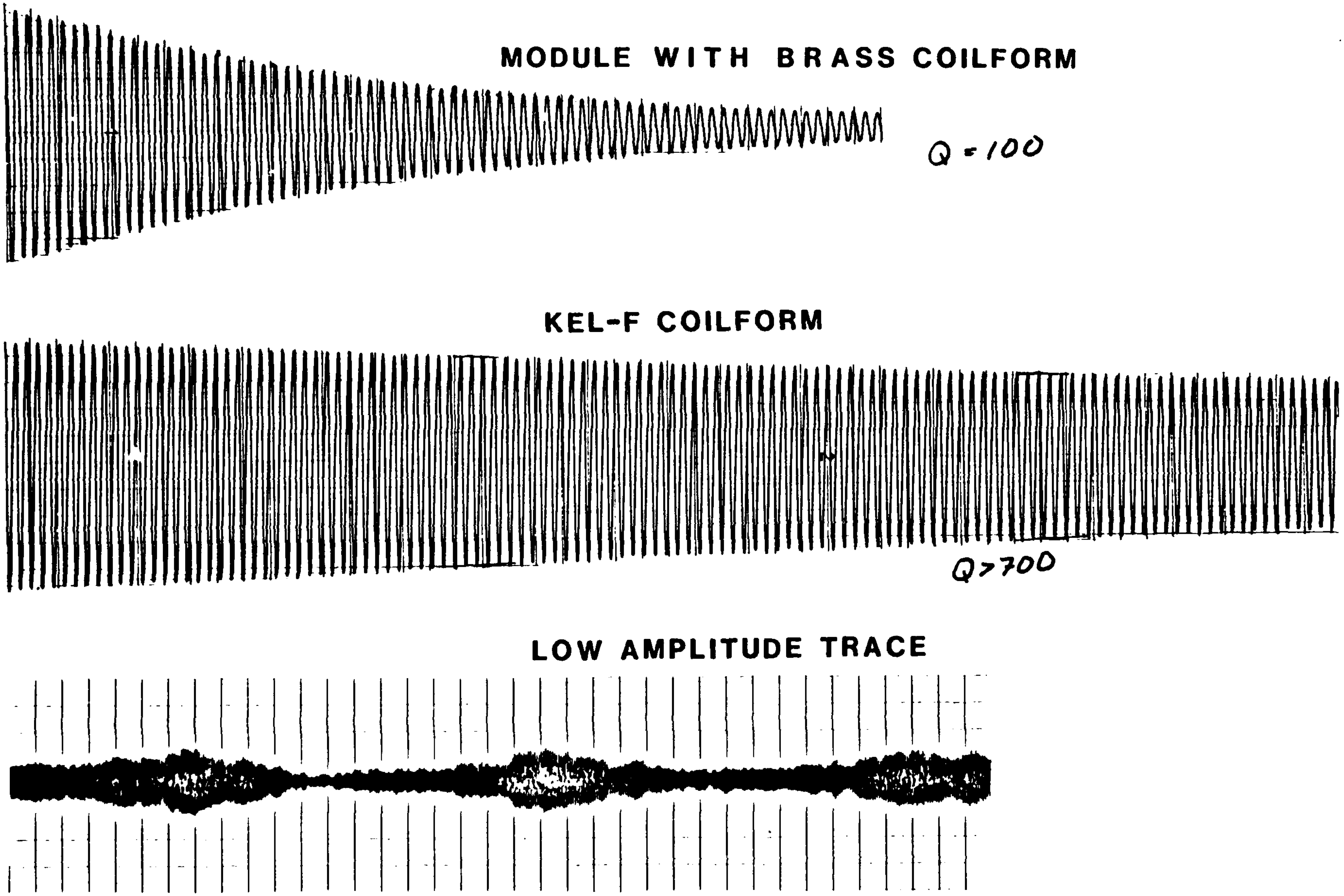
FOR SUSPENSION :

$$F_d = r\dot{x} \qquad r = \frac{2\pi M f_o}{Q}$$

Q CALCULATION ;

$$Q = \frac{N\pi}{\ln\left(\frac{A_o}{A_N}\right)}$$

RING-DOWN "Q" MEASUREMENT



MODULE WITH BRASS COILFORM

Q = 100

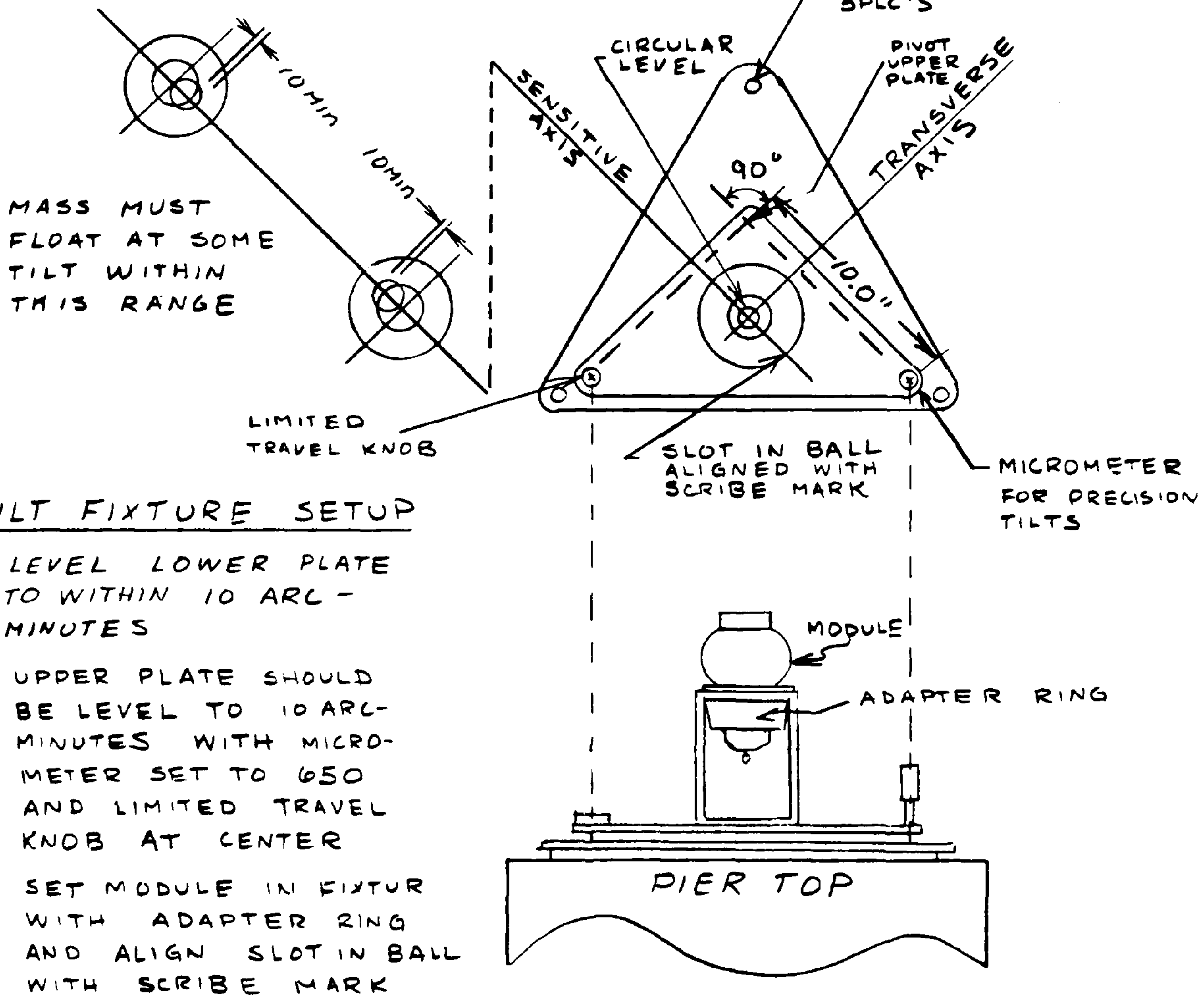
KEL-F COILFORM

Q > 700

LOW AMPLITUDE TRACE

RING-DOWN COMPARISON

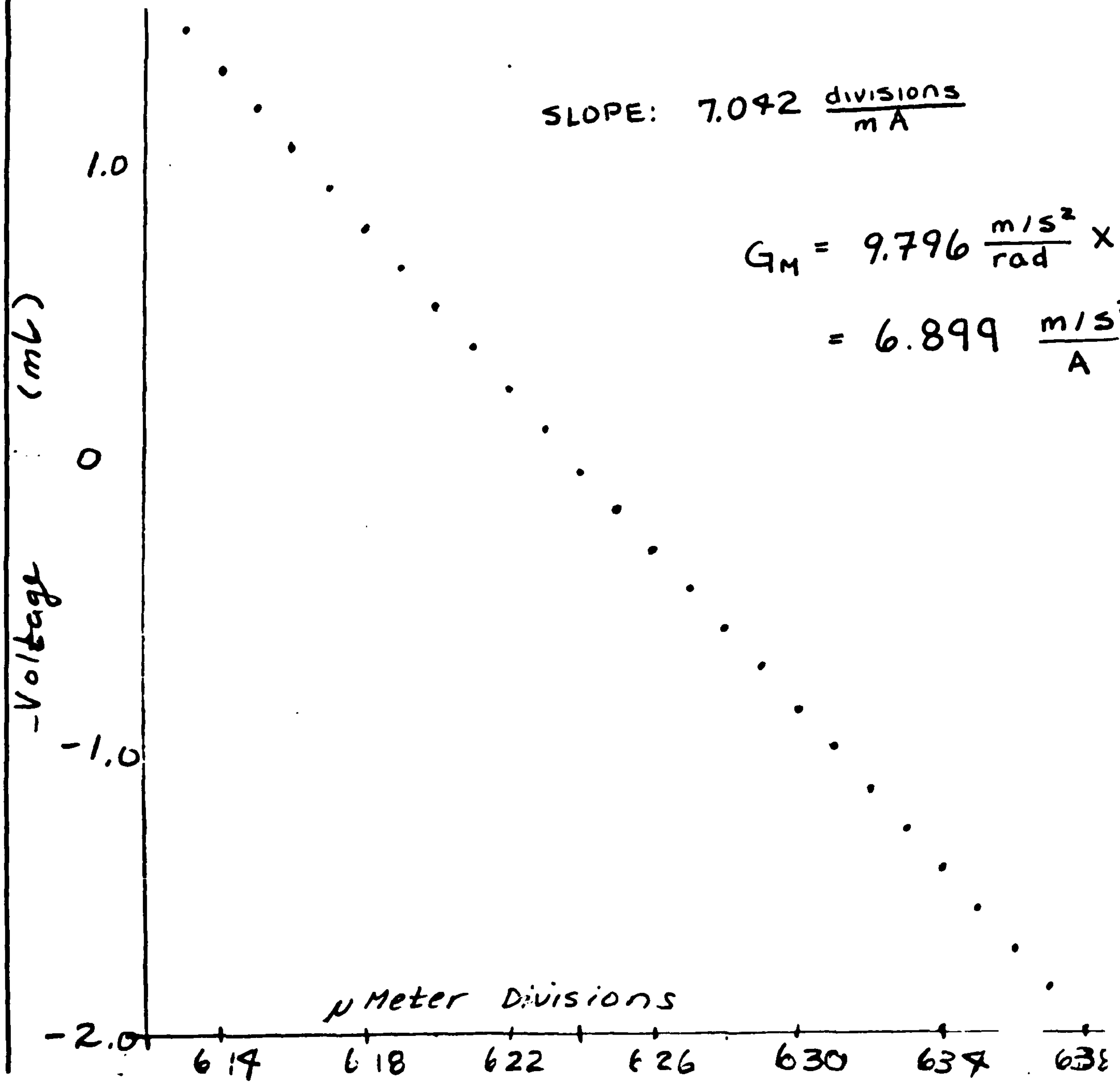
FIGURE 7: TILT FIXTURE FOR FINAL HORIZONTAL TESTS



TILT FIXTURE SETUP

1) LEVEL LOWER PLATE TO WITHIN 10 ARC-MINUTES
2) UPPER PLATE SHOULD BE LEVEL TO 10 ARC-MINUTES WITH MICROMETER SET TO 650 AND LIMITED TRAVEL KNOB AT CENTER
3) SET MODULE IN FIXTUR WITH ADAPTER RING AND ALIGN SLOT IN BALL WITH SCRIBE MARK USING ALIGNMENT TOOL

SIZE	CODE IDENT NO.	DWG. NO.	
A	99019	990-	
SCALE		REV.	SHEET



SLOPE: $7.042 \ \frac{\text{divisions}}{\text{mA}}$

$$G_M = 9.796 \ \frac{m/s^2}{rad} \times 10^{-4} \ \frac{rad}{div} \times \text{SLOPE} \ \frac{div}{A}$$

$$= 6.899 \ \frac{m/s^2}{A}$$

COIL CALIBRATION

5.1.3 DYNAMIC CHARACTERISTICS

WITH VARIOUS KNOWN CARRIER EXCITATION VOLTAGES, THE COIL IS DRIVEN BY AN EXTERNAL SINEWAVE SOURCE. THE FREQUENCY AT WHICH THE OUTPUT IS 90 DEGREES OUT OF PHASE WITH THE INPUT DRIVE IS DETERMINED.

RESULT:

TRANSDUCER SENSITIVITY - F_T

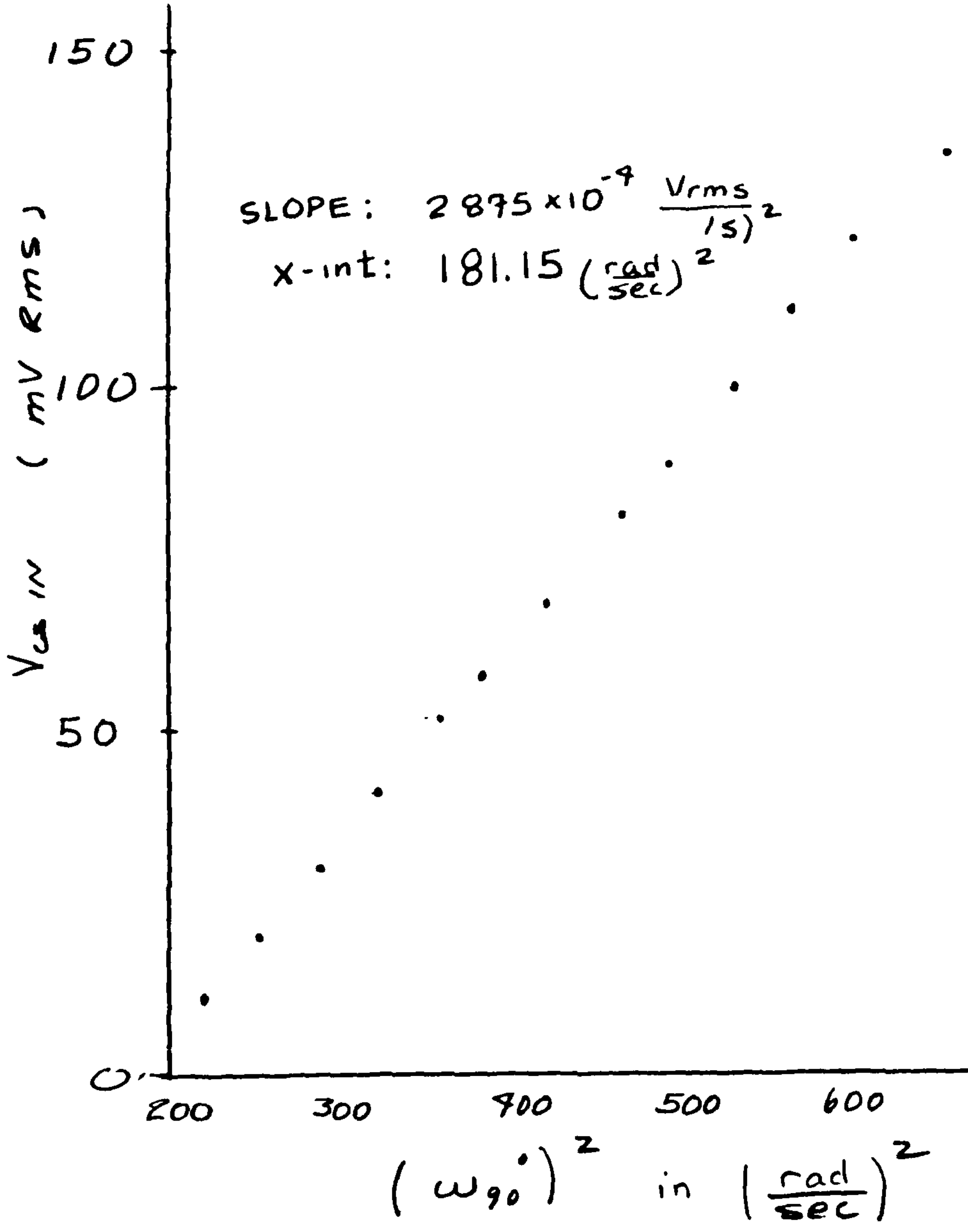
5.1.4 VERTICAL TRANSLATION

THE MASS IS MOVED A PRECISE AMOUNT VIA THE MASS POSITION MOTOR. BOTH THE TRANSDUCER OUTPUT AND THE CURRENT NECESSARY TO NULL THAT OUTPUT ARE MEASURED.

RESULT:

TRANSDUCER SENSITIVITY - F_T

MOTOR CONSTANT - G_M



SLOPE: $2875 \times 10^{-4} \frac{V_{rms}}{/s)^2}$

x-int: $181.15 \left(\frac{rad}{sec}\right)^2$

$$\omega_{90°}^2 = \omega_0^2 + \frac{\mathcal{F}_D K_{susp} G_M}{R_K} V_{csin}$$

$$K_{susp} = \frac{R_K - \frac{V}{A}}{\left(G_M \frac{m/s^2}{A}\right) \cdot \left(\mathcal{F}_D \frac{V}{V_{rms}}\right) \cdot \left(SLOPE \frac{V_{rms}}{(rad/s)}\right)}$$

$$= 1.24 \times 10^5 \ V/m$$

$$f_0 = \sqrt{\frac{x\text{-int}}{2\pi}} = 2.14 \ Hz$$

FROM RING-DOWN

$f_0 = 2.15$ Hz

0.5 % DIFFERENCE

DYNAMIC TRANSDUCER CALIBRATION

5.1.5 SPRING MODE TEST

THE FIRST AND SECOND OVERTONE FREQUENCIES FOR THE VERTICAL SPRING ARE MEASURED.

RESULTS:

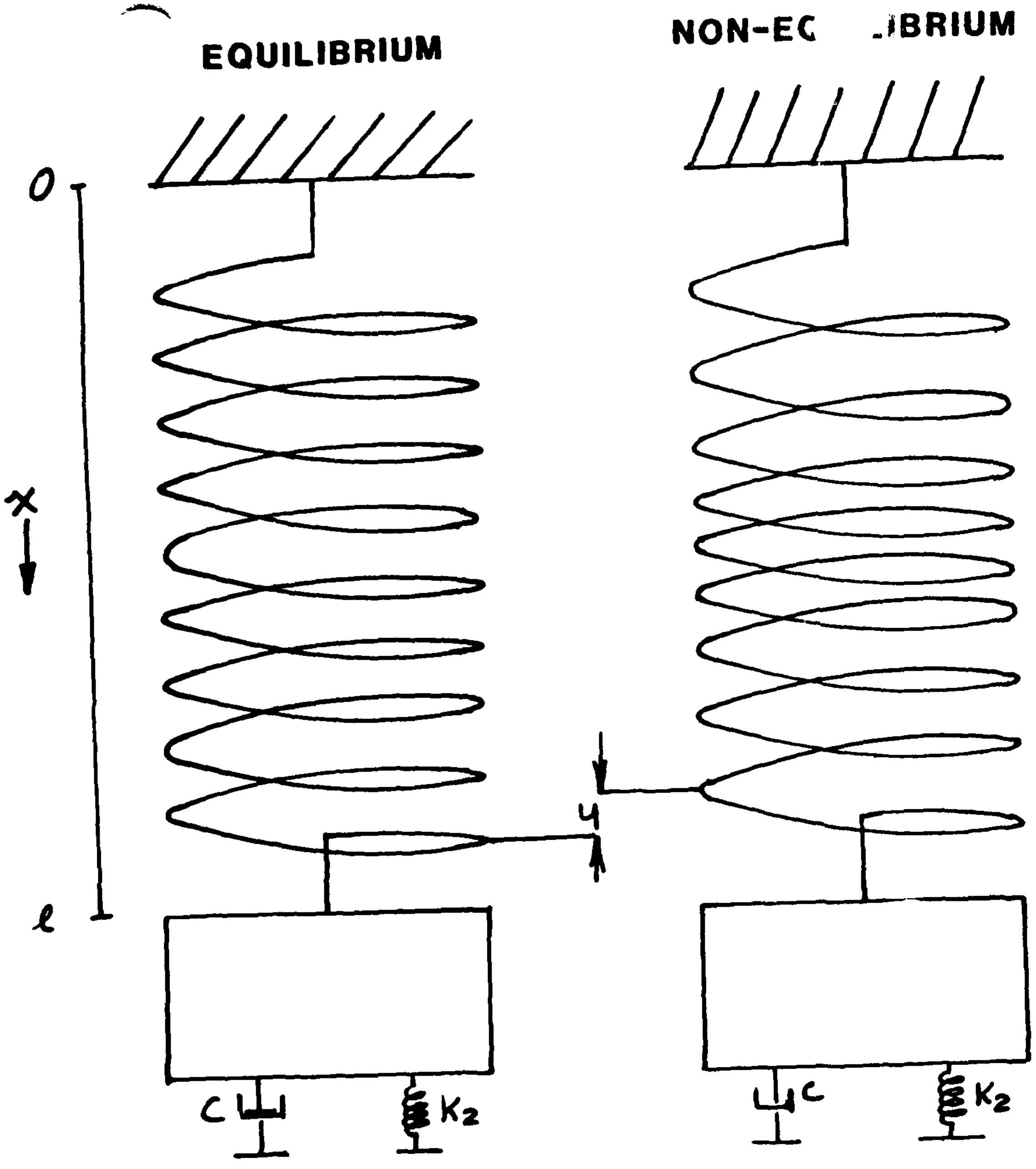
SPRING CONSTANT: K

THIS MEASUREMENT IS NEEDED FOR TWO REASONS:

1. THE SPRING ACTS AS A MEDIUM FOR WAVE PROPAGATION DUE TO ITS FINITE MASS. THIS CONTRIBUTES TO THE NATURAL (FUNDAMENTAL) FREQUENCY. THEREFORE,

$$W_o^2 \neq \frac{K}{M}$$

2. FLEXURES IN THE SUSPENSION CONTRIBUTE TO THE OVERALL RESTORING FORCE SIGNIFICANTLY.



WAVE EQUATION:

$$\frac{\partial^2 y}{\partial t^2} = \frac{K\ell^2}{M_s}\frac{\partial^2 y}{\partial x^2}$$

BOUNDARY CONDITIONS:

$$y(0,t) = 0$$

$$M\frac{\partial^2 y}{\partial t^2} = -K\ell\frac{\partial y}{\partial x} - C\frac{\partial y}{\partial t} - K_2 y + F_{ext}\Big|_{\ell,}$$

SOLUTIONS:

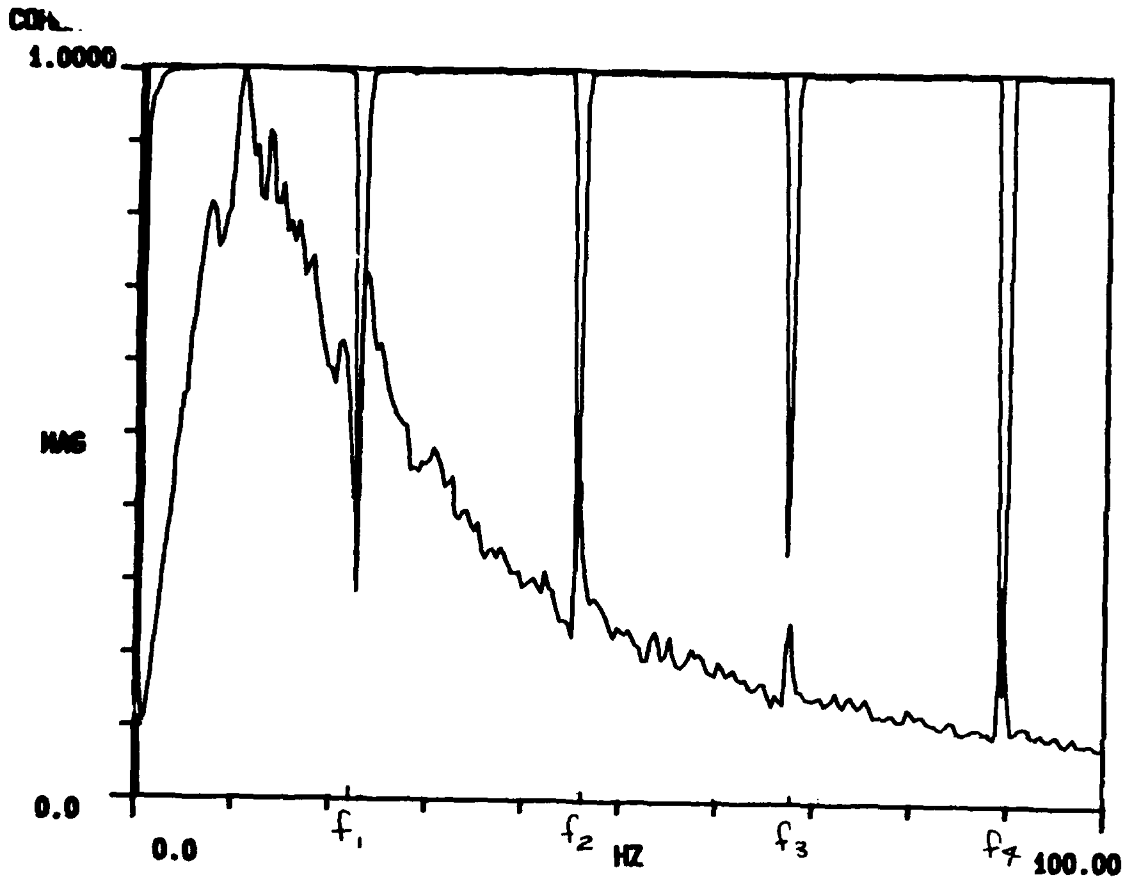
$$F_{ext} = F_o e^{-i\omega t}$$

$$y = Y_o \sin\frac{\omega}{c}x\, e^{-i\omega t}$$

$$c = \sqrt{\frac{K\ell^2}{M_s}}$$

$$Y_o = \frac{F_o}{\left[K_2 + i\omega C - M\omega^2\right]\sin\frac{\omega\ell}{c} + \frac{K\ell\omega}{c}\cos\frac{\omega}{c}}$$

SPRING MODE THEORY



$$f_1 = .5037\sqrt{\frac{K}{M_s}}$$

$$f_2 = 1.002\sqrt{\frac{K}{M_s}}$$

$$f_N = \frac{N}{2}\sqrt{\frac{K}{M_s}}$$

EIGENFREQUENCIES

EIGENFREQUENCY EQUATION:

$$\left[K_2 - M\omega^2\right] \sin \frac{\omega}{c} l = -\frac{K\omega l}{c} \cos \frac{\omega}{c} l$$

HIGHER ORDER SPRING MODES

5.2 BENCH TESTS

5.2.1 CONTINUITY

5.2.2 POWER SUPPLY

5.2.3 CONTROL FUNCTIONS

- LEVELER MOTORS, POLARITIES
- CALIBRATION CONNECT
- SIGNAL PATHS

5.2.4 LOOP BOARDS

- DEMODULATION PHASE
- FORWARD GAIN SETUP
- FEEDBACK COMPONENT SELECTION

5.2.5 SYSTEM TEST

- LEVELING
- CALIBRATION
- COHERENCE

5.3 BOREHOLE TESTS

5.3.1 INSTALLATION AND LEVELING

- DUAL HORIZONTAL CONFIGURATION
- LONG TERM STABILITY OF LEVEL
- MAGNETIC INTERACTION OF MOTORS AND FEEDBACK TRANSDUCER

5.3.2 CALIBRATION

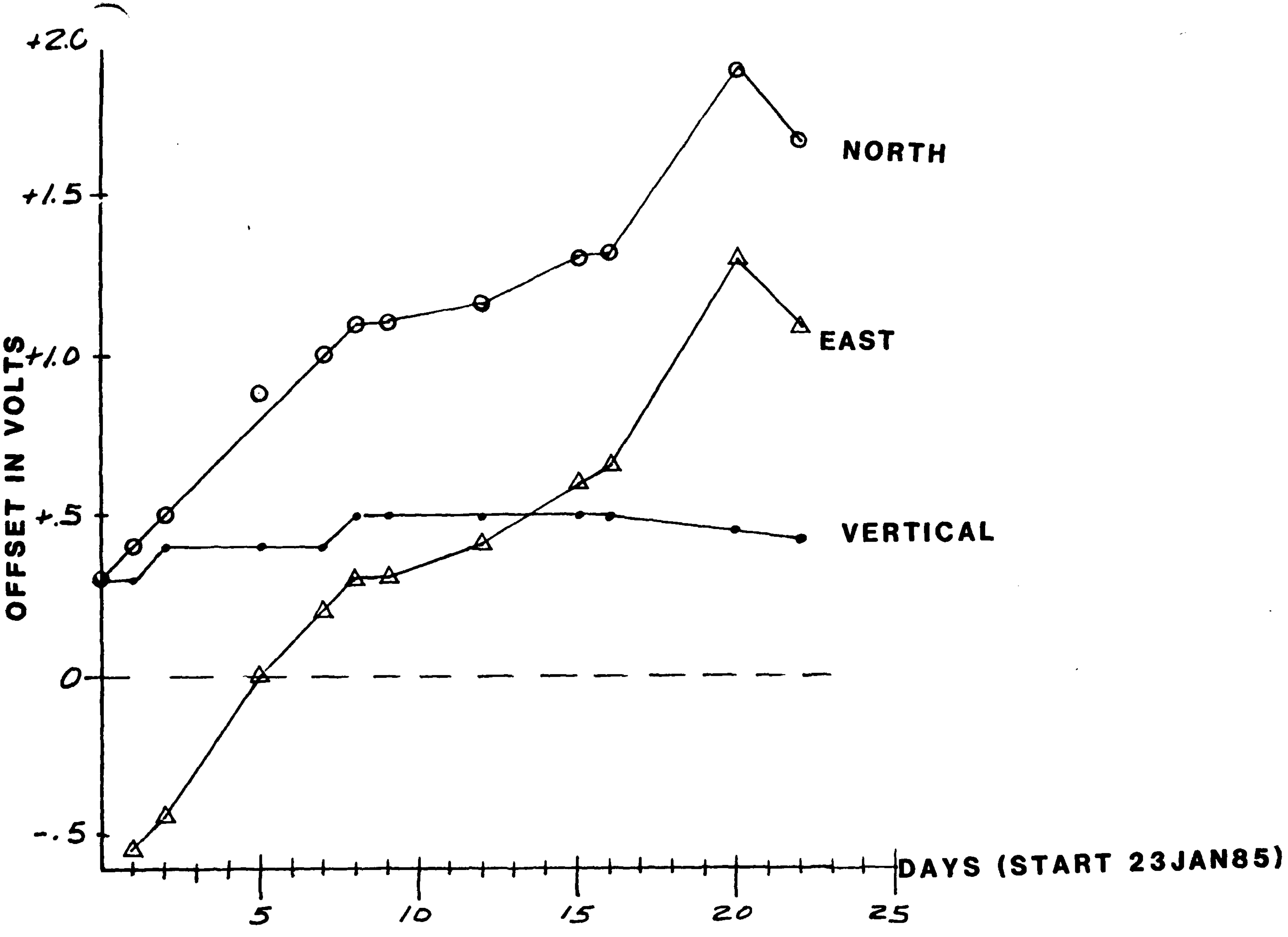
- VERIFY DESIRED, PREDICTABLE RESPONSE

5.3.3 LINEARITY

- TWO FREQUENCY DRIVE
- MEASURE DIFFERENCE FREQUENCY OUTPUT

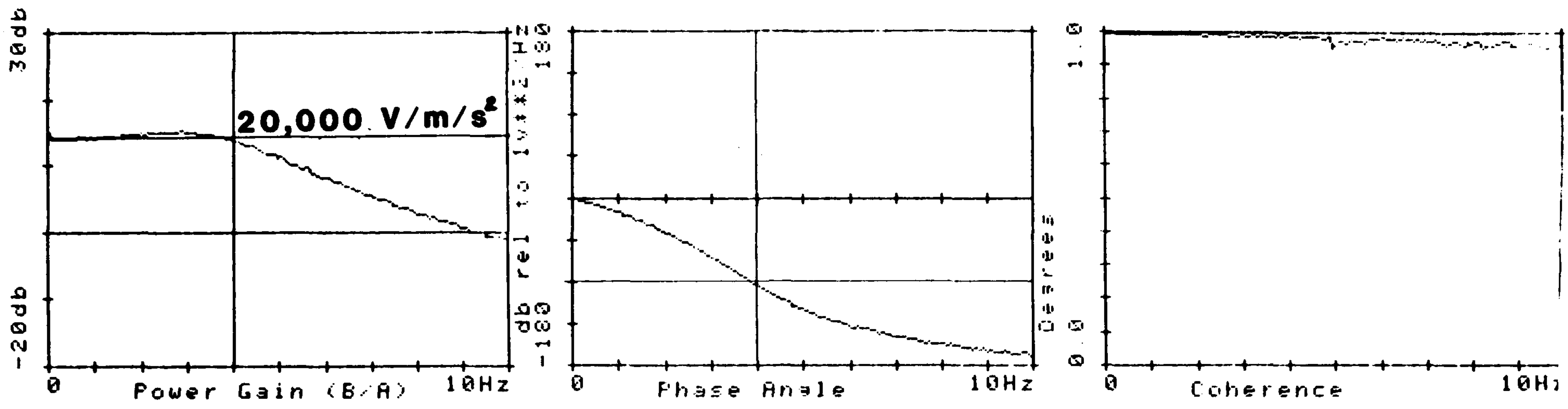
5.3.4 DUAL SENSOR TESTS

- SHORT PERIOD
- LONG PERIOD
- BROAD BAND
- MID PERIOD
- TIME RECORDS



OFFSET vs. TIME

VERTICAL MODULE

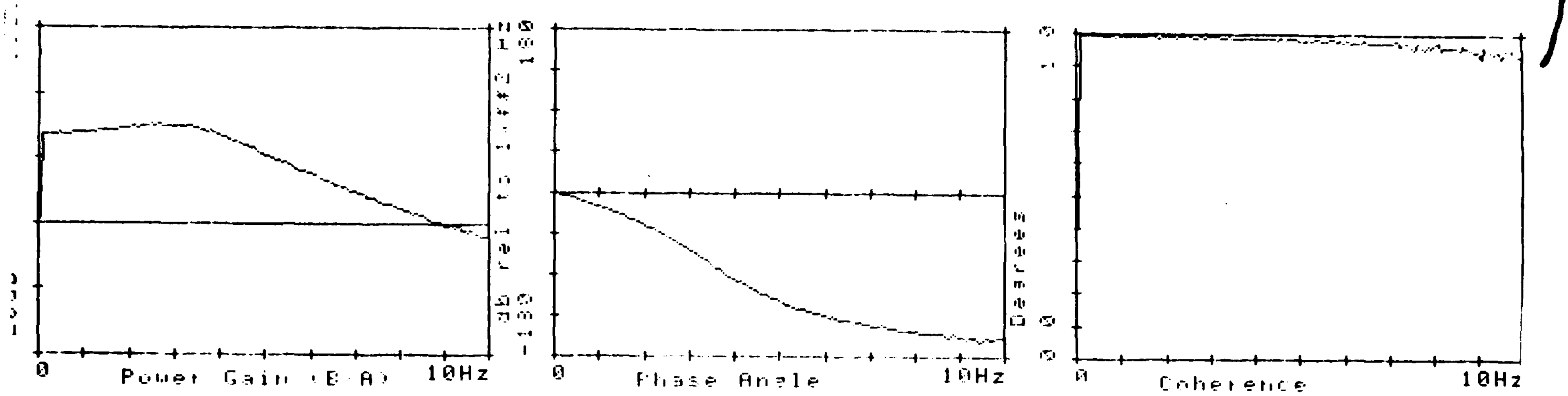


CAL CONSTANT:

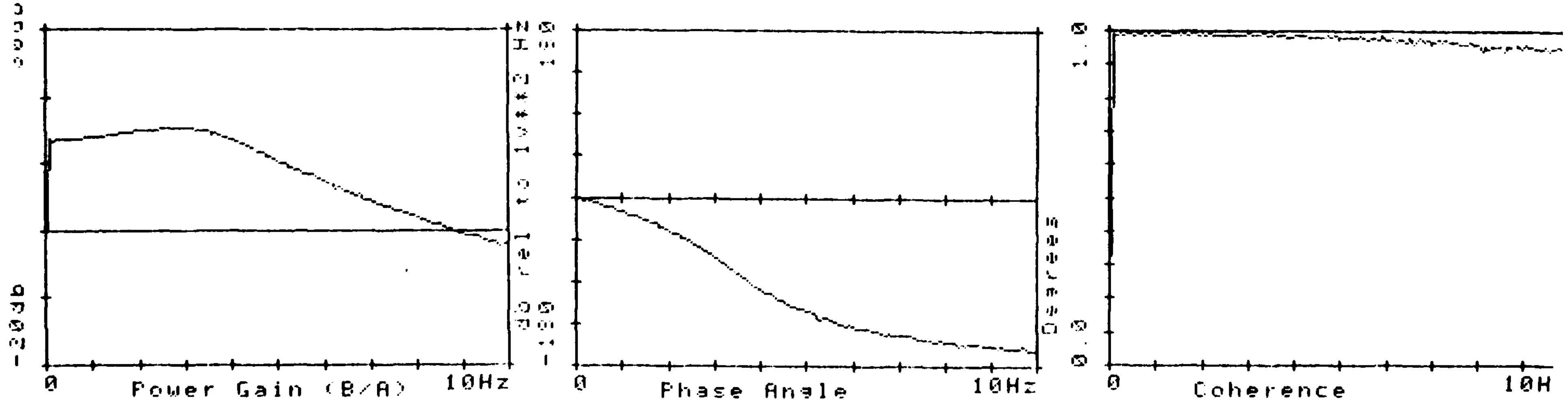
$$5.0 \times 10^{-4} \frac{m/s^2}{V} = \frac{G_M}{R_{CAL}}$$

CALIBRATION EXAMPLE

NORT..



EAST



HORIZONTAL CALIBRATION

FOR A SYSTEM WITH GAIN A:

$$V_{OUT} = A\left(x + \alpha x^2\right) \qquad x = \frac{S_{INPUT}}{S_{MAX}}$$

DIFFERENCE FREQUENCY TEST:

$$x = a\left(\sin\omega_1 t + \sin\omega_2 t\right)$$

$$x^2 = a^2\left[1 - \frac{1}{2}\cos 2\omega_1 t - \frac{1}{2}\cos 2\omega\, t + \cos(\omega_1 - \omega_2)t - \cos(\omega_1 + \omega_2)t\right]$$

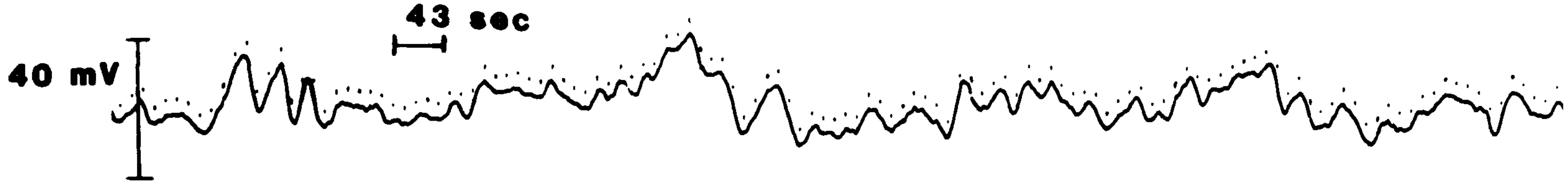
MEASURE RATIO OF INPUT TO DIFFERENCE:

$$R = \frac{a}{\alpha a^2} = \frac{1}{\alpha a}$$

NONLINEARITY:

$$\alpha = \frac{1}{Ra}$$

NONLINEARITY DEFINITIONS



LP FILTER GAIN 160 at 0.024 Hz

DRIVE VOLTAGE: 0.2V P-P (0.952 and 0.977 Hz)

$$a_{in} = .2V_{P-P} \times 5\times10^{-4}\frac{m/s^2}{V} = 1\times10^{-4}\ m/s^2\ P\text{-}P$$

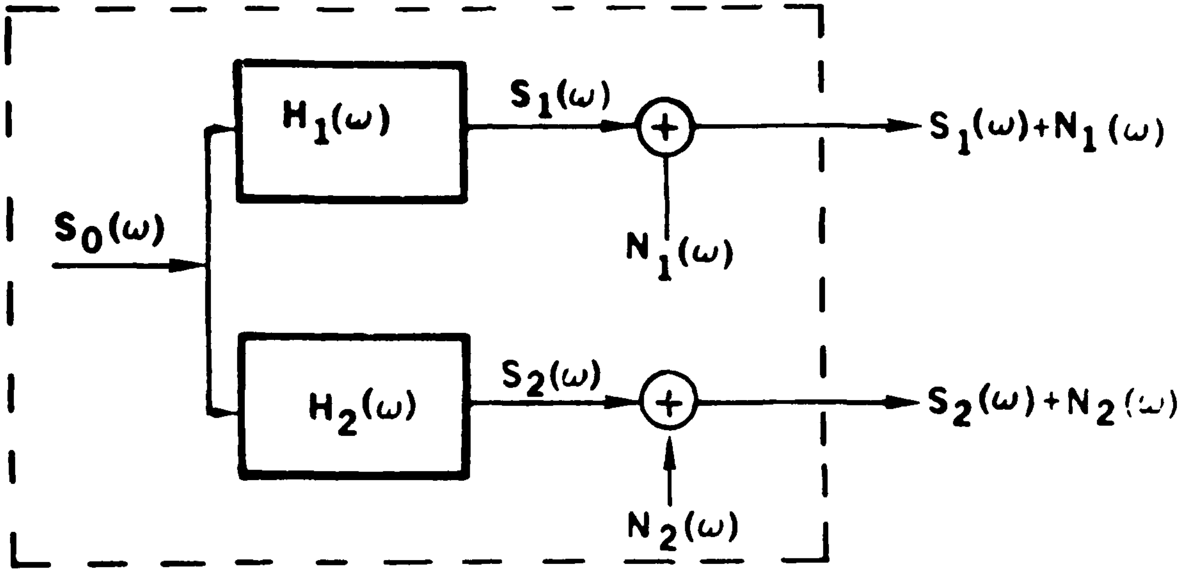
OUTPUT VOLTAGE: 10 mV P-P (0.024 Hz)

$$a_{OUT} = .01\ V_{P-P} \times \frac{1\ m/s^2}{20{,}000\ V} \times \frac{1}{160} = 3.1\times10^{-9}\ m/s^2\ P\text{-}P$$

NONLINEARITY:

$$\alpha < 10 \times \frac{3\times10^{-9}}{1\times10^{-4}} = 3\times10^{-4}$$

NONLINEARITY CALCULATION (EAST CHANNEL)



ASSUME:

(1) $H_1(\omega) \approx H_2(\omega)$

(2) $N_1(\omega) \approx N_2(\omega)$; $S_1(\omega) \approx S_2(\omega)$

(3) HIGH COHERENCE

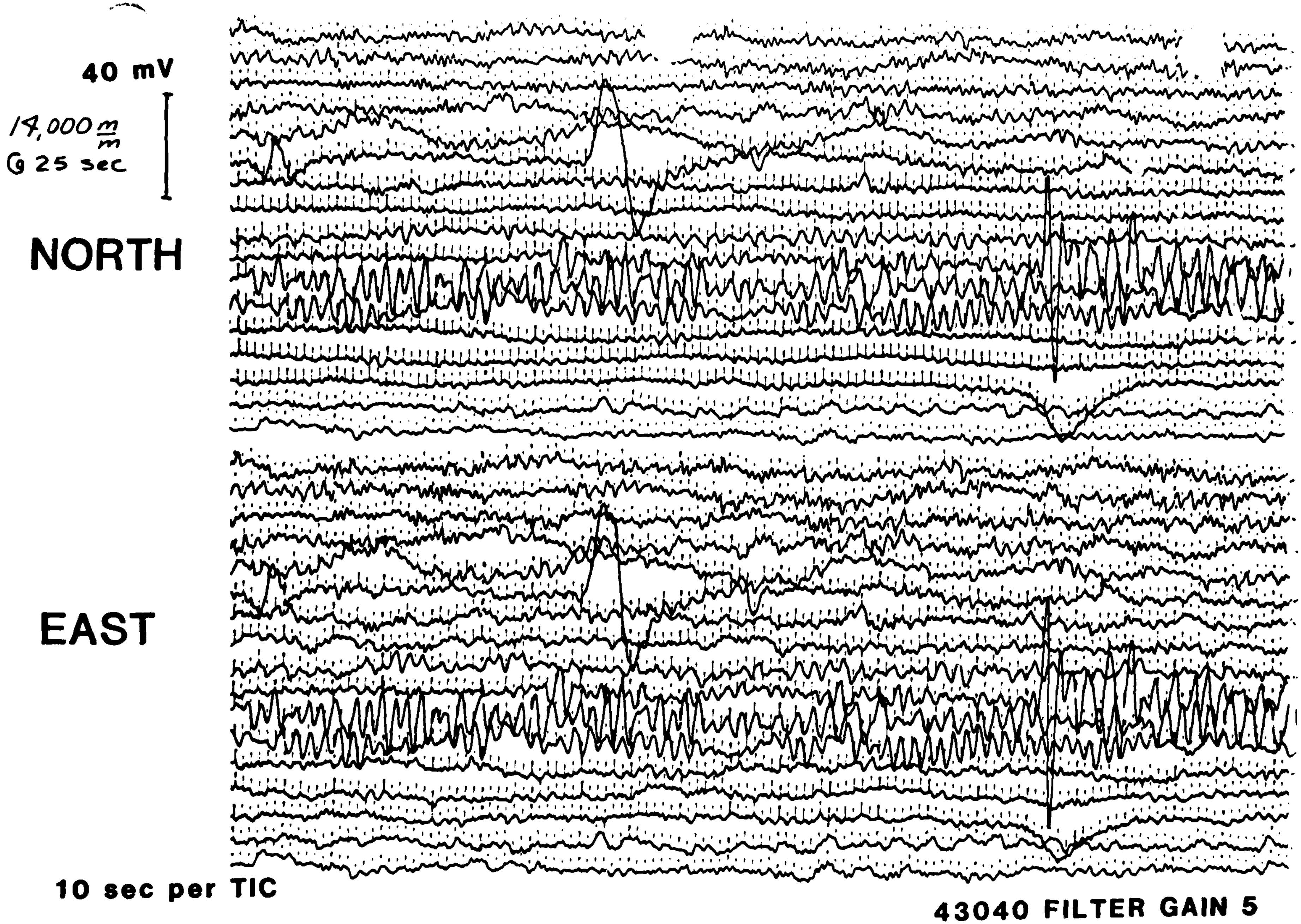
THEN:

$$|C(\omega)|^2 \approx \frac{[S_1(\omega) \cdot S_2(\omega)]}{[S_1(\omega)+N_1(\omega)] \cdot [S_2(\omega)+N_2(\omega)]}$$

$$|C(\omega)| \approx \frac{S_n(\omega)}{[S_n(\omega)+N_n(\omega)]}$$

$$N_n(\omega) \approx [1-|C(\omega)|] \cdot [S_n(\omega)+N_n(\omega)]$$

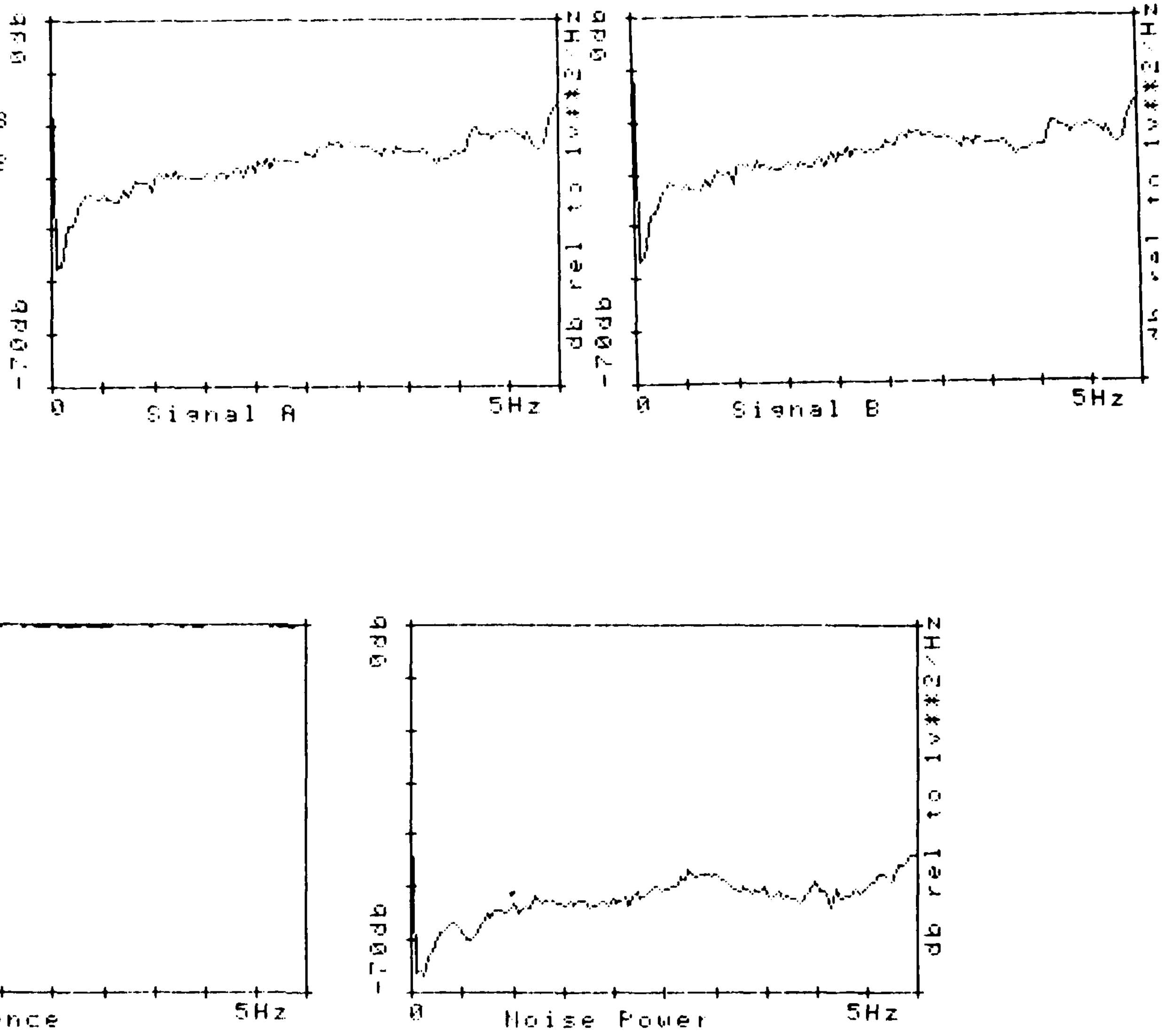
DUAL ALIGNED SENSOR ANALYSES



TYPICAL TIME TRACE (LP CHANNEL)

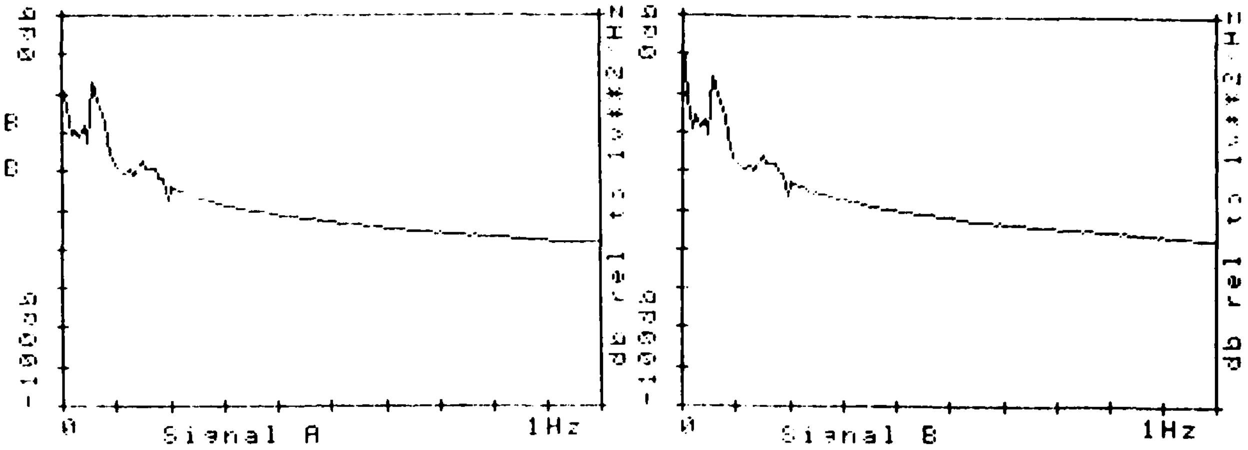
```
Date        25JAN85
Time        12:30
Experiment DUAL HORIZ SP TEST

A Chan.    NORTH
  Sensitivity= 0db       DC CALIB
B Chan.    EAST
  Sensitivity= 0db       DC CALIB

Weighting function= UNIFORM **
Average= RMS
Number=  64
Input mode= BOTH CHANNELS
  ** Screen values on 3582A
  are correct for UNIFORM only
```

43050 FILTER GAIN 50

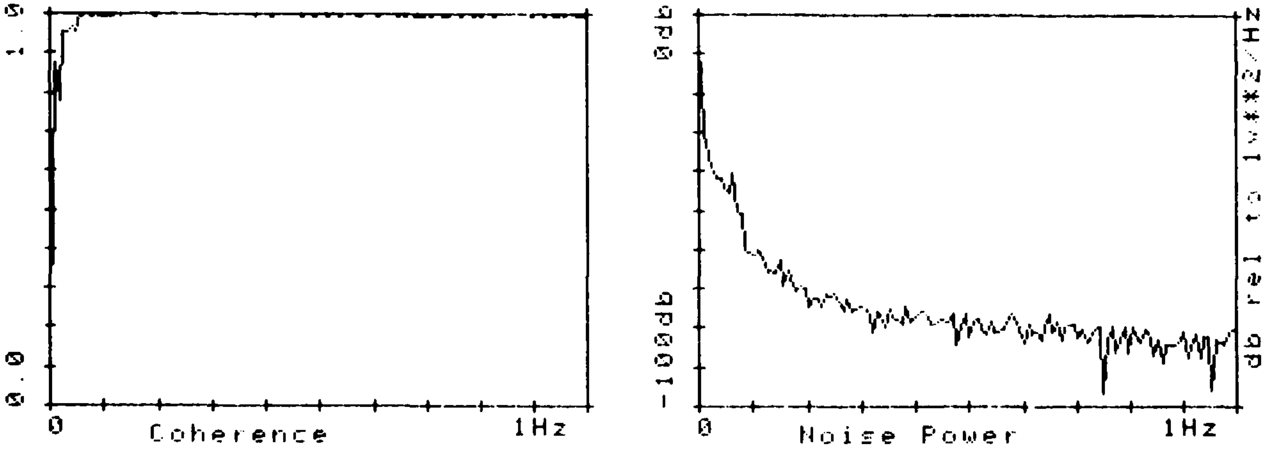


DUAL HORIZONTAL SP TEST

```
Date        13FEB85
Time        1:00
Experiment DUAL LP HORIZ

A Chan.    NORTH THRU 43040
   Sensitivity= -20db    DC CALIB
B Chan.    EAST THRU 43040
   Sensitivity= -20db , DC CALIB

Weighting function= UNIFORM **
Average= RMS
Number=  4
Input mode= BOTH CHANNELS
  ** Screen values on 3582A
   are correct for UNIFORM only
```

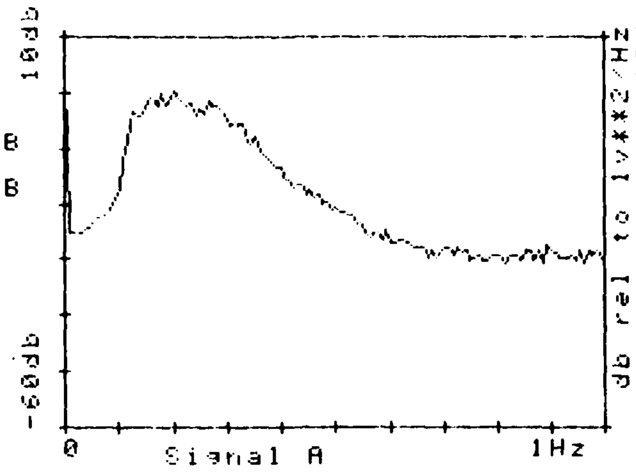


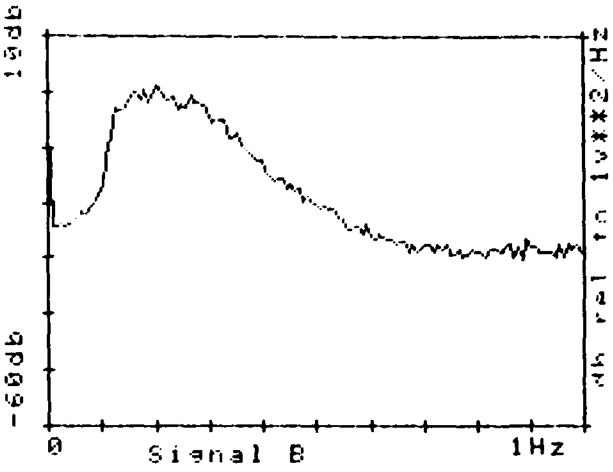
43040 FILTER GAIN 50



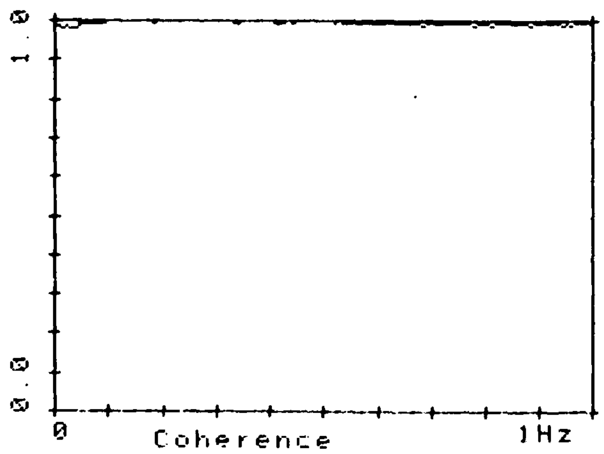
HORIZONTAL LP TEST

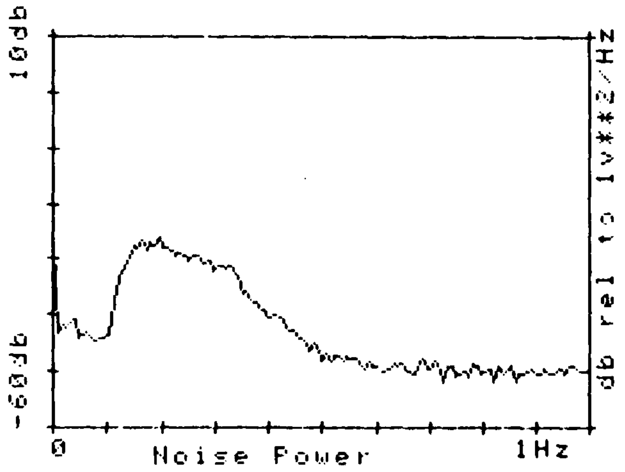
```
Date        7FEB85
Time        4:00
Experiment DUAL HORIZ

A Chan.    NORTH THRU BSC
  Sensitivity= 10db     DC CALIB
B Chan.    EAST THRU BSC
  Sensitivity= 10db     DC CALIB

Weighting function= UNIFORM **
Average= RMS
Number=  32
Input mode= BOTH CHANNELS
  ** Screen values on 3582A
  are correct for UNIFORM only.
```





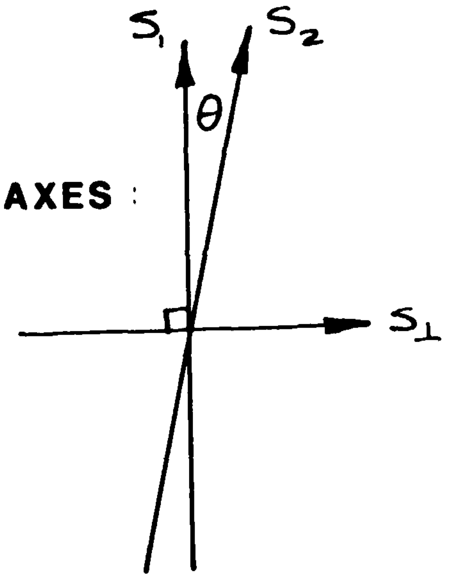
BSC HAS 100 GAIN WITH 0.15Hz LOW-PASS





DUAL HORIZONTAL TEST THRU BSC

SENSITIVE AXES :



SENSOR 2 OUTPUT:

$$S_2 = S_1 \cos\theta + S_\perp \sin\theta$$

FOR SMALL ANGLES

$$\theta \ll 1 \qquad \cos\theta \approx 1 \, , \ \sin\theta \approx \theta$$

ASSUME:

$$|\, S_1(\omega) \,| \approx |\, S_\perp(\omega) \,|$$

SENSOR 2 OUTPUT SIMPLIFIES TO:

$$S_2 = S_1 + S_\perp \cdot \theta$$

APPARENT NOISE:

$$\frac{N_2}{S_1} = \theta \quad , \quad SNR = \frac{1}{\theta}$$

EXAMPLE CASE:

$$\theta = 1^\circ \qquad SNR = 35 \text{ dB}$$

SENSOR AXIS ALIGNMENT EFFECTS

6.0 CONCLUSIONS

6.1 RESULTS SUMMARY

6.1.1 MODULES

- PREDICTABLE PERFORMANCE
- GOOD Q, SEEKING IMPROVEMENT FOR HORIZONTAL
- VACUUM INTEGRITY OVER LONG TERM STILL TO BE PROVEN

6.1.2 DUAL HORIZONTAL SYSTEM

- COHERENCE HIGH EXCEPT LP TESTS
- WELLHEAD LP FILTERS SUSPECT
- DATA ACQUISITION BANDWIDTH PROBLEM WITH H/P 3582A

6.2 PROBLEMS

6.2.1 DATA ACQUISITION

SMALL BANDWIDTH OF LP FILTERS CAUSES COHERENCE ERROR WITH H/P 3582A.

6.2.2 CONFLICTING DATA

"BROAD" BANDWIDTH (>0.1 HZ) FILTERS SHOW HIGH COHERENCE

NARROW BANDWIDTH (<.05 HZ) FILTERS SHOW LOW COHERENCE

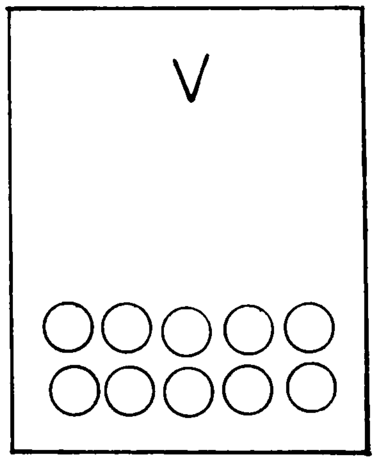
6.3 PLANS

6.3.1 DUAL VERTICAL TEST

6.3.2 FILTER TEST

6.3.3 DATA ACQUISITION - FIELD TEST

KNOWN SURFACE AREA SAMPLE OF KEL-F PLACED IN VOLUME AND BAKED UNDER VACUUM. CHAMBER IS PINCHED OFF AND PRESSURE MONITORED IN TIME.



$$\text{PRESSURE} = \frac{K \cdot S \cdot T}{V}$$

S = SURFACE AREA
K = OUTGASSING RATE CONSTANT
T = TIME
V = VOLUME

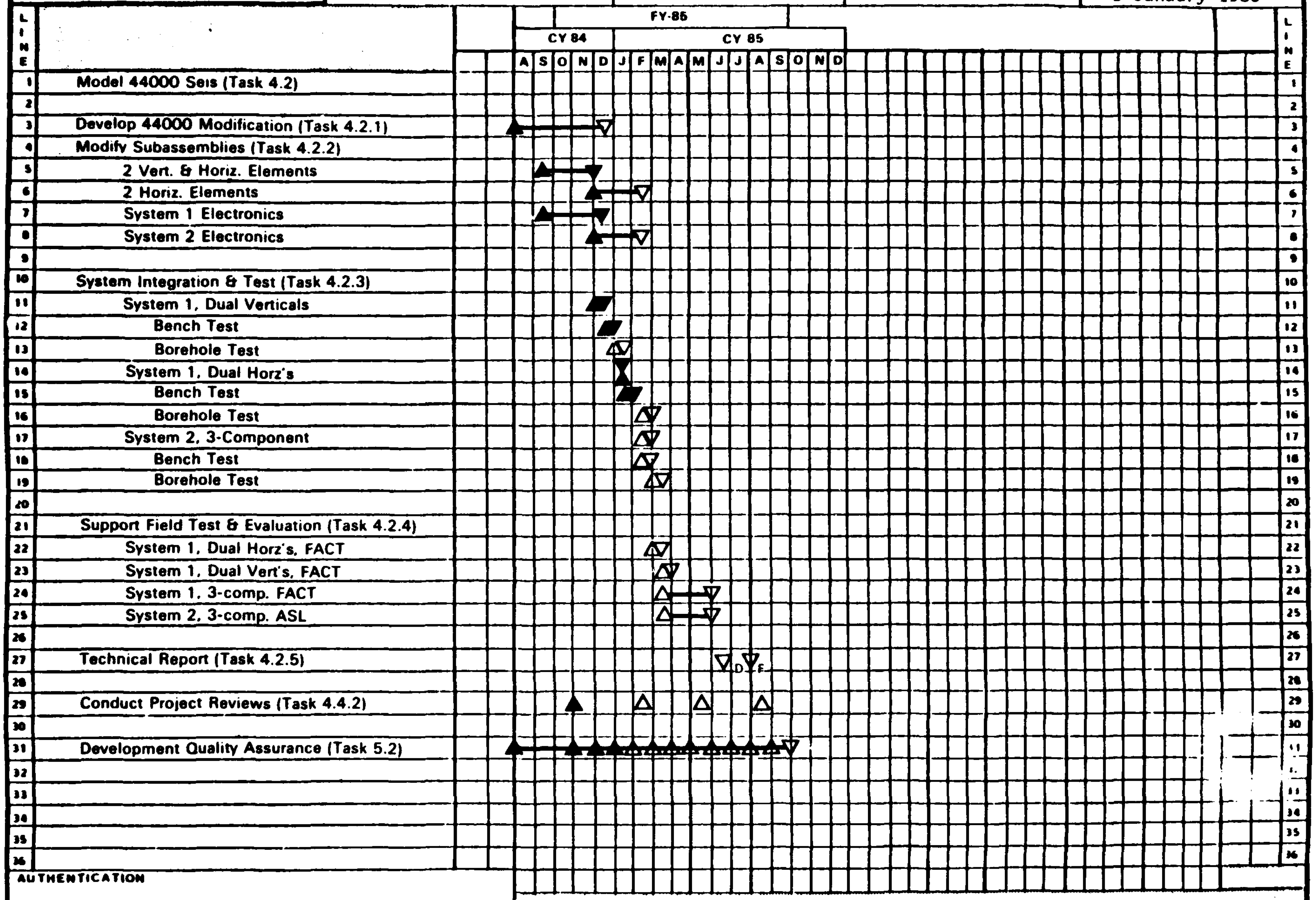
10 KEL-F DISKS 5/8" DIA X .060" THICK

SURFACE AREA = 4.72×10^{-3} M^2

VOLUME = 1.87×10^{-4} M^3

OUTGASSING TEST

PROGRAM SCHEDULE	SYSTEM (Project) NUMBER	SUBSYSTEM	TYPE OF SCHEDULE	AS OF DATE
	AFTAC T4142/B/PMP	MODEL 44000 SEIS		1 January 1985



44000 DEVELOPMENT SCHEDULE

PRIME ITEM DEVELOPMENT SPECIFICATION
FOR THE
MODEL 52900 BOREHOLE SEISMOMETER SYSTEM PROTOTYPE
TYPE B1

TELEDYNE GEOTECH
3401 Shiloh Road
Garland, Texas 75041

Contract No. F08606-84-C-0023

Authenticated by ______________________ Approved by ______________________
(Procuring Activity) (Contractor)

Date ______________________ Date ______________________

102/1

May 1990

1. SCOPE

1.1 This specification establishes the performance, design, development, and test requirements for the Model 52900 borehole seismometer system.

2. APPLICABLE DOCUMENTS

2.1 Government Documents. The following documents of the issue in effect on the date of this specification form a part of the specifications to the extent specified herein.

MIL-STD-454 -	Standard General Requirements for Electronic Equipment
MIL-STD-1472 -	Human Engineering Design Criteria for Military Systems, Equipment and Facilities
MIL-STD-1521 -	Technical Reviews and Audits for Systems, Equipment, and Computer Programs.
MIL-HDBK-217 -	Reliability Prediction of Electronic Equipment

2.2 Non-Government Documents

2.2.1 Specifications. Teledyne Geotech Specification for Design, Fabrication and Test of Electronic Equipment (Process Control Procedure), Number 40000-9700.

2.2.2 Control Drawings.

Item	Geotech Drawing Number
Seismometer	990-44000
Holelock	990-51108
Stabilizer	990-51123
Cable Strain Relief	990-51114
Alignment Probe	990-51134
Pilot Adapter	990-51202
Seismometer Connector	990-38312
Cable Connector Assembly	990-36633
Sensor Subassembly	990-51129
Electronics Subassembly	990-51138
Holelock Installation Tool	990-51096
Holelock Gyro Adapter	990-51315
Wellhead Terminal	990-53380

3. REQUIREMENTS. The Model 52900 Seismometer System shall contain the hardware required to sense and output three components of seismic data in a long-period passband and three components in a short-period passband. The data outputs shall be electrical analogs of earth motions imparted through the holelock. The system shall be designed for installation and operation in a four inches inner diameter cased borehole with allowable tilt up to fifteen degrees off vertical. To meet the requirements for remote unmanned operation, the system shall have low power drain, have high reliability and be expandibly capable of interfacing with commonly used analog and digital acquisition systems and communications systems.

3.1 Item Definition. The Model 52900 system covered by this specification shall consist of two major components and a set of associated installation and handling equipment. The two major components shall be the Borehole Seismometer Assembly, Model 44000, and the Wellhead terminal, Model 53380. The Borehole Seismometer assembly shall contain a Sensor Subassembly, 51129, and an Electronics Subassembly, 51138. The sensor subassembly shall be designed to sense input accelerations from earth motion in one vertical and two orthogonal horizontal axes. The sensors shall use feedback to center their suspended masses and a mechanical adjustment on the vertical sensor shall allow for installation at any latitude without factory adjustments. The suspensions shall be housed in modular cases designed to maintain long-term (five years) vacuum integrity. The modules shall be leveled by a system designed to allow for operation in boreholes which have up to 15° of tilt with respect to the local gravity vector and can be leveled to within 10^{-5} radians along the sensitive axis. The electronics subassembly shall contain the electronics necessary to interface to the sensor subassembly and the electronics in the wellhead terminal. It shall receive electrical analogs of the sensed accelerations and feedback voltages to the sensors to control their mass position and provide calibration signals. It shall provide signal conditioning and transmission of broadband electrical analog signals to the wellhead terminal and receive and transmit commands to the Sensor Subassembly from the wellhead terminal for module leveling, vertical mass centering, and system calibration. The electronics subassembly shall also condition and distribute power from the wellhead terminal for the circuits in the electronics subassembly and the Sensor Subassembly. The wellhead terminal shall receive three channels of broadband analog data from the electronics subassembly and condition each channel by filtering to provide both long-period and short-period passbands. Calibration and leveling commands received from external interfaces shall be interpreted and transmitted to the borehole seismometer. It shall condition and distribute power from an external source to the circuits in the wellhead terminal and to the borehole seismometer. The wellhead terminal shall also provide transient protection at the external interface. The associated installation and handling equipment shall include a holelock to support and orient the borehole seismometer assembly and a holelock installation tool to place the holelock assembly in the borehole. In addition, a stabilizer shall be required at the top of the borehole package. A cable strain relief, a borehole cable, borehole seal and insulation material shall also be provided as part of the installation related equipment. The installation of the Model 44000 Seismometer shall be compatible with the use of winch and mast assemblies already in use with the Model 36000 Borehole Seismometer Systems in the field.

3.1.1 Item designs. Figure 1 is a functional diagram for the system. Figure 2 is a function diagram of a tyical channel of the Borehole Seismometer. Figure 3 is a functional diagram of the wellhead terminal.

3.1.2 Interface definition. The Model 52900 Seismometer System shall have external interfaces to the borehole, to the monitor and control circuits, to the output data circuits and to the power source. Internal interfaces shall be provided between the major components within the system. The interfaces are illustrated in figure 4.

3.1.2.1 Borehole interface. The elements of the borehole interface shall provide the following functions:

a. Holelock. The holelock shall provide a mechanical coupling between the borehole package and the borehole, and package orientation.

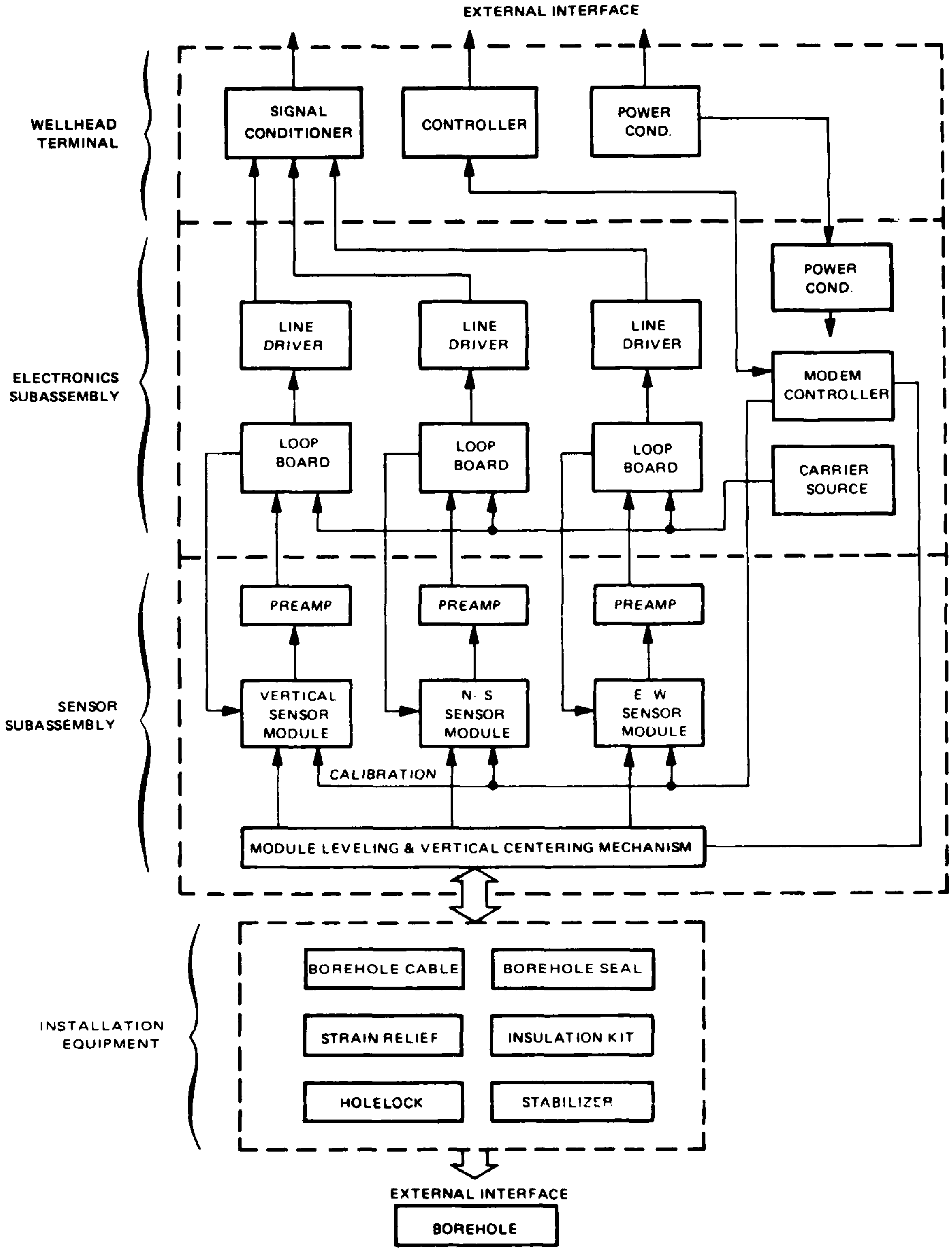


FIGURE 1. MODEL 52900 SYSTEM, FUNCTIONAL DIAGRAM

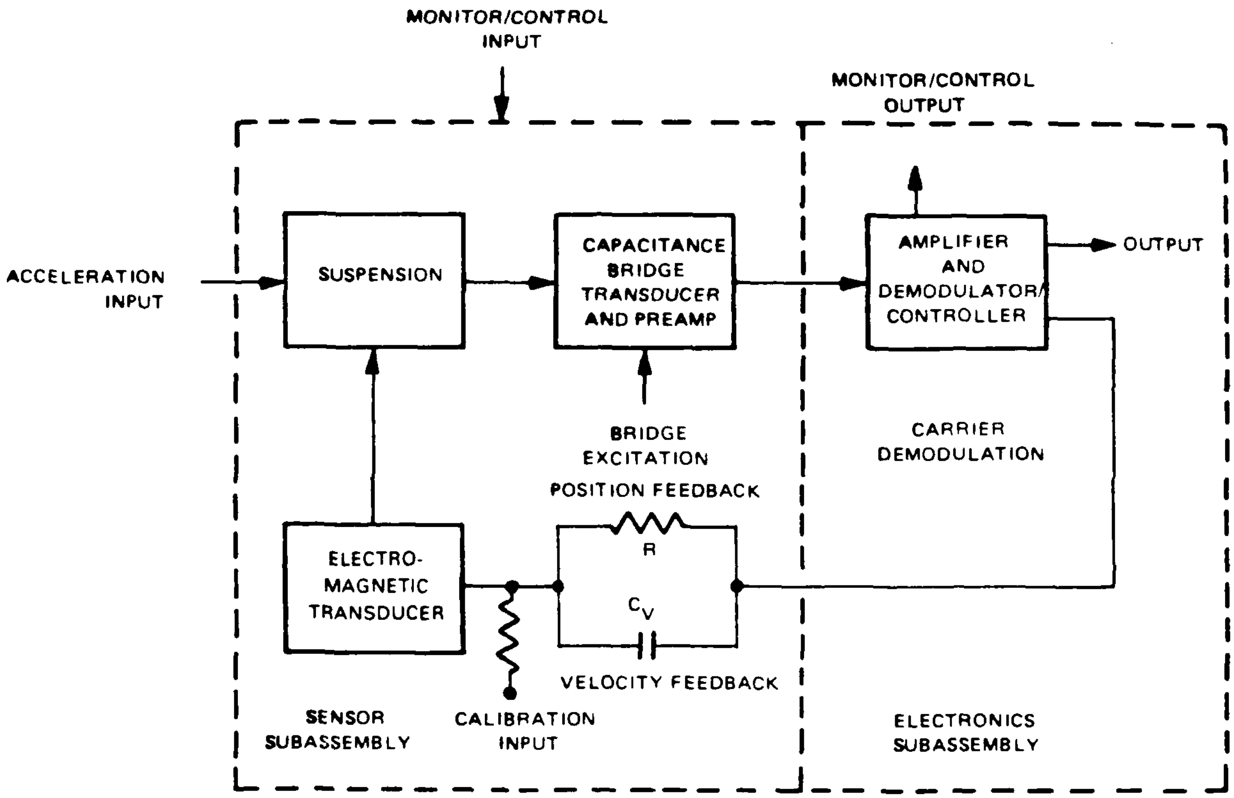


FIGURE 2. FUNCTIONAL DIAGRAM OF THE BOREHOLE SEISMOMETER FOR A TYPICAL CHANNEL

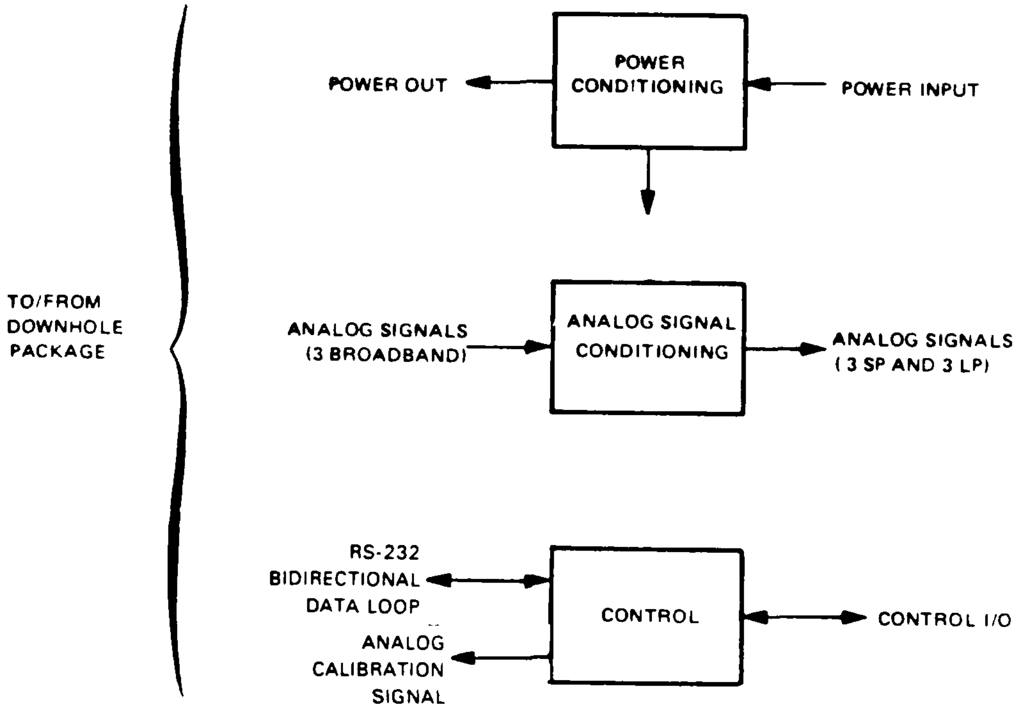


FIGURE 3. FUNCTIONAL DIAGRAM FOR THE WELLHEAD TERMINAL

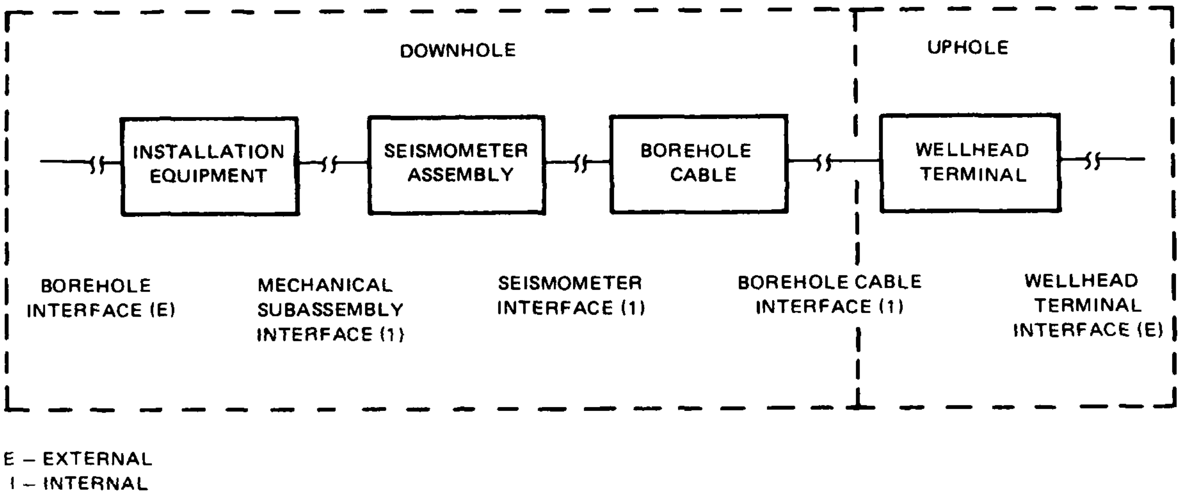


FIGURE 4. MODEL 52900 SEISMOMETER SYSTEM INTERFACES

b. Stabilizer. The stabilizer shall center the top of the borehole package in the casing. The stabilizer shall be compliant in the direction of the borehole axis to isolate the sensor package from casing strain.

c. Cable strain relief. The cable strain relief shall isolate borehole cable movements from the sensor subassembly.

d. Borehole seal. The borehole seal shall isolate the borehole from the direct effects of external atmospheric pressure changes and provide cable interface between borehole cable and uphole cable.

e. Insulation kit. Insulation shall be used to reduce the tendency for air convections and acoustic standing waves to be sustained in the borehole.

f. Borehole cable. The borehole cable shall provide both electrical connections between the borehole seismometer assembly and the top of the borehole and the load bearing requirements for the instrument during installation.

The physical interfaces for these items are defined in the following control drawings:

Item	Geotech Drawing Number
Seismometer	990-44000
Holelock	990-51108
Stabilizer	990-51123
Cable strain relief	990-51114
Borehole seal	SJP-820215-2
Borehole cable	990-40839

3.1.2.2 Borehole seismometer interface. The functions of the seismometer assembly interface shall be to provide for the sensor package orientation and to provide a compliant electrical connection between the borehole cable and the top of the seismometer. The physical interfaces for these system elements are defined in the following control drawings:

Item	Geotech Drawing Number
Seismometer alignment probe	990-51134
Pilot adapter	990-51202
Seismometer connector	990-38312

3.1.2.3 Borehole cable interface. The borehole cable shall be a 12 conductor armored cable, United States Steel 12J465B or equivalent. The interface shall be designed to allow up to 1000 feet of cable between the seismometer and the top of the borehole. Provisions shall be made to connect the borehole cable to the wellhead terminal and provide a pressure seal for the cased borehole which will retain 30% of an initial test pressure after a 24-hour period.

3.1.2.4 Wellhead terminal interface. The wellhead terminal interface shall provide for termination of the borehole cable conductors and external electrical connection. Transient protection from all external electrical connections shall also be provided when the external lines exceed runs of 25 feet. When external analog lines exceed runs of 25 feet, optional signal conditioners should be used to buffer the wellhead terminal filters and convert the single ended analog output circuits to differential circuits. These optional signal conditioners are not a part of the development of this system.

3.1.2.5 Power Interface.. The operating power for the Model 44000 Seismometer shall not exceed the primary power source baseline established for the Model 36000 Borehole Seismometer System.

3.1.3 Major component list. The following is a list of the major components of the Model 52900 Borehole Seismometer System.

Description	Qty	Part Number	Manufacturer
Seismometer	1	990-44000	Teledyne Geotech
Wellhead Terminal	1	990-53380	Teledyne Geotech
Installation & Handling Equip.	1 set	990-52900-00 Reference	Teledyne Geotech

3.1.4 Government furnished property list. The Model 52900 Borehole Seismometer System shall not require the incorporation of government furnished property to meet functional objectives.

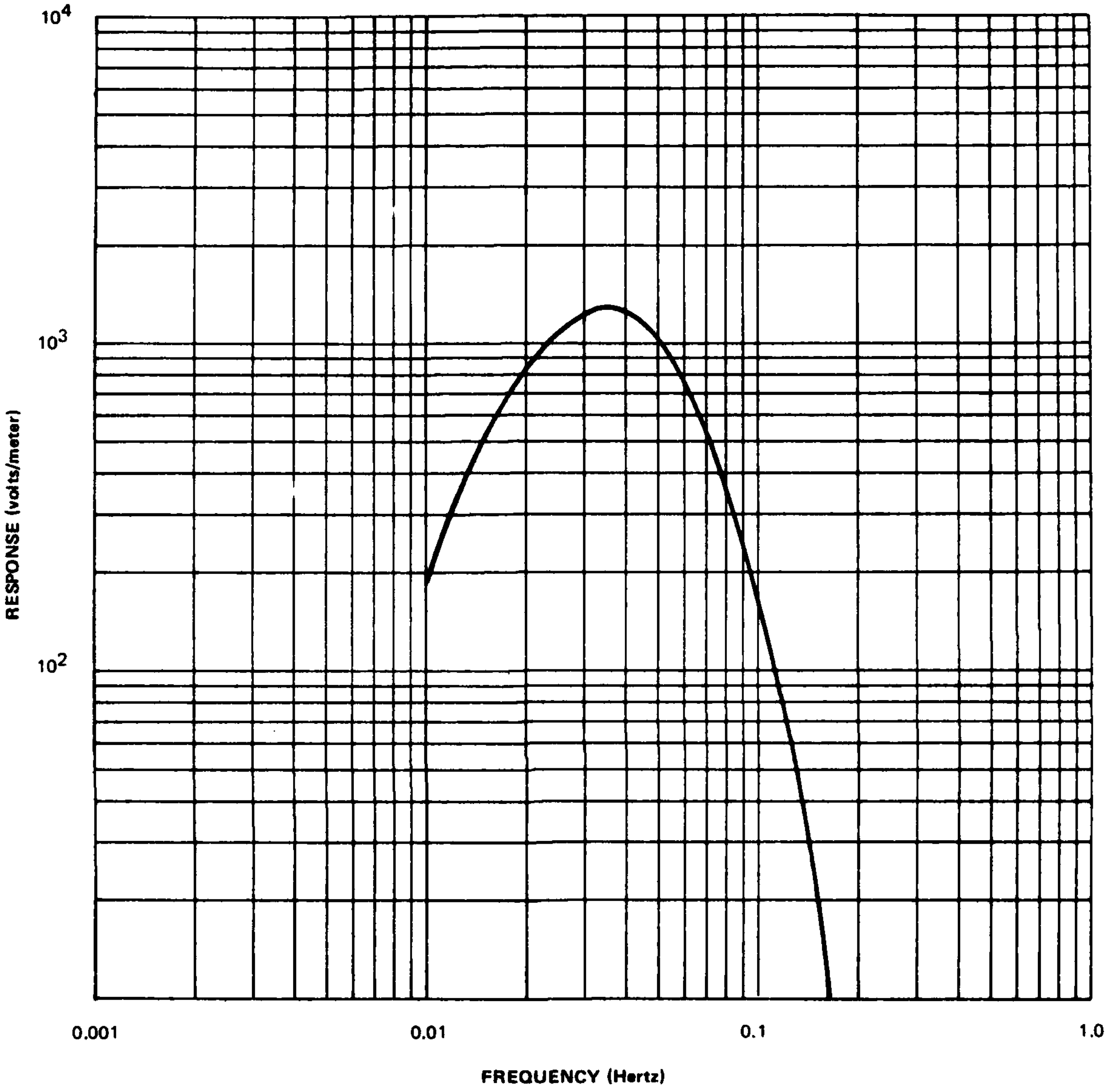
3.1.5 Government loaned property list. The loan of government property shall not be required to complete the system development.

3.2 Characteristics.

3.2.1 Performance. The borehole seismometer in the Model 52900 Borehole Seismometer system shall provide three broadband (0 to 4 Hz) outputs that are electrical analogs of the input earth acceleration in the three sensitive axes of the seismometer. The wellhead terminal shall receive these three channels of broadband data and shall filter each channel to provide long-period and short-period data channels with the response illustrated in figures 5 and 6.

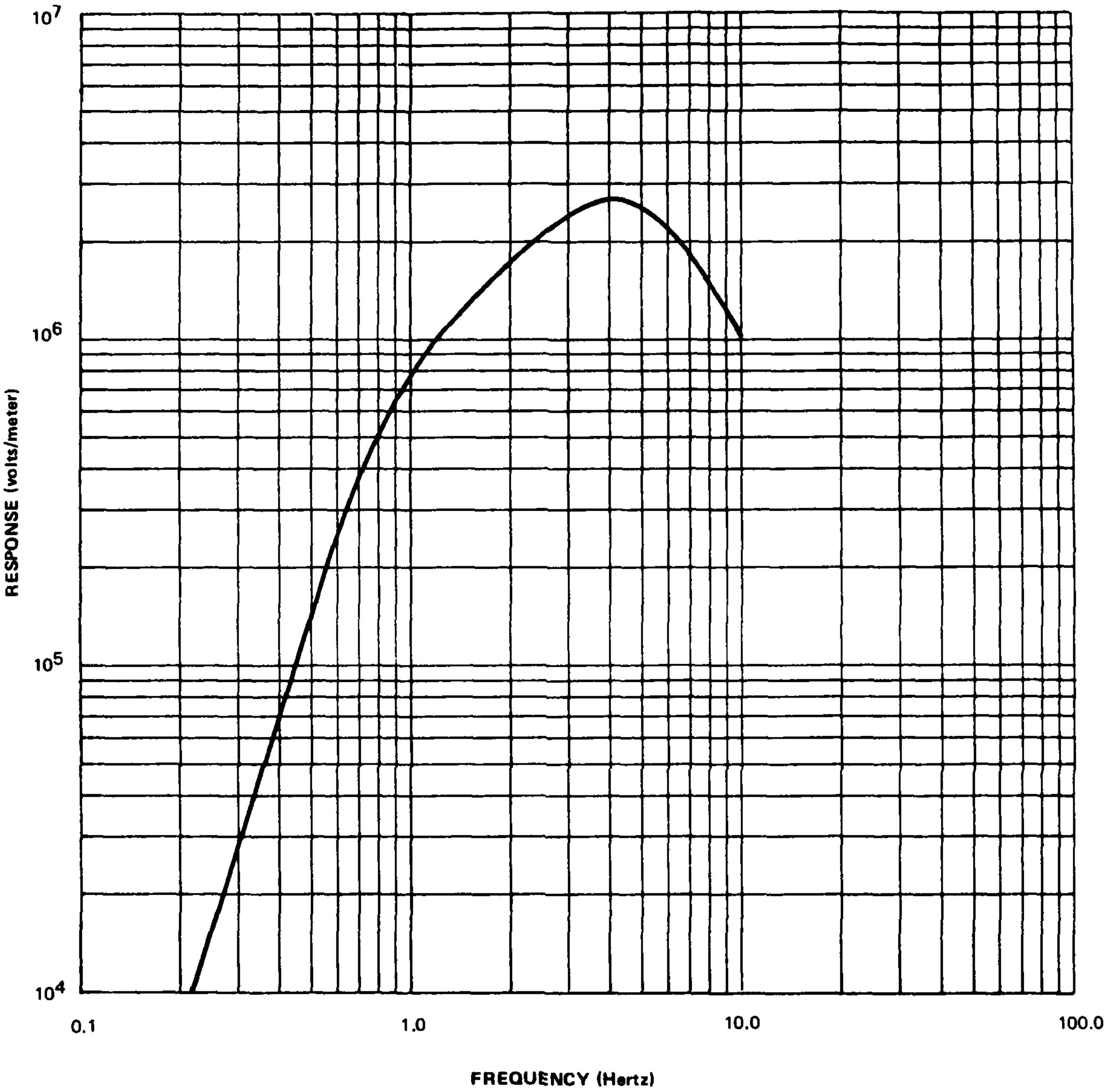
3.2.1.1 Borehole seismometer operating characteristics. The borehole seismometer shall have the following characteristics:

Inputs, Seismic	Three orthogonal suspensions 0.208 kg mass



FREQ (Hz)	RESPONSE (V/m)	TOLERANCE (%)
0.01	5.07×10^3	±30
0.0125	9.30×10^3	±25
0.02	1.25×10^4	±20
0.025	1.66×10^4	±15
0.033	2.00×10^4	±10
0.04	2.00×10^4	–
0.05	1.67×10^4	±10
0.067	9.27×10^3	±20
0.10	2.40×10^3	±25

FIGURE 5. MODEL 52900 SEISMOMETER SYSTEM RESPONSE AND SENSITIVITY - LONG-PERIOD CHANNELS



FREQ (Hz)	RESPONSE (V/m)	TOLERANCE (%)
0.5	3.33×10^4	±10
0.8	1.30×10^5	± 5
1.0	2.00×10^5	–
1.5	3.17×10^5	± 5
2.0	4.13×10^5	± 5
2.5	5.07×10^5	±10
3.0	5.96×10^5	±10
4.0	6.88×10^5	±15

FIGURE 6. MODEL 52900 SEISMOMETER SYSTEM RESPONSE AND SENSITIVITY - SHORT-PERIOD CHANNELS

Upper Suspension	Signal channel 1 or Z
Sensitive Axis	Vertical within 0.1 degree of gravity vector. Positive earth motion upward
Middle Suspension	Signal channel 2 or N-S
Sensitive Axis	North-south ±3 degrees. Positive earth motion to north
Bottom Suspension	Signal channel 3 or E-W
Sensitive Axis	East-west ±3 degrees. Positive earth motion to east.
Maximum Input Acceleration	±0.001 m/s^2 along sensitive axes
(0 to 4 Hz passband)	(±15 mm @ 0.04 Hz) (±25 microns @ 1.0 Hz)
Noise - (0.04 to 4 Hz passband)	2.0 x 10^{-20} (m/S^2)^2/Hz max.
(equivalent earth acceleration power spectral density)	(See figure 7)
Sensitivity - (0 to 4 Hz passband)	2 x 10^4 volts/m/s^2 (1.26 x 10^3 V/m @ 0.04 Hz) (7.9 x 10^5 V/m @ 1.0 Hz)
Maximum voltage output	± 10 volts, each line to ground (40 volts peak-to-peak, line-to-line)

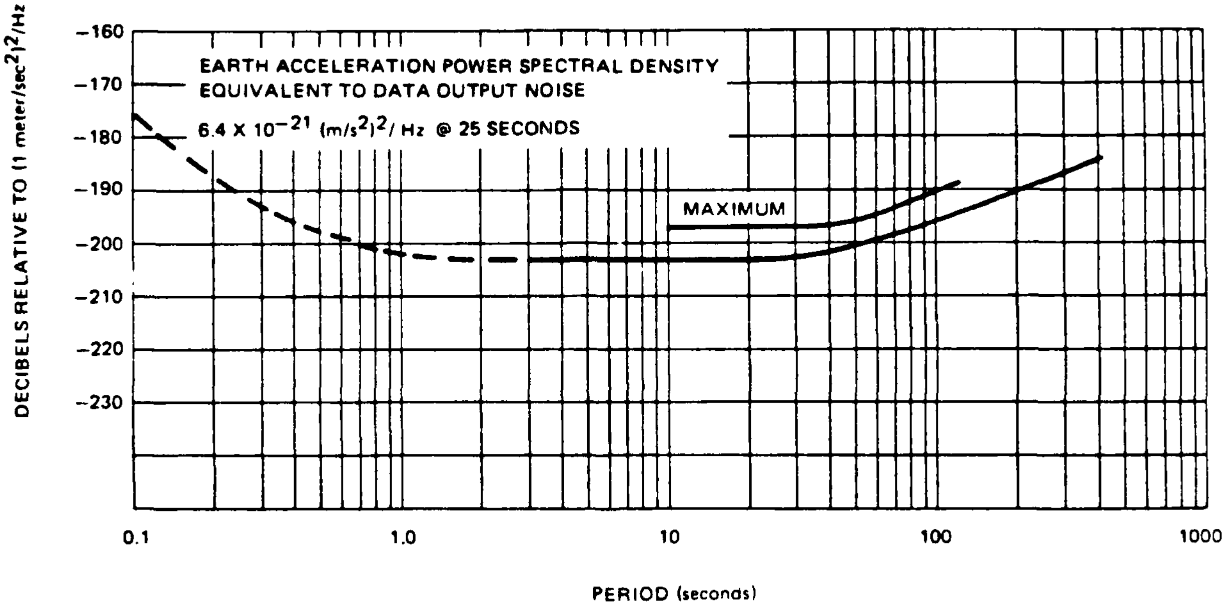


FIGURE 7. NOISE POWER SPECTRA

Response	Flat to acceleration 0 to 4.0 Hz (see figure 8)
Linearity	Better than one part in 10^3

3.2.1.2 The wellhead terminal shall have the following characteristics:

Noise	Shall not exceed an equivalent noise input of 2.0×10^{-20} $(m/s^2)^2/Hz$ in LP passband, $1 \times 10^{-18}(m/s^2)^2/Hz$ in SP passband
Sensitivity	2×10^4 V/m @ 0.04 Hz 2×10^5 V/m @ 1.0 Hz
Maximum Output	±10V, single ended, maximum linear range
Dynamic Range	
Long-period passband	120 dB
Short-period passband	120 dB

3.2.2 Physical characteristics. The Model 52900 seismometer system shall be configured in two primary packages, the borehole package and the wellhead terminal.

3.2.2.1 The Borehole Package.

3.2.2.1.1 Weight. The borehole package shall weigh no more than 45.4 kg (100 pounds) when assembled for borehole installation. It shall weigh no more than 90 kg (200 pounds) when packed for shipment. The borehole cable shall be wrapped on a disposable reel. The cable weight shall be 0.15 kg (0.331 pounds) per foot plus about 18 kg (40 pounds) for the cable reel.

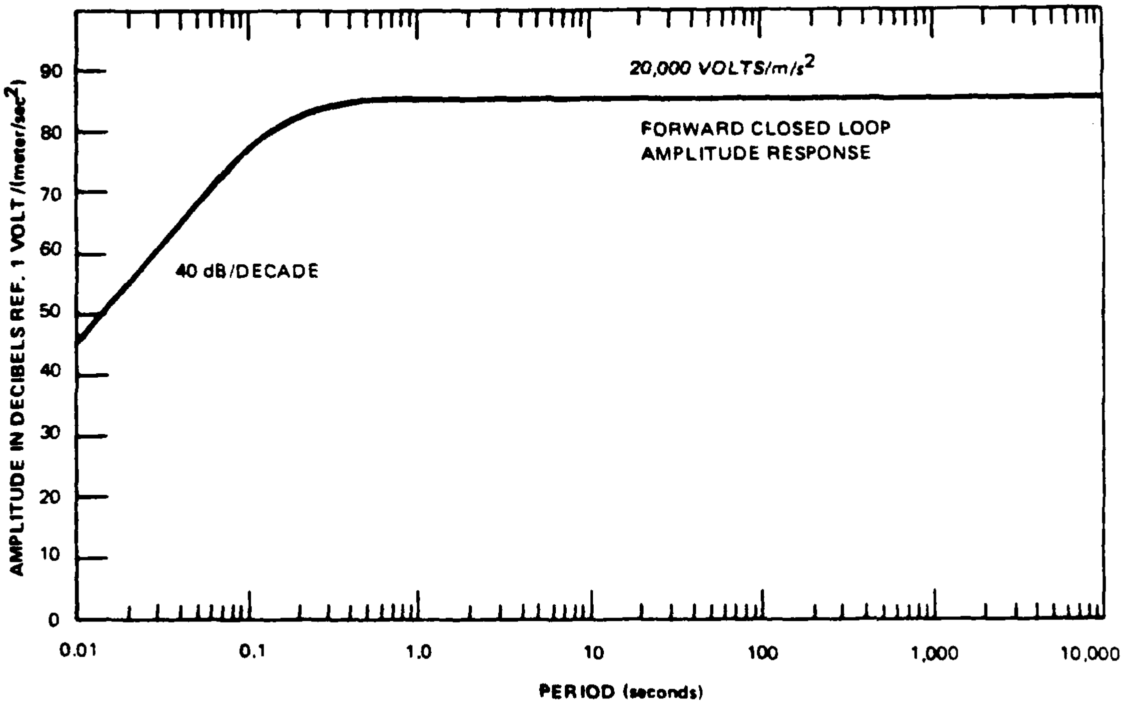


FIGURE 8. FREQUENCY RESPONSE AT THE SEISMOMETER OUTPUT

3.2.2.1.2 Dimensions. The borehole package shall be 9.53 cm (3.75 in.) in diameter and not over 3.7 m (12 feet) long when assembled for installation.

The cable reel shall be approximately 0.9 m (3 ft) in diameter by 0.6 m (2 ft) wide.

3.2.2.1.3 Packing and Crating. A reusable shipping crate(s) shall be provided for the borehole seismometer and holelock installation tool system. The crate(s) shall be designed to withstand a shock up to 50 g's in any direction without damage to the instrumentation. The cable shall be shipped on a disposable cable reel with protective covers on the cable connections. Disposable crates shall be used for packing all other installation and handling equipment. Good commercial practices shall be used in the fabrication of all crates.

3.2.2.2 The wellhead terminal.

3.2.2.2.1 Weight and dimensions. The wellhead terminal enclosure shall weigh not more than 45.4 kg (100 pounds), and shall be a sealed steel box having dimensions not exceeding 0.6 m (2 ft) x 0.6 m (2 ft) x 0.45 m (1.5 ft).

3.2.2.2.2 Packing and crating. The wellhead terminal shall be packed in a disposable crate using good commercial packing for overseas shipment.

3.2.2.3 Health and safety criteria. The system shall have no material or characteristic that present a hazard to personnel. Installation equipment shall be developed and procedures shall be documented to assure safe handling during system installations.

3.2.3 Reliability. The system consists of three major components or equipment groups: the Borehole Seismometer Assembly, the installation and handling equipment, and the Wellhead Terminal. To determine the contribution of each of these components to the total system reliability, it is necessary to consider (a) the function each element in a group is to perform, (b) the environment in which each element is to operate, and (c) what constitutes a failure for a given element or component.

All elements pertinent to the continued operation of the system after it has been successfully installed and determined to be operational were considered. The operating environment provided for the Borehole Seismometer is inert, stable, and equivalent to the Ground Benign conditions described in MIL-HDBK-217B. The environment in which the support and the wellhead terminal will be used is equivalent to the Ground Fixed conditions.

For the purposes of estimating reliability, a failure is defined as any change within the system that causes an interruption of any of the six data channels or that causes the analog data being collected to exceed the specified operational tolerances. Failures occuring prior to or during installation of the system shall not be considered since it is presumed that any such failures would be repaired before the system is made operational.

The only element in the support group which will affect the performance of the seismometer after installation is the seismometer cable assembly. Computed by the Part's Stress Analysis Method presented in MIL-HDBK-217B, the failure rate for this cable assembly is less than 0.5 failure per million hours.

The failure rate for each of the four groups has been estimated as follows:

Sensor subassembly: $_S$ = 15 failures per million hours

Electrical subassembly: $_E$ = 23 failures per million hours

Mechanical subassembly: $_M$ = 0.5 failure per million hours

Wellhead terminal: $_W$ = $\underline{11.5}$ failures per million hours

Total 50 failures per million hours

The MTBF of the system is therefore:

$$MTBF_{SYSTEM} = \frac{1}{50 \times 10^{-6}} = 20{,}000 \text{ hours}$$

The estimates for the group failure rates shall be verified at the completion of the prototype development using the Parts Count Reliability Prediction method specified in MIL-HDBK-217B.

Field repair of a failed system shall be accomplished by replacement of the complete borehole package. The meantime to accomplish such field repair shall not exceed eight hours after the required tools and equipment are on site.

3.2.4 Maintainability. The system shall require technical capabilities equivalent to an AF level 5 technician for field replacement and an AF level 7 for depot repair. A test interface module shall be required to accomplish maintenance in the field and at the depot. Special tools and handling equipment shall be provided to handle the instrumentation in the field.

3.2.4.1 Requirements for preventative maintenance. The system shall be designed for remote unmanned operation and no preventative maintenance except for routine calibration shall be required.

3.2.4.2 System maintenance concepts. System maintenance shall be accomplished at three levels. (1) Field level maintenance shall be accomplished by replacement of the borehole package or electronic modules. (2) Depot level repair shall include fault isolation to the module level and repair and test of all failed system components except the loop boards, the carrier source boards and the sensor modules. (3) Loop boards, carrier source boards and sensor modules shall be returned to the manufacturer for repair.

3.2.4.3 System repair requirements. The system with its associated handling and test equipment shall be designed so that borehole package replacement can be accomplished in no more than eight hours after the personnel and equipment are at the borehole site.

Depot repair includes fault isolation, repair, and testing to verify performance to specifications. Test procedures shall be provided to assure rapid fault isolation to the module level. The system shall be designed to be disassembled to the module level in not more than four hours. All electronic modules, except the loop boards, shall be designed to allow the use of a maintenance test set and/or standard laboratory electronic test equipment and hand tools. The mechanical design shall be such that any mechanical part on a module can be replaced in less than three hours after the module has been removed from the system. The sensor modules are exceptions to this requirement.

After a seismometer has been repaired, it shall be installed in a suitable borehole and tested to assure that all performance specifications are met.

3.2.5 Environmental conditions.

3.2.5.1 Operating environment. The borehole seismometer shall be designed to be operated in a shallow borehole environment. It shall operate at any temperature between -20°C to +60°C with a rate of change of temperature not to exceed 10^{-3}°C per minute or 0.5°C in any 24-hour period. The borehole shall not have convecting air. The relative humidity may be as high as 100% without condensation, but the system shall not be submerged in water or other liquid. The borehole must be sealed to isolate the sensor from the direct effects of atmospheric pressure changes. The borehole seal shall have a time constant not less than 24 hours (where one time constant is defined as the time period over which an initial test pressure is allowed to leak down to 30% of the initial pressure). The system shall be designed to operate in a cased borehole that is tilted not more than 15° from the local gravity vector.

The wellhead terminal shall operate over a temperature range of -20°C to +60°C and in relative humidity of 0 to 95% without condensation.

3.2.5.2 Storage or shipping environment. The system when packed shall be capable of storage or shipment without damage within a temperature range of -55°C to +60°C, a relative humidity range from 0 to 95%, a pressure altitude range of 0 to 50,000 feet and a vibration range of 0.04 inch peak-to-peak up to 50 Hz. The packing case for the seismometer shall be designed so that a shock of 50 g's to the packing case shall not be transmitted as more than 10 g's to the instrument.

3.2.6 Transportability. The system shall be packaged for shipment by commercial or government air carrier using standard commercial practices. The borehole package shall be enclosed in padded containers with handles to facilitate handling. All other parts and components shall be packed as necessary to ensure against loss or damage during shipment. Total system may be airlifted by helicopter to remote locations.

3.3 Design and construction. The electronic equipment used in the Model 52900 system shall conform in general design to the requirements of Teledyne Geotech Specifications for Design and Test of Electronic Equipment (Process Control Procedure), number 40000-97-00. All active components shall be hermetically sealed. Components selected for use in the system shall be available from at least two independent sources when possible. Mechanical designs shall be developed to the extent possible to be compatible with standard shop practices.

3.3.1 Materials, processes and parts.

3.3.1.1 Materials. System design requires careful selection and use of materials for the purpose of temperature compensation to maximize the stability of the mechanical system; however, no strategic or highly specialized materials shall be required in the design of the system.

3.3.1.2 Processes. The material for the springs in the vertical module is made by a patented process owned by John Chatillon and Sons, Inc., Kew Gardens, New York. The material is an "isoelastic" spring steel designed to have a low temperature coefficient of expansion.

The capacitor plates in the vertical and horizontal modules are made with fabricated quartz plates with a vacuum-deposited metal film. The processes involved are well developed and no new technology will be required.

The sensor modules are evacuated to a vacuum level somewhat higher (lower pressure) than that required in previous seismometers of this type. Because high vacuums of sub-millitorr level must be held for a period of five (5) years, special processes are required. These processes include special cleaning techniques to minimize outgassing within the module. Also module seals that will maintain their integrity for a period of five (5) years must be developed and tested. Processes to efficiently evacuate modules and eliminate subsequent outgassing must be developed.

3.3.1.3 Parts. The springs for the vertical module are wound in a prestressed condition to produce an effective "zero length" spring. The methods to produce zero length springs are generally understood, but Chatillon and Sons, Inc., is the only company known to have the capability and equipment required to fabricate springs that meet the requirements.

The drive capacitors used in the capacitance bridge shall be selected through special test procedures to obtain components with precise values and low current leakage. The required procedures are developed, but must be documented.

The operational amplifiers for the loop circuits and the first stages of preamplification will be selected from quantities of off-the-shelf operational amplifiers. These devices shall be selected for low noise. In the selection process the operational amplifiers shall be classified according to noise level and part numbers shall be assigned to designate suitability for use in the various circuits of the system.

3.3.2 Electromagnetic radiation. Standard commercial practice for preventing electromagnetic interference shall be employed in the design of the Model 52900 system.

3.3.3 Nameplates and product marking. All equipment shall be identified in accordance with requirement 67 of MIL-STD-454F.

3.3.4 Workmanship. The Model 52900 system shall be manufactured and assembled in accordance with Requirement 9 of MIL-STD-454F.

3.3.5 Interchangeability. Provisions for interchangeability of items in accordance with Requirement 7 of MIL-STD-454F shall be followed to the extent possible. Where possible, components shall be selected to meet this requirement. In some cases items such as capacitors, low-noise operational amplifiers and springs for the vertical sensors may not have more than one source.

The system design shall be developed in a modular configuration such that like modules or subassemblies are interchangeable.

3.3.6 Safety. All equipment developed for the Model 52900 Borehole Seismometer System shall be designed to meet Requirement 1 of MIL-STD-454F. All hardware for installing and retrieving the borehole instrumentation shall be designed to be fail safe and safety features shall be incorporated to prevent personnel injury and equipment damage.

3.3.7 Human performance/human engineering. System design and packaging for borehole use imposes constraints on the ability to provide an instrument with easy access to modules and parts. The design concept is that the system shall operate for long periods of time without personnel/equipment interactions other than routine system calibration. To the extent possible, engineering design principles will be in accordance with MIL-STD-1472 to minimize demands upon human skill, training, and manpower.

3.4 Documentation. All documentation for the Model 52900 Borehole Seismometer System shall be in accordance with the Contract Data Requirements List (CDRL).

3.5 Logistics.

3.5.1 Maintenance.

3.5.1.1 Maintenance concept. The maintenance concept for the Model 52900 borehole seismometer system(s) is formulated around two basic assumptions which are (1) field restoration of a field instrument or electronics modules will be by complete replacement of the borehole package or module, and (2) complete borehole seismometers will be spared only at the depot.

3.5.1.1.1 Field level maintenance. Assuming that the Model 52900 system will not be disassembled or repaired to any extent in the field, field level maintenance shall include:

a. Incoming inspection to verify proper functional operation of the seismometer prior to installation,

b. Installation and removal of the seismometer,

c. Verification of proper operation of the seismometer after installation,

d. Downhole troubleshooting of the seismometer using an interface module to determine if the seismometer has failed,

e. Fault isolation and repair to the module or board level of uphole accessory electronics,

f. Calibration of the seismometer and bandpass filters.

3.5.1.1.2 Depot level maintenance. Depot level maintenance shall include:

a. Disassembly/assembly of the seismometer

b. Fault isolation and repair to the component level of any control logic, power regulation or line driver board in the borehole electronics subassembly.

c. Fault isolation and repair to the board level in the low-noise analog section of the borehole electronics subassembly (e.g., analog loop boards and carrier source).

d. Fault isolation and repair to the individual mechanical module level (including the leveling system) in the mechanical subassembly.

e. Fault isolation and repair to the component level of any up hole electronics board returned to the depot from the field.

f. Verification of depot and factory repairs and proper operation of the seismometer prior to shipment.

3.5.1.1.3 Factory maintenance. Factory maintenance shall include:

a. Fault isolation and repair to the component level of the low-noise analog loop electronics and carrier source boards.

b. Fault isolation and repair to the component or piece part level of the individual mechanical modules and their leveling systems.

3.5.1.2 Use of multipurpose test equipment. To the maximum practical extent, the Model 52900 system shall be designed to permit on-site maintenance as defined for field level maintenance by the use of standard tools and test equipment such as oscilloscopes and multimeters.

3.5.1.3 Use of programmable automatic test equipment (PATE). To the maximum practical extent, the Model 52900 system shall be designed to be maintained at the depot level by use of Programmable Automatic Test Equipment (PATE). To ensure that components and subassemblies of the system are compatible with PATE, it is important that the physical characteristics, analog and digital input and output connections, and electrical specifications of these units follow the guidelines listed below. However, any components that exceed these guidelines shall be identified and the guideline exceptions described. The PATE has the following characteristics:

a. Analog boards shall be testable through the use of 36 input test signals and 36 output test signals;

b. Power requirements of the boards shall not exceed 4 amps up to 10 Vdc, 2 amps up to 24 Vdc, and 0.5 amps up to 80 Vdc;

c. Complex waveforms (other than sine, triangle, and square) shall not be required to test PC boards;

d. Digital boards shall meet the following characteristics:

    (1) 216 - I/O pins, exclusive of power and grounds, maximum

    (2) Logic levels ±15 volts dc maximum

3.5.1.4 Maintenance and repair cycles. No preventive maintenance shall be required for the Model 52900 Borehole Seismometer system.

3.5.2 Supply. The design of the Model 52900 Borehole seismometer system will introduce a new and unique item into the supply system. With the exception of the common electronics components used, the uniqueness of the design and the small quantities produced will preclude it from being an off-the-shelf item for resupply from the manufacturers. Lead times of one year or more should be considered for resupply and the depot spares level will, of necessity, be greater than the equipment reliability would indicate.

3.5.3 Facilities and facilities equipment.

3.5.3.1 Facilities. The facilities required to support the system are:

a. A borehole cased with 4-1/2 inch API casing shall be required at the installation site.

b. A small structure to house the wellhead terminal shall be required. The structure shall be adequate to provide shelter during maintenance, but no heating or air conditioning shall be required.

3.5.3.2 Equipment. The support equipment items required to support the system are listed below:

Item	Teledyne Geotech Drawing or Model Number
Tilt Mast Assembly	SJP-820215-1
Holelock installation tool	990-51096
Winch	Model 38760
Holelock gyro adapter	Drawing 990-51315
Maintenance Test Set	Keysheet 990-52900-00 Reference

3.6 Personnel and training.

3.6.1 Personnel. The Model 52900 Borehole seismometer system does not require the performance of routine operating procedures, therefore, an increase in the staff of the operating facility will not be required. Maintenance of the seismometer and its subassemblies will require trained personnel with a minimum technical capability equivalent to that of an Air Force Level 7 Technician possessing basic knowledge in digital electronic circuits. Initially, from four (4) to six (6) qualified personnel will require specialized installation and maintenance training to assure the availability of competent personnel for these functions. Subsequent maintenance support of the equipment will normally require the availability of two (2) to three (3) trained technicians.

3.6.2 Training. Installation, operation and maintenance training will be conducted on the system at the manufacturers facility at the time of delivery of the first production systems. A minimum of eighty (80) and a maximum of one-hundred-twenty (120) hours of formal classroom and "hands on" performance training shall be provided to each class of students. This training course shall familiarize the student with the theory of operation and provide practical demonstration of installation and maintenance procedures and techniques.

3.7 Major component characteristics. The performance and physical characteristics of the major components and functions are given in this section. The characteristics that relate directly to data quality (i.e., noise level, linearity, dynamic range) cannot be measured at the component level and have therefore not been included in the list of major component characteristics.

3.7.1 Seismometer

3.7.1.1 Sensor

Number	3 per system
Mass	0.208 kg ±2%
Suspension natural period	
Horizontal	2.1 Hz ±10%
Vertical	2.6 Hz ±10%
Suspension losses (mechanical Q)	200 immediately after evacuation and shall not reduce to less than 100 in 5 years.
Spurious resonance	Non self-sustaining
Capacitance bridge sensitivity	10^5 volts/meter

3.7.1.2 Leveling

Motor stepping rate	244 steps/second max
Maximum time to level	1 hour
Leveling precision	10^{-5} radian

3.7.1.3 Vertical Module Centering

Motor stepping rate	244 steps/second max
Maximum time to center after leveling	½ hour
Centering precision	±5 microns

3.7.1.4 Calibrator

Type	Electromagnetic
Motor constant	6-8 newton/amp

3.7.1.5 Electronics

3.7.1.5.1 Power Conditioning

Input	22 to 28 Vdc at 1.5 amp max
Quiesent	3.6 watts
Output	
Regulated	±15 Vdc ±0.2 Vdc, 0.05% regulation at ±50 mA nominal. +5 Vdc ±0.1 Vdc, 0.5% regulation at 20 mA nominal. 24 Vdc ±0.2 Vdc, 1% regulation at 1 amp maximum.

3.7.1.5.2 Downhole Communication Controller

Function	Provides downhole control of command and status communication between seismometer and wellhead terminal.
External	External access to controller is through the modem (see 3.7.1.5.3).
Internal Interfaces	Provides interfaces for all internal control functions (i.e., leveling, calibration) and one auxiliary logic level I/O port.
Power Requirements	+5 Vdc ±0.1 Vdc at 10 mA nominal.

3.7.1.5.3 Modem

Function	Interfaces downhole communication controller to external communication circuit (i.e., cable to wellhead terminal).
Type	Asynchronous, 300 bps.
Power Requirements	±15 Vdc ±0.2 Vdc at ±5 mA nominal +5 Vdc ±0.1 Vdc at 5 mA nominal

3.7.1.5.4 Level Controller

Function	Provides for internal, automatic leveling of all 3 sensors, automatic centering of vertical mass, and manual leveling and centering.
Control Interface	Downhole communication controller.
Output Interface	Leveling mechanisms.
Power Requirements	12 Vdc ±0.2 Vdc at 1 amp maximum. +5 Vdc ±0.1 Vdc at 10 mA nominal.

3.7.1.5.5 Calibration Controller

Function	Generates and controls calibration signal.
Calibration Signals	
Program A	Steady-state sine wave. 24 frequencies from LP through SP passbands at 8 amplitude levels covering a 42 dB range.
Program B	Steady-state two frequency signal for linearity determination.
Control Interface	Downhole communication controller.
Output Interface	Calibrator.
Power Requirements	±15 Vdc ±0.2 Vdc at ±5 mA nominal.

3.7.1.5.6 Carrier Source

Supply Voltage	±15 Vdc at ±5 mA nominal +5 Vdc at 1 mA nominal
Outputs	
Frequency	15625 Hz ±0.001%
Sine Wave	5 Vrms ±1%
Square Wave (3 outputs)	0 to +5 V

3.7.1.5.7 Loop Board

Number	3 per system
Supply Voltage	±15 Vdc at ±10 mA nominal +5 Vdc at 1 mA nominal
Input	Modulated carrier 0 to 1 volt rms
Outputs	
Data	Demodulated analog signal at ±10 V, 0 to 4 Hz
Feedback	Demodulated analog signal, each line +2.5V to +12.5V (differential)

3.7.1.5.8 Line Driver

Number	3 per system
Supply Voltage	±15 Vdc at 10 mA nominal
Input	Analog signal at ±10 V p-p, 0 to 4 Hz passband.
Outputs	Analog signal at 40 V p-p differential, 0 to 4 Hz passband.

3.7.2 Wellhead terminal. The wellhead terminal shall provide the surface interface to the system. The wellhead terminal enclosure shall be a heavy duty, self-supporting, weathertight, steel container. A hinged front door shall provide maintenance access. Electrical connections shall be made through the bottom panel with weathertight bulkhead connectors. The wellhead terminal enclosure shall be connected to the borehole casing with a (4/0, sheathed) cathodic protection cable. The wellhead terminal is intended for sheltered operation over a temperature range of -20°C to +60°C (storage range -55°C to +60°C).

3.7.2.1 Power conditioning

Input	22 to 28 volts dc, 2 amps maximum
Output	22 to 28 Vdc, 1.5 amp maximum

3.7.2.2 Signal conditioning

Input channels	3
Type	Differential
Level	40 V p-p
Common mode rejection ratio	80 dB (0 to 4 Hz)
Common mode signal level	±10 volts maximum
Output channels	6
Type	Single ended
Level	±10 volts
Response	
Short-period	See figure 6.
Long-period	See figure 5.
Polarity	Positive voltage for ground motion up, south to north, and west to east
Dynamic range	120 dB

3.7.2.3 Seismometer Control

Functions	Provides control and monitoring of seismometer leveling and calibration operation from wellhead terminal system external device.
Operator I/O	Control panel with controls, indicators, and test points.
Seismometer Interface	Wellhead terminal communication controller and modem provide interface through seismometer cable to compatible units in seismometer.
External Interface	Architecturally inherent, addition of interface module(s) required.

3.7.3 Installation and handling equipment

3.7.3.1 Holelock installation tool

Power Requirements	115 Vac, 6.5 amps
Physical Characteristics	Dimensions - 3.75 in. diam. x 38.375 in. long Weight - 29.7 Kg (65.5 pounds)

3.7.3.2 Holelock

Diameter	3.75 inches o.d.
Operating range	Expand to 4.25 inches o.d. maximum

3.7.3.3 Holelock orientation adapter

Diameter	3.75 inches o.d.
Mating threads	Provided with a 1-1/4-12NF female thread

3.7.3.4 Stabilizer

Diameter	3.75 inches o.d.
Operating range	Expand to 4.25 inches o.d.

3.7.3.5 Strain relief

Diameter	3.75 inches o.d.
Operating range	Extend to 4.25 inches o.d.

3.7.3.6 Borehole plug

Number required	2
Diameter	3.75 inches o.d.
Length	10 feet

3.7.3.8 Borehole cable

Type	U. S. Steel 12J465B
Number of conductors	12-#20 AWG
Diameter	0.464 ± .006 inches
Length	Up to 300 meters (1000 feet)
Resistance	11.1 ohm/1000 ft.
Capacitance	58 pF/ft.
Voltage rating	300 volts
Breaking strength	17,000 pounds

3.7.3.9 Tilt mast adapter for 4-1/2 inch API casing. Adapts a 4-1/2 inch API casing collar to fit a tilt mast assembly designed for 7-inch API casing collar.

3.8 Precedence. If a conflict occurs in any of the documents referenced in section 2 or in the detailed requirements of this specification, the requirements of this specification shall be considered superseding requirements.

4. QUALITY ASSURANCE PROVISIONS.

4.1 General. The Model 52900 Borehole Seismometer System shall be tested and evaluated to verify its compliance with the requirements of this specification. Testing and verification shall include part, subassembly, component and system level testing. Because of extremely low noise levels, small relative displacements and high sensitivity to environmental changes, testing below the system level will necessarily be limited to functional verification tests. Many of the parts and subassemblies cannot be tested in sufficient detail to verify that all of the parameters meet the requirements. Final verification shall be determined by assembling the system, installing it in a borehole and conducting detailed system level tests.

A test program plan shall be developed. This program shall include plans for measuring those parameters that can be measured at the part and subassembly level and for rejecting nonconforming parts as early in the assembly process as possible. The plan shall also include detailed instructions for final system test as required to demonstrate conformance to all system requirements defined in Section 3.

4.1.1 Responsibility for tests. Tests conducted in accordance with the approved test program will be the responsibility of the contractor. Detailed system tests for final verification of conformance to the requirements shall be conducted at a seismically quiet site. The government shall select the organization to be responsible for these tests.

4.1.2 Special tests and examinations. Special tests and examinations shall be conducted on selected parts for the critical performance requirements. The capacitors to be used in the bridge circuits and other critical circuits shall be selected for close tolerances on leakage, temperature coefficients and capacitance value. Operational amplifiers shall be tested and classified in accordance with their measured parameters. Classifications shall define the performance requirements for the various circuit elements within the system. The sealed and evacuated sensor modules shall be tested for losses in the suspension mechanical Q.

4.2 Quality conformance inspections.

4.2.1 Reliability testing. The quality provisions do not include detailed plans for reliability testing. System design effort, parts selection and manufacturing and test methods that are developed for the Model 52900 system shall rely on the experience derived from the development of previous seismograph systems similar to the Model 52900.

4.2.2 Test levels. System test and verification shall be accomplished at five levels as follows:

a. Part and subassembly level testing shall be accomplished to identify defects and errors at lower levels of testing before system assembly and test are started.

b. Functional testing to verify that all elements of the assembled system are operating. These tests shall be accomplished on a test stand in the laboratory.

c. Preliminary system performance tests shall be conducted in a borehole at the contractor's facility and shall include all tests not limited by the high seismic noise levels at the contractors facilities.

d. Final system performance tests shall be conducted at a seismically quiet site and all tests necessary to verify conformance to system requirements will be conducted.

e. The level at which each specification requirement is verified shall be defined in detailed test plans and procedures prepared by the contractor and approved by the government.

The following paragraphs contain expanded descriptions of the four levels of testing required to verify conformance to system requirements.

4.2.2.1 Part and subassembly level testing. The purpose of this level of testing shall be to assure that the parameters that can be measured will meet the requirements. All parts and subassemblies shall be tested. The major areas of testing are:

a. Testing the critical parameters on all parts. Inspect all parts for errors and defects.

b. Testing all subassemblies for satisfactory operation over the temperature range.

c. Test the sensor modules for the mechanical losses (Q) of their suspensions and the integrity of the seals.

d. Test all electronic circuits for noise, response, linearity and other parameters, as required.

e. Test the leveling systems to determine that they are functioning properly.

f. Test the vertical module to determine that the mass centering actuator is functioning.

4.2.2.2 System functional tests. The purpose of the system functional tests shall be to determine that all system elements are functioning properly. The tests shall determine the following:

a. That all circuits are properly connected.

b. That all electrical control and power circuits function properly.

c. That the leveling system responds properly to commands.

d. That the vertical mass centering element responds properly.

e. That all suspensions appear to be floating free.

4.2.2.3 Preliminary system performance tests. These tests will give the first indication of system performance relative to requirements and it is possible at this stage to conduct detailed testing. It shall be the objective to measure all system parameters and to prepare a detailed report on the results of the tests. Two systems shall be operated simultaneously in adjacent boreholes for the purpose of making comparative measurements. The following shall be accomplished during this phase of the test program:

a. Evaluate the installation instructions.

b. Test and evaluate the module leveling subsystem and procedures.

c. Test and evaluate the calibration subsystem.

d. Measure system linearity using the two frequency method.

e. Measure system response.

f. Measure coherence between each of the three pairs of components of the two systems.

g. Estimate the system noise level in each channel of the two systems. Because of high ambient seismic noise levels, it will probably not be possible to verify that system noise meets the requirements specified in Section 3.

h. Prepare a report that defines system performance relative to the requirements. Submit to the government with recommendations for subsequent program activities.

4.2.2.4 Final system performance tests. The tests conducted at this level shall be the same as those conducted during the preliminary system performance tests (4.2.2.3). The site selected for these tests shall be a known quiet site. The purpose of this test phase shall be to make precise measurements of the following critical system requirements:

a. Linearity

b. Frequency response

c. System noise level

d. System dynamic range

In addition it shall be an objective to test documented installation and operating instructions.

5. PREPARATION FOR DELIVERY.

Packing for the Model 52900 Seismograph System shall be in accordance with good commercial practice. The instrumentation packing design shall incorporate the design concepts developed for similar seismograph systems. Drawing set no. 43300-0101 will be used as a guide. All containers shall be clearly marked with "FRAGILE" or other special handling instructions as required.

6. NOTES.

"This section is not applicable to this specification."

AUTOMATIC LEVELING PROGRAM

AUTOMATIC LEVELING PROGRAM

This is a generalized description of the Automatic Leveling Program developed by Teledyne Geotech for leveling and positioning horizontal and vertical seismometer modules utilizing the Teledyne Geotech Rotational-Translational Leveling Mechanism.

Figures 1 and 2 are included for reference. Figure 1 depicts the geometrical relationships of the seismometer modules and the leveling mechanisms for the Model 44000. The relationships are the same for the Model 54000 except that the seismometer modules are those used in the Model 36000. Figure 2 gives an overview of the leveling algorithm.

The Program can be implemented on an 8-bit microprocessor operating at 2 MHz with eight output ports, three input ports, four serial flag inputs, one serial output, and single level interrupt. The processor is supported by a programmable counter for motor stepping rate and data sampling rate, a programmable timer for delay timimg, and a programmable multiplexed analog-to-digital converter.

For the machine level Program the memory is comprised of 8K by 8-bit programmable read only memory (PROM), 1K by 8-bit random access memory (RAM), 64 by 8-bit non-volatile (NV) random access memory, and 1K by 8-bit read only memory (ROM) for 16-bit arithmetic subroutines.

RAM ALLOCATION

Random access memory is organized into several working stacks as follows.

MSTK's. A 32 by 8-bit stack is set-up for each mechanical actuator. Each MSTK is used to hold the addresses for the parameters of the specific mechanism, output bytes for actuating the mechanism, and links with calling routines.

DSTK's. A 32 by 8-bit stack is set-up for each of the three seismometer channels. Each DSTK holds the data samples for that channel.

ASTK. A 32 by 8-bit stack is set-up for each of the two horizontal seismometers and used in arithmetic operations.

RSTK. A single 32 by 8-bit stack is set-up for use in square root computations.

CSTK. A single 32 by 8-bit stack is set-up for use in communications.

Non-volatile RAM is organized as an 8 by 8-bit stack for each mechanism. Each NV stack contains the position, limit status and activity status of the mechanism.

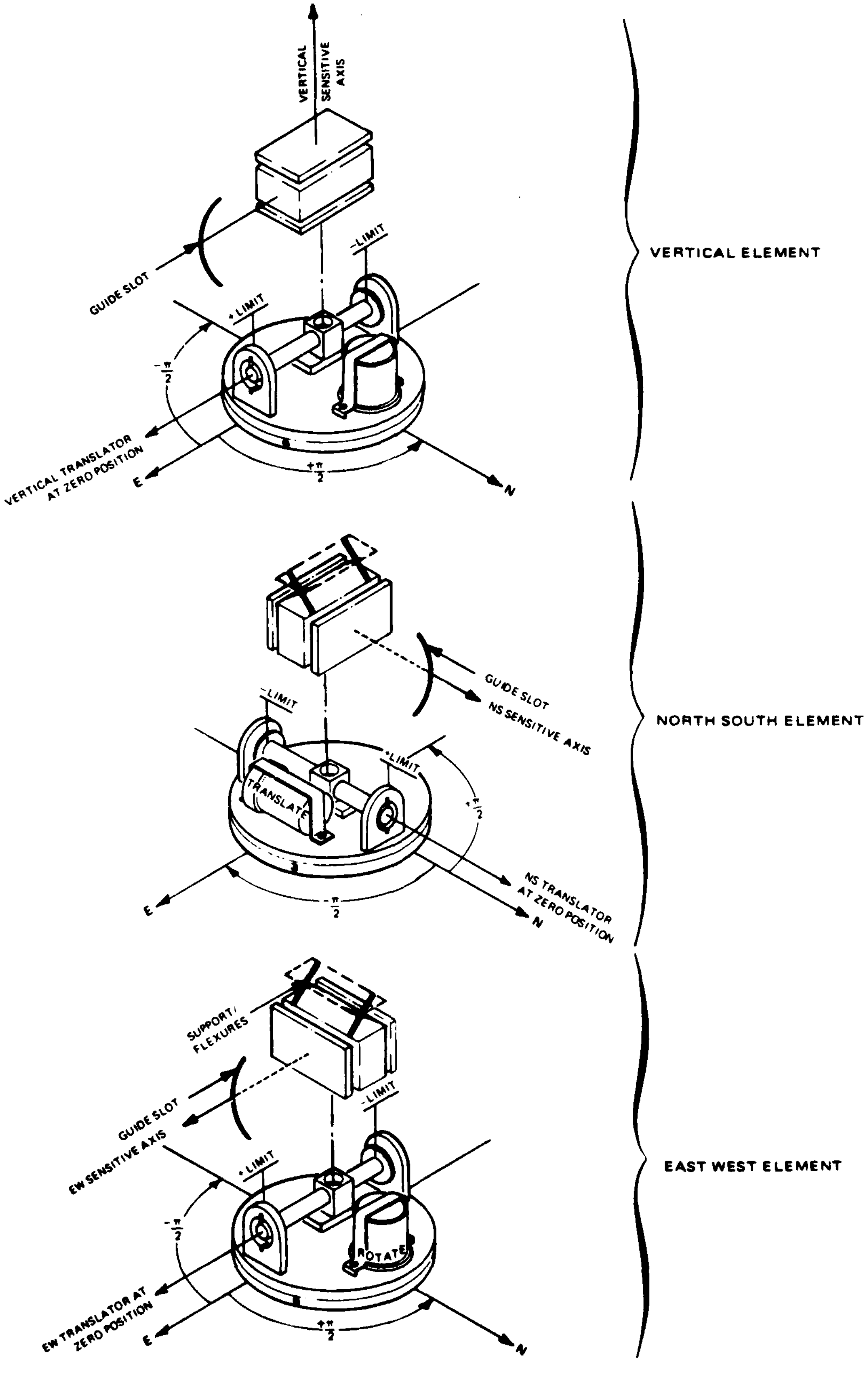


Figure 1. 44000 ALIGNMENT DIAGRAM

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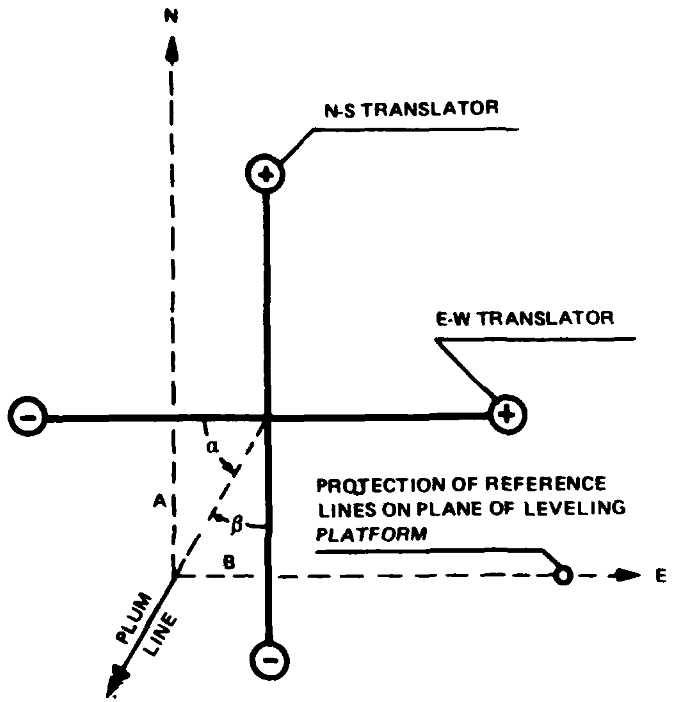

OBLIQUE VIEW OF REFERENCE FRAME LOOKING DOWNHOLE NORMAL TO THE PLANES OF THE N-S AND E-W LEVELING PLATFORMS. PLATFORMS ARE IN THE STARTING POSITION.

- N-S AND E-W PLATFORMS AT ZERO LOCATIONS N-CHANNEL OUTPUT POS, E-CHANNEL OUTPUT POS
- TRANSLATE N-S IN NEGATIVE DIRECTION UNTIL N-CHANNEL OUTPUT SWITCHES NEG. THIS DETERMINES DISTANCE A.
- TRANSLATE E-W IN NEGATIVE DIRECTION UNTIL E-CHANNEL OUTPUT SWITCHES NEG. THIS DETERMINES DISTANCE B.
- COMPUTE DIAGONAL $D = \sqrt{A^2 + B^2}$, β = ARC SIN (B/D), $\alpha = 90^\circ - \beta$.
- IF D CORRESPONDS TO LESS THAN 1-DEGREE HOLE SLANT, COMPLETE LEVELING WITH TRANSLATORS.
- IF D CORRESPONDS TO 1-DEGREE OR MORE HOLE SLANT, INCREASE TRANSLATIONS TO DISTANCE D FROM ZERO.
- ROTATE N-S CLOCKWISE THROUGH ANGLE B TO FINAL POSITION.
- ROTATE E-W VERTICAL COUNTERCLOCKWISE THROUGH ANGLE α TO FINAL POSITION.

FIGURE 2. MODULE LEVELING EXAMPLE

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SUBROUTINES

In addition to call and return subroutines and 16-bit arithmetic subroutines, the Program uses the following ten special purpose subroutines.

Subroutine IMS The initialization section of Main contains the parameters for each mechanism. IMS is called to load the addresses of these parameters into the MSTK for the specific mechanism. In addition, IMS gets the position for each mechanism from its NV stack, determines rotor position, computes the detent drive for this position, and loads the detent drive bytes into the MSTK output section. This avoids extraneous drive when motor power is applied.

Subroutine CMD The Program does not permit an interrupt for a communications request. Only an impending power loss can generate an interrupt. This arrangement has been used to avoid interruption of a critical drive sequence. For example, the motion resulting from two 10-step drive sequences is not necessarily the same as that resulting from a 20-step sequence.

To provide timely communications, the Program checks for a communications request at various non-critical points and calls CMD to service the request. CMD stores the contents of active registers, receives the serial 3-byte command, and processes the command as follows. If a command can not be recoginized, then CMD waits for the next communication request.

COMMAND	RESPONSE
Limit Status	Get Limit and Mechanism Activity bits from NV stacks for all mechanisms, format a 3-byte message, and serially transmit +Limit, -Limit, Active, restore contents of active registers, and return to calling location.
Position Status	Determine mechanism specified, get the position of the mechanism from the NV stack, serially transmit the 3-byte position, restore contents of active registers, and return to calling location.
Auto Level	If Auto Level was in process, restore registers and resume from calling location. If Auto Level was not in process, then restore registers and return to initiate Auto Level.
Stop Level	Restore contents of active registers and return to Base location.

Adjust Commands (Manual Level)	If Auto Level in process then command is illegal - wait for next communication request. Otherwise, determine mechanism specified, convert steps specified from BCD to binary, determine drive direction, restore registers, and go to appropriate location in Main.

<u>Subroutine SQRT</u> Subroutine SQRT computes the square root of the 32-bit integer (N) in RSTK by

$$D(n+1) = 1/2 * [D(n) + Q(n)]$$

$$Q(n) = N / D(n)$$

$$SQRT [N] = D(n+1) \quad \text{when} \quad D(n+1) - D(n) < 0010 \text{ hex.}$$

<u>Subroutine INLZ</u> This subroutine is called by Autolevel for each mechanism to initialize the mechanism. Using the position of the mechanism maintained in its NV stack and the SLK (slack) parameter in its MSTK, INLZ drives the mechanism to its zero position. Zero position is defined for positive drive to zero where the number of positive drive steps is equal to or greater than the SLK parameter of the mechanism.

<u>Subroutine TRQ</u> This subroutine determines the detent motor drive for the rotor position passed to it. Mechanism drive routines pass the next-rotor-position to TRQ which returns the output drive bytes for the next-rotor-position.

<u>Subroutine AVE</u> This subroutine takes 256 8-bit data samples at 75 samples per second on the object channel output, counts negative full scale (-FS) and positive full scale (+FS) samples, forms a SUM of all sample values, and tests the results as follows. All mechanisms are assumed to be static when AVE is called.

TEST	RESPONSE
IF - FS count = 0 AND + FS count not 0	Return to location in Main for FAST NDX
IF - FS count not 0 AND + FS count = 0	Return to location in Main for FAST PDX
IF BOTH - FS AND + FS Counts = 0 OR IF NEITHER = 0, THEN	
IF SUM greater than or equal to Positive test parameter	Return to location in Main for SLOW NDX
IF SUM less than or equal to Negative test parameter	Return to location in Main for SLOW PDX

IF SUM < Positive test parameter AND IF SUM > Negative test parameter	Return to location in Main for NO DRIVE

<u>Subroutine PDX</u> This subroutine performs the positive drive to an axis crossing at a drive/sample rate passed by the calling routine. When called PDX sets the NV mechanism activity status for the object mechanism. PDX computes a running average RAVE for the channel output during the drive sequence. The initial value of RAVE is that computed by AVE. For each rotor step, the NV stack is updated, the mechanism position is checked against the maximum positive range parameter (+FR), the channel output is sampled, the sample is summed with the previous RAVE value, and the RAVE value tested as follows.

TEST	RESPONSE
Overflow of 16-bit RAVE value	Divide by 2, (shift right)
Previous and new values of RAVE are both Negative	Take next rotor step and sample
Previous and new values of RAVE are both Positive	Take next rotor step and sample
Previous RAVE Negative and new RAVE Positive	Return to calling routine

<u>Subroutine PD</u> This subroutine performs a positive drive for the number of steps passed by the calling routine. When called PD sets the NV mechanism activity status for the object mechanism. For each step, PD updates the NV stack and checks the mechanism position against the maximum positive range parameter (+FR).

<u>Subroutine NDX</u> This subroutine performs the negative to an axis crossing at a rate passed by the calling routine. NDX is similar to PDX, but checks the mechanism position against the maximum negative range parameter (-FR), and returns to the calling routine when the value of RAVE changes from positive to negative.

<u>Subroutine ND</u> This subroutine performs a negative drive for a number of steps passed by the calling routine. ND is similar to PD, but checks mechanism position against the maximum negative range parameter (-FR).

MAIN LEVELING ROUTINES

The main leveling routines are organized into several functional sections. These sections are briefly discussed in the following.

Main: Power-on This section performs the power-on initialization. Input ports and outports are cleared, and basic pointers are set-up. Application of power to the leveling processor automatically causes data in the NV stacks to be restored. The power-on routine resets the mechanism activity status bits in the NV stacks.

Interrupt service is initiated by an impending power outage. The interrupt routine executes the actual non-volatile store cycle to maintain the positions of all mechanisms. The non-volatile memory used in the downhole processor does not use batteries, but it is only capable of a finite number, (1000 to 5000) non-volatile store cycles. To avoid unnecessary NV store cycles, the interrupt routine returns to the beginning of the power-on routine which leaves the interrupt disabled until a mechanism drive command is executed.

Main: Base After power-on initialization, program control moves to the Base section. Using the IMS subroutine, the Base routine initializes the mechanism MSTK's to set-up pointers to the mechanism parameters contained in Base.

After setting up pointers and computing rotor detent outputs, the program then waits for a communication request. After command execution, all routines will (eventually) return to this location in Base;Comm. When a communications request is detected, subroutine CMD is called to service the request.

Main: Manual This section contains the routines for manual or operator controlled leveling. When subroutine CMD receives a manual adjust command (ADJ CMD), control goes to the manual adjust routine for the specified mechanism and direction of drive. Subroutine PD is called for positive drive and subroutine ND is called for negative drive.

After the mechanism has been driven the specified number of steps or to a range limit (+FR or -FR), the routine checks for a communication request. If so, CMD is called to service the request. When CMD returns or if no communication was requested, the NV mechanism activity status is set inactive and control returns to Base;Comm.

Main: Autolevel When the Start Auto command is received, control goes to this section of the program. For electrostatic feedback type seismometer modules, all loop circuits are put in an open circuit condition. The delay timer (DT) is set for a two minute stabilization period. For electromagnetic feedback types, this procedure is unnecessary and not normally implemented.

Autolevel; Initial All mechanisms are initialized one at a time to their zero positions as follows. Pointers are set for the object mechanism and subroutine INLZ is called to drive the mechanism to zero position. INLZ returns to the the calling routine. If there has been a communications request, subroutine CMD is called to service the request. CMD processes the command and returns to one of three addresses. Auotlevel:Initial provides return addresses for three legal commands: Status Request; Start Auto; and Stop Auto. The return for Status Request rechecks for another communications request before proceeding. The return for Stop Leveling resets the mechanism NV activity status and returns control to Base;Comm. The Start Auto command is not required for autoleveling to proceed and the command is interpreted as a resume auto command. After communications are completed at this point, the mechanism NV activity status is reset and the program proceeds to the next mechanism.

Autolevel; IEAXT

When all mechanisms are at their zero positions and after the open loop delay timer has expired, the program proceeds as follows.

a) The output of the E-W horizontal channel is measured using subroutine AVE.
b) Based on the AVE results, subroutine PDX or NDX is called to drive the E-W translator and move the E-W module to its axis crossing.

IEAXT contains the Positive and Negative test parameters used by AVE and step/sample rates used by PDX and NDX. After the module is at its axis crossing, A request for communication is checked as in Autolevel; Initial. The E-W translator NV activity status is reset and the program proceeds with INAXT. Note the E-W translator position in its NV stack is equal to the number of steps between the zero position and the axis crossing.

Autolevel; INAXT

The procedure described in IEAXT is then performed for the N-S horizontal channel to position the N-S module at its axis crossing. Note also that the N-S translator position stored in its NV stack is equal to the number of steps between its zero position and its axis crossing.

Auto; DIAG

The E-W and N-S translators have been used to measure the two sides of a rectangle and the results of the measurement are contained in the NV position data. DIAG uses the position data to compute the diagonal of this rectangle and then drives each translator to its diagonal position. When DIAG is completed both E-W and N-S translators have been moved the distance of the diagonal from their zero positions. The direction of translator travel is along the sensitive axis of the seismometer module and passing through its axis crossing.

DIAG uses the the 16-bit arithmetic, SQRT, PD and/or ND subroutines to form the sum of squares, compute the square root of the sum, determine the additional translation needed, and drive the translators to their diagonal positions. Allowable travel ranges exceed the range of the 16-bit, 2's complement arithmetic and provisions are included to float the computations.

If the full range travel parameters, +FR and -FR, are encountered, then the translator will be positioned at the limit and the NV limit status set, but leveling will proceed. In this eventuality, the position of the seismometer after autolevel may allow the seismometer to operate but with an error in its cross-axis alingment. The opertor should be aware of this possibility, verify the condition with status commands, and determine if such operation is acceptable.

The leveling mechanisms for the vertical seismometer element are oriented like those of the E-W element, and the Z translator is driven to the same diagonal positon as the E-W translator.

DIAG services communication requests, resets NV mechanism activity status, and passes program control to Autolevel;ROT.

Autolevel; ROT With all translators at their diagonal position, ROT drives the rotational platform, or rotator, until each horizontal module again reaches its axis crossing. The vertical sensor platform is rotated the same as the E-W platform, leaving all three sensors aligned to within approximately 1-degree of the gravity vector.

It is convenient to sample either the noninverted or inverted channel outputs in utilizing the PDX and NDX subroutines for rotational drive to an axis crossing. The output polarity selected depends on direction of hole slant relative to the horizontal sensitive axes. ROT selects PDX or NDX for the required direction of rotation and sets the MUX/ADC to sample the appropriate channel output polarity. The initial value of RAVE is given a small bias to stabilize axis crossing detection.

Autolevel; Finl FINL sets the delay timer for a two minute count and proceeds with the vertical positioning mechanism adjustment, (54000 does not have this mechanism). Subroutine AVE is called for the vertical channel to determine drive direction and develop the initial value for RAVE. PDX or NDX is then called to drive the vertical positioner for a zero crossing. This leaves the vertical element in its final condition. Communication requests are serviced, the posititioner NV activity status is reset and the program proceeds to the N-S final.

When the 2-minute timer has expired, subroutine AVE is called for the N-S channel. Based on the AVE results, PDX or NDX is then called to drive the N-S translator to it final position. Communication requests are serviced, N-S translator NV activity status is reset, and the program proceeds to the E-W final.

Subroutine AVE is called for the E-W channel. Based on the AVE results, PDX or NDX is then called to drive the E-W translator to its final position. Communication requests are serviced, E-W translator NV activity status is reset. If sensors were put in an open-loop condition, then sensors are set for operation, and program control returns to Base;Comm.

MANUAL ADJUSTMENTS

Depending on surface to borehole temperature difference and the magnitude of hole slant or leveling time required, it may be desirable to manually adjust or trim offsets after the installation has stabilized for a few days. Efforts have been made to reduce motor heating. It is possible to drive some stepper motors with a duty cycle and reduce power dissipation from watts to tenths of watts. However, for the motors tested, normal load conditions can cause the motor to misinterpret a duty cycle drive and run backwards at twice the intended rate.

Consequently, the Autolevel Program does not use duty cycle motor drive, but all motors are off except when they are being driven. In addition, the Program allows time for moderation of temperature gradients. However motor heat is still a limiting factor in levleing-positioning accuracy.

TR 88-9

TECHNICAL REPORT NO. 88-9
TEST REPORT ON THE
MODEL 44000 SEISMOMETER SYSTEM

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August 1988

628/50

TEST REPORT

MODEL 44000 SEISMOMETER SYSTEM

Summary

Teledyne Geotech has completed long period subsurface vault tests on four individual 44000 modules; two horizontal and two vertical. Each type of module is tested in tandem by comparing the outputs of aligned sensors. The latest data is outstanding, particularly that of the horizontal. At a period of 20 seconds, both vertical and horizontal channels show incoherent noise power of approximately -180 dB relative to 1 $(m/s^2)^2$ / Hz. At a period of 64 seconds, the horizontal data is some 20 dB quieter than any previous borehole data and furthermore shows no increase with period, even at periods as long as 250 seconds. This performance is remarkable for a non-borehole installation. The vertical data shows excellent performance, although some temperature effects seem to be present. A detailed explanation of the experimental history and current tests follows.

CONTENTS

ILLUSTRATIONS

1. HISTORY OF THE 44000 SEISMOMETER TEST

1.1 BOREHOLE NOISE PERFORMANCE

After final borehole tests in 1985, we realized that the 44000 seismometer suffered from two major difficulties: (1) long period horizontal noise and (2) short period vertical noise. The long period horizontal noise was characterized by high offset drift rates in the time series data. This time behavior translated to noise frequency spectra that increased with increasing period (decreasing frequency). Figure 1-1 shows the typical noise performance for the 44000 in a borehole at the Sandia Facility for Acceptance, Calibration and Test (FACT). Note that the horizontal incoherent noise power rises at close to 10 dB per decade for periods greater than 1 second. Compare the vertical noise spectrum for the same test. At periods greater than 10 seconds, the vertical channel is approximately 20 dB quieter than the horizontal channel.

In comparison with another high quality long period seismometer, the 44000 horizontal shows its long period weakness. Figure 1-2 depicts spectral data from the 44000 seismometer and the Seismic Research Observatory (SRO) instrument (Teledyne Geotech Model 36000) at the Albuquerque Seismic Laboratory (ASL). While the two seismometers compare favorably at periods from 10 to 20 seconds, the 44000 horizontal is in excess of 20 dB noisier than the SRO seismometer for periods in excess of 40 seconds. The 44000 horizontal was plainly inadequate as a high resolution long period seismometer.

The 44000 vertical also did not perform as hoped. Instead of long period noise problems, the vertical channel produced excessive noise at short periods. The time series of a 44000 vertical channel shows unpredictable implusive spikes. See figure 1-3 for a comparison of three vertical channels. Note that one channel shows a "spike" at various times that neither other channel reflects. This spike translates to unpredictable increases in noise spectra, depending upon whether the sampled interval contains a spike

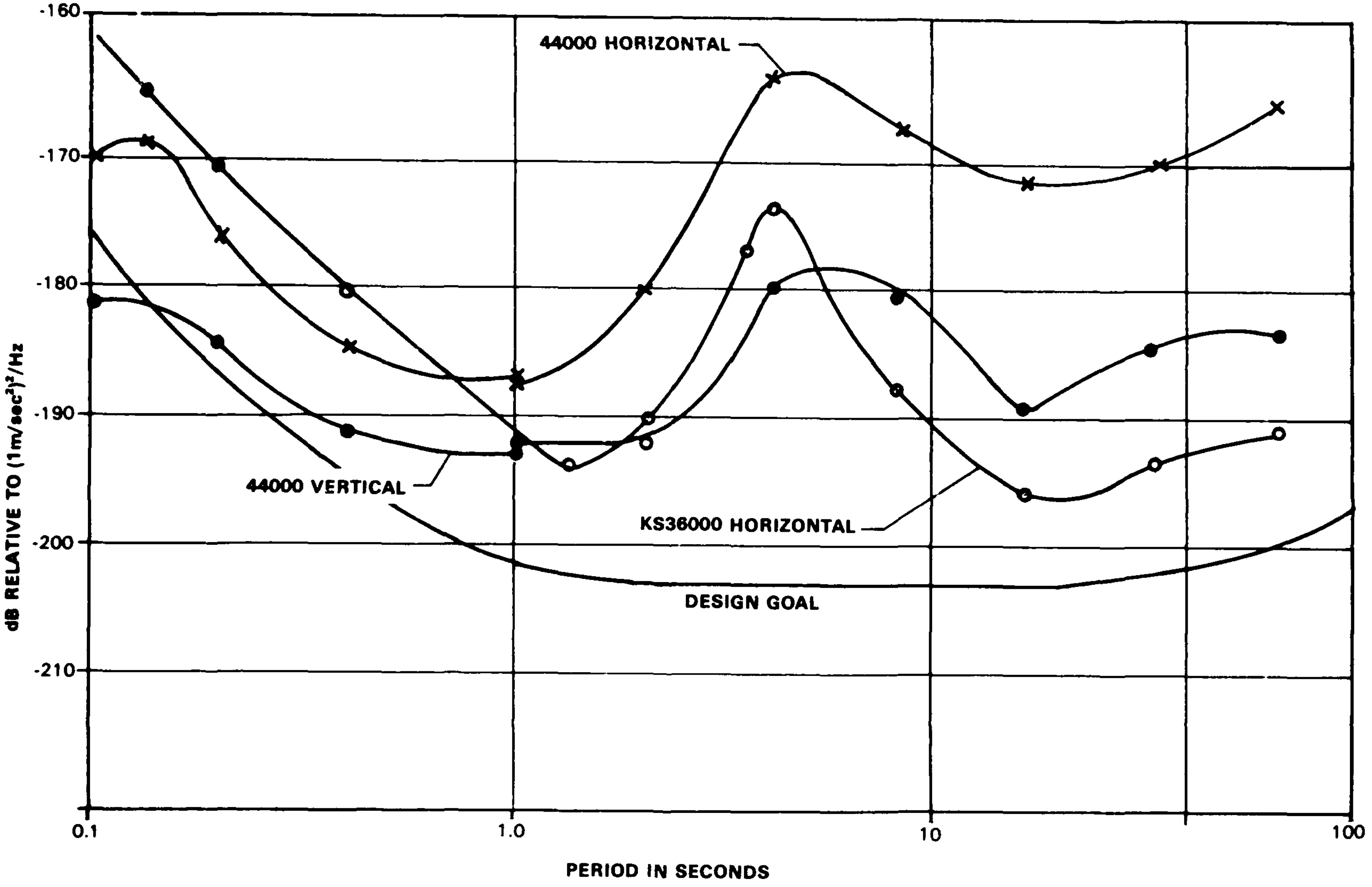


Figure 1-1. Sandia FACT Site Test Summary

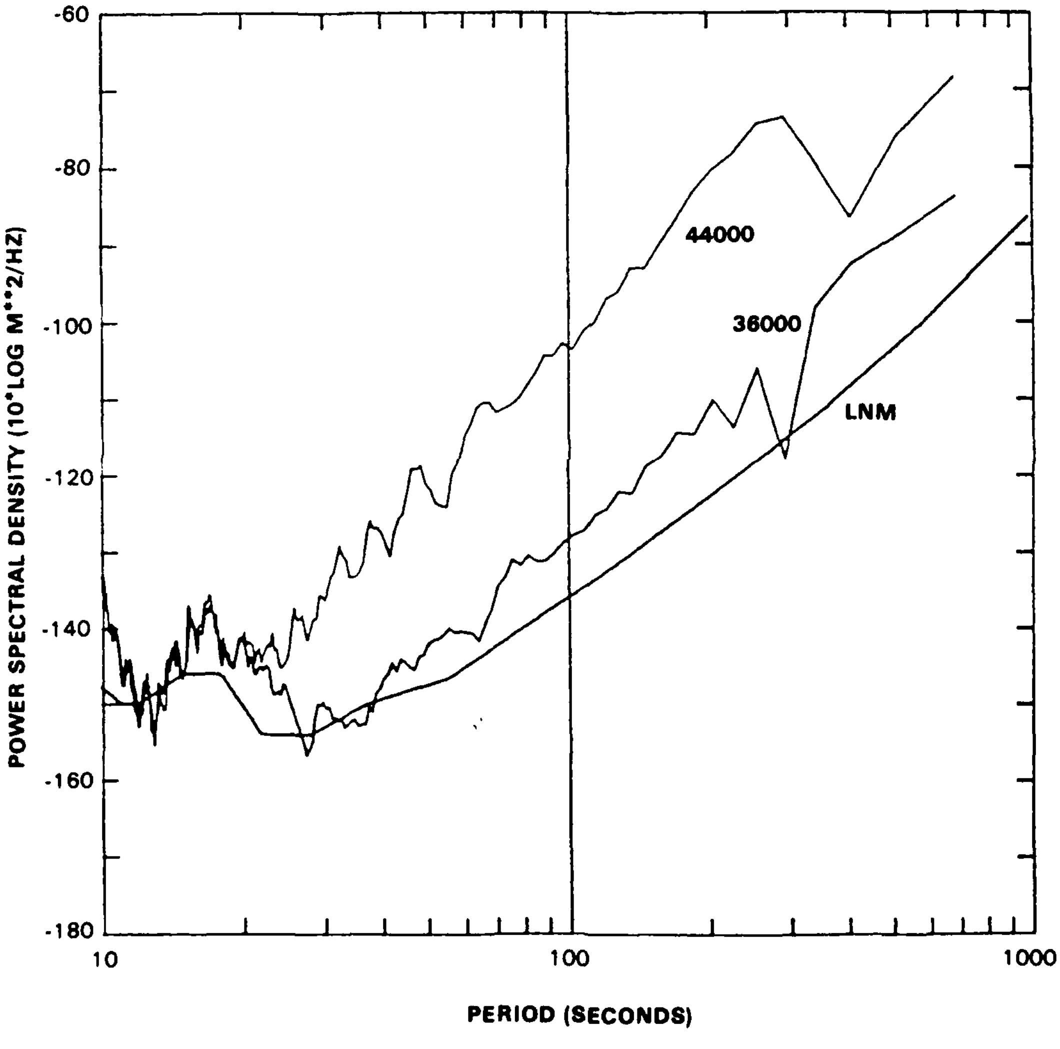


Figure 1-2. 44000 North vs. 36000 North (SRO) ASL

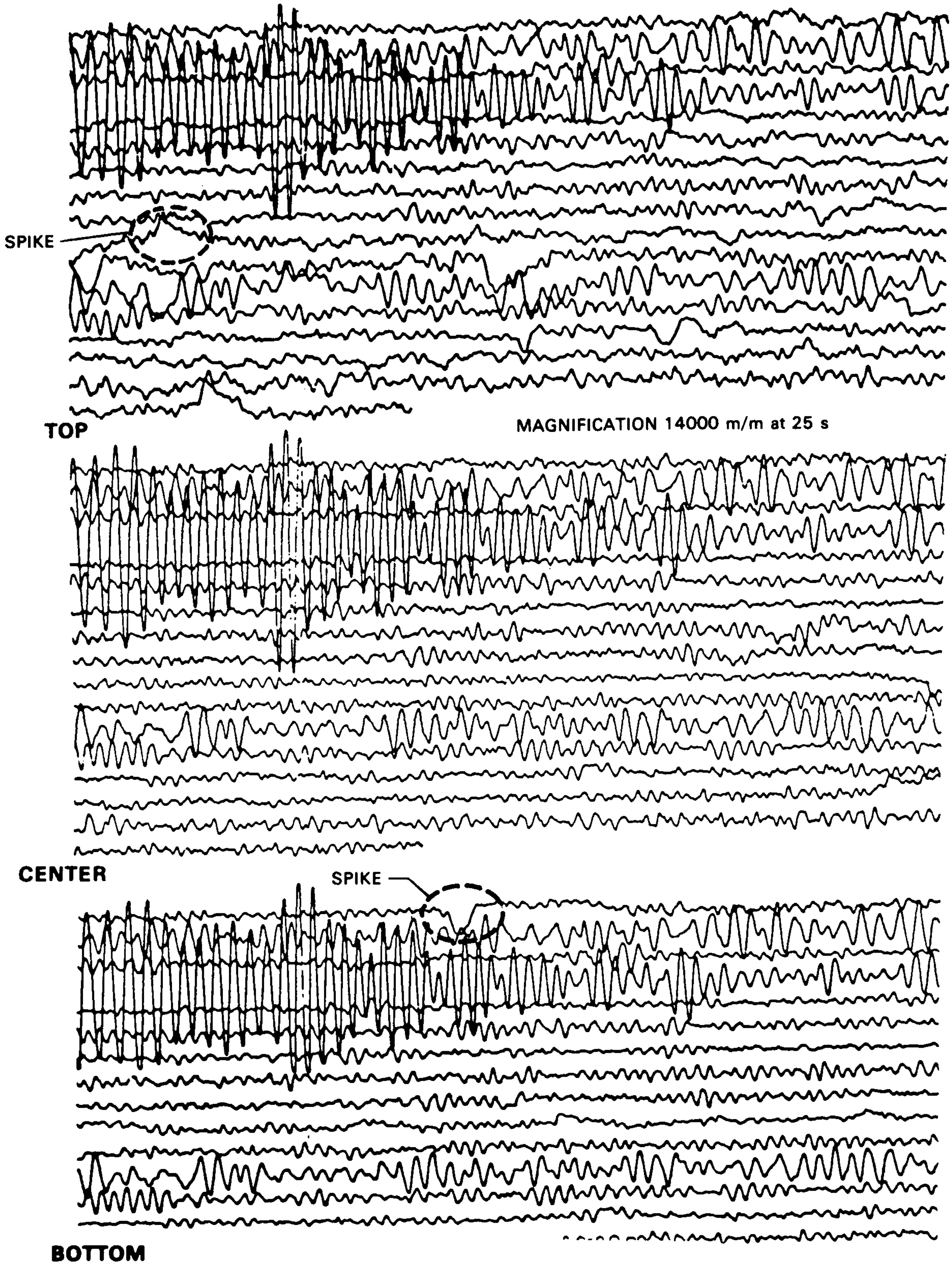


Figure 1-3. Triple Vertical LP Record

or not. Obviously, one cannot count on events of interest occurring only during spike-free intervals.

The 44000 vertical, however, performs well at long periods. Figure 1-4 shows the SRO vertical and 44000 vertical power spectral densities. Note the similarity in amplitudes at all measured frequencies. We knew that if we could solve the noise "spike" problem, the 44000 vertical would serve well as a high resolution long period seismometer.

1.2 NOISE SOURCES

1.2.1. Vertical

We believe that the module suspension causes the vertical noise. Figure 1-5 shows a cross section of the 44000 vertical module. The proof mass moves linearly (no pivot points) with a helical spring counterbalancing the gravitational force. This spring is one of the critical differences between the horizontal and vertical modules. Since the horizontal modules show no noise spikes, we believe the vertical spring-based suspension is the vertical noise source. This theory comports with spring related problems we have experienced in the past with the 36000 vertical module.

The vertical noise impulses are characteristic of materials defects or spring termination imperfections. A polycrystalline material, like the 44000 vertical spring, has many crystal boundaries. Microcracks are often located at these boundaries. Further cracking at these interfaces causes a small shift in the total spring length. This shift is impulsive in time and has an essentially white noise spectrum for frequencies small in comparison with the reciprocal of the time it takes for the crack to form. Hence, small cracking events may produce the observed spikes in the seismometer output time series.

Spring termination may also be the culprit. As the spring stretches or contracts, this force is transmitted to the ends of the spring. Each end of

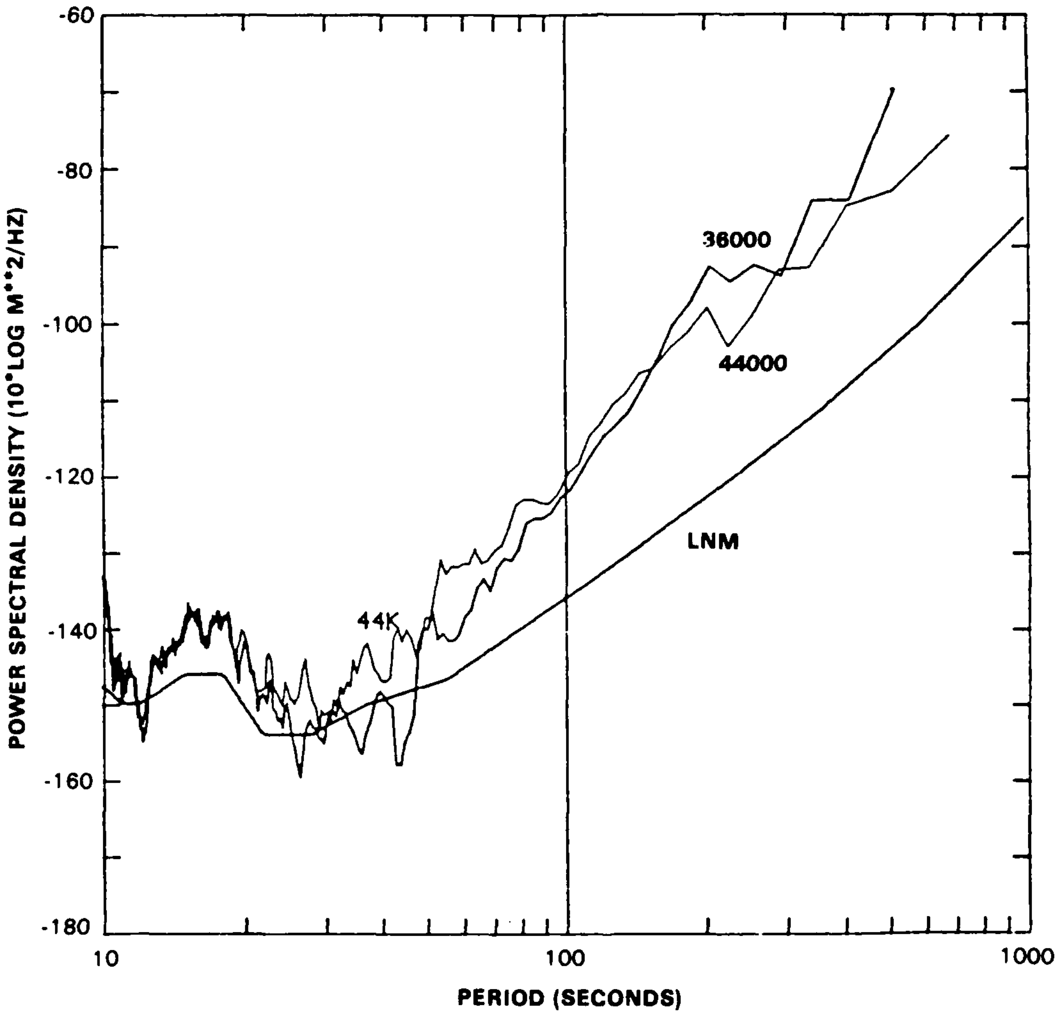


Figure 1-4. 44000Z vs. 36000Z (SRO) ASL

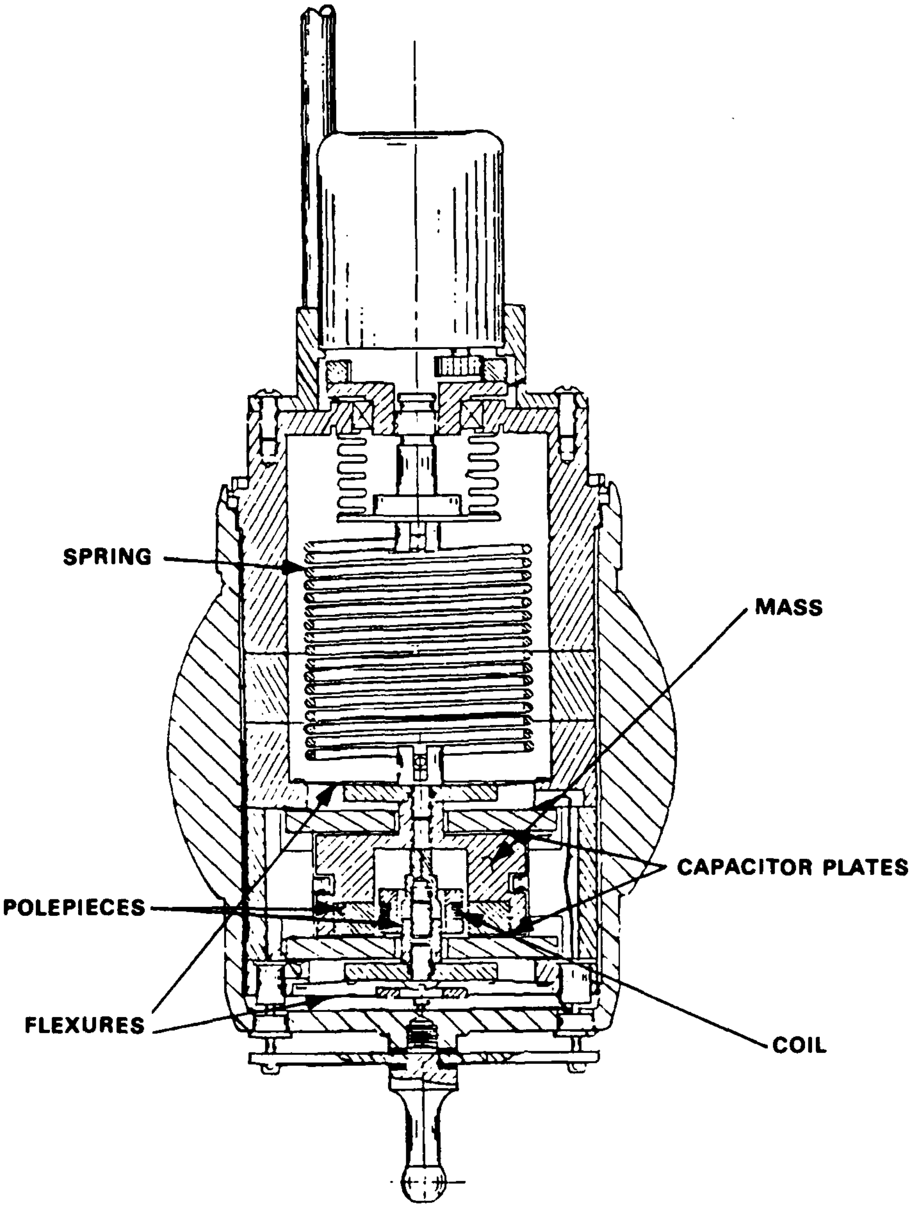


Figure 1-5. 44000 Vertical Module Cross Section

the spring is attached to an adapting terminator, which in turn connects to the frame at one end and proof mass at the other. The transmitted force has both linear and torsional components. The spring end tries to twist in the terminator as the spring length changes. If this torsional force builds up and then the spring suddenly twists a tiny amount, this will cause an impulsive change in the overall length of the spring. Like the microcracking, this will produce a spike in the seismometer output.

The forces and distances are tiny: generally less than 10^{-8} meters. It is difficult to abstractly visualize the processes at work. The closest real-life analogy is a garage door with a counterbalancing spring. When opening a garage door, the helical counterbalance spring often "pops" during the process. The theoretical 44000 vertical noise process is similar, although on a vastly smaller scale.

The tests we have performed at Garland are long period and do not effectively address this potential noise source. We feel that the cost in changing design and/or material of the vertical module internal parts is prohibitive, especially considering the time and money constraints for this follow-on work. The test data discussed in section 3 reflects this decision.

1.2.2 Horizontal

We believe that the horizontal noise is caused by a form of creep. This creep causes a time dependent tilt of the module with respect to the mechanical stack. The horizontal module shows creep noise more than the vertical since any tilt causes gravity to become part of the horizontal signal. While the vertical module is also sensitive to tilt, this sensitivity is second order in comparison to the horizontal module's sensitivity. The vertical module thus shows much less long period noise than the vertical module.

The 44000 module has an integral 2.5 inch spherical surface, which is used to hold the module in the mechanical stack. See figure 1-6 for a cross section of the module. The module's spherical surface contacts a conical seat ring

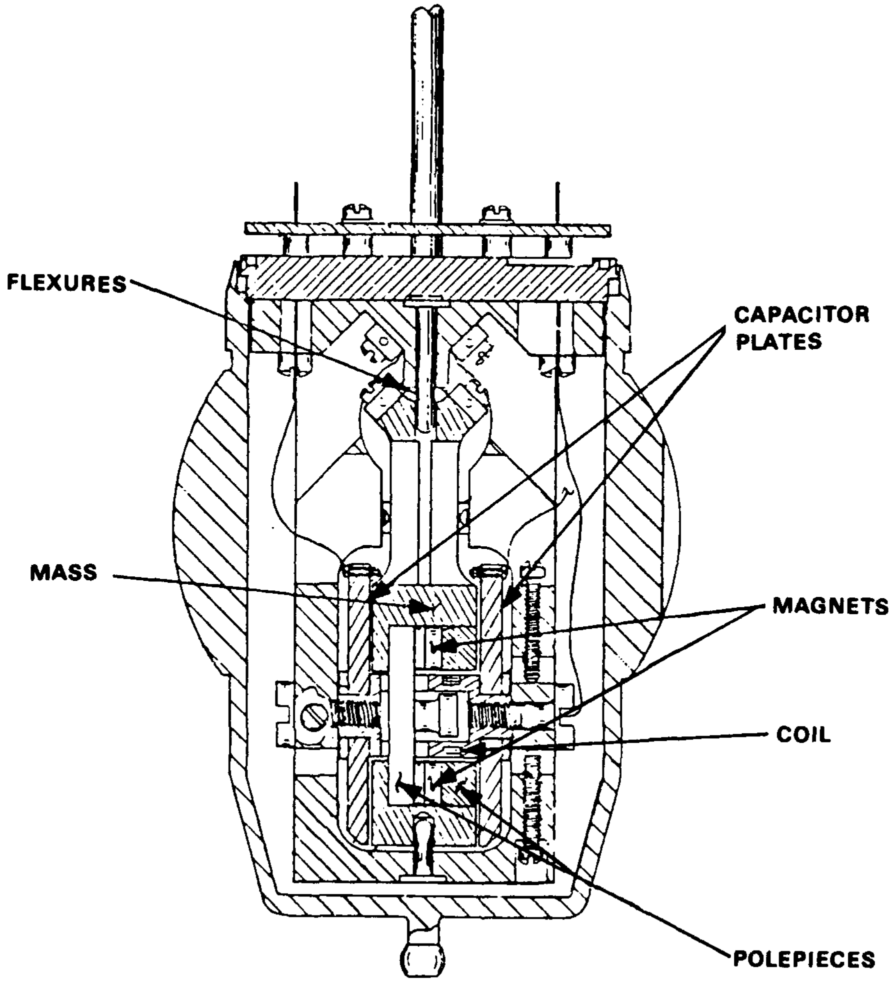


Figure 1-6. 44000 Horizontal Module Cross Section

in the mechanical stack. Another conical ring, directly above the seat ring, is spring loaded and also contacts the module. See figure 1-7 for a simplified diagram of the current module-to-mechanical stack interface (seat) design. To level the module, the leveling assembly slides the module relative to the conical seat until the module's center axis is aligned with the local gravity vector. After the leveling process, the leveling mechanism backs away from the module to remove any further force from the module. Instead of staying in position, however, the module slowly slides or creeps with time along the surface of the seat ring. Any force tending to push the module away from its initial position increases this creep rate. Furthermore, any significant vertical forces temporarily reduce the gravitational force of the module seat against the ring. Since the sliding surfaces thereby have a momentarily smaller contact force, they slide across one another more quickly. Thus, high vertical background signal, including high frequency vibrations, increase the creep rate.

The spring-loaded upper clamping ring can add to the overall creep rate. As the module slides during the leveling procedure, the clamping ring's sliding friction causes the ring to move along with the module until the force applied by the leveling mechanism overcomes this friction. Even after the leveling procedure, the spring on the upper clamp ring will tend to force the module in the direction opposite to that moved in the last leveling operation. This nonzero force will therefore induce a sliding creep.

We believe the solution to the 44000 horizontal noise lies in reducing the tendency of the module to creep relative to the seat ring. Our approach in the tests that follow relies upon reducing the forces tending to push the module away from the leveled position. While material and design changes might also be effective, we felt that identification of the noise source at a low cost was the appropriate first step.

1.3 Testing At Sandia Facility for Acceptance, Calibration and Test (FACT)

Teledyne Geotech has performed little work on the 44000 borehole seismometer

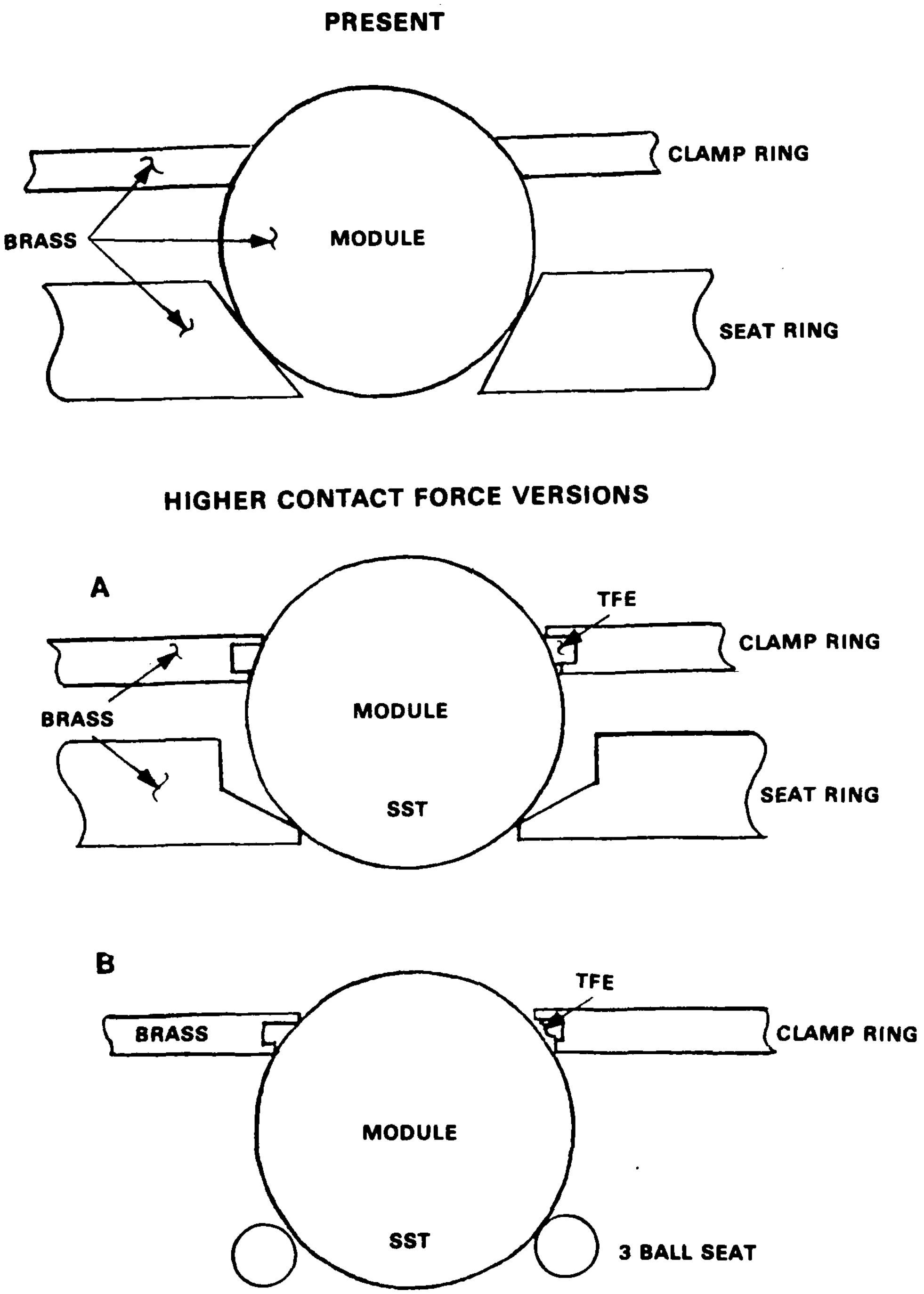


Figure 1-7. 44000 Module Seat Options

test project since the spring of 1985. The 44000 seismometer system has not performed as hoped, particularly at long periods (periods greater than 5 seconds). As noted above, this long period noise is particularly prevalent on the horizontal axes.

In order to identify the long period horizontal noise sources, Geotech devised a five step test plan to identify suspected noise sources. This plan involves a series of different configurations set up in a subsurface vault, rather than a borehole. The steps are briefly outlined below:

- Step 1: Mechanical stack, without steel cover, set up on test stand in vault to provide baseline data.
- Step 2: Loop parameter changed in electronics to provide minimum electronic noise, mechanical setup unchanged.
- Step 3: Each element of mechanical stack broken down and individually mounted to pier in vault. The only other change from step 2 is removal of the spring-loaded upper clamp ring on each module. A fourth module (vertical) added to provide two channels of vertical and horizontal data.
- Step 4: Each element removed from its stack mounting location and leveling mechanism. The four modules will be placed in a common metal plate and leveled as a unit.
- Step 5: Similar to step 4, except that each module will be leveled in a bed of anhydrous, uniformly sized sand or glass beads.

The basic premise of this test plan is that the excessive horizontal noise results from the module to stack interface, namely the brass module sliding along the sintered bronze seat. Thus, the test plan involves several changes in element mounts.

Geotech, with the cooperation of Jim Durham and George Patton at Sandia National Labs, substantially completed steps one through three at the Sandia Facility for Acceptance, Calibration and Test (FACT) in Albuquerque, New Mexico. The most notable aspect of the data is a comparison of the stack baseline and the separated modules without clamp rings. Figure 1-8 shows spectral data for the modules in the stack and for separated modules at periods from .1 second to 100 seconds. At periods greater than 10 seconds, the separated modules perform significantly better than those in the stack. At 50 seconds, for example, simply removing the clamp ring and placing the modules separately on the vault floor reduced the incoherent noise by 10 dB.

Figure 1-9 compares the separate module data with FACT borehole data on the same modules. Note that even in the vault, without the protective environment of casing and borehole, the noise levels are very similar. Such a significant change in noise for a small change in experimental setup was promising. We believe this data supports the seat noise source theory. As the Garland data shows, we have further reduced the horizontal noise by avoiding creep-inducing forces.

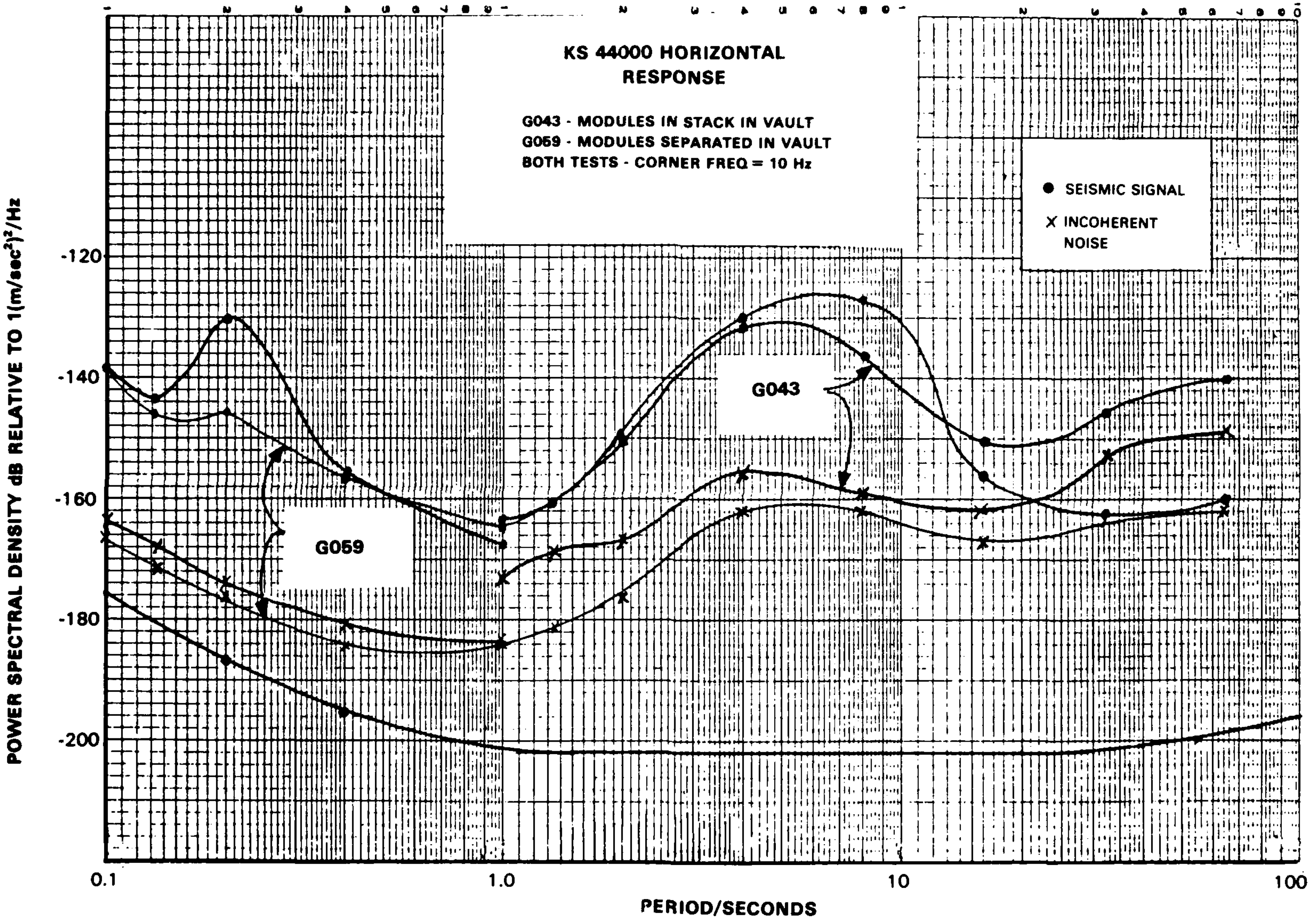


Figure 1-8. Comparison of 44000 Modules In the Stack and Modules Separated

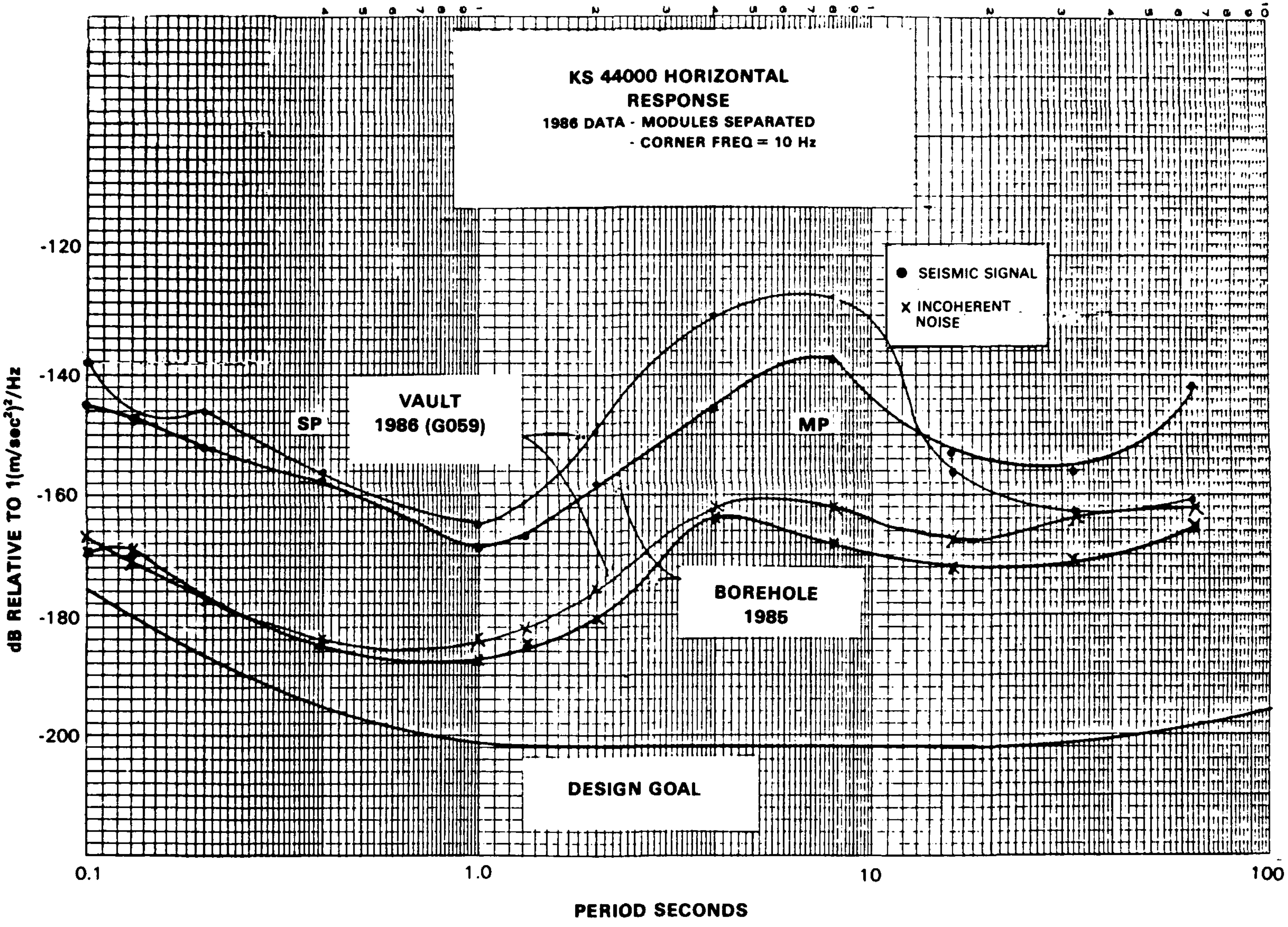


Figure 1-9. Comparison of 44000 Separate Modules With Borehole Installation

2. CURRENT TESTING

2.1 CONFIGURATION AND EQUIPMENT

We have recently duplicated the step 3 configuration at our Garland, Texas facility. Each seismometer element is securely bolted to a plate which is in turn grouted to a pier in our underground test vault. The horizontal element's sensitive axes are aligned, as are the vertical axes. We ran into some difficulty at the setup stage, as the horizontal module damping had increased to unacceptable levels (the modules, now over four years old, contained excessive gas). We simply pumped the modules down to high vacuum and baked them out again.

The modules and loop electroncis are each set up with a nominal loop gain of 2×10^4 V/m/s^2 from dc to 4.0 Hz. This gain, while slightly low, is suitable for the higher short period background at Garland. Significantly higher gain causes leveling, drift and clipping problems.

In the results reported below, we have performed no magnetic, electrostatic or temperature shielding other than what the vault naturally provides. The dramatic improvement in the horizontal data is so outstanding that we feel that there is no benefit to be gained in carrying out steps 4 and 5 of the original plan, and that immediate analysis and reporting is appropriate.

Above the vault, the broadband seismic data passes through long period filters and on to helicorder records. The filtered data also goes to our data acquisition system.

The data acquisition system is centered around an 8 channel, 16-bit, analog to digital converter. The software oversamples the data and digitally filters and decimates down to one sample per second. We then analyze the data via DADiSP™. The coherence estimate is based upon the technique explained in

Samuel D. Stearns, Application of the Coherence Function in Comparing Seismometers, Sand 79-1633 (December 1979) [especially equations (5), (7), and (11)].

2.2 RESULTS

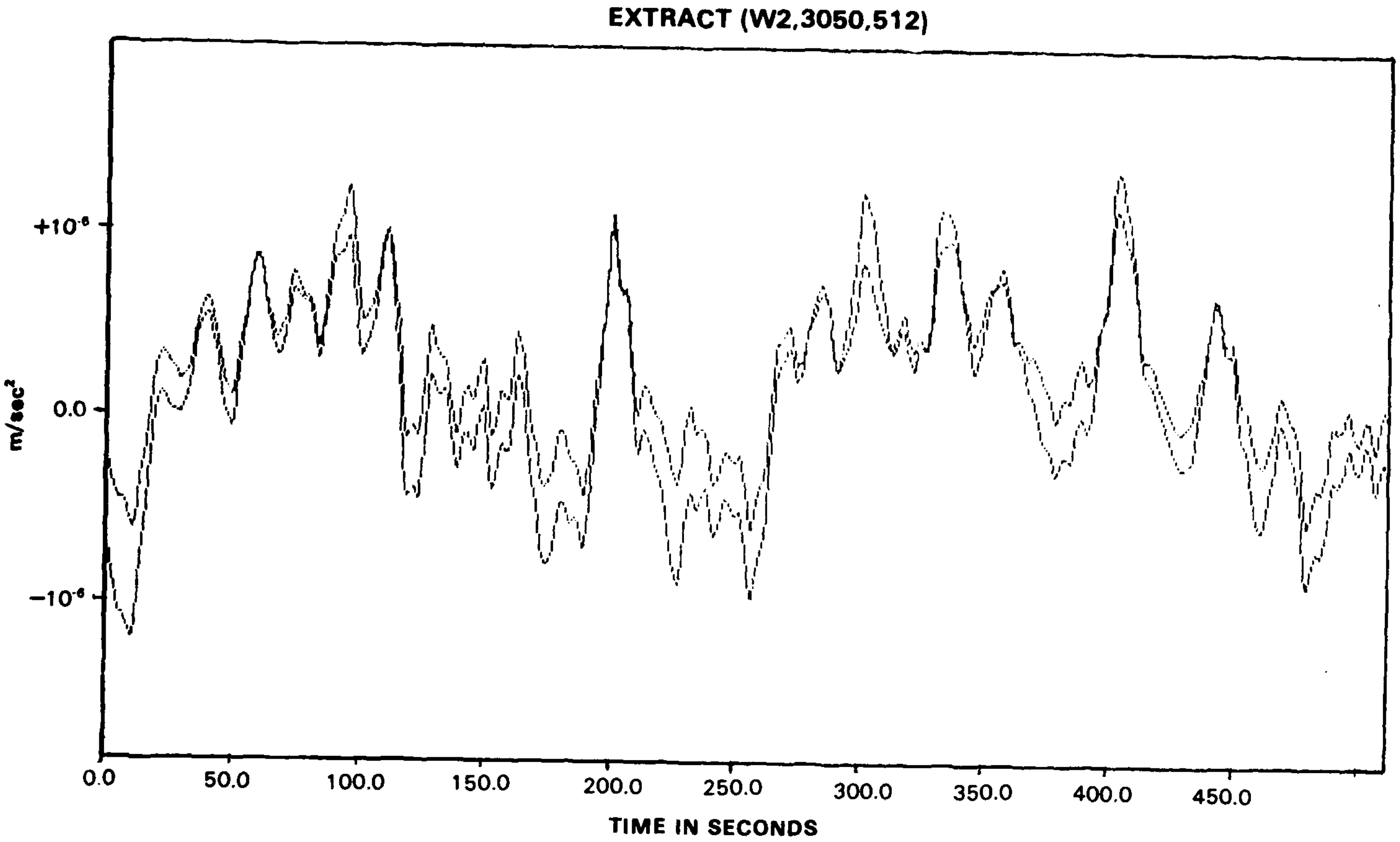
2.2.1 Vertical

Figure 2-1 depicts the time series for a pair of vertical modules in the early morning hours of March 23, 1988. The differences between the signals is noticeable, as the coherence measurement of figure 2-2 quantitatively shows. Figure 2-3 contains the auto spectrum and incoherent noise estimate for channel one.

For frequencies above 0.08 Hz, the incoherent power is comparable to that of the borehole data. Compare figure 1-1 to figure 2-3. The longer period data increases with period, however, reaching a peak of approximately -160 dB re 1 $(m/s^2)^2$ /Hz. at periods in excess of 50 seconds. As the time series for these calculations is 512 seconds long, the frequency data extends down to approximately 0.004 Hz.

The long period noise on the vertical channels is somewhat troubling, but probably results from the non-optimal installation in the vault. The borehole environment has more temperature stability and the package is filled with helium to prevent convection. The vault has a much lesser degree of thermal stability and the air can support convection. The 44000 spring in the vertical module may therefore simply be sensing these temperature changes.

Environmental variation can also influence secondary long peiod noise processes in the mechanisms discussed for the vertical suspension. Microcracking can produce a long period spectral component. The data does not show the typical spikes that we have noticed before. We feel confident,



EXTRACT (W2,3050,512)

Figure 2-1. Comparison of Two 44000 Vertical Modules

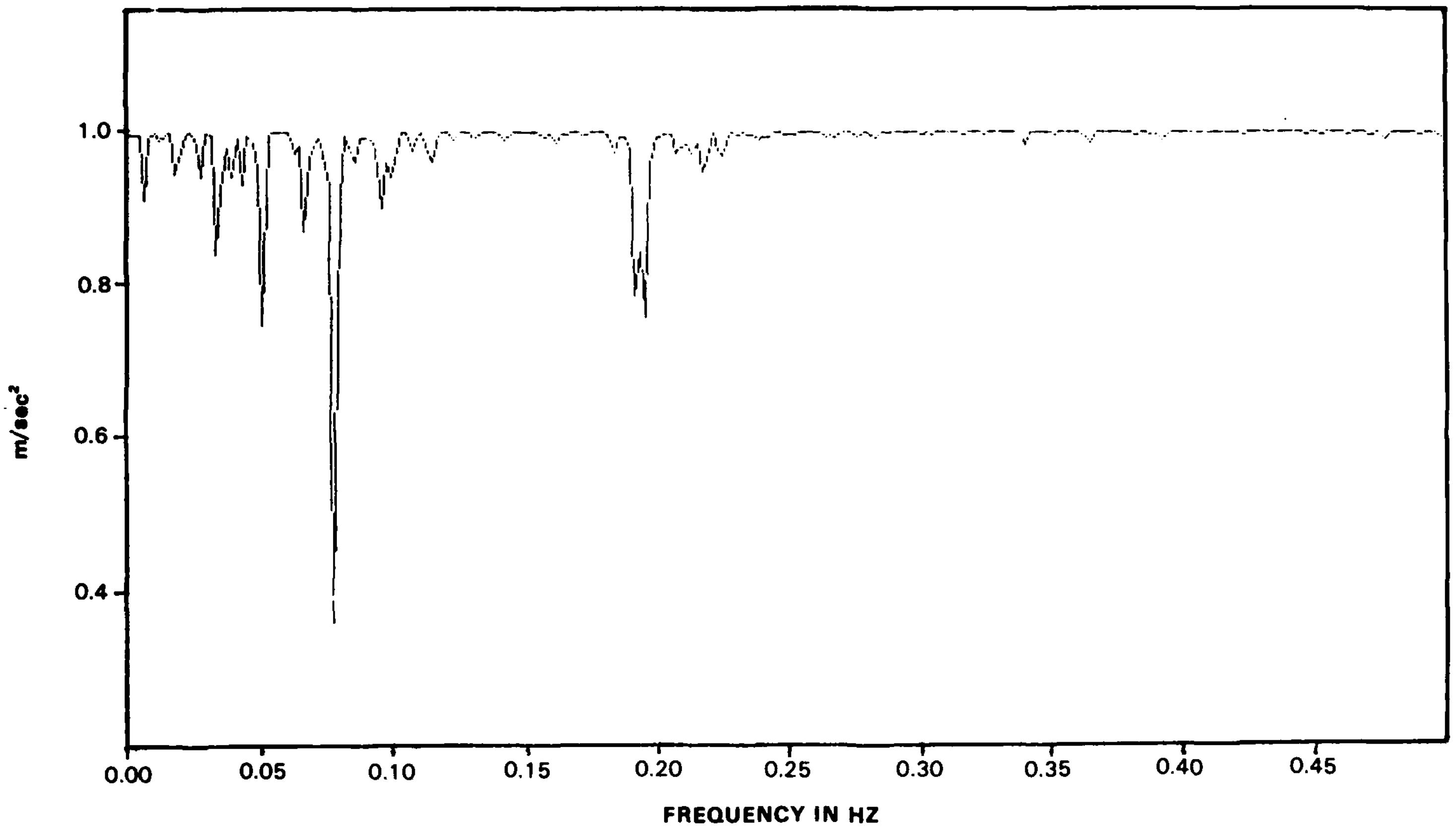


Figure 2-2. Coherence of Signals in Figure 2-1

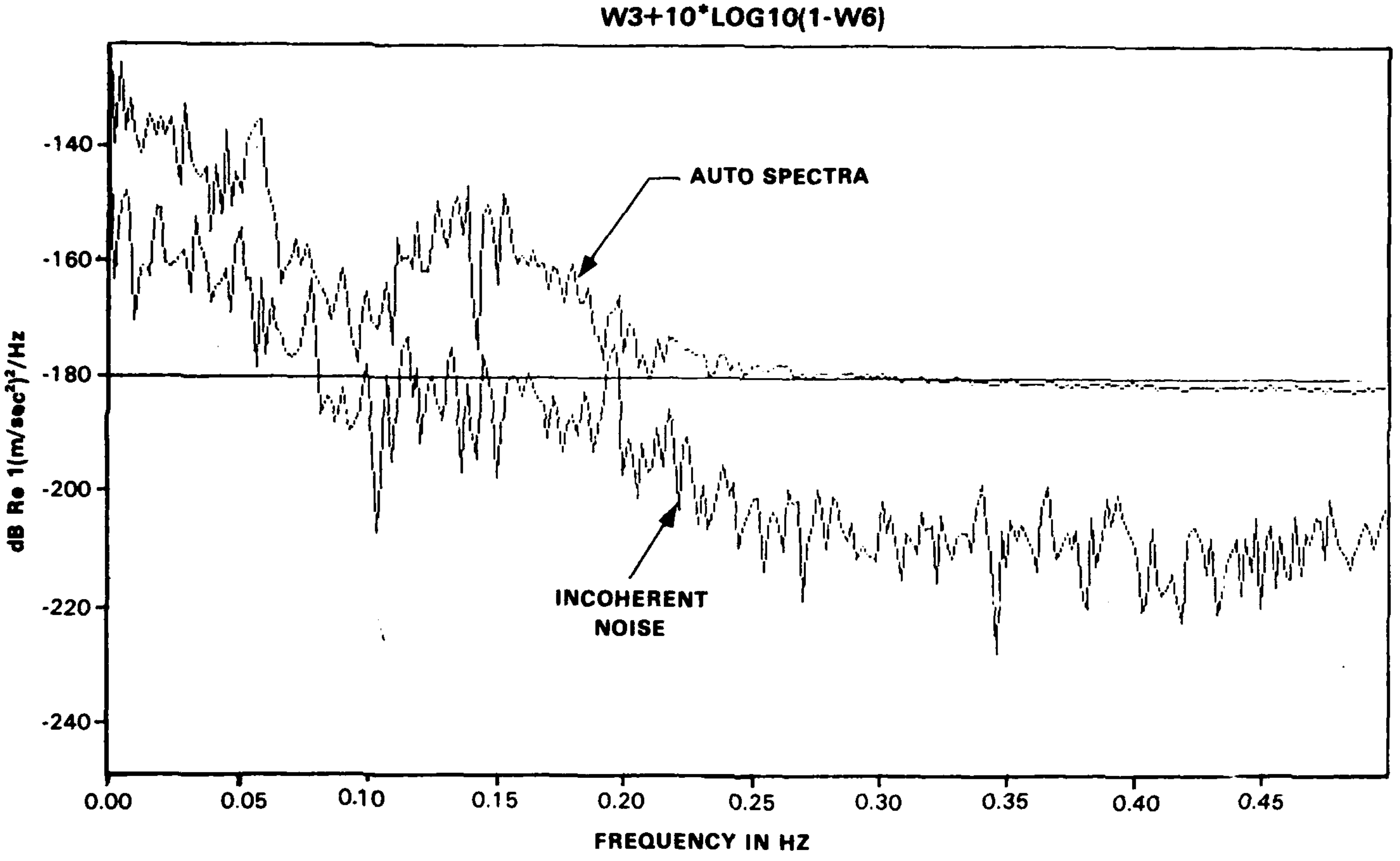


Figure 2-3. Autospectra and Incoherent Noise Estimate of Vertical 44000 in Vault Test At Teledyne Geotech, Garland, Texas

therefore, that the vertical noise is a function of this particular installation.

2.2.2 Horizontal

The horizontal performance has dramatically improved over any we have measured before. Figure 2-4 shows time series data taken during the early morning hours of March 26, 1988. The two channels overlay almost perfectly, as the long period coherence in figure 2-5 quantitatively shows. The incoherent noise is no greater than -180 dB relative to 1 $(m/s^2)^2/Hz$ from .004 Hz to 0.5 Hz as shown in figure 2-6. At 100 seconds, this surface data at the Garland site is over 70 dB quieter than the 1985 borehole data at ASL. The Garland noise data at 64 seconds is some 20 dB less than any ever taken at FACT (see figure 1-1) and, more importantly, shows no increase with period. The earth background during these tests is approximately equal to the ASL low noise model.

We believe that this dramatic improvement is due solely to changes in the module installation technique. During leveling, we removed the leveling mechanism to avoid any possible contact with the module. We further set up all wiring leading to the module so that it applied no force tending to pull the module away from level. Finally, we accelerated any drift by setting up vibrations in the frame and adjusting the module so that high levels of vibration caused no appreciable drift.

As a result of this modified installation and leveling procedure, we have seen drift rates smaller than those in earlier borehole installations. We have reduced the incoherent noise power almost beyond our ability to measure at long periods. The noise estimate data shows no appreciable tendency to increase with increasing periods.

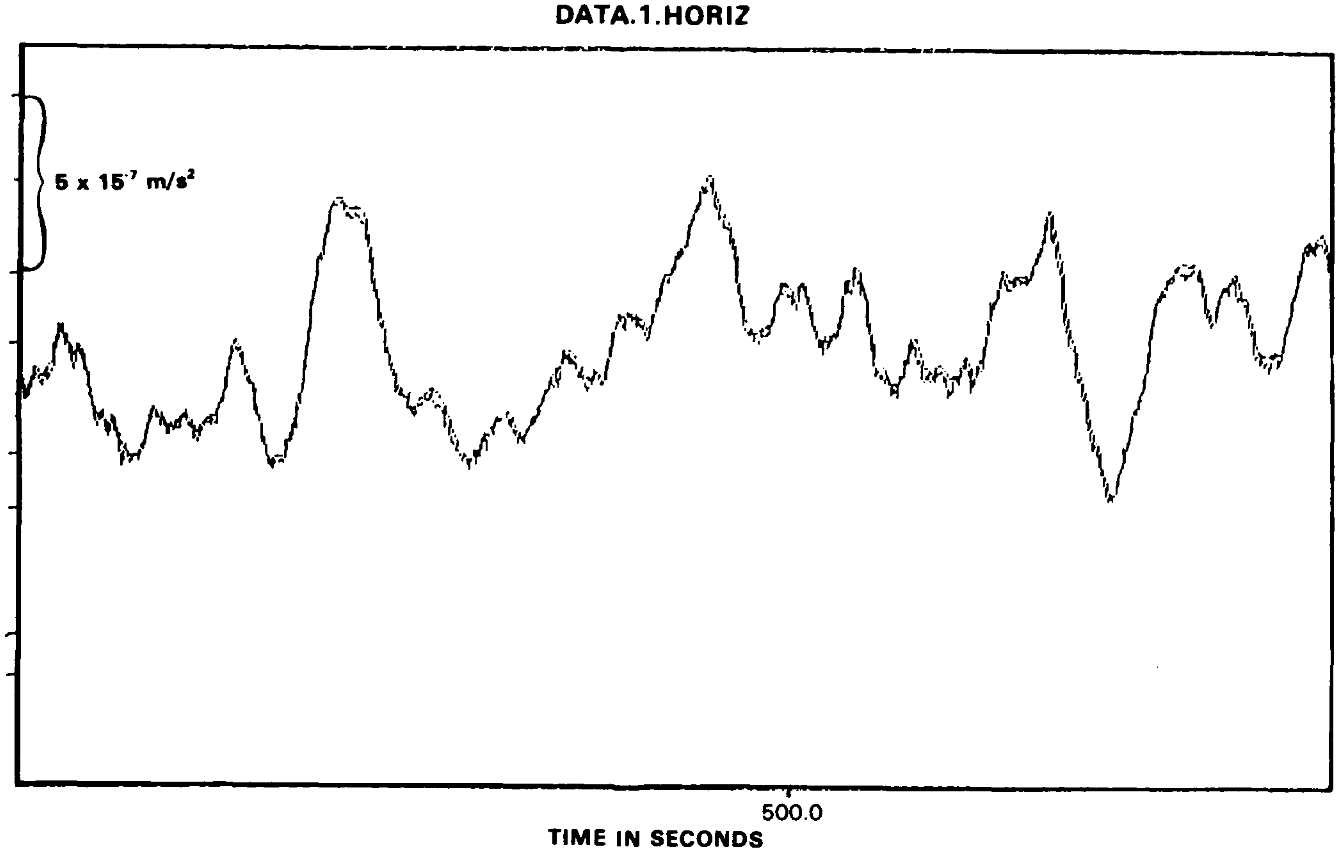


Figure 2-4. Comparison of Two 44000 Horizontal Time Traces

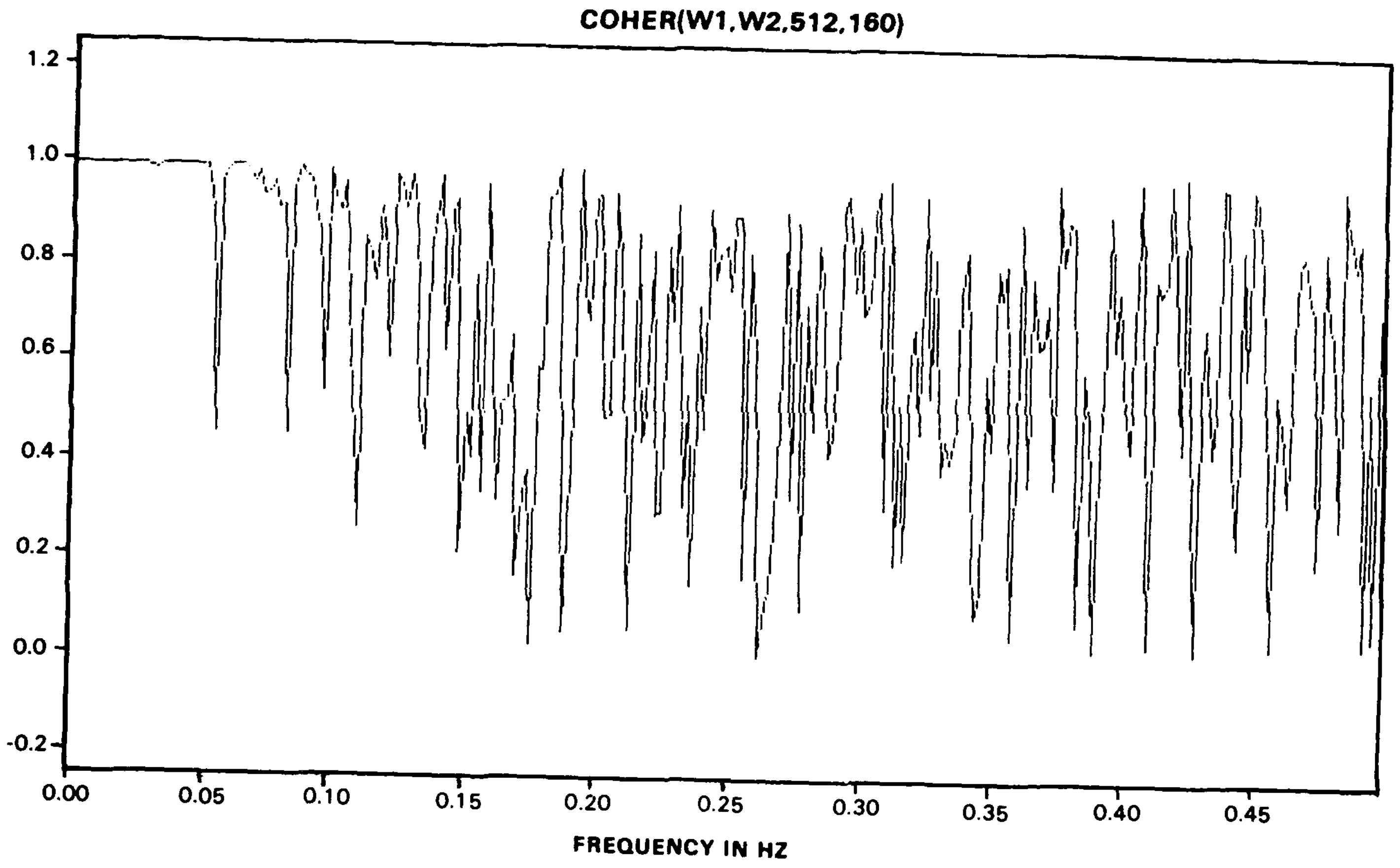

COHER(W1,W2,512,160)

Figure 2-5. Coherence of Figure 2-4 Signals

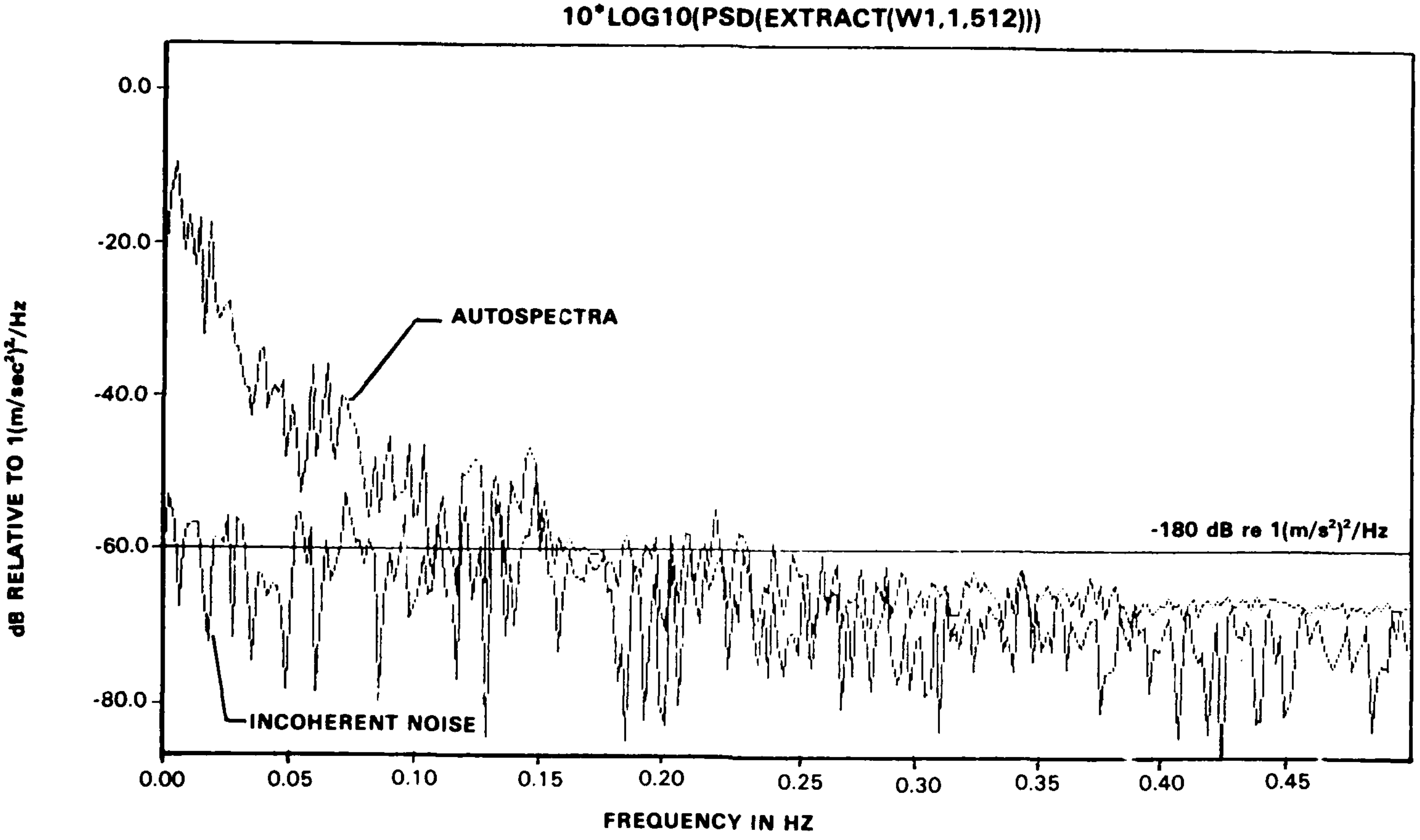


Figure 2-6. Incoherent Noise of 44000 Horizontal Modules For Vault Test At Teledyne Geotech, Garland Texas

3. CONCLUSION

3.1 HORIZONTAL RECOMMENDATIONS

The horizontal noise performance shows dramatic improvement. Since the improvement followed specific efforts planned to reduce the noise, we believe that we have identified the most significant noise source on the 44000 Horizontal modules.

To take adavantage of this information, we must change the design of the seismometer system. The upper clamping ring must be eliminated from the system. Furthermore, we must minimize all non-equilibrium forces on the modules. Electrical connections cannot be permitted to apply forces. We should consider different materials for the seat to avoid the typically high coefficient of friction between like materials. Finally we should test these changes in the vault environment where we have good baseline data from the tests to date.

3.2 VERTICAL RECOMMENDATIONS

We have not performed a controlled test on the vertical module to determine the source of the short period noise. To do so, we must disassemble subject modules and make internal changes. We may need to weld the spring terminations and/or change the spring material. Furthermore, the mass position adjustment mechanism may require modification. A piezoelectric stepper motor may provide adequate resolution in movement without the present mechanical parts.

In the long period passband, the vertical module has historically performed adequately. The seat design improvements should further improve this operation. We feel confident that the vertical module can be made to perform at least as well as the model 36000 at all frequencies.

After publication and distribution of this report, some funding will remain from budgets for field travel, step 4 and step 5. This funding should be sufficient for the purchase, and preliminary evaluation of , a piezoelectric micropositioning assembly. To our knowledge, this is a relatively new drive method which may provide important benefits in seismic instrumentation.