STABLE TEST PADS FOR INERTIAL NAVIGATION SYSTEMS**

by
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INTRODUCTION

There are many challenging civil engineering problems in aerospace projects. Most of these problems are associated with ground support facilities such as roads, buildings, drainage systems, dams and causeways, power stations, water supplies, launch pads, docks and wharves, special equipment handling devices, fuel manufacture and storage, and assembly and testing of missile components. One of these problems, which is the subject of this paper, is the design and construction of foundations which support testing equipment used in the calibration of inertial navigation systems and their individual components.

An inertial navigation systems is a self-contained combination of motion-sensitive devices with appurtenant mechanical and electronic subassemblies. When mounted in a vehicle, the system not only determines vehicle position continuously but does it automatically, and also directs the craft to its destination. One unique feature of inertial navigation is that it requires no contact with the outside world after takeoff. Inertial navigation systems were initially developed by Dr. C. Stark Draper, Professor and head of the Department of Aeronautics and Astronautics, Director of the Instrumentation Laboratory, Massachusetts Institute of Technology.

The primary sensing instruments in inertial navigation are gyroscopes and accelerometers. The performance of an

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inertial navigation system is dependent upon the product of the precision of each component. Therefore, in order to build a high-performance system, it is necessary to make each component as precise as possible.

In the past, components such as gyroscopes and accelerometers were calibrated satisfactorily on test equipment that was mounted on the basement floor of a building or on a concrete pad resting directly on the ground. In recent years the instruments being tested have become so sensitive that this method of mounting test equipment has become inadequate. The problem of providing a good support for test equipment has become so important that various groups in the aerospace industry have held meetings and symposia on the subject of test pad stability. The American Institute of Aeronautics and Astronautics has a special subcommittee on this subject.

The purpose of this paper is to review some of the environmental conditions that affect the problem of constructing a stable test foundation, and to describe some present solutions. Environmental conditions include geology of the site, variations in temperature and humidity, seismic vibrations, and wind and barometric pressure.

SOME BASIC APPROACHES

There are at present three known basic approaches to the construction of stable foundations on which are mounted test equipment for calibration of motion-sensitive instruments with varying performance specifications.

1. Find an environment which meets the test pad performance specifications and construct a test pad at this site. Specifications for a test facility may require an environment which has the least possible natural seismic noise. The quickest way to find such an environment is to look at a map similar to that shown as Fig. 1, choose a location, and confirm the map data with tests in that locality. This map shows that the shoreline areas have the greatest seismic disturbances and the Rocky Mountain regions have the smallest seismic disturbances.

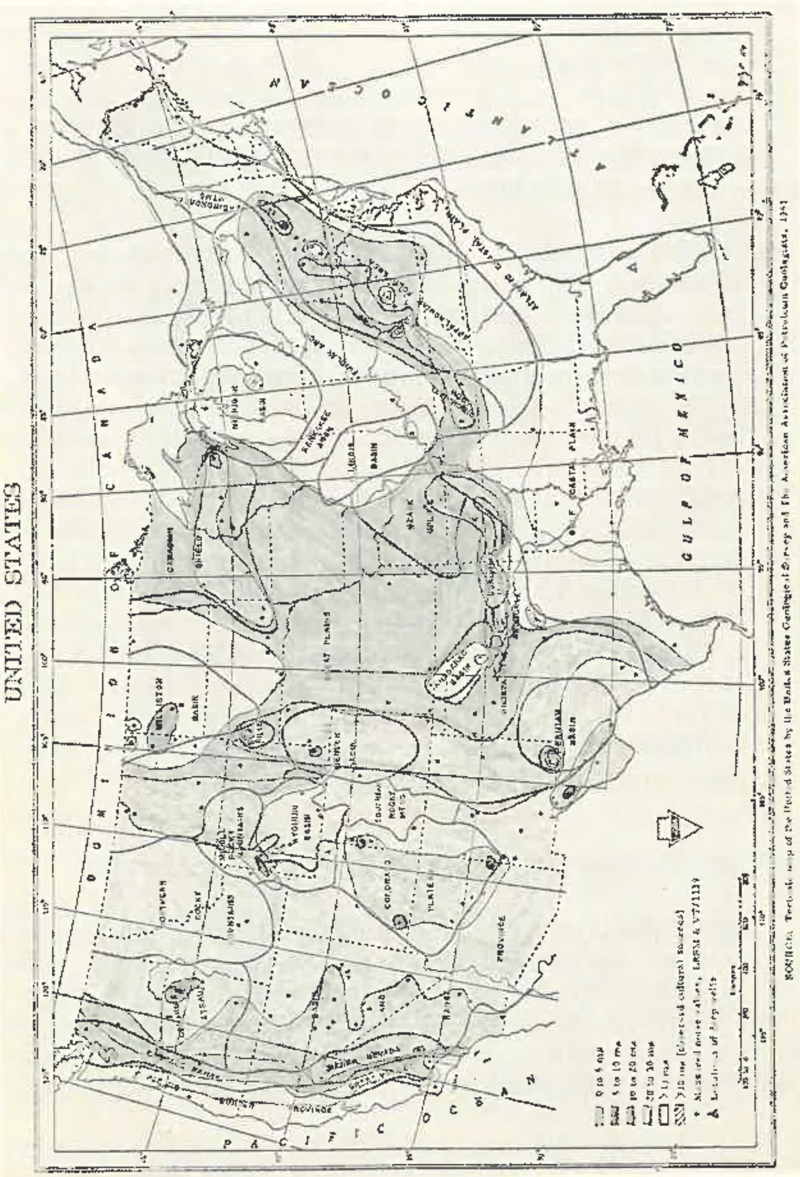

Fig. 1. Map Showing Background Seismic Noise

2. Accept a poorer environment but monitor all foundation motions in order to apply corrections to the test results. This method means that the corrections to be applied to the test results are only as accurate as the equipment used to monitor the motions of the foundation. Monitoring equipment errors lead to uncertainties in the test results. Improper application of corrections will also cause erroneous calibrations.

3. Design and build a servo-stabilized test foundation that is optimized and tuned to meet the particular needs of the test. An ideal stabilized platform is isolated from the six degrees of motion of the ground. These six degrees of motion are the linear motions along the three orthogonal axes and angular motions about the same axes. This ideal has not been attained. Most servo-stabilized platforms today are limited to the isolation of two or three degrees of freedom and have limitations of the range of isolation for each degree of freedom. Some of these systems are isolated for low frequencies which have periods of less than 10 seconds per cycle. Complete servo-isolation has not been attained for frequencies higher than 1/10 cps. A few test foundations have been isolated with passive elastic devices for frequencies of 10 cps and higher. No system, servo-driven or passive, has been developed to completely isolate the test foundation for frequencies between 1/10 cps and 10 cps.

TEST FACILITY IN A QUIET ENVIRONMENT

One of the best test foundations located in a quiet seismic environment was built by the Martin Company in Denver, Colorado. This test facility was described by (Ref. 1) L. O. Mathis, Chief, Facilities Engineering, Martin Denver, at the American Institute of Aeronautics and Astronautics Guidance and Control Conference held in Minneapolis, Minnesota, on August 16, 1965.

Fig. 2 shows the location of the selected site after a geological study of the area was conducted, and after measurements were made with seismographs to determine the charater of the vibrations in the ground.

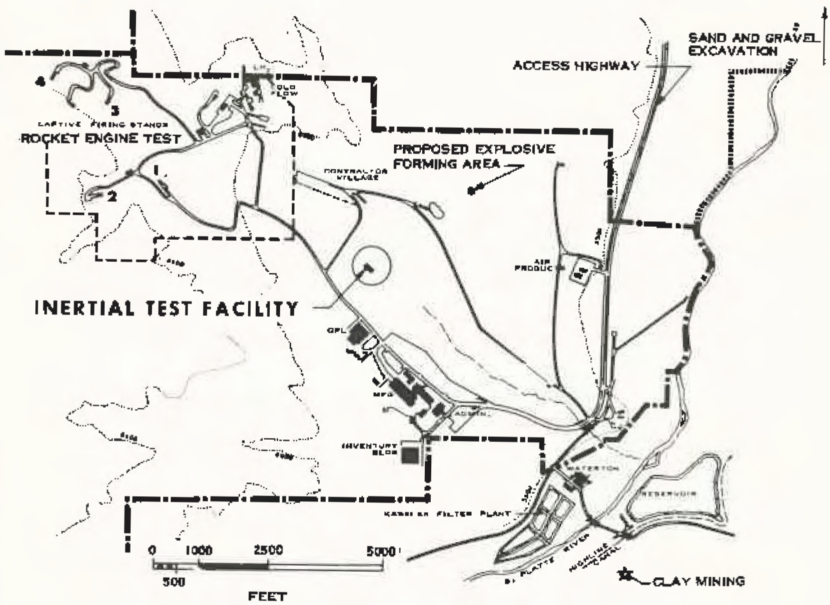

Fig. 2. Martin-Denver Area Plan

The Martin test pad is located in the eastern quadrant of the inertial test facility building, which is approximately 62 ft. by 96 ft. in plan. The pad is about 23 ft. by 39 ft. in plan, and approximately 8 ft. thick. It rests on fresh rock and is surrounded by compacted soil fill 7 to 8 ft. thick. The fill is held away from the pad by a retaining wall which rests on about 8 inches of styrofoam plastic at the rock surface, which is level with the bottom of the pad. The retaining wall is about 11 ft. high, and it is supported at mid-height by a footing extending back into the compacted fill. A false floor on soft springs spans over the pad. Concrete piers from the pad pass through holes in the false floor and extend about six inches above it. The holes in the floor are larger than the piers so that there is no physical floor-pier contact. Test instruments are mounted on the piers. All mechanical equipment such as the boiler, air conditioning blowers and compressors is mounted on mechanical spring isolators.

The Martin test facility is shown in the following figures:

Fig. 3 is a floor plan of the inertial test facility building.

Fig. 4 is a plan view of the structural framing and test pad.

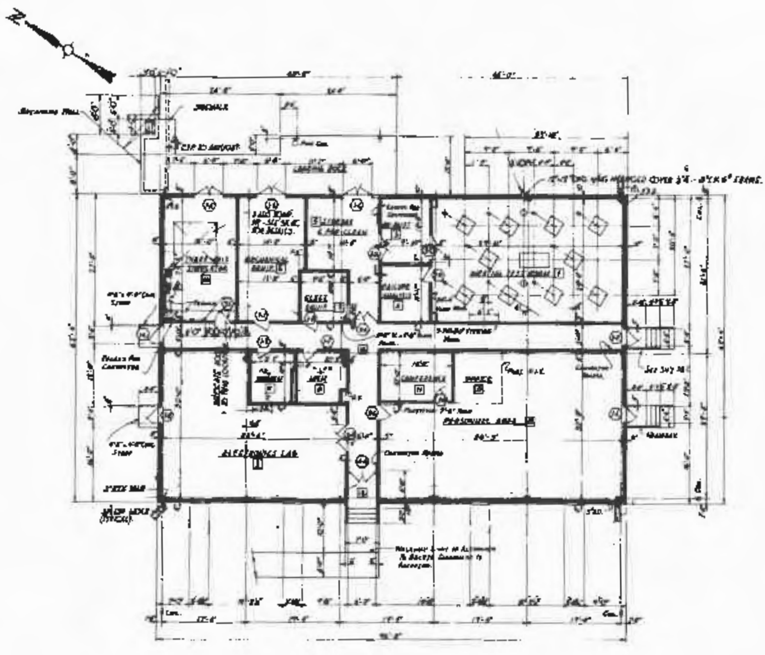

Fig. 3. Floor Plan

Fig. 5 is the east-west section of the test pad.

Fig. 6 is a photograph of the completed inertial test room.

Fig. 7 is a close-up view of the soft spring supports for the false floor.

Fig. 8 shows the tilt and vibration sensing instrumentation for testing the piers. There are three seismographs, one for each orthogonal axis, and one tilt meter.

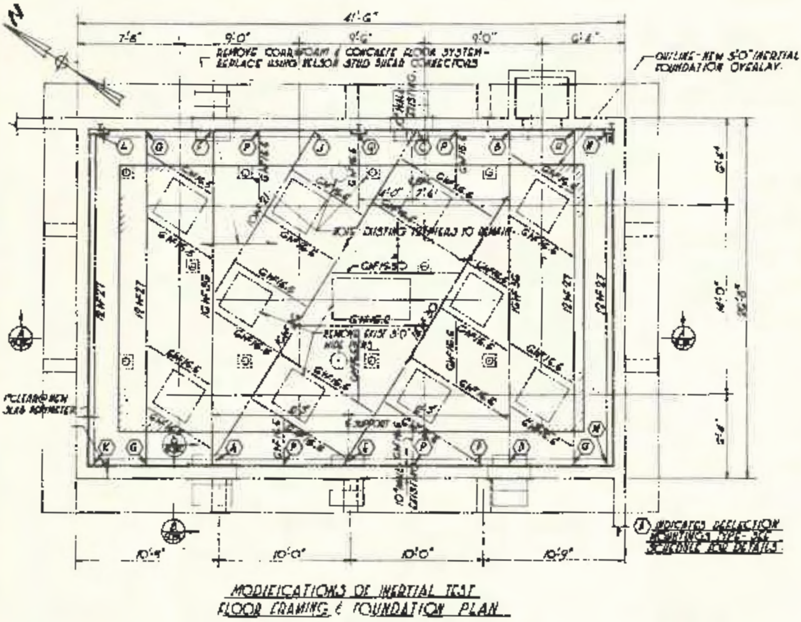

Fig. 4. Plan View of Structural Framing and Test Pad

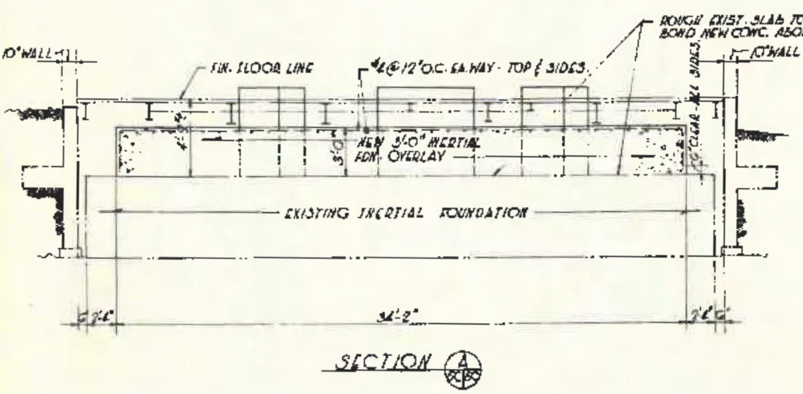

Fig. 5. East-West Section of Test Pad

Fig. 6. Inertial Test Room

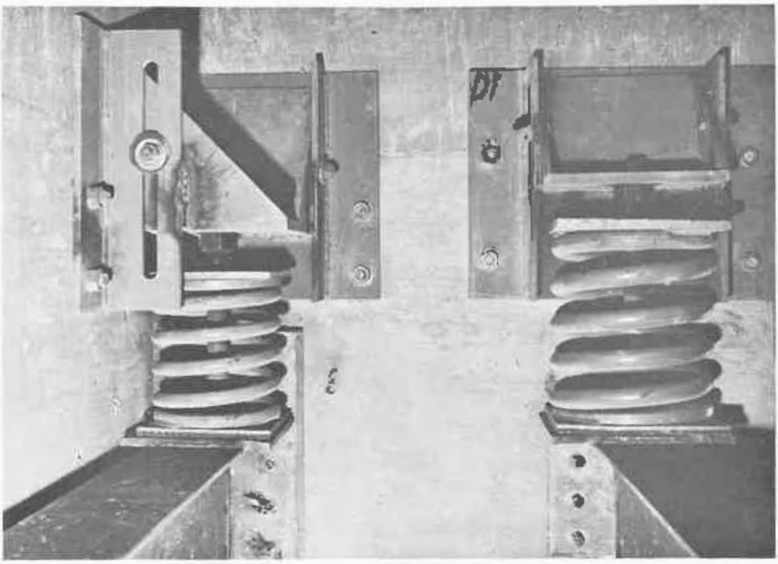

Fig. 7. Soft Spring Supports for False Floor

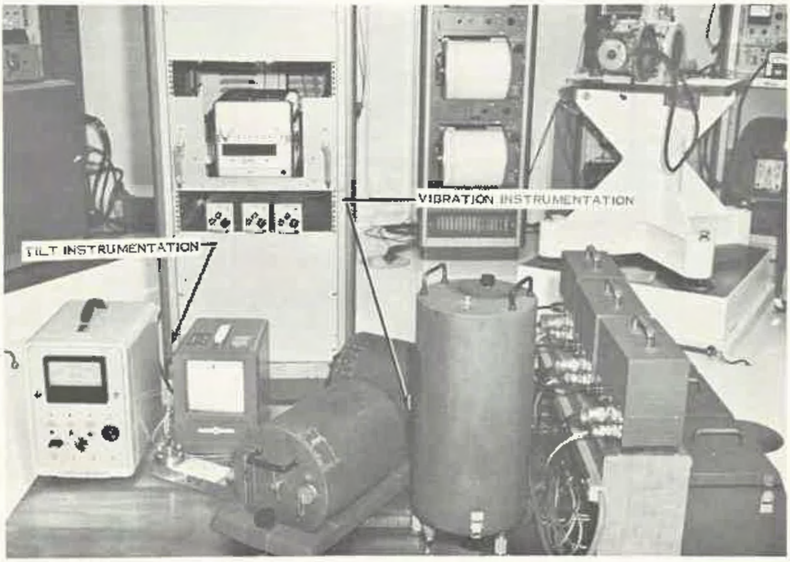

Fig. 8. Tilt and Vibration Sensing Instrumentation

The performance of this inertial test pad is summarized for vibration in Fig. 9 and for tilt in Fig. 10. Tilts are defined as angular vibrations of long periods.

Performance specifications for the Martin test pad were a maximum acceleration of 50 micro-g's and a tilt stability of 2 arc seconds within 24 hours. The summarized vibration and tilt measurements show that these specifications were fulfilled except in unusual cases for vibration such as (1) when personnel walked outside the building adjacent to the test pad, (2) when a 2-1/2 ton truck with solid tires crossed an outcrop of the test pad bedrock formation, 700 ft. away, and (3) when rocket engines were fired 8000 ft. away from the test pad.

TEST CONDITION	ACCELERATIONS					
	VERTICAL		HORIZONTAL			
			N-S		E-W	
	a µg	f cps	a µg	f cps	a µg	f cps
1. AMBIENT CONDITIONS						
a. All Equipment OFF	0.4	4	0.7	4	1.0	5
b. All Equipment OFF. (Gusty Winds)	3(T) ④	9	19(T)	22	29(T)	31
c. All Equipment ON - Normal Operation	21	25	21	25	34	25
2. AIR CONDITIONERS						
a. AC #1B Start and Run	6(T)	14	NIL ①		6(T)	14
b. AC #4 Start and Run	17	25	40	25	42	25
3. WALKING						
a. On Suspended Floor in Inertial Test Room	0.6	4	2	4	3	4
b. Corridor Adjacent to Inertial Test Room	14	28	34	32	21	28
c. Personnel Room	NIL		24	28	20	28
d. Outside Building Adjacent to Test Pad	40	28	75	28	85	28
4. DOORS CLOSING						
a. Air Lock Entrance to Inertial Test Room	NIL		10	27	NIL	
b. Inertial Test Room Door	24	27	42	30	29	29
5. BOILER START (HEATING SYSTEM)	8	36	10	26	10	27
6. REMOTE DISTURBANCES						
a. Light Van at Loading Dock	28	25	28	25	48	25
b. Shakers in Env. Lab (1300 Feet)	NIL		NIL		7	7
c. Semi-Trailer Tank Truck (700 Feet)	6	10	5	10	9	9
d. Truck - 2½ Ton, Solid Tires, (700 Feet) ②	62	13	113	13	54	13
e. Simulated Explosive Forming - (3800 Feet) ③	23	5	9	4	13	5
f. Rocket Engine Firing (430,000 lbs. Thrust) - 8000 Feet ③	2900	182	3100	125	3700	60

Notes:

① "NIL" Signal Not Distinguishable from Ambient

② Truck Crossed Outcrop of Bedrock Formation on Which Test Pad is Located.

③ Measured on Bedrock Prior to Installation of Test Pad.

④ (T) Indicates Transient Occurrence

Fig. 9. Summary of Vibration Measurements on Test Pad

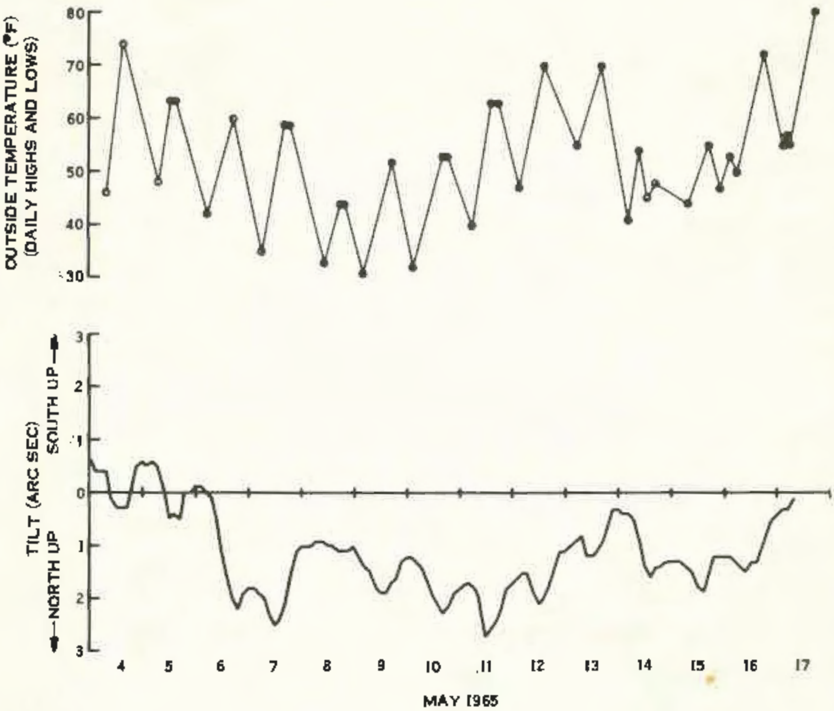

Fig. 10. Test Pad Tilt

HONEYWELL INERTIAL TEST SLAB STABILITY STUDY

A very extensive series of tests for measuring tilts of the ground has been carried out by Honeywell, Inc. of Minneapolis, Minnesota. The purpose of this study was to determine the principal causes of long period test slab motion. Results of these tests were presented (Ref. 2) by Ralph T. Berg, Honeywell Development and Evaluation Laboratory Engineer, at the AIAA Guidance and Control Conference of August 16, 1965.

In the Honeywell study, concrete slabs were positioned strategically on common geological formations of the upper midwest area, both on the surface and underground. Typical formations included sandstone, silica sand, granite, quartzite and sand over clay. The test sites of this study were: Roseville, a suburb of Minneapolis; Zimmerman, a rural area north of Minneapolis; St. Peter Sandstone, a sand mine tunnel in St. Paul, Minnesota; St. Cloud, Minnesota, northwest of Minneapolis; and Baraboo, Wisconsin, located between Milwaukee and Minneapolis.

The Honeywell investigations consisted of measuring low frequency ground tilts with precision level vials and recording the bubble positions photographically. Fig. 11 shows the construction of one of the precision level vials used in the study.

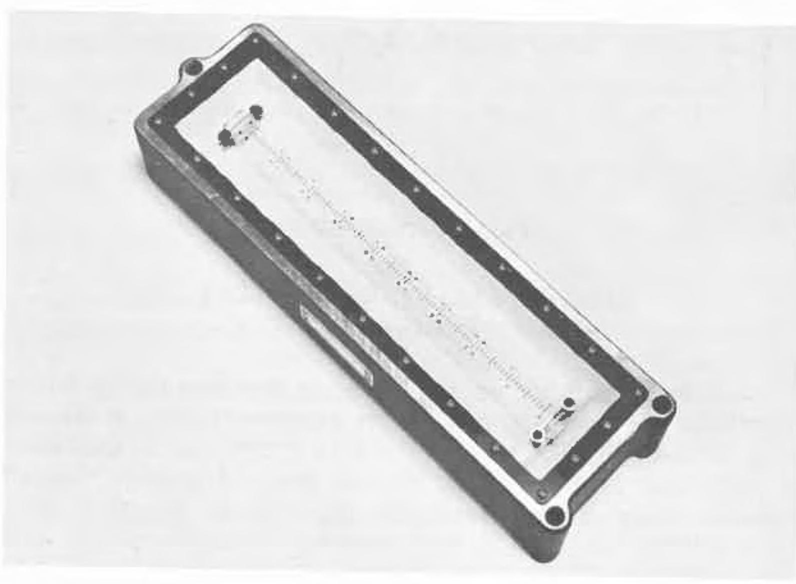

Fig. 11 Precision Level Vial

Fig. 12 shows the array of level vials, clock and counter assembled on a triangular plate. This plate rests on the concrete slab or on the surface to be measured. Fig. 13 shows how the level vial positions are recorded photographically.

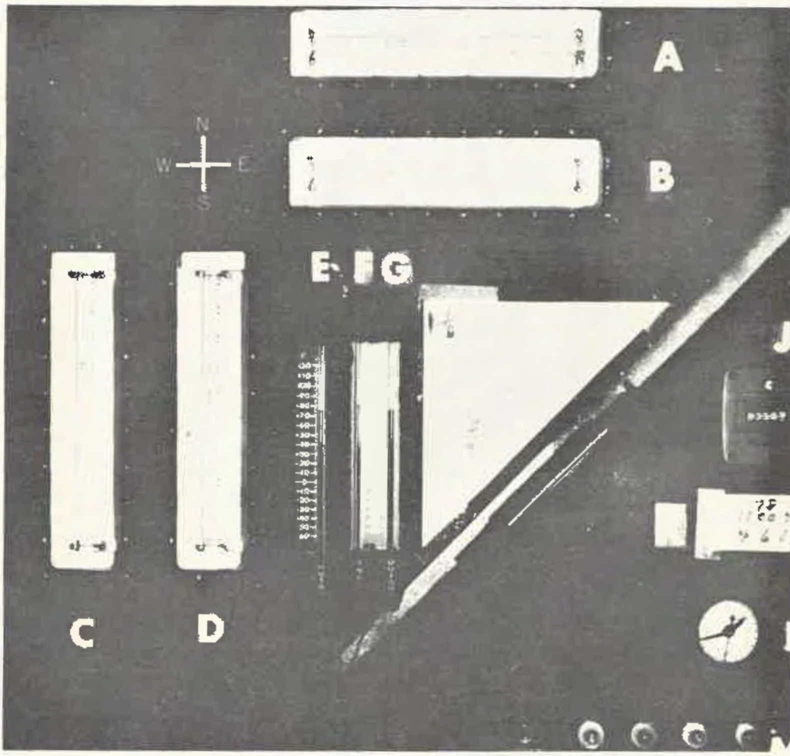

Fig. 12 Typical Data Frame

Roseville Sites

There were four slabs on ground in a building located at Roseville. They are shown in plan view as Fig. 14. Roseville No. 1 was a square slab. Roseville No. 2 was a square slab built for a concrete stability test. Stainless steel studs were inserted in the slab and measurements were made with a

Fig. 13 Camera Mount Set-Up

level to determine relative heights of the studs as the concrete aged. Roseville No. 3 was a square slab mounted on sand and clay. Roseville No. 4 was a circular slab mounted in clay surrounded by 4 ft. of sand.

Tests results for the period April, 1963, to January, 1964, are given in Fig. 15 for Roseville No. 1 and on Fig. 16 for Roseville No. 3. Fig 17 gives test results for Roseville No. 4 for the period May, 1963, to January, 1964. Fig. 18 gives results of the Roseville No. 2 concrete slab stability test. This graph shows the creep rate or distortion with age of this 12 ft. square slab.

Results of tests at Roseville stations 1, 3 and 4 show the slabs had daily oscillations of from 2 to 4 arc seconds, and long period tilts of 6 to 12 arc seconds. Roseville No. 2 tests showed that creep was rapid for the first two months after casting, but the creep rate was slower for the next eight

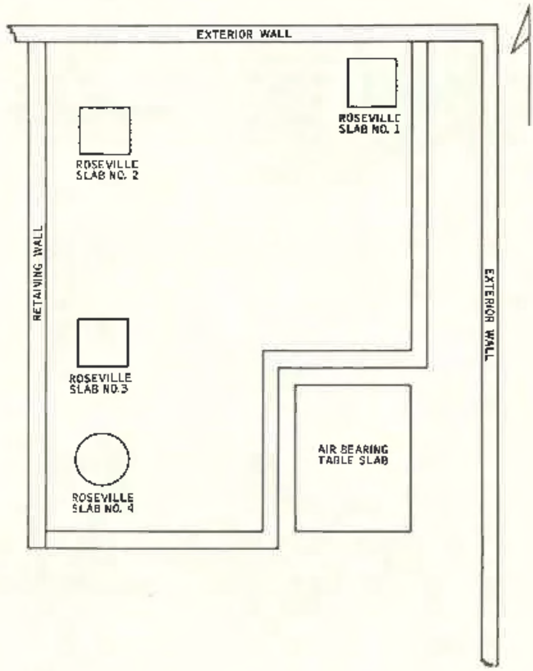

Fig. 14. Roseville Test Site

months. This seems to indicate that the concrete slab will continue to distort for a long time before reaching a dimensionally stable condition.

Zimmerman

At the Zimmerman test site, a housing was built around a concrete slab resting on silica sand. The depth of the sand was 225 ft., and the water table was at a level 8 to 10 ft. below ground surface. Ground temperature was measured by thermocouples placed at 2 ft., 4 ft. and 6 ft. below ground level. In addition to surface tests for tilts caused by natural disturbances, thermal tests and underground tests were conducted at this site.

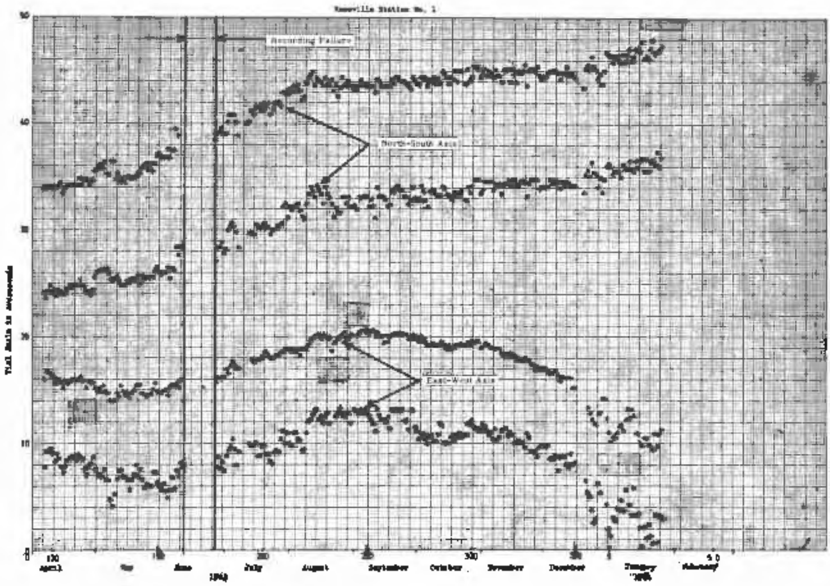

Fig. 15. Test Results Roseville #1

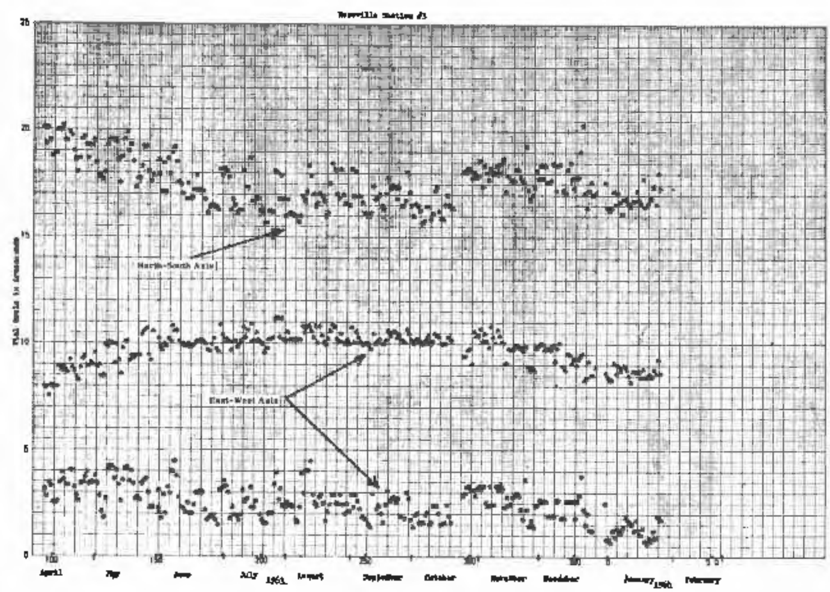

Fig. 16. Test Results Roseville #3

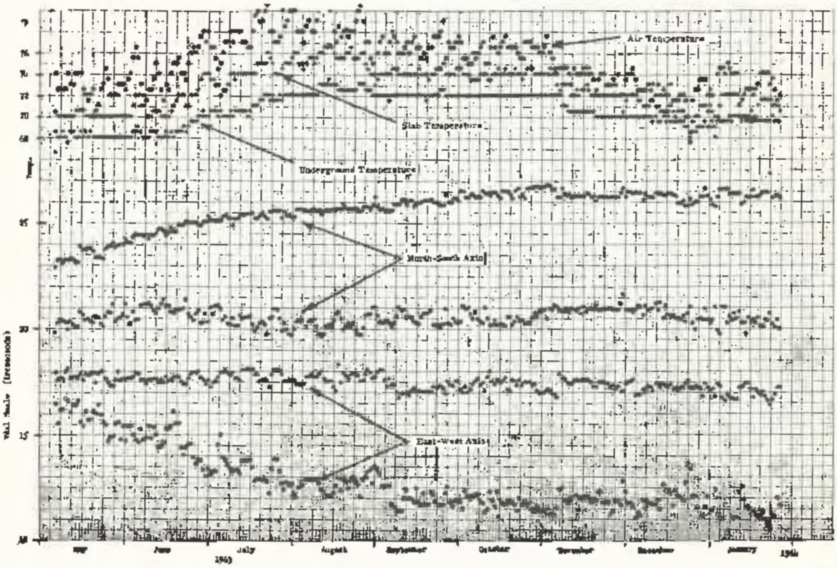

Fig. 17. Test Results Roseville #4

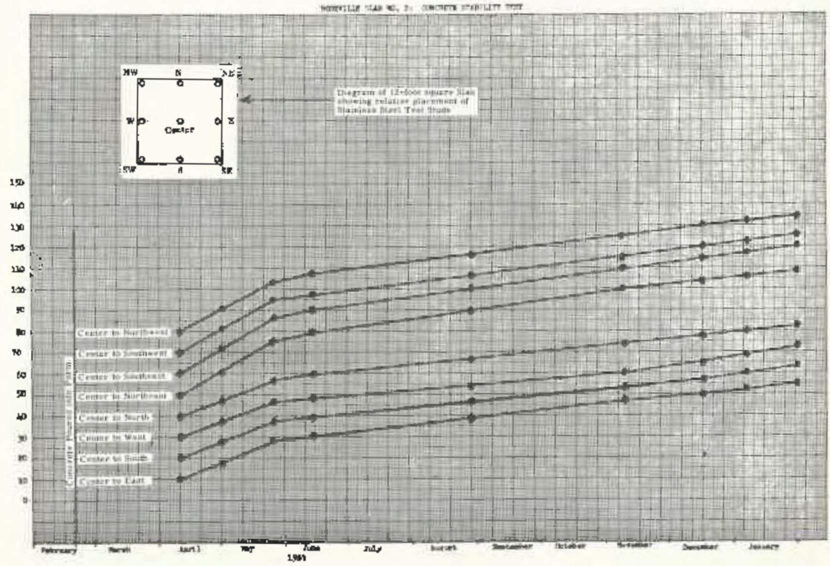

Fig. 18. Concrete Slab Stability Test Roseville #2

After approximately five and a half months of tilt measurement for natural causes, an artificial heat pulse was introduced into the supporting soil 4 ft. south of the slab and 2 ft. below ground level. In order to introduce the heat pulse rapidly into the soil, aluminum rods were driven 30 inches into the base of the pit. Eight hundred pounds of petroleum coke were burned in this pit over a period of four days.

At the time the fire was extinguished, there was little change in slab orientation. However, monitoring thermocouples indicated that a heat pulse was moving to the soil supporting the slab. The maximum deflection of the slab occurred nine days after the beginning of the pulse. The maximum slab tilt in the east-west axis was about 7 seconds, and the maximum tilt in the north-south axis was about 5 seconds. The purpose of this test was to confirm that horizontally stratified thermal gradients cause test slab tilts.

Since thermal gradients exist near the ground surface, it was decided to test for tilts below the ground surface. A test station was placed at a depth of 7 ft. below ground. This location was a foot above the water table at the site. It was theorized, and later confirmed, that the relatively high thermal conductivity of water would reduce thermal gradients to a minimum. The instrument mounting plate was placed directly on the sand. Test equipment indicated rotational and thermal gradient stability for two months, after which tilts of the instrument plate were observed. The cause of the tilts was determined to be the drying out of the surrounding sand. This test indicated that changes in moisture content of the soil also cause ground tilts.

In addition to the preceding tests at Zimmerman, soil temperature measurements were taken at depths of 2 ft, 4 ft. and 6 ft., from July, 1964, through December 1964. The temperature records show that a uniform ground temperature of 50° F was reached in December. This ground temperature of 50° F was noted at all of the underground test sites. It was also found that local thermal gradients occurred in the shadows of buildings and trees. Computations were made which indicated that yearly fluctuations in ground temperature will not be observed at a depth of 52 ft. or more. Fig. 19 is a record of the tilts measured at this site from December, 1963, to December, 1964. This record included the artificial heat pulse experiment. Fig. 20 shows Minneapolis temperatures which were similar to weather which occurred at Zimmerman, 45 air miles distant. Fig. 21 is a record of the test 7 ft underground at Zimmerman. This graph shows the effect of the change in moisture content of the surrounding sand at the test location. Fig. 22 is a record of the Zimmerman site ground temperature at depths of 2 ft, 4 ft and 6 ft for the period July, 1964, through December, 1964.

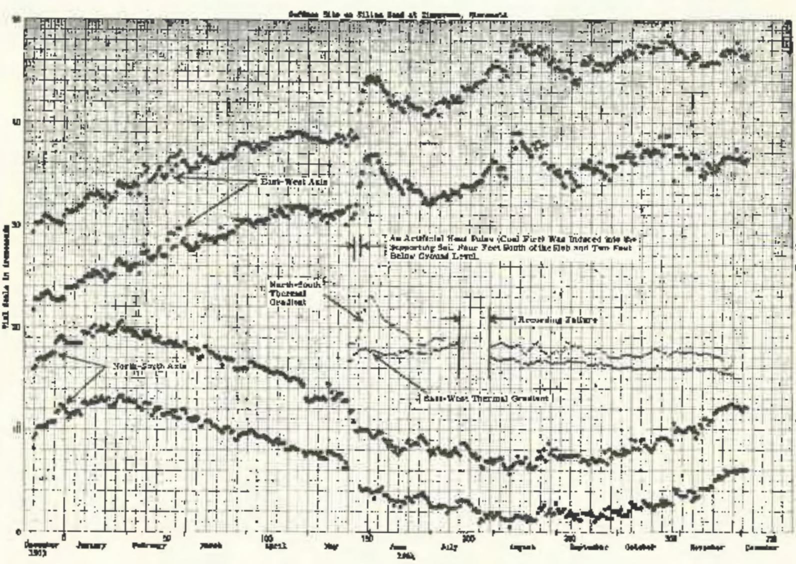

Fig. 19. Test Results Zimmerman Surface Site

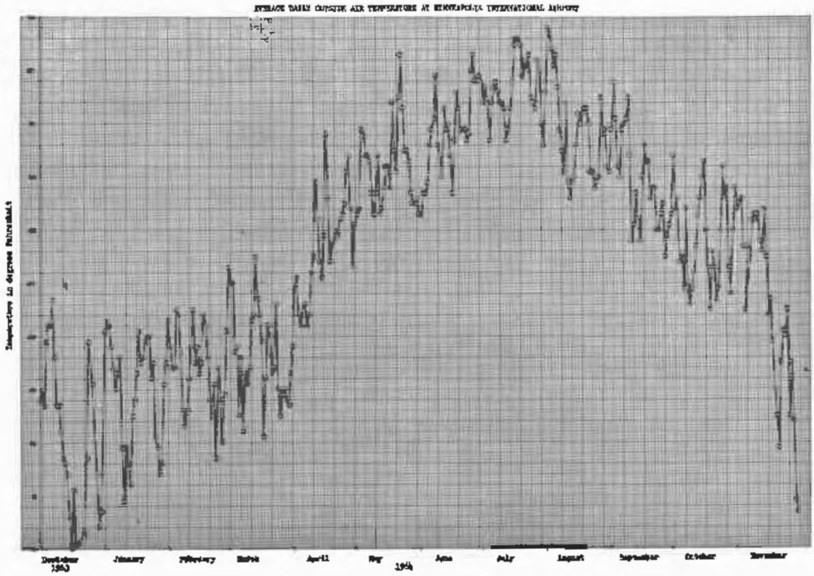

Fig. 20. Minneapolis Average Daily Outside Air Temperature

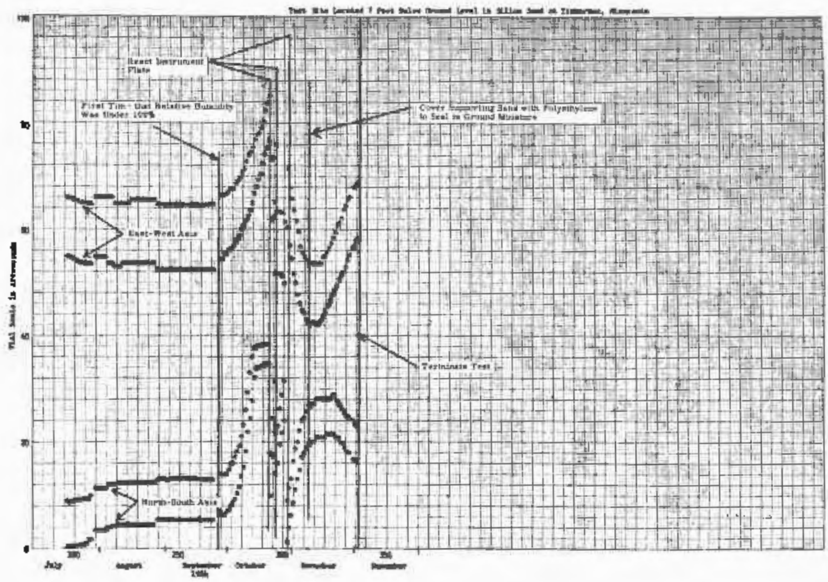

Fig. 21. Test Results Zimmerman Underground Test Site

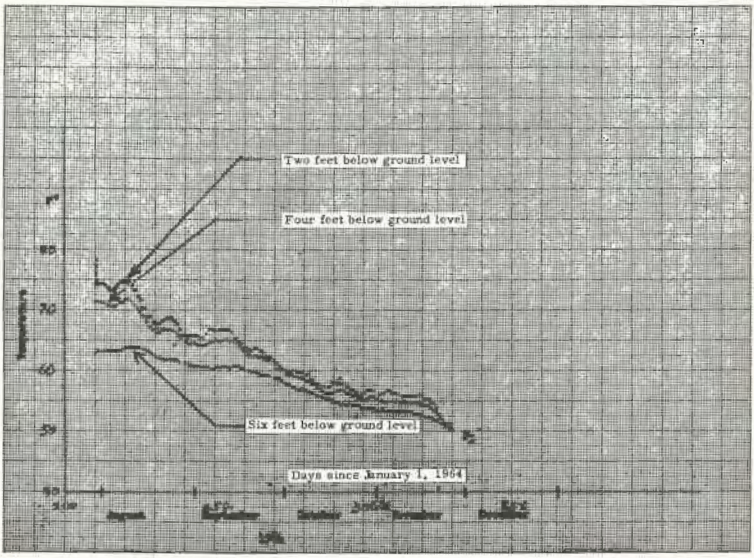

Fig. 22. Zimmerman Ground Temperature

St. Peter Sandstone

A test site was located 2500 ft. into a tunnel of sandstone mine at St. Paul, Minnesota, at a point 140 ft. below ground level. The geological formation here is called the St. Peter sandstone. The test station was isolated from climatological variables, and was found to be the most stable site in the Minneapolis area. Tilt records show that this site has a stability of one arc second for a one-year period, but it is subject to disturbances from large earthquakes. Fig. 23 is a photograph of the test site in the sandstone mine tunnel at St. Paul. Fig. 24 is a long period test record of this site. Fig. 25 is an enlarged section of this record showing the effect of the April, 1964, Alaskan earthquake.

Fig. 23. St. Peter Sandstone Test Site

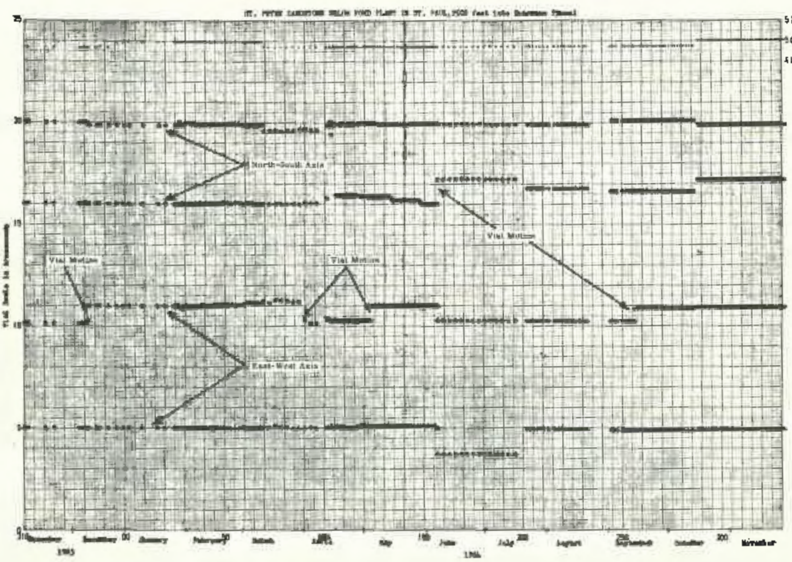

Fig. 24. Test Results St. Peter Sandstone Test Site

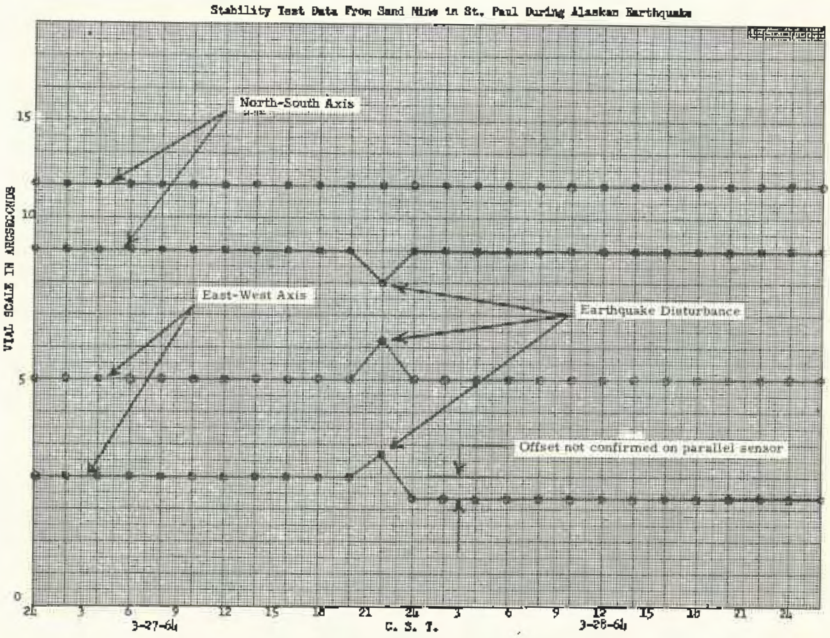

Fig. 25. Alaskan Earthquake Effects
at St. Peter Sandstone Test Site

Granite Outcrop at St. Cloud, Minnesota

Tilt measurements were taken at a granite outcrop in St. Cloud, Minnesota. The instrument mounting plate was placed directly on a horizontally ground surface of the rock. The tilt records showed a pronounced tilt about the east-west axis of approximately 17 arc seconds which varied in an annual cycle correlated to seasonal temperature changes. The tilt about the north-south axis did not have the pronounced cyclical variations. The maximum peak-to-peak tilt about this axis was approximately 3 arc seconds. The cause of the pronounced tilt about the east-west axis was found to be stratified thermal gradients in the rock. The irregular topography of the site caused differential solar heat absorption in the rock outcrop.

Fig. 26 is a photograph showing the irregular topography of the St. Cloud site, and Fig. 27 is a record of tilt measurements taken. It shows that a solid rock formation may not be the best location for a test pad.

Fig. 26. Granite Outcrop St. Cloud, Minnesota

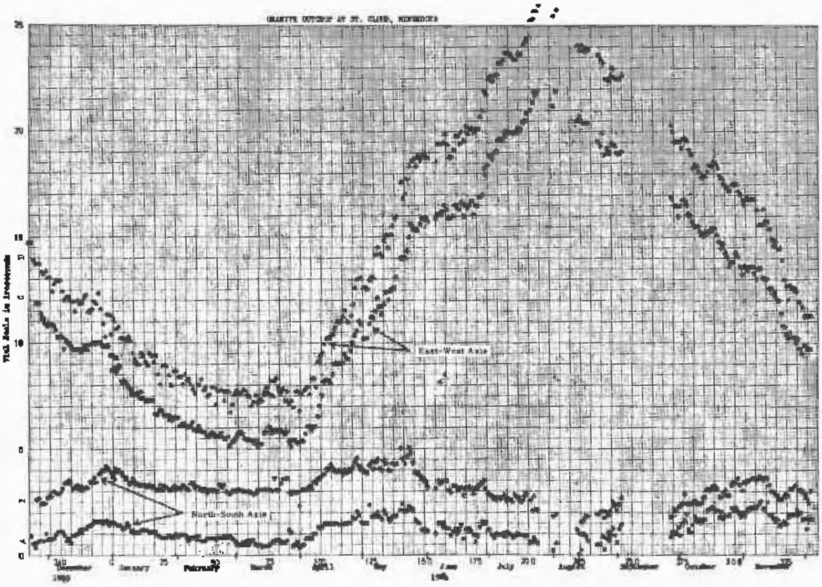

Fig. 27. Tilt Measurements at St. Cloud Granite Outcrop

Baraboo, Wisconsin Quartzite

Data was taken at Baraboo, Wisconsin, for a period of 9 months. The geological formation at this site is quartzite. Test readings showed a tilt of the slab between August, 1963, and February, 1964, of 5 arc seconds about the north-south axis, and 5 arc seconds about the east-west axis. The tilt about the north-south axis was gradual, while the tilt about the east-west axis peaked in January. It was again believed that the irregular topography of the site produced differential heat absorption, and that the consequent thermal heat gradients caused the tilts. Fig. 28 is a record of the tilts at Baraboo.

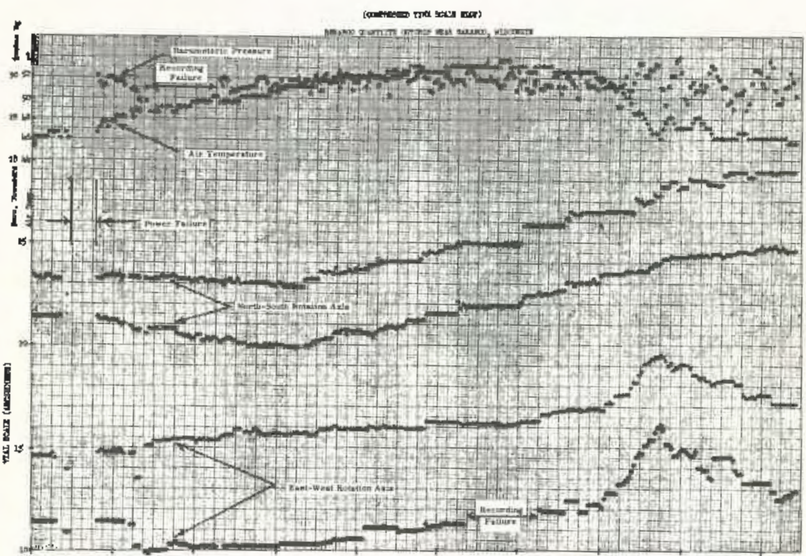

Fig. 28. Tilt Measurements at Baraboo, Wisconsin Quartzite Outcrop

Recommendations in Honeywell Paper

The recommendations in Mr. Berg's paper for optimum conditions for a test pad can be summarized as follows:

Construct a circular concrete slab located in an underground chamber with at least a 50-ft-thick uniform overlay of unconsolidated, homogeneous soil of adequate load bearing capacity in a flat, isolated, treeless area; provide constant air temperature and humidity and a false floor for supporting operating personnel around the test pad.

TEST PAD IN AN URBAN AREA

Many inertial guidance test laboratory locations are not favored by geography and/or geophysical environment. One of these is the M.I.T. Instrumentation Laboratory in Cambridge, Massachusetts. Its location in a city on the Atlantic seaboard introduces extremely difficult environmental disturbances which prevent the construction of simple slab-on-ground test platforms for modern motion-sensing instruments.

In approaching the problem of providing a test platform for Cambridge, a study was made to determine all of the known physical sources of disturbances. (Ref. 3 through 23) This study places the sources in the following categories:

1. Motions of the earth
   a. Earthquake waves
   b. Earth tides
   c. Microseismic waves
   d. Earth tremors and local earth disturbances
   e. Wandering of the poles
   f. Precession of the polar axis
   g. Change in speed of rotation of the earth
2. Thermal distortion of buildings and surrounding ground
3. Subsidence of building on soft foundation material
4. Acoustic noise
5. Local temperature changes
6. Variations in humidity, changes in barometric pressure, dust and wind
7. Stray electromagnetic fields

Some of the general characteristics of stray disturbances are discussed in a paper (Ref. 24) presented at the AIAA Test Pad Stability Symposium held in Dallas, Texas, on February 19 and 20, 1964. The multiplicity of disturbances and difficulty of isolation for all six degrees of motion of the ground made it necessary to narrow the isolation problem to the design of a stable test pad for calibration of gyroscopes. One of the studies made at the Instrumentation Laboratory to determine the general effects of stray disturbances on gyro tests was reported in Ref. 25. This study indicated that the:

1. high and low frequency linear stray motions had minor effects on the precision of gyro test results
2. high frequency angular stray motions also had minor effects
3. low frequency angular stray motions (ground tilts) were the most serious causes of errors in gyro test results.

Based on these results, the decision was made to build an experimental test platform isolated from low-frequency stray ground tilts. This specification required maintaining the platform level to within 0.2 seconds of arc (1 micro-radian) in order to minimize the effect of ground tilt on the results of gyro calibrations.

Geotilt Recorder

In order to design a stable platform within the required accuracy, measurments had to be made to determine the maximum amplitudes of low-frequency ground tilts. These measurements were made by a Geotilt Recorder, (Ref. 26) a new instrument developed at the Instrumentation Laboratory. The Geotilt Recorder, Fig. 29, has four major components:

1. Primary sensing unit and ionization transducer
2. Electronic galvanometer-amplifier
3. Esterline-Angus recording ammeter
4. Decker Delter transducer excitation source

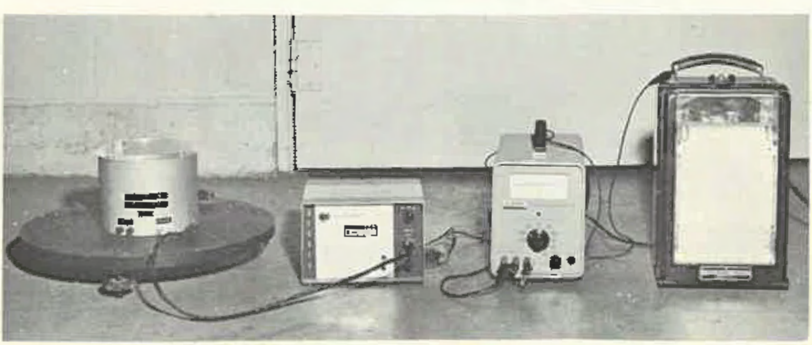

Fig. 29. Geotilt Recorder in Operating Position

The relationship of these major components is shown in Fig. 29. The primary sensing unit, Fig. 30, is a liquid level vial to which three capacitor electrodes are attached. These electrodes are connected in a differential mode to the ionization transducer, which is energized by the excitation oscillator. When a downward ground tilt occurs, the bubble of the level vial is displaced from null. This displacement is detected as a capacitance change between the electrodes, and causes the ionization transducer to produce a positive d-c voltage. An upward ground tilt will produce a negative d-c voltage. The d-c output voltage of the ionization transducer is directly proportional to the capacitance change at the electrodes, and is monitored by the galvanometer-amplifier. The output of the galvanometer-amplifier is an amplified signal that is used to drive the pen of the Esterline-Angus recording ammeter. The plot on the recording ammeter is a continuous record of the displacement of the level bubble caused by ground tilts.

Fig. 30. Geotilt Recorder Primary Sensing Unit Assembly

Floor Tilt Measurements

Measurements of floor tilts were taken at the proposed locations for gyro test facilities. Measurements were made with the level vials parallel to the building walls and also roughly along north-south and east-west directions. The Geo-tilt Recorder was placed directly on the floor as shown on Fig. 29. Measurements were made for periods varying from a few hours to several days. During these periods, no special efforts were made to divert personnel or other sources of disturbances from the vicinity of the test area. Fig. 31 is a record of one of these tests.

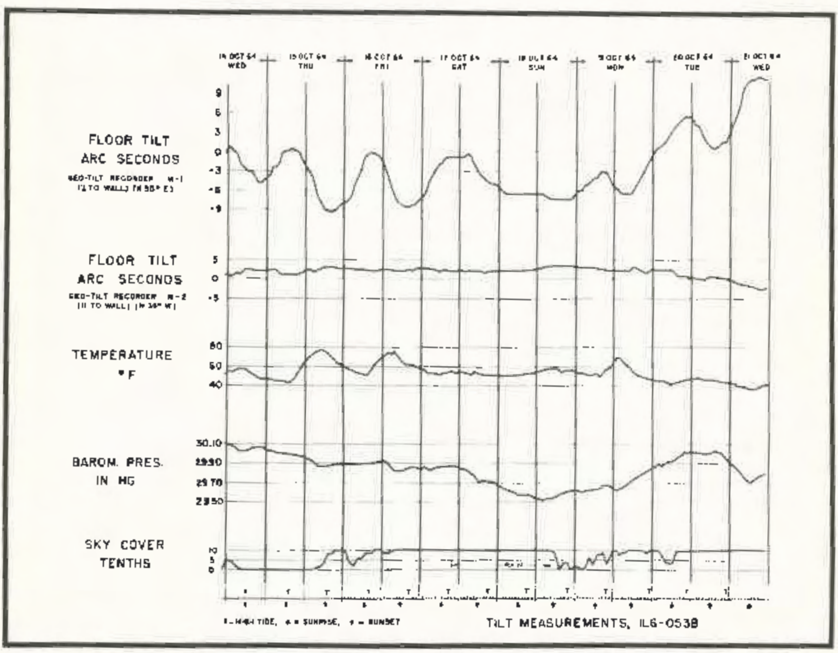

Fig. 31. Record of Floor Tilt Test

Ground tilts occurred at rates varying from several milliseconds of tilt per minute to several seconds of tilt per hour to many seconds of tilt per day. A summary of the measurements of the various test locations indicated that the maximum tilt angle to be expected was plus or minus 20 seconds of arc. However, for the purpose of designing the ground tilt isolation platform, an operating range of plus or minus 120 seconds of arc was chosen for the following reasons:

1. The measurements were taken over a relatively short period of time.
2. Knowledge of local soil conditions, Fig. 32, gained from test borings, indicated that the laboratory building rested on a thick layer of soft blue clay and the possibility of large tilt amplitudes existed between the seasons of the year.

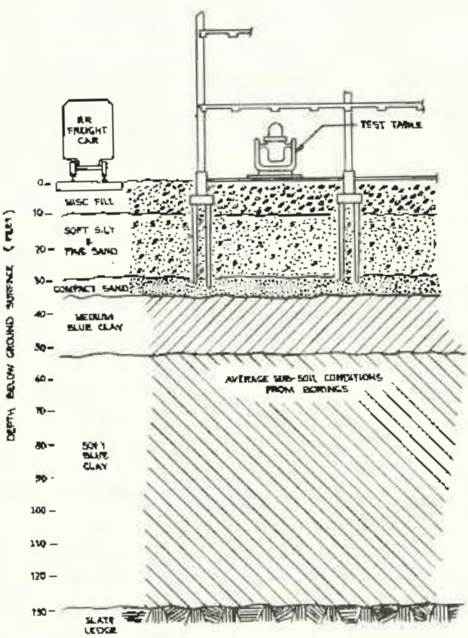

Fig. 32. Cross-section of Soil Conditions Under Instrumentation Laboratory

Experimental Platform

In order to fulfill the specification for ground tilt isolation, an experimental servo-driven test platform was built. It was triangular in design, and consisted of floor plates, micromotion drives, base triangle, intermediate triangle, and mounting plate (Fig. 33). The base triangle is composed of three equal-length aluminum I-beams held together at each corner with top and bottom apex plates. The intermediate triangle is a smaller but similarly unit bolted to the base triangle. The mounting plate is bolted to the intermediate triangle. During tests of the platform, lead blocks were placed on the mounting plate to simulate the weight of a gyro test table with its associated equipment. The two triangles and mounting plate form the superstructure that is supported by three highly-refined servo-driven hydraulic jacks, which are called micromotion drives. Two micromotion drives are actuated by electric servo motors, and the third is operated manually for initial calibration. Heavy floor plates support the micromotion drives.

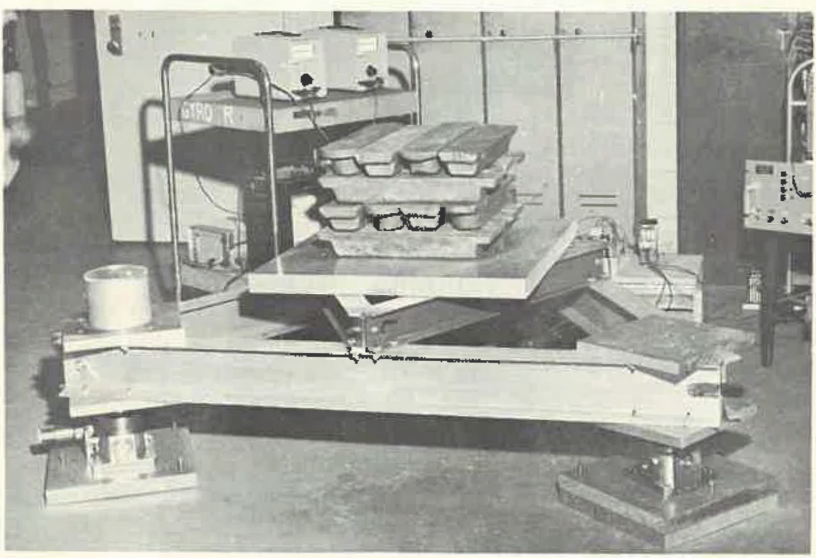

Fig. 33. Experimental Servo-Driven Test Platform

The platform has two horizontal axes of motion, 60 degrees to each other. When a ground tilt causes disturbances about these axes to tilt the platform, two separate servo systems activate the micromotion drives that return the platform to a level position. Each servo system consists of a Geotilt Recorder located on a top apex plate, a servo amplifier, and a servo motor that activates the corresponding micromotion drive. Fig. 34 is a block diagram of a servo system for one horizontal axis. One Geotilt Recorder is aligned with its level axis parallel to one horizontal axis of the test platform. This alignment makes the level vial insensitive to motions about this horizontal axis but sensitive to the other horizontal platform axis. The second Geotilt Recorder is aligned with its level vial axis parallel to the other horizontal platform axis.

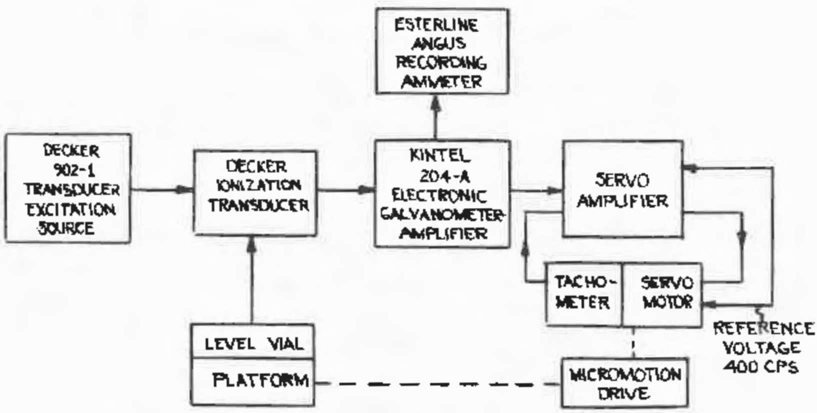

Fig. 34. Block Diagram of Servo Drive for One Horizontal Axis

Operation of Servo System to Control Platform

When a ground tilt occurs, the level bubbles of the Geotilt Recorders are displaced from null. These displacements cause both servo systems to act simultaneously but independently. The action of both servo systems maintains the platform in a level position. The action of one servo system is:

1. The displacement of the bubble in the level vial causes a change in the capacitance between the electrodes.
2. The capacitance change causes the ionization transducer

produce a d-c voltage proportional to the magnitude of the ground tilt.

3. The d-c voltage is monitored by the galvanometer-amplifier, recorded on the recording ammeter, and applied to the input of the servo amplifier.
4. The output voltage of the servo amplifier activates the servo motor of the micromotion drive.
5. The micromotion drive moves the platform back to a level position about one horizontal axis.

Platform Performance

The performance of the experimental ground tilt isolation platform about one horizontal axis of motion was determined by obtaining simultaneous recordings of variations in ground tilt and of variations of the platform position from null. The test setup is shown in Fig. 33. Length of tests varied from a few minutes to several hours. One of the results of these tests is shown in Fig. 35. Test results showed that the platform was stabilized to within 0.2 seconds of arc. It was assumed that stabilization about the other horizontal axis could be maintained simultaneously.

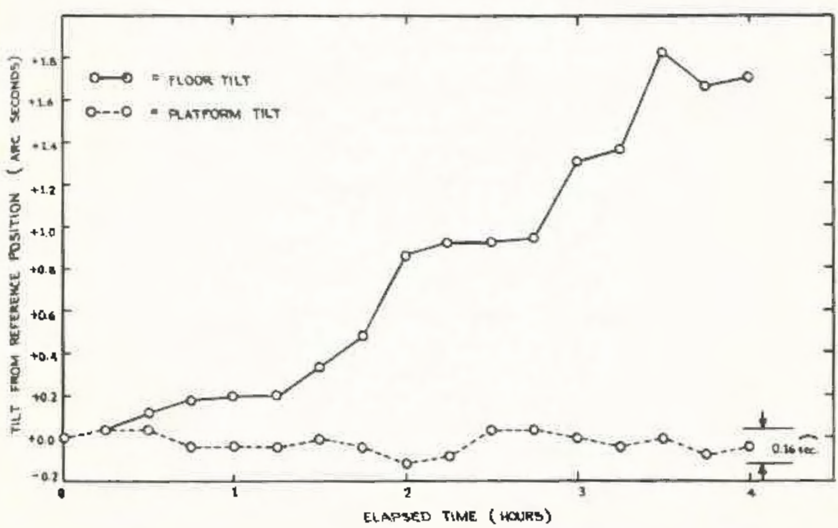

Fig. 35. Performance of Ground Tilt Isolation Platform Compared to Floor Tilt

Gyro Test Table Platform

The success of this experimental platform led to the construction of a ground tilt isolation platform for a large gyro test table which is shown on Fig. 36. This platform is circular in plan to support the circular test table. There are three brackets 120 degrees apart which rest on micromotion drives. Two of these brackets support Geotilt Recorders. The third bracket supports two Decker transducer excitation sources. The gyro to be tested is mounted on the top surface of the test table. A working platform for operating personnel which rests on the floor but is separated from the isolation platform is located along the periphery of the platform. The control and recording equipment for the entire system is housed in a short console.

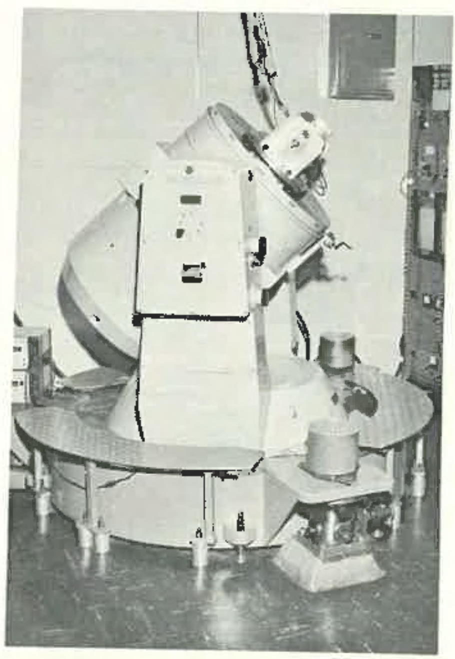

Fig. 36. Ground Tilt Isolation Platform Assembly

Fig. 37 is a close-up view showing the relationship of the Geotilt Recorder, the bracket of the isolation platform, the micromotion drive and the floor. The area between the bottom of the micromotion drive is the grouting that was required to bring the system to a level position because the floor slab was not level.

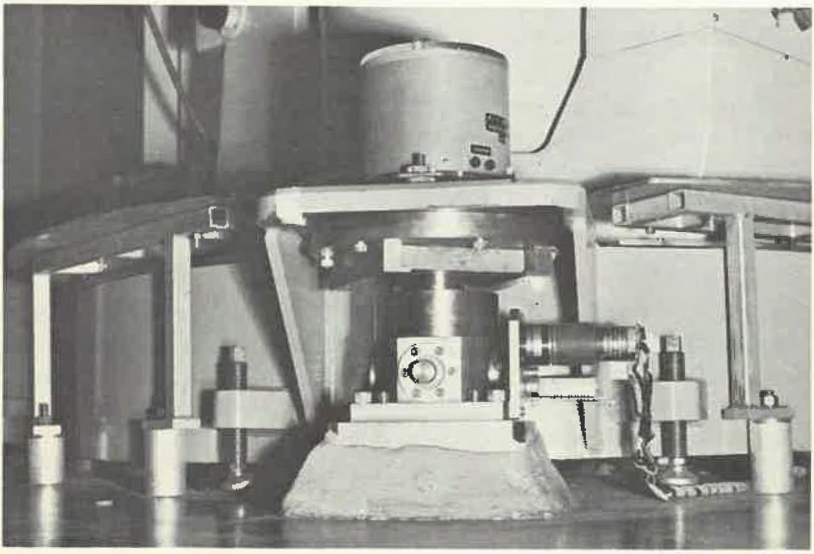

Fig. 37. Close-up View of
Geotilt Recorder and Micromotion Drive

Performance of Gyro Table Stable Platform

Short term tests of the ground tilt isolation platform with both servo systems operating have shown that the platform has remained level well within the specification of 0.2 arc second for long period ground tilts. Long period ground tilts are defined here as those oscillations which require 10 seconds or more for one cycle. Long term performance tests are still being conducted.

CONCLUSION

Since there is no known naturally vibration-free location on the earth, difficult problems are encountered in the construction of stable test platforms for the calibration of modern, highly precise motion sensitive instruments. Specifications for these test platforms vary with the instruments to be tested and the particular requirements of each test facility for geophysical environment and cost of construction.

Gyroscopes and accelerometers, which are the primary motion-sensing components in an inertial navigation system, require the most stable test pads for calibration. These test pads may also be used to calibrate the entire inertial navigation system.

The solutions described here required aid from personnel in many fields such as geology, seismology, soil mechanics and dynamics, materials, structures, meterology, astronomy, feedback control, electronics, fluid mechanics, thermodynamics, and applied mechanics and dynamics.

Although the test pads described in this paper are suitable for testing present-day instruments, they do not have the range of isolation necessary for testing the next generation of instruments. This means that more research with an interdisciplinary approach is required to develop sophisticated platforms for the calibration of projected instruments.

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REFERENCES

1. Mathis, L.O., Stephens, J.R. and Wright, S.C., "The Design and Construction of an Inertial Test Facility," Technical paper presented at American Institute of Aeronautics and Astronautics Guidance and Control Conference, Minneapolis, Minnesota, August 16-18, 1965.
2. Berg, R.T., "Inertial Test Stability Study," Technical paper presented at American Institute of Aeronatuics Guidance and Control Conference, Minneapolis, Minnesota, August 16-18, 1965.
3. Alsop, L.E., Sutton, G.H. and Ewing, M., "Free Oscillations of the Earth Observed on Strain and Pendulum Seismographs," Journal of Geophysical Research, Vol. 66, No. 2, pp. 631-641, February, 1961.
4. Benioff, H., Press, F. and Smith, S., "Excitation of the Free Oscillations of the Earth by Earthquakes," Journal of Geophysical Research, Vol. 66, No. 2, pp. 605-619, February, 1961.
5. Bullen, K.E., SEISMOLOGY, Methuen's Monographs on Physical Subjects, John Wiley & Sons, Inc., New York, 1954.
6. Byerly, P., SEISMOLOGY, Prentice-Hall, Inc., New York, 1942.
7. Creskoff, J.J., DYNAMICS OF EARTHQUAKE RESISTANT STRUCTURES, McGraw-Hill Book Company, Inc., New York, 1934.
8. Daly, R.E., STRENGTH AND STRUCTURE OF THE EARTH, Prentice-Hall, Inc., New York, 1940.
9. Gutenberg, B., "Seismological and Related Data," AMERICAN INSTITUTE OF PHYSICS HANDBOOK, pp. 2-201 to 2-114, McGraw-Hill Book Company, Inc., New York, 1957.
10. Gutenberg, B. and Richter, C.F., SEISMICITY OF THE EARTH AND ASSOCIATED PHENOMENA, Princeton University Press, 1949.
11. Krogdahl, W.S., THE ASTRONOMICAL UNIVERSE, Macmillan Company, New York, 1952.
12. Leet, L.D., PRACTICAL SEISMOLOGY AND SEISMIC PROSPECTING, Appleton-Century-Crofts, New York, 1938.
13. Lina, L.J. and Maglieri, D.J., "Ground Measurements of Airplane Shock-Wave Noise at Mach Numbers to 2.0 and at Altitudes to 60,000 feet," NASA Technical Note D-235, National Aeronautics and Space Administration, Washington, D.C., March, 1960.
14. MacDonald, G.J.F., "The Earth's Free Oscillations," Science, Vol. 132, No. 3491 November, 1961.

15. Maglieri, D.J. and Carlson, H.W., "The Shock-Wave Noise Problem of Supersonic Aircraft in Steady Flight," NASA Memorandum 3-4-59L, National Aeronautics and Space Administration, Washington, D.C., April, 1959.
16. Maglieri, D.J., Hubbard, H.H. and Lansing, D.L., "Ground Measurements of the Shock-Wave Noise from Airplanes in Level Flight at Mach Numbers to 1.4 and at Altitudes to 45,000 Feet," NASA Technical Note D-48, National Aeronautics and Space Administration, Washington, D.C., 1959.
17. National Bureau of Standards, "Time Adjustments in WWV and WWVH Standard Broadcasts," NBS Technical News Bulletin, Vol. 45, No. 9, p. 157, September, 1961.
18. National Bureau of Standards, "NBS and Navy Announce Change in Standard Frequency Broadcasts," NBS Technical News Bulletin, Vol. 46, No. 2, p. 24, February, 1962.
19. National Bureau of Standards, "Adjustment in Phase of Time Signals," NBS Technical News Bulletin, Vol. 47, No. 12, p. 219, December, 1963.
20. Ness, N.F., Harrison, J.C. and Slichter, L.B., "Observations of the Free Oscillations of the Earth," Journal of Geophysical Research, Vol. 66, No. 2, pp. 621-629 February, 1961.
21. Neumann, F., "Earthquake Investigation in the United States," Special Publication No. 282, Revised Editions (1953)(1958) (1962), Coast and Geodetic Survey, U. S. Department of Commerce, Washington, D.C., U. S. Government Printing Office, 1952.
22. Terzaghi, K. and Peck, R.B., SOIL MECHANICS IN ENGINEERING PRACTICE, John Wiley & Sons, Inc., New York, 1948.
23. Wilson, James T., "Underground Shocks," International Science and Technology, Vol. 1, No. 1, p. 47, January, 1962.
24. Tsutsumi, K., "A Ground Tilt Isolation Platform," E-1508, M.I.T. Instrumentation Laboratory Report, Cambridge, Mass., January, 1964.
25. Weinstock, H., "Specification for the Permissible Motions of a Platform for Performance Evaluation of Single-Degree-of-Freedom Inertial Gyroscopes," E-1267, M.I.T. Instrumentation Laboratory Report, Cambridge, Mass., December, 1962.
26. Hopewell, F., King, R., Merenda, F. and Tsutsumi, K., "Precision Level Vial Assembly - Preliminary Model," M.I.T. Instrumentation Laboratory Note C-719, Cambridge, Mass., February, 1962.