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Inertial Navigation System for Directional Surveying

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Stewart M. Kohler

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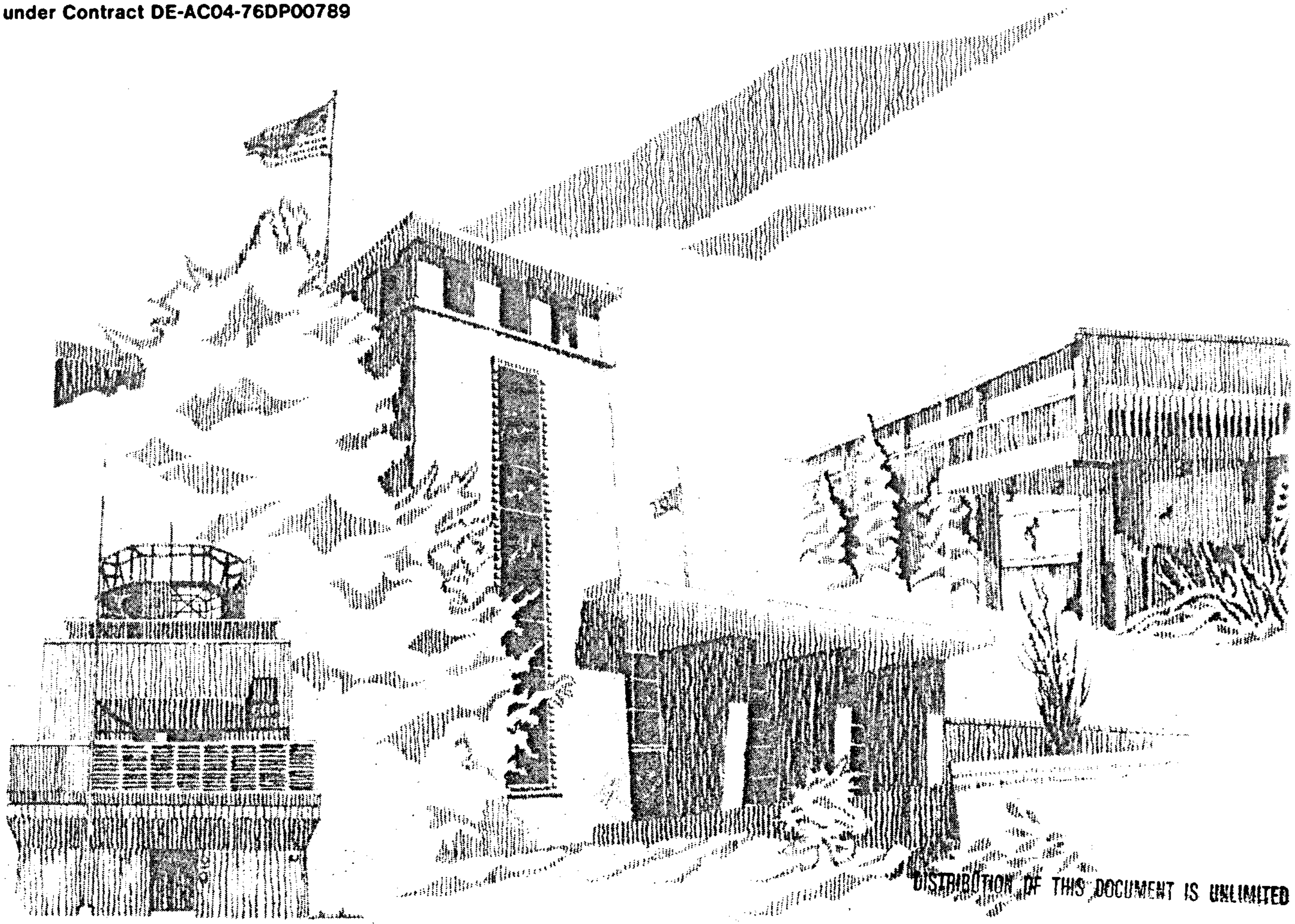

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Inertial Navigation System for Directional Surveying

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Abstract

Sandia National Laboratories has recently developed and successfully tested a Wellbore Inertial Navigation System (WINS). Developed for directional surveying of geothermal, oil, and gas wells, the system uses gyros and accelerometers to obtain survey errors of less than 10 ft (~3 m) in a 10 000-ft (~300-m) well. The tool, which communicates with a computer at the surface, is 4 in. (~10 cm) in diameter and 20 ft (~6.1 m) long. The concept and hardware is based on a system developed by Sandia for flight vehicles.

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G. M. Heck, Supervisor
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Inertial Navigation System for Directional Surveying

Summary

In 1972, development began at Sandia National Laboratories on an inertial measurement system for flight vehicle instrumentation. The system uses a single-gimbal platform mounted such that the gimbal's roll axis is parallel to that of the vehicle. It is called the Roll-Stabilized Inertial Measurement System (RIMS). Either three single- or two dual-axis gyros, plus three single-axis accelerometers are mounted on the gimbal, which is stabilized against rotation by a servo loop containing one of the gyros, and may be treated as a strapdown system in which the angular rate about the roll axis is nominally zero. This mechanization eliminates the inaccuracy of a conventional strapdown system when measuring the large roll angles that can occur in a spinning vehicle.

A computer continuously combines the gyro outputs to determine the vehicle's attitude relative to a reference coordinate system. This information and the accelerometer outputs are used to calculate the vehicle's velocity and position.

On three occasions since 1979, versions of RIMS have been successfully tested in flight. In the first test, RIMS data were telemetered to the ground and, after the flight, the vehicle's attitude, velocity, and position were calculated. During the last two tests, an on-board computer did the calculating on a real-time basis.

In 1979, Sandia began developing an experimental wellbore directional-surveying tool based on the RIMS concept: the Wellbore Inertial Navigation System (WINS). An error analysis indicated that, with gyros and accelerometers of moderate accuracy—as used in RIMS—survey errors of less than 10 ft (~3 m) in a 10 000-ft (~3000-m) borehole could be obtained.

The WINS tool, although packaged differently from the RIMS, has an inertial measuring unit that is functionally identical, both electrically and mechanically. Including its pressure barrel, it is 4 in. (~10 cm) in diameter and 20 ft (6.1 m) long, and its battery pack has enough capacity for about 4 h of operation. It communicates with a computer at the surface through a standard, seven-conductor logging cable.

In March 1982, a WINS was successfully tested in a well at the DOE's Nevada Test Site.

Introduction

State-of-the-Art Directional Surveying

A complete directional survey of the borehole of an oil or gas well determines displacement of the borehole's path in all three directions (X, Y, Z axes) relative to the wellhead. This information is especially useful when numerous wells are drilled toward different geological targets from a single location. For example, most geothermal resources are in environmentally sensitive areas. To minimize the number of drilling pads, two to five wells can be drilled from each pad. In the case of offshore oil and gas fields, economics requires that multiple wells be drilled from one platform. Accurate knowledge of the borehole's path allows wells to be properly spaced and assures that target formations are reached.

At present, most instruments used to obtain directional surveys measure the attitude (or angular orientation) of the tool as it is lowered by a cable into the borehole. Accelerometers or tilt sensors measure tool inclination, while gyroscopes or magnetic compasses indicate the heading or direction, relative to north. Displacement of the tool is calculated by projecting each incremental increase in cable length in the direction shown by the tool's attitude. With this method, errors in measuring displacement may amount to 100 ft (~30 m) for every 10 000 ft (~3000 m) of wellbore; these errors are usually due to inaccuracies in gravity and direction-sensing devices, misalignments between the sensing devices and the borehole, and inaccuracies in measuring cable length.

The Inertial Navigator as a Surveying Tool

Recently, the application of inertial navigation systems to directional surveying has been studied. In such a system, the outputs of accelerometers and gyroscopes are manipulated inside a computer to determine velocity and displacement. Cable length does not have to be measured and accuracy is not affected by misalignments between the system and the borehole. Another advantage is that the calculated velocity is useful for calibration purposes.

Unaided inertial navigation systems of reasonable size and cost are not sufficiently accurate for use in directional surveying. In fact, 1 hour of unaided operation of a typical high-accuracy inertial navigation system would result in errors in calculated position of at least 5000 ft (~1500 m). However, a system may be aided by periodically sampling the indicated (calculated) velocity when the system is at rest, then using the measured velocity error obtained to estimate both the true state of the system and various error parameters associated with the system's inertial instruments. This technique is feasible because the error dynamics of an inertial navigator are well known and may be modeled by linear differential equations. This, in turn, allows optimal filtering techniques to be applied so that errors in the system can be estimated and corrected.

The first step in the operational sequence of surveying with a tool, based on an inertial navigation system, is to hold the tool motionless at the surface for a few minutes while the system determines initial attitude from gyroscopic measurements of the direction of north (the earth's rotational vector) and accelerometer measurements of verticality (the gravity vector). The tool is then run into the hole as fast as possible. Periodically, the system is brought to a stop for calibration by measuring the velocity error and estimating navigator errors.

The Single-Gimbal Platform

Broadly speaking, there are two types of navigation system mechanization: gimballed and strapped down. In a gimballed system, the sensor block (platform) containing the gyroscopes and accelerometers is supported by a set of gimbals that isolate the sensor block from rotations of the vehicle. In normal operation, it remains virtually motionless (rotationally) and maintains its approximate initial or reference alignment. The outputs of gyroscopes on the sensor block are used in null-seeking servo loops that drive the gimbals so that no rotations of the sensor block occur. An advantage of a gimballed system is that the gyroscopes need not measure large angular rates, but operate instead in a more benign, nominally zero-angular rate environment. However, an important disadvantage is its high mechanical complexity.

Strapped-down systems have no gimbals, so any angular rate of the instrument case is transmitted directly to the sensor block. The gyroscopes must therefore measure a wide range of angular rates, from zero to perhaps several hundred degrees per second. On the other hand, the systems are mechanically simpler and are usually smaller than gimballed systems.

A hybrid inertial navigation system offers advantages in a spinning vehicle. This hybrid is a single-gimbal platform in which the sensor block is stabilized against rotations about the vehicle's spin axis. As in the conventional gimballed system, a gyroscopic measurement of sensor block rotation is used in a null-seeking servo loop that prevents the sensor block from rotating about its gimbal axis. Angular rates of the sensor block about axes perpendicular to the gimbal axis are measured by gyroscopes as they are in the strapped-down system; three accelerometers measure acceleration.

The hybrid may be viewed as a special strapped-down system in that the angular rate of the sensor block about the gimbal axis is practically zero. As in the conventional system, the angular rate and acceleration data are transmitted to a computer which calculates vehicle displacement from the starting point.

Advantages of the single-gimbal platform in the directional surveying application include the potential for small size, for mechanical simplicity, and for ease in calibrating the system. Also, compared to fully strapped-down systems, it is insensitive to high angular rates of the survey tool about its longitudinal axis. The tool has a relatively low moment of inertia about this axis and is susceptible to spinning induced by cable twists or the action of borehole fluids or tool centralizers as the tool is raised or lowered. If these rotations are rapid, the angular rate range of a strapped-down gyro may be exceeded, and large angle-measurement errors will occur. If the rotation rates are slower, yet result in many revolutions of the tool, a sizable gyro scale factor error (a percentage of the total angular excursion) may result.

Development

Since 1972, SNLA has been developing RIMS for flight vehicles. Versions of RIMS have been tested in flight on several occasions and performed well. Because of the small quantities, RIMS was designed, developed, fabricated, and assembled in-house at Sandia. Recently, RIMS became Sandia's standard flight inertial instrumentation system, and several units per year are being produced by an outside contractor: Space Vector Corp of Northridge, CA. The systems use Incosym® Mod III-E, tuned-rotor, two-axis gyroscopes and Sundstrand® QA-1200 single-axis accelerometers.

Because of Sandia experience in single-gimbal platform technology and its applicability to wellbore directional surveying, the decision was made to develop and test an experimental surveying tool based on the RIMS concept: The Wellbore Inertial Navigation System (WINS). It consists of the downhole tool with the single-gimbal platform, electronics, and battery pack, as well as a computer at the surface that calculates tool velocity and position from data transmitted over an electrical cable. During development,the emphasis was on proof-of-concept rather than on developing a commercial surveying tool. To reduce expense, we followed the existing RIMS design whenever possible, even if when it was not optimum for WINS. For instance, the gyro and associated electronics can measure rotational rates as high as 100°/s although a much lower limit would be adequate. The diameter of the WINS tool (4 in.) is determined mainly by the size of the gyros which originally supported RIMS development; smaller gyros are available.

In other words, ultimate development was not allowed to compromise the primary goal of the effort: to demonstrate, as early as possible, the feasibility of a relatively-small-diameter, inertial navigation system as a directional surveying tool. Figure 1 is a layout drawing of the WINS single-gimbal platform. Design details are discussed in the Appendix.

Tests

WINS was tested in the spring of 1982 at the DOE's Nevada Test Site (NTS). The major reason for choosing this location was availablility of Sandia field support.

Facility

The test well was Pahute Mesa Exploratory Hole 1, ~7500 ft (~2500 m) deep, almost vertical, and cased with 9-⅝-in-dia casing. The upper 2000 ft are dry and bottom temperature is ~60°C (140°F). Although we would have preferred a slanted hole, there was none at NTS.

Figure 2 is a photograph of the test facility around the well. Inside the calibration shed is a granite slab on steel legs standing on a concrete slab. During calibration, an aluminum fixture (Figure 3) holding the single-gimbal platform assembly is rotated to various orientations on the granite slab.* In addition to the computer, the trailer houses several tape recorders and an area for electronics repair. Wireline service was provided by Birdwell, Inc, a resident contractor at NTS.

Preliminary Tests

In the fall of 1981, a pressure barrel was lowered to 7000 ft (~2300 m) and returned, verifying that the well was unobstructed and that the pressure barrel was free of leaks.

The WINS hardware and the computer trailer were delivered to NTS in February 1982. In the next 2 months, several calibrations were run to obtain data on inertial sensor parameters (Table 1). To obtain short term stability data, we calibrated the system two consecutive times on the same day without turning the system off. Long-term results are from calibrations which are 1 to 2 weeks apart.

Table 1. Inertial Sensor Stability

Calibration Parameters	Short Term (4 Samples)	Long Term (2 Samples)
Accelerometer bias	20 μg	34 μg
Gyro mass unbalance	0.04°/h/g	0.04°/h/g
Gyro drift	0.08°/h	0.23°/h
Gyro scale factor	18 ppm	27 ppm
Accelerometer scale factor	207 ppm	190 ppm

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*R. Wardlaw, Jr., *The Wellbore Inertial Navigation System (WINS) Software Development and Test Results,* SAND82-1954 (Albuquerque, NM: Sandia National Laboratories, September 1982).

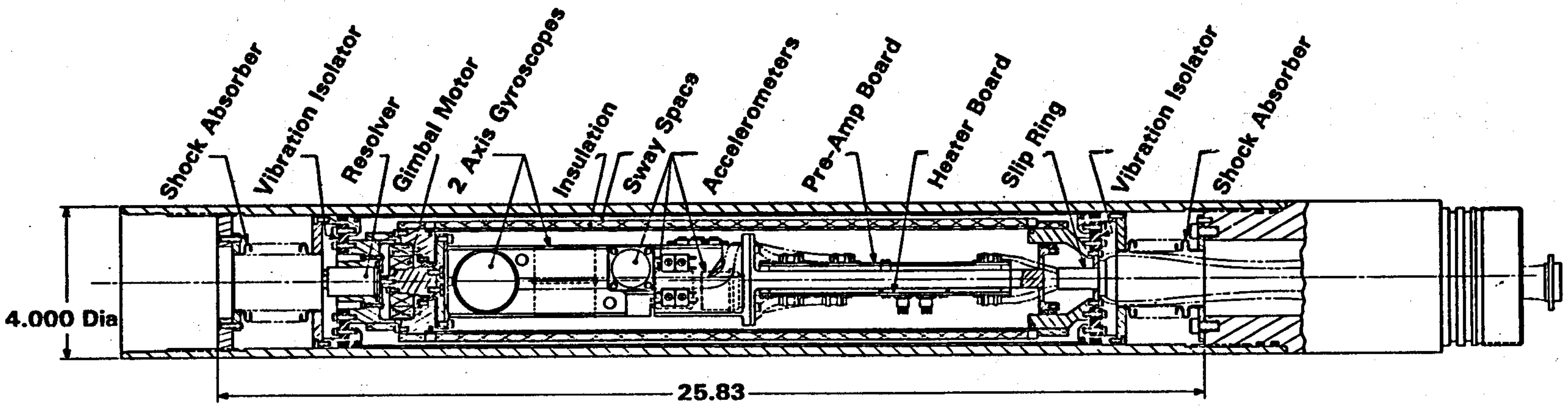


Figure 1. WINS Single-Gimbal Platform

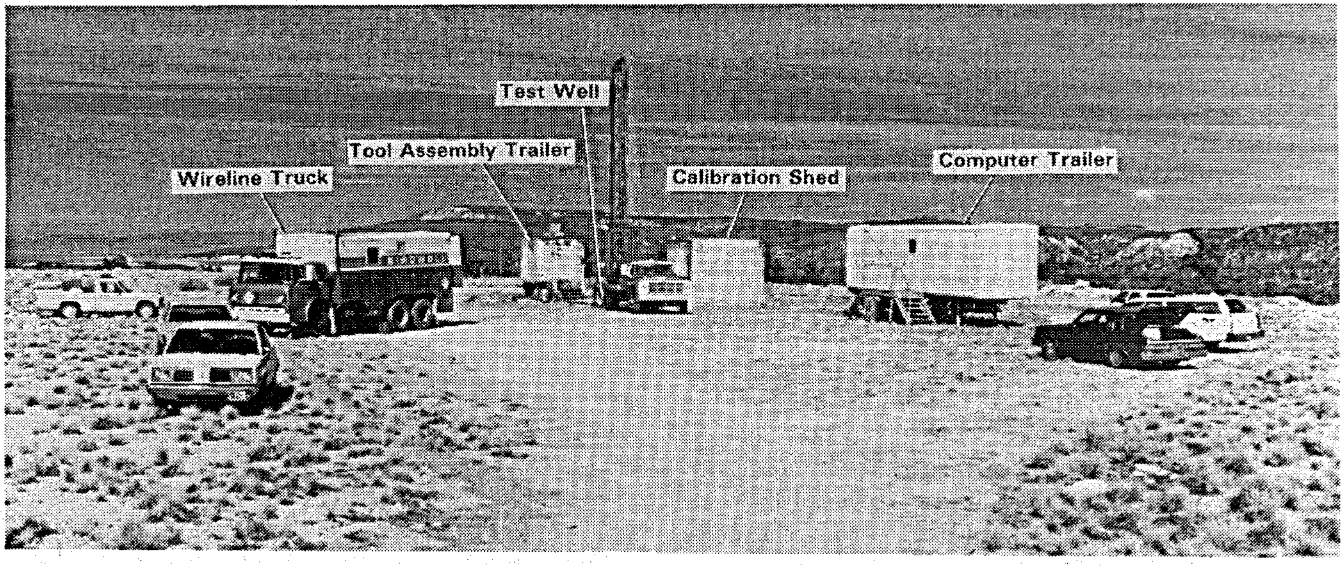


Figure 2. NTS Test Facility

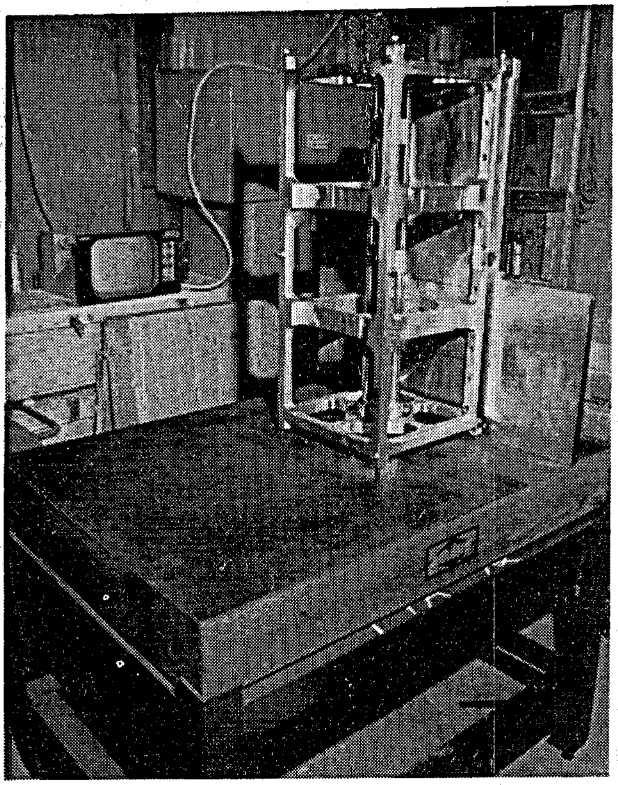


Figure 3. Calibration Table and Fixture

Except for the variability in the accelerometer scale factor, we considered this range of values adequate to meet project goals. The variability in the accelerometer scale factor was probably caused by lack of control of the platform temperature. Before each calibration, we ran the system for a couple of hours so the temperature would stabilize. However, a 1.0° to 2.0°C swing in the temperature of the stable element was not unusual from one calibration to the next and could account for most of the variation in the scale factor.

In contrast, stability of the gyro scale factor was excellent, probably because gyro temperatures were tightly controlled by individual control circuitry and a heater and temperature sensor on each gyro.

At first, we were not successful at navigating the system inside the wellbore because of defects in the software that estimates initial alignments, the unexpectedly large variations in vertical accelerometer scale factor, and unreliable transmission of data up the wireline. During March 1982, changes were made in the software that corrected the defects in initial alignment. The variable-scale factor problem was circumvented by inserting the accelerometer scale factor instead of bias into the parameter-estimation software (Kalman filter). This enabled us to frequently update the scale factor, which is much more variable than bias, so as to accomodate wide variations. We eliminated the data-transmission problem by adding a capacitor and resistor to the line driver-board in the I/O module, which sharpened the rise times of the data pulses.

Navigation

On May 4, 1982, we calibrated a WINS tool and performed a static navigation test; performance was excellent, with errors in calculated displacement of less than 1 ft after an hour. On May 5, we installed a battery pack, made a final check of accelerometer scale factors, attached the tool to the cable (Figure 4), and suspended it in the alignment fixture at the top of the hole (Figure 5). After a few minutes to estimate the initial alignment, the trip downhole began at ~350 ft/min (115 m/min), limited by the capability of the winch. Every minute, for 1 min, the tool was stopped for Kalman filtering, which assumes zero tool velocity. After the tool reached ~7000 ft in ~40 min, it was hoisted back to the surface at ~175 ft/min (57 m/min), with a stop every minute. At the surface, we replaced the battery pack and repeated the experiment. During the trips, both the raw data (as received over the cable) and navigation results (as calculated) were recorded.

Results

Navigation

Navigation results for north and east were generally excellent. Repeatability between data from the descent portions of the two trips averaged better than 3 ft.*

Angular Motions

During each survey, the tool rolled counterclockwise during descent and clockwise during ascent (Figure 6); 25 revolutions during the ascent portion of the second survey alone. Tool and centralizer asymmetries, plus twists in the cable possibly account for the rolling. The maximum roll rate was ~160°/s. Although conventional strap-down gyroscopes can function through such rates, the relaxed accuracy requirement for the gyro scale factor, and the high roll-rate capability offered by the single-gimbal platform mechanization suggest that it is preferred for this application. At higher survey rates of ~1000 ft/min, roll rates could exceed the capability of the conventional strap-down gyros.

Although stabilized in roll, the platform gimbal experienced momentary roll rates of up to 15°/s. Maximum gimbal roll angle was ~1.0°. Pitch and yaw angular oscillations tended to be very small: <0.1°, at frequencies of a few hertz. These frequencies are high enough, however, to affect selection of computer calculation rates.* Maximum rates observed were <6.0°/s.

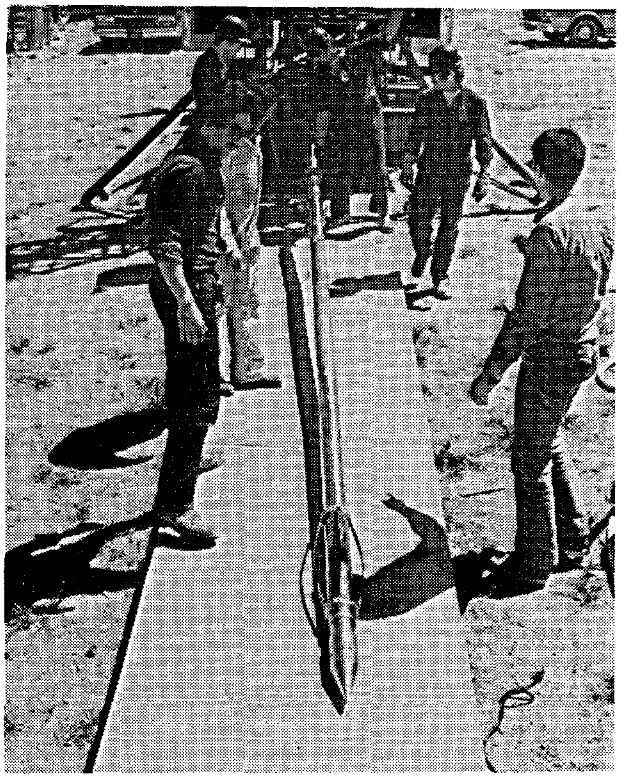


Figure 4. WINS Tool

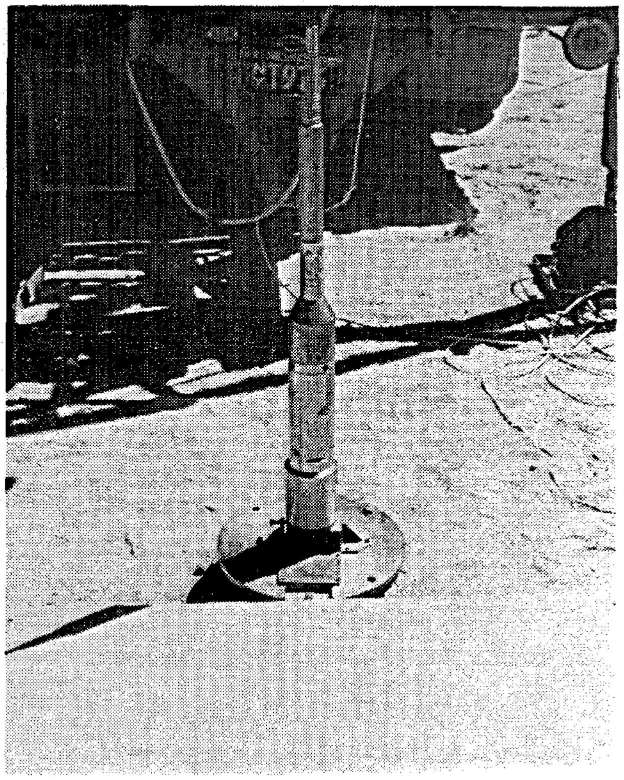


Figure 5. WINS Wellhead Alignment Fixture

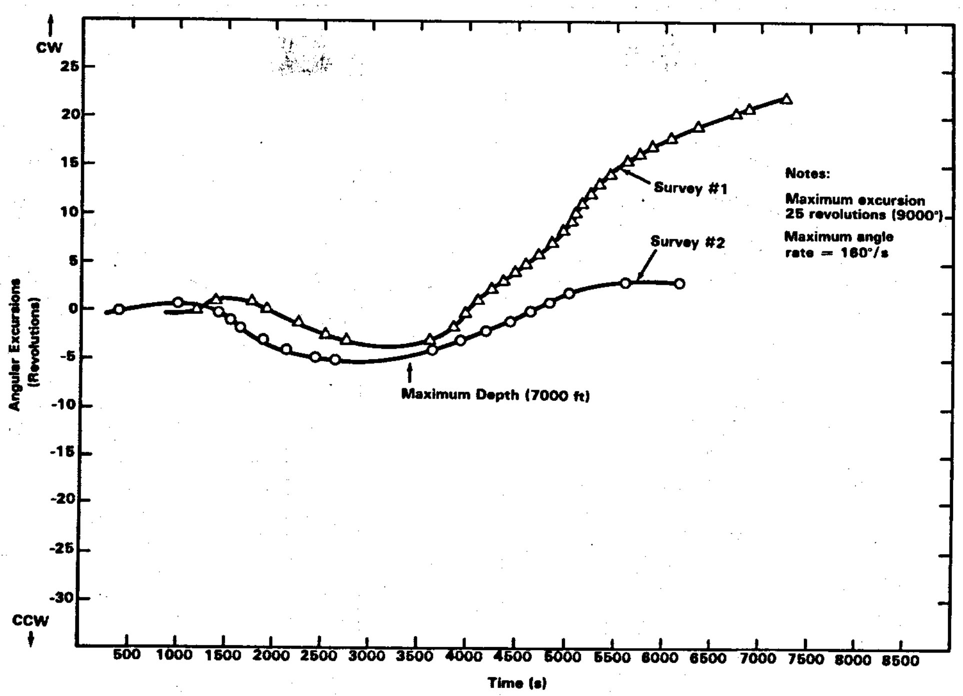


Figure 6. Tool Roll History

Linear Accelerations

Linear accelerations of the tool were well under 1 g. We observed oscillations at frequencies of several hertz. The low amplitudes demonstrate that the centralizers are effective in isolating the tool from shock and vibration.

Thermal Behavior

When the platform acts as the heat sink, it allows the gyro temperature to remain under tight control throughout a survey (see Appendix, Figure A7). Since temperature of the platform and therefore the accelerometers may vary over a wide range, there must be some way to compensate for accelerometer scale factor when it varies with the temperature. At first, we considered straightforward modeling in which the computer software accounts for dependence of accelerometer scale factor on platform temperature. However, this approach was abandoned because of the unexpectedly high sensitivity of the digitized acceleration output to temperature changes in the electronics of the analog-to-frequency (A/F) converter. To avoid a time-consuming study on temperature compensation, we included the vertical accelerometer scale factor among the system states to be estimated by the Kalman filter software. Since the test well is vertical, only the scale factor of the vertical accelerometer has an effect. During the NTS test well surveys, a new value for this scale factor was obtained each time we stopped the tool for Kalman filter error-reduction.

Figure 7 plots platform, gyro, pressure-barrel air, and wellbore temperatures against time for the second survey. As expected, gyro temperature control is lost when the platform temperature approaches the gyro control temperature.

Figure 8 shows platform and vertical accelerometer A/F electronics temperature, as well as the accelerometer scale factor plotted against time for the second survey. The correlation among curves indicates a dependence of scale factor on A/F electronics temperature. Since the accelerometers are temperature-sensitive, we expect scale factor to depend on platform temperature also. However, we were unable to discover a linear relationship between the two temperatures and the scale factor, perhaps because of time shifts in the data that resulted from physical separation between temperature sensors and the items of interest.

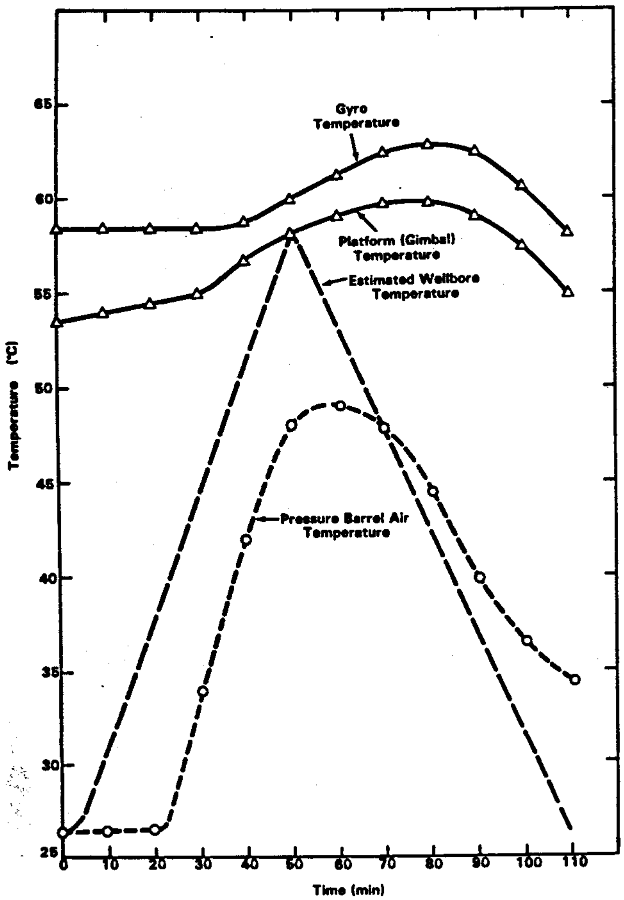


Figure 7. Temperature Data vs Time

Before the tests, we had estimated an accelerometer scale factor sensitivity to platform temperature changes of 150 ppm/°C, and to A/F temperature changes of <10 ppm/°C. This estimate was obtained from temperature tests of A/F electronics, of identical design, which were part of a RIMS flight vehicle instrumentation system. When tested alone after the tests, the WINS A/F electronics exhibited a temperature coefficient of 42 ppm/°C. The reasons for the higher temperature sensitivity of the WINS A/F electronics have not been determined.

Conclusions and Recommendations

Using the single-gimbal navigator and updating it with Kalman filtering is a means of obtaining accurate directional surveys in a wellbore. The gimbal is desirable because of large-angle excursions and rates about the axis of the tool. With the single gimbal, a gyro input angular rate range of ±25°/s and an accelerometer range of ±10 g is probably adequate.

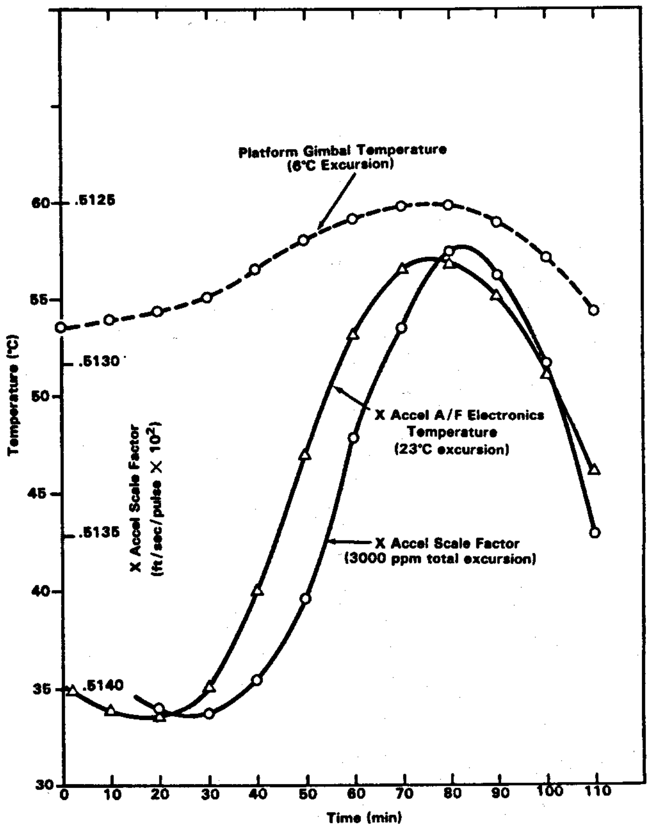


Figure 8. Platform, A/F Electronics Temperature and X Accelerometer Scale Factor vs Time

We recommend active temperature control of the entire stable element to increase accelerometer bias and scale factor stability. The sensitivity of the A/F electronics to temperature should be reduced.

The tool centralizers provide good shock and vibration protection in a cased wellbore. Therefore, internal radial sway space in the platform could be eliminated, either to reduce tool diameter or to make room for additional insulation.

Size Reduction

The diameter of WINS is determined mainly by gyro size. Figure 9 is a layout of a platform designed around smaller (~1.0-in.(2.5-cm)-diameter) Litton G7 gyros. With this platform, the OD of the tool would decrease from 4 in. to 2.75 in. (~10 to 7 cm).

Packaging the electronics would be more difficult in the smaller diameter; density could be increased with multilayer printed circuit boards (PCBs) and hybrid circuitry. A less costly approach would be to try saving some of the considerable board area which is now used up to route signals from one end of a board to the other. These signals could be routed on a bus paralleling the board. The bus could be a narrow PCB.

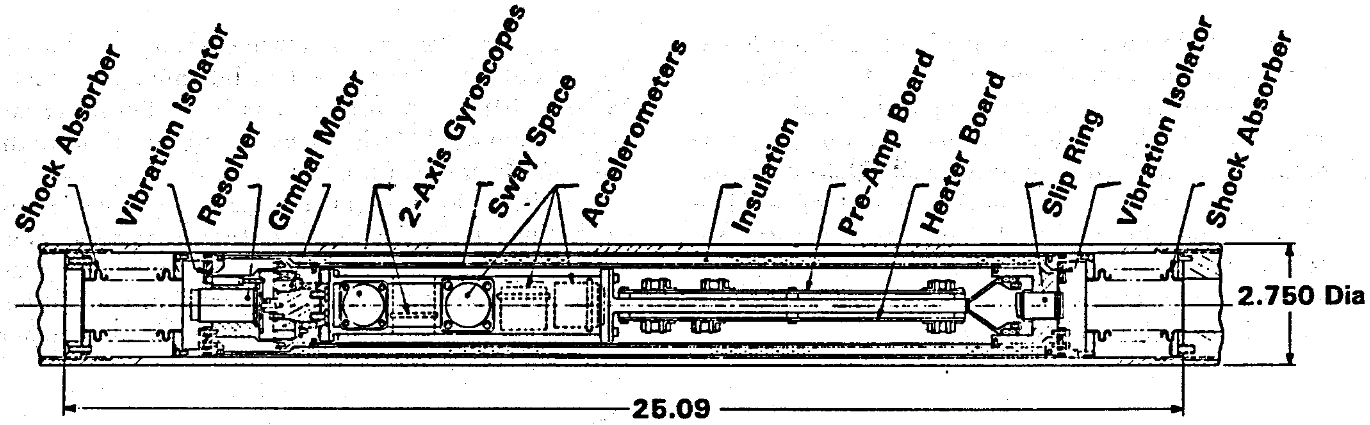


Figure 9. WINS Layout With Litton G7 Gyros

Tool length could be reduced by eliminating most of the battery pack. A several-hundred-volt, 2-A power source at the surface would deliver the 30 V needed by the tool. A small battery pack inside the tool could take care of momentary power outages.

Enhanced Temperature Capability

Better insulation and various heat-sink compounds could be used to increase the time that the tool can operate in hot formations. Improvements in these areas should make it possible to survey most of the deepest oil and gas wells and many geothermal wells.

Another way to increase the temperature capability is to increase the temperature range of components of the system. Although the electrical components are rated to 125°C, many will operate at considerably higher temperatures. We do not know the ultimate temperature ranges of the gyros, accelerometers, gimbal torque motor, resolver, and slip ring. Experiments are needed to identify those items that are relatively sensitive to heat.

Uncased Holes and Measurement-While-Drilling

The temperature capability of WINS would probably have to be improved for open hole and measurement-while-drilling (MWD) use. Roughness in walls of the uncased hole could necessitate slower survey rates and longer exposure to the higher temperatures in the deeper part of the well. In an MWD application, the tool should be able to withstand soaking at 200°C.

Vulnerability to shock and vibration is another problem area. Since radial sway space is severely limited, isolating the gyros (probably the most sensitive items) from shock with a soft suspension system inside the pressure barrel is impossible. We expect, however, that the ruggedness of the typical gyro will gradually be improved from the present 100-g shock-survival limit to perhaps 500 g. Since there is a tradeoff between accuracy and ruggedness, data on expected environments are required if optimum gyro characteristics are to be determined.

Most of the other components in WINS and related systems have passed large amplitude shock and vibration tests during weapon development. However, vibration tests are generally short—a minute or less. The shock test may consist of only a single shock along each axis. When in an uncased hole, and even more so during MWD, repeated shocks and hours-long periods of vibrations are encountered. How components respond to long periods of dynamic inputs requires more study.

Downhole Computing

At present, a general-purpose minicomputer performs the navigation calculations at the surface. Lately, however, advanced technology has developed computers of equal capability that can be packaged inside a 2- to 3-ft-long section of 4-in.-OD pressure barrel. We forecast a further 70% reduction in volume in 2 yr. We should soon be able to perform the same calculations downhole.

The main advantage of performing the calculations downhole is that the accuracy of the system is not affected by momentary dropouts of data in the suspension cable. With a downhole computer, these data would consist of tool position and velocity information that is generated independently of wireline transmission. Presently, the surface computer receives the gyro and accelerometer output over the wireline, and a dropout causes large errors in calculated position and velocity of the tool.

Another advantage of downhole computing would be a reduction in wireline data-bit rate by at least a factor of 10 from the present 4000 bit/s. The lower rate data stream would be less sensitive to variations in the cable's transmission properties.

A disadvantage of putting the navigation computer in the tool is that it must then withstand more severe environments and must be extremely rugged. Also, the tool itself would cost much more and, if lost or destroyed, the loss would be proportionally higher.

APPENDIX

Design of the Wellbore Inertial Navigation System

Mechanical Design

Partitioning

The WINS tool consists of seven major parts: a pressure barrel, a single-gimbal platform, a gyro servo and analog-to-frequency (A/F) electronics module, an input/output (I/O) electronics module, a power converter, a battery pack, and cabling. Figure A1 is a schematic of the tool, without the pressure barrel.

Pressure Barrel

The pressure barrel assembly is 4 in. in outside diameter (OD), about 20 ft (6.1 m) long, and has a wall thickness of 0.25 in. (0.64 cm) (Figure A2). Its pressure rating is 10 000 lb/in.^{2} The shock-nose assembly contains a large spring that absorbs some shocks that may be encountered during handling.

Single-Gimbal Platform

The platform contains two Incosym® Model III-E, tuned-rotor gyros and three Sundstrand® QA-1200 single-axis accelerometers (see Figure 1). The slip ring, dc torque motor, ac resolver, and bearings are commercially available, off-the-shelf items. Two printed circuit boards contain gyro-heater control and gyro-preamplifier circuitry. The dc torque motor provides torque in response to gyro output to counteract bearing friction and keep the gimbal essentially motionless if the tool rotates about its longitudinal axis. The resolver measures the gimbal angle relative to the barrel.

Electronics Packaging

The gyro-servo—A/F module, I/O module, and power converter consist of circuit boards attached to each side of an aluminum plate that provides structural support as well as heat sinking for high-power electric components (Figures A3, A4, and A5). The interconnect packages associated with the modules each contains two boards holding 153 wire-wrap, solder-pot pins (Figure A6). Pins are interconnected to other pins on the same board if entering signals are to exit through another connector, or to pins on the opposite board if the signal is required inside the module. The complete versatility and ease of rerouting signals are reasons for choosing such a scheme for a complex, experimental system like the WINS.

Temperature Control

The gyros are the only elements of the WINS that have active temperature control. Heaters and a temperature sensor on each gyro, in conjunction with temperature control electronics, bring the gyros to a control temperature of 60°C within 10 min after the electronics are turned on. Other temperature-sensitive components include the accelerometers and the A/F converters whose temperatures are monitored so that compensation may be provided in the computer software.

The WINS electronics are generally off-the-shelf commercial items with an advertised operating temperature of 125°C. Since this limit may be easily exceeded in deep wells, insulation must be provided between the inner wall of the pressure barrel and the inside of the tool. We chose silicone rubber foam because it is inexpensive and readily available, and can withstand more than 200°C. Much better but more expensive insulation, such as the vacuum bottle type, is available but was not necessary for our purposes.

The graph in Figure A7 shows how the WINS platform behaved during a laboratory oven test. The oven simulated the temperature profile that might be expected in an 8500-ft-deep vertical well. A few minutes after being turned on, the gyros reached the control temperature, and the temperature of the platform on which the gyros were mounted gradually increased until it exceeded the control temperature. At this point, positive control of the gyro temperature was lost. By the end of the test, gyro temperature had reached 62°C. In the future, we may use computer modeling of gyro temperature effects to maintain system accuracy when control of gyro temperature is lost.

In deep wells, there is a limited amount of time allowed for surveying before the builtup, internally-generated heat, plus that of the geological formation that has transferred to the tool, causes the upper operating temperature limit of the electronics to be exceeded. Figure A8 contains plots of the estimated temperature within the tool compared to depth; these plots were compiled for two survey rates. Figure A9 illustrates the effects that a phase-change, heat-sink compound has on temperature. Although the WINS platform will accept cannisters of such material, it was not considered necessary for proof-of-concept.

The amount of heat tolerated by the tool is also affected by the heat capacity of its contents. Fluids, ceramic-filled urethane foams, and ceramic sands are substances that can fill voids in the electronics packages to raise the thermal mass; sand may be the best choice for WINS because it can be removed easily from the package if it has to be repaired. Also, its relatively high conductivity will distribute heat away from the hot spots, increasing the time before excessive heat is built up at any particular spot. The computer monitors temperatures at several locations in the WINS tool and will shut off power if the tool overheats.

Shock and Vibration

As illustrated in Figures 1 and 10, the single-gimbal platform is suspended on vibration isolators that reduce transmission of high-frequency radial and axial vibrations into the sensor block. The isolators are cut from a sheet of silicone foam rubber and are clamped between aluminum rings. In addition, the platform is suspended on a set of axial shock absorbers consisting of metal bellows. O-rings at each end of the assembly further dampen vibration through friction with the pressure barrel. When we subjected the assembly to radial and axial shocks of about 100 g for 1 ms, the axial shock was attenuated by a factor of about 3, but the radial shock came through unattenuated.

Vibration tests revealed an axial natural frequency of about 80 Hz, with a magnification at resonance of less than 3 to 1. Radial natural frequency was about 130 Hz with a magnification at resonance of 7.5 to 1. Obtaining good isolation against shock and vibration in the radial direction is difficult because of the small amount of radial sway space available within the tool. However, the centralizers on the pressure barrel (below) should provide good radial isolation when the tool is in the wellbore. It is during transportation and handling that radial shocks are the greatest danger because they could easily exceed the gyro's shock capability of 100 g.

Angular Resonance Tests

To measure angular resonance, an empty pressure barrel was suspended on a set of centralizers within a cased wellbore. The barrel was then forced into angular oscillation by applying and quickly removing a lateral force at one end. The system exhibited an angular oscillation natural frequency of about 9 Hz, with a damping factor of 25% of critical. Oscillation decayed in about 0.5 s, indicating that the duration of oscillations induced by passage of the centralizers over casing points is small, relative to the total survey time. In any case, however, a 32-Hz attitude calculation rate is used so that the 9-Hz oscillations can be tracked with adequate precision.

Electrical Design

The five electrical modules of the WINS are the single-gimbal platform, the power converter, the gyro servo-A/F converter module, the I/O module, and the battery (Figure A10).

Platform - Mounted Electronics

Two printed circuit boards are mounted on the platform gimbal (Figure A11). The heater board contains two gyro heater control circuits and each gyro has an integral heater and temperature sensor. The output from the temperature sensor, along with a reference voltage, feeds into an amplifier, which generates an output that is proportional to the difference between the two values. This error signal feeds into a power stage that drives the heater. Gyro control temperature, presently set at about 60°C, is determined by the selected reference voltage (Figure A11.a).

The gyro preamplifier board contains four preamps, one for each gyro pickoff, that is, two per gyro (Figure A11.b). The 54-kHz ac pickoff signals are also filtered on this board.

Power Converter Module

The power converter module contains two boards: the power supply board (Figure A12) for producing dc and the inverter board (Figure A13) for producing ac.

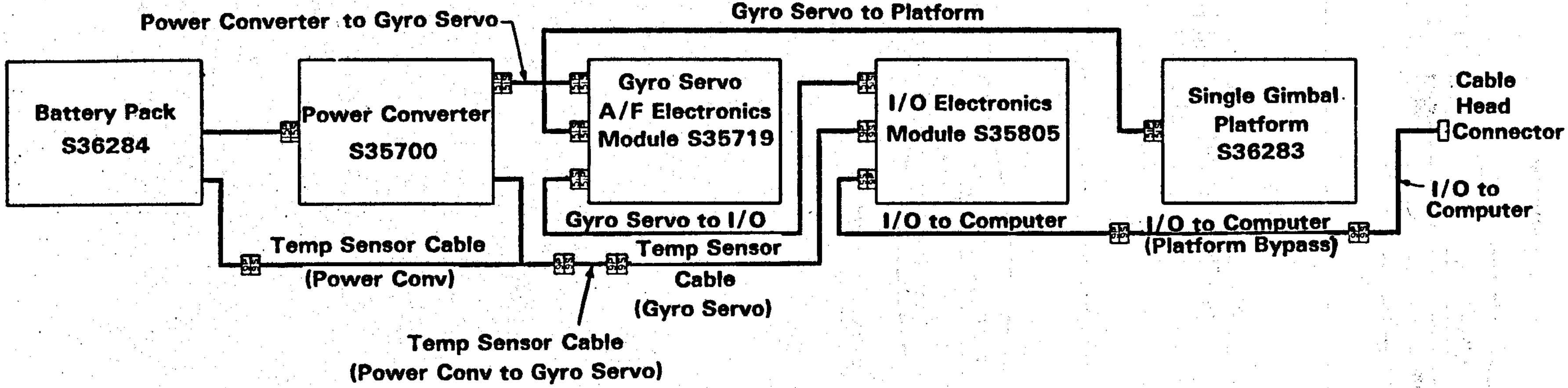
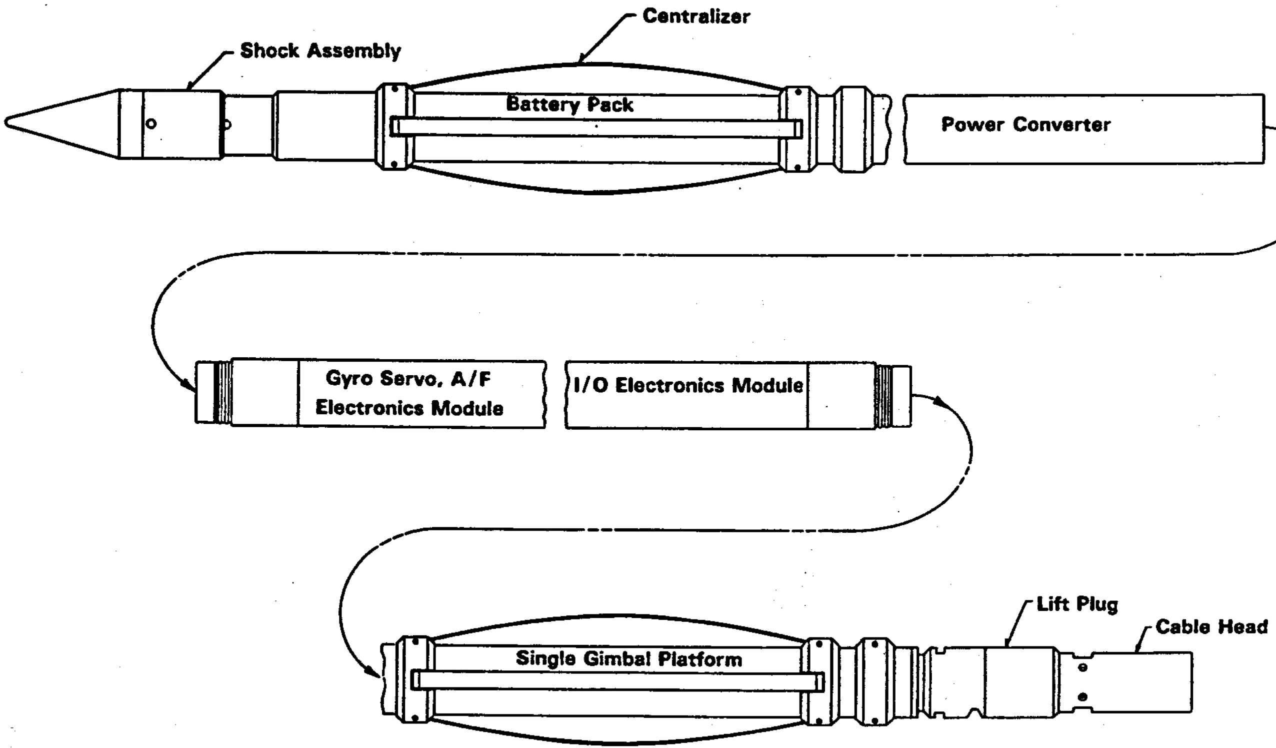


Figure A1. Schematic of WINS Tool



WINS PRESSURE BARREL ASSEMBLY
TOTAL LENGTH: 19FT.

Figure A2. WINS Pressure Barrel Assembly

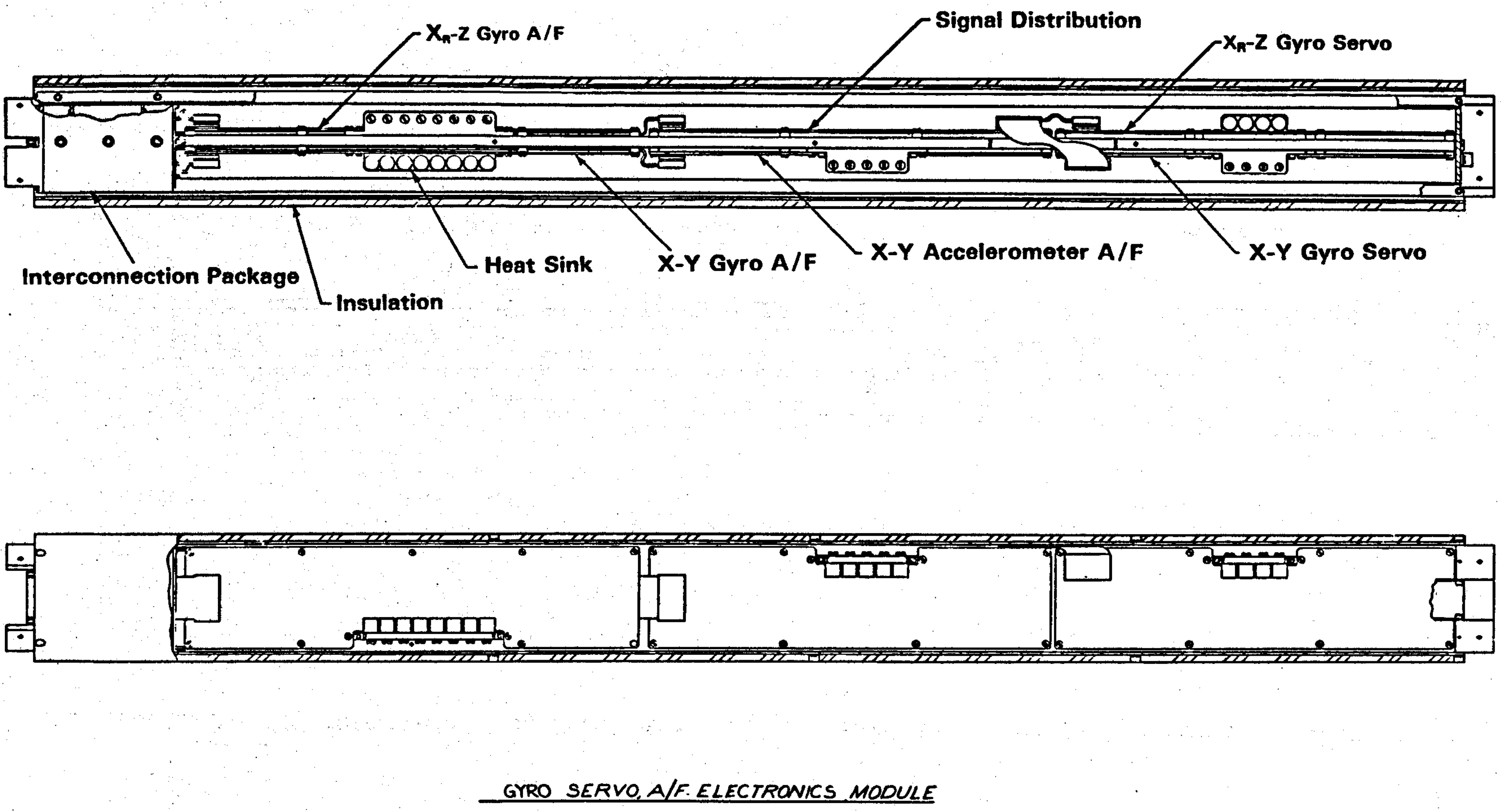


Figure A3. Gyro Servo-A/F Electronics Module

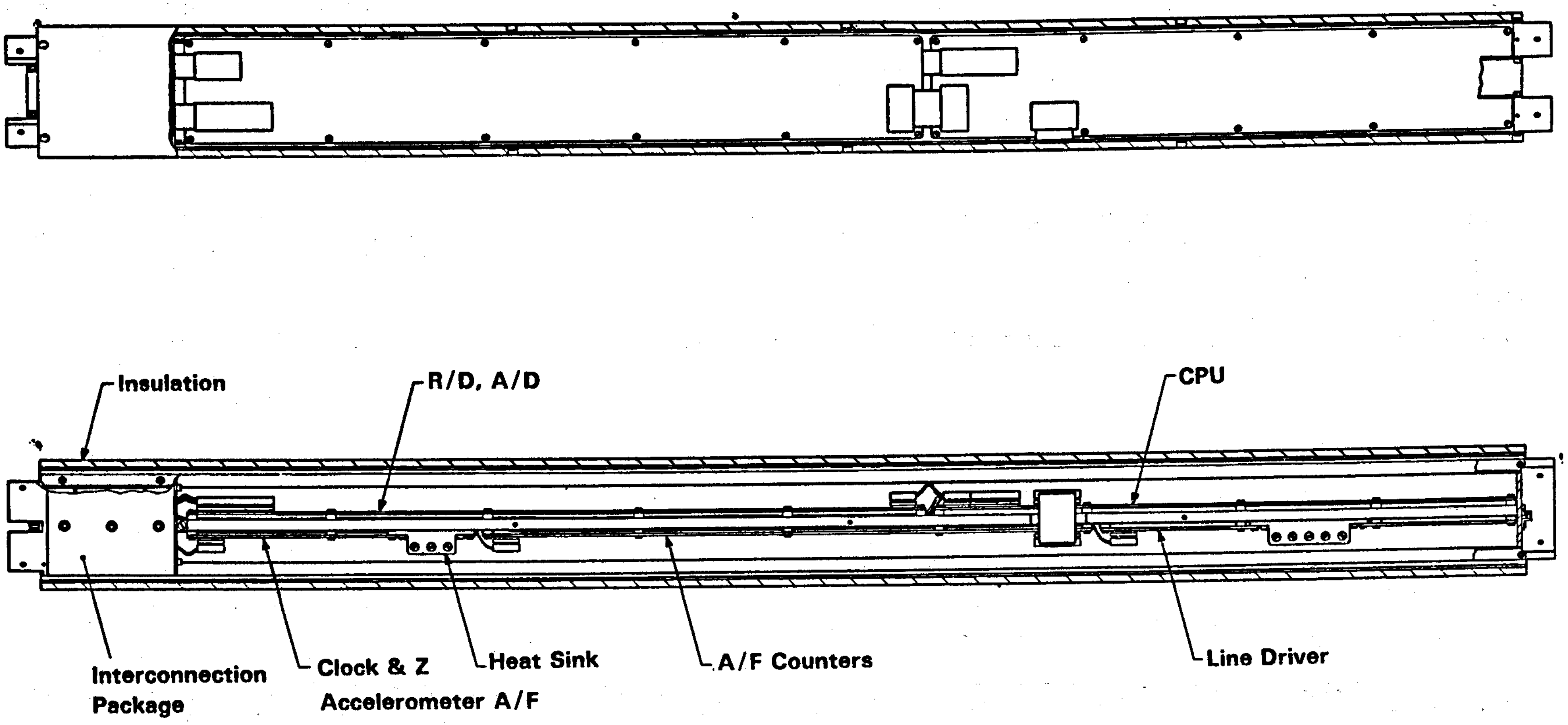


Figure A4. I/O Electronics Module

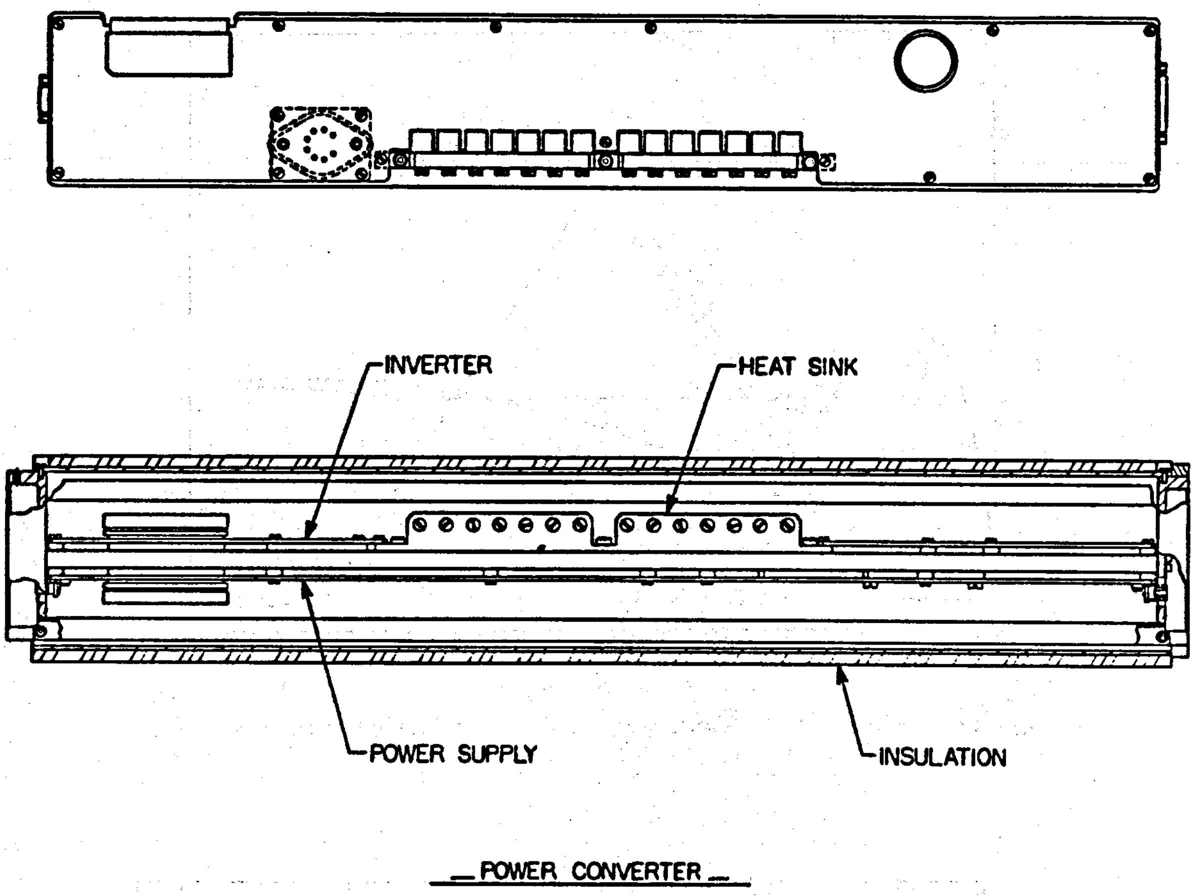


Figure A5. Power Converter Module

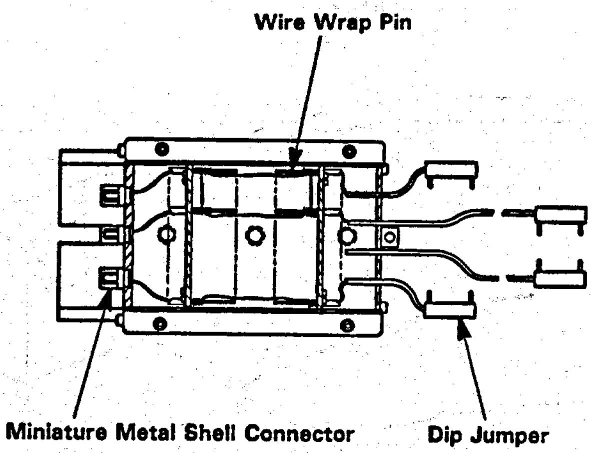


Figure A6. Interconnect Package

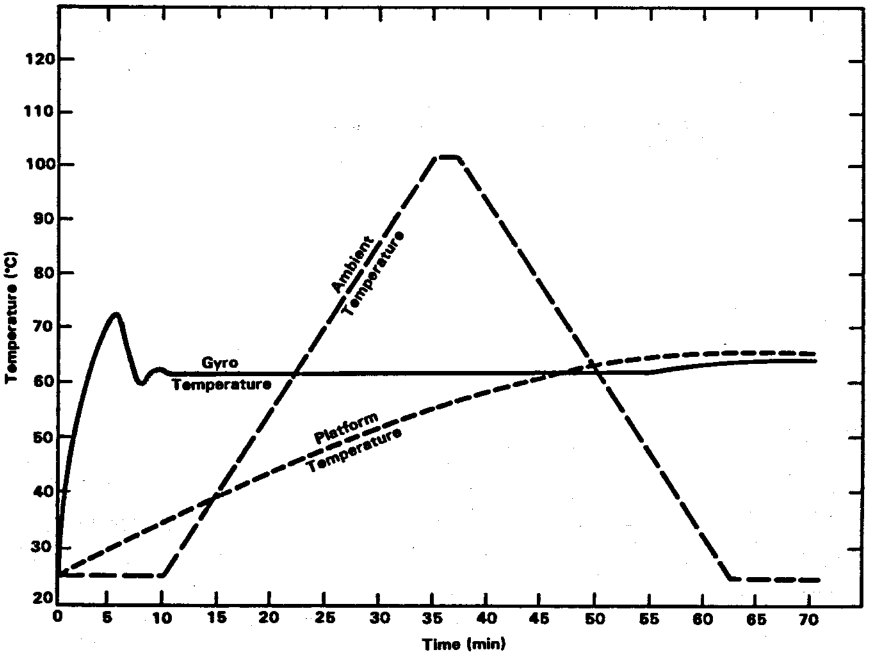


Figure A7. Temperature vs Time; WINS Laboratory Test (300 ft/min survey rate; simulatd 8500-ft (2591-m) well)

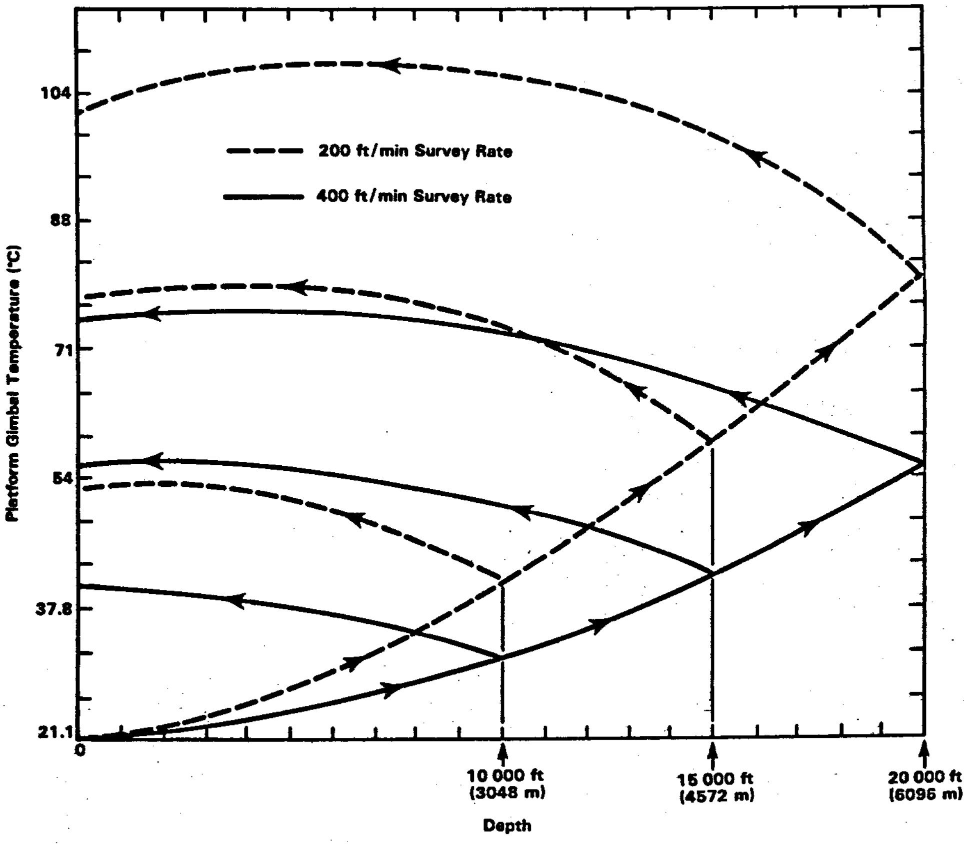


Figure A8. Predicted WINS Platform Gimbal Temperature vs Depth

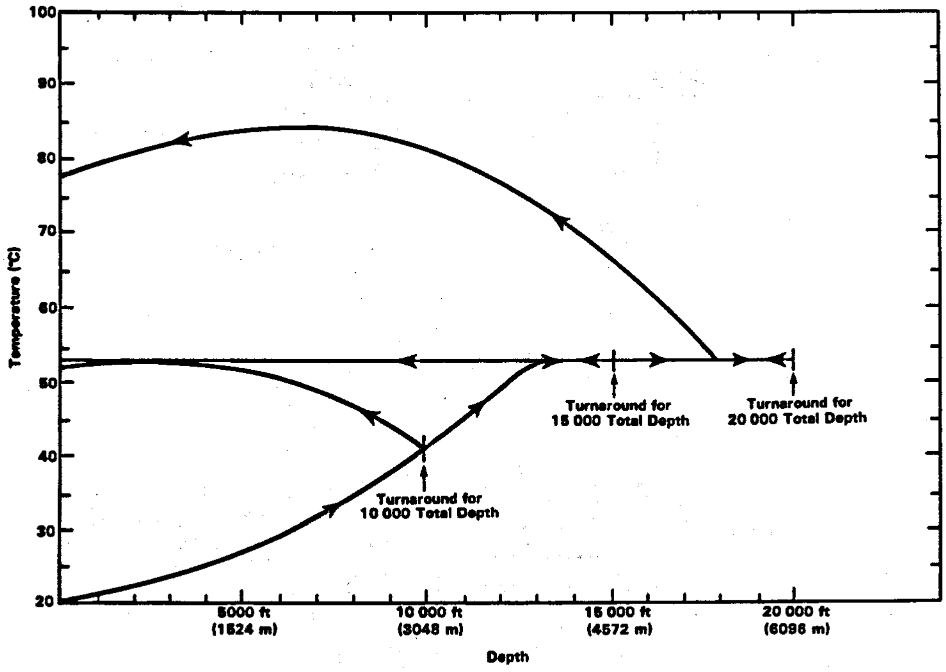


Figure A9. Predicted Platform Temperature vs Depth; With Heat Sink (200 ft/min survey rate; 4 lb nickel nitrate heat sink in platform)

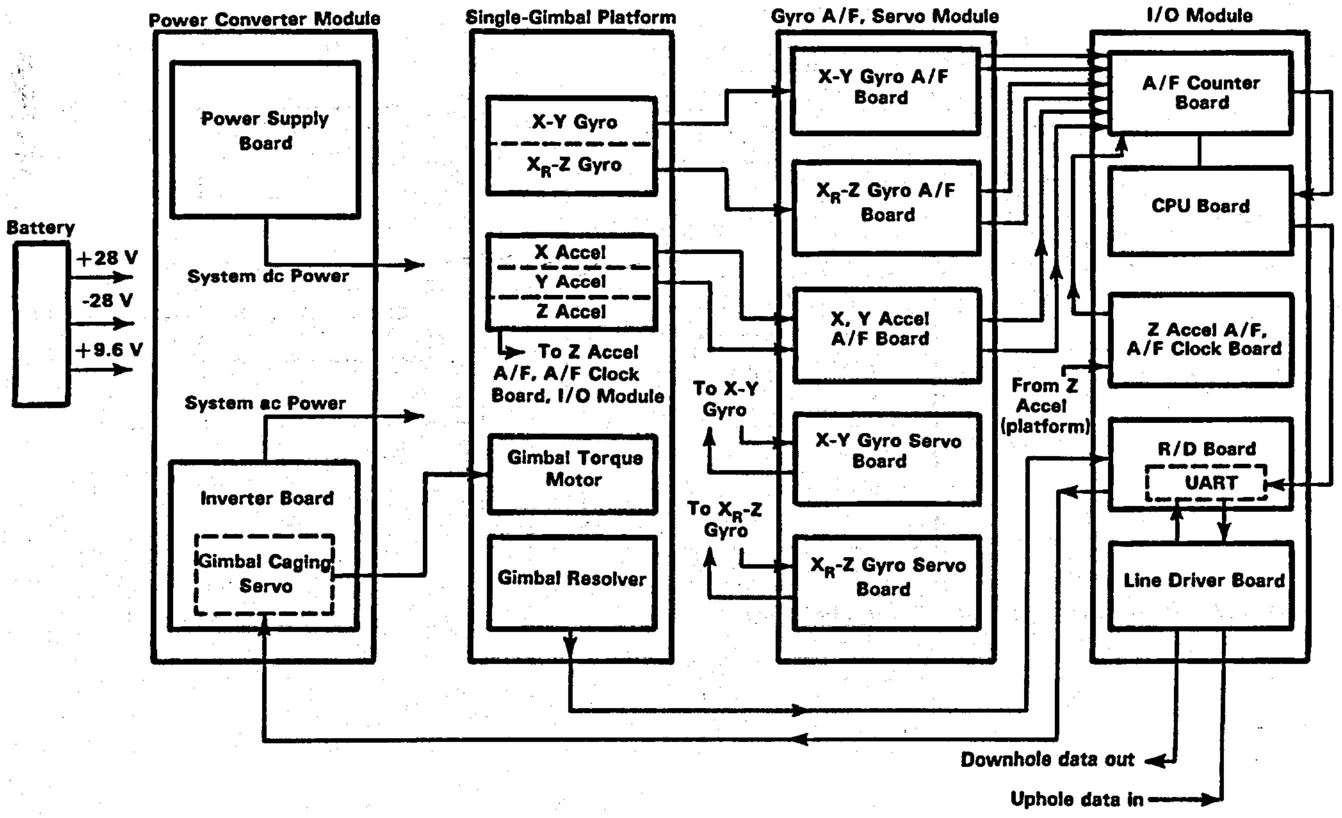
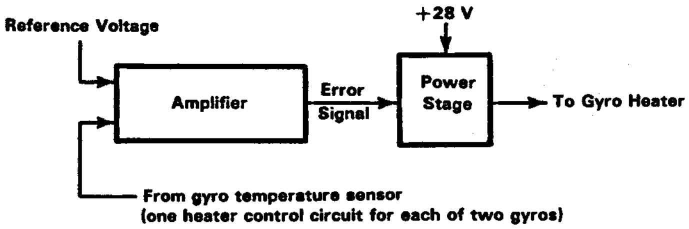
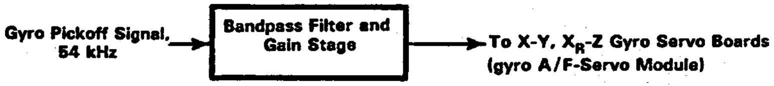


Figure A10. Schematic of WINS Major Functional Relationships



a. Heater Control



(One preamp for each of four gyro pickoff signals: X, Y, X_R, and Z)

b. Gyro preamplifier

Figure A11. Platform Gimbal Printed Circuit Boards

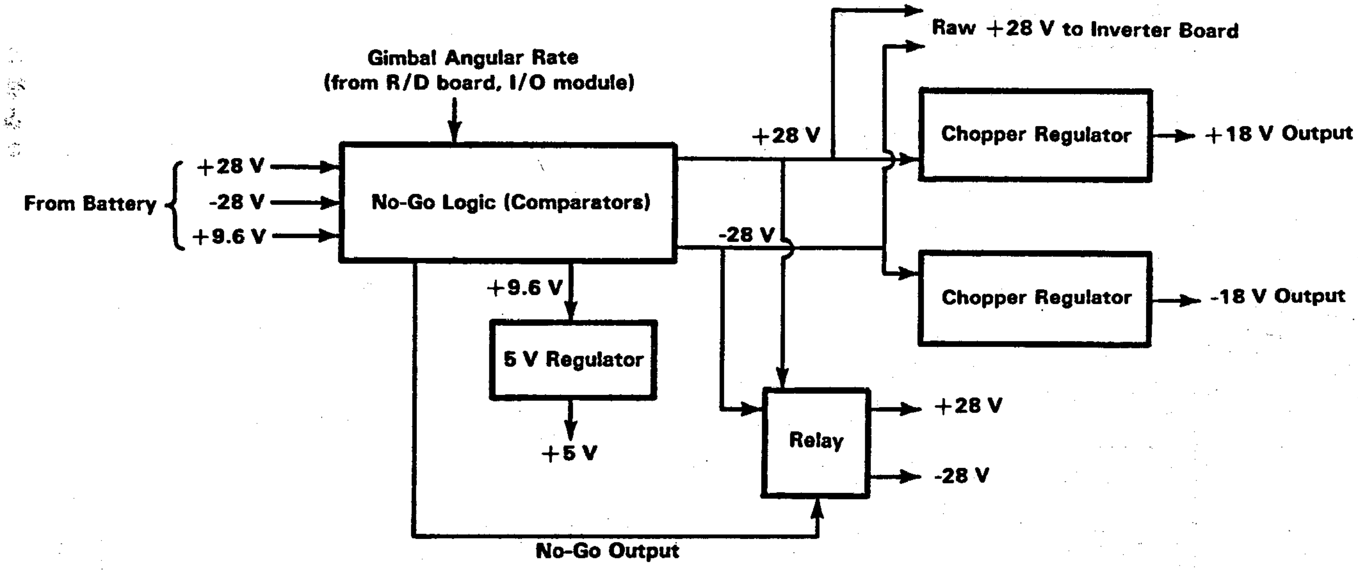


Figure A12. Power Converter's Power-Supply Board

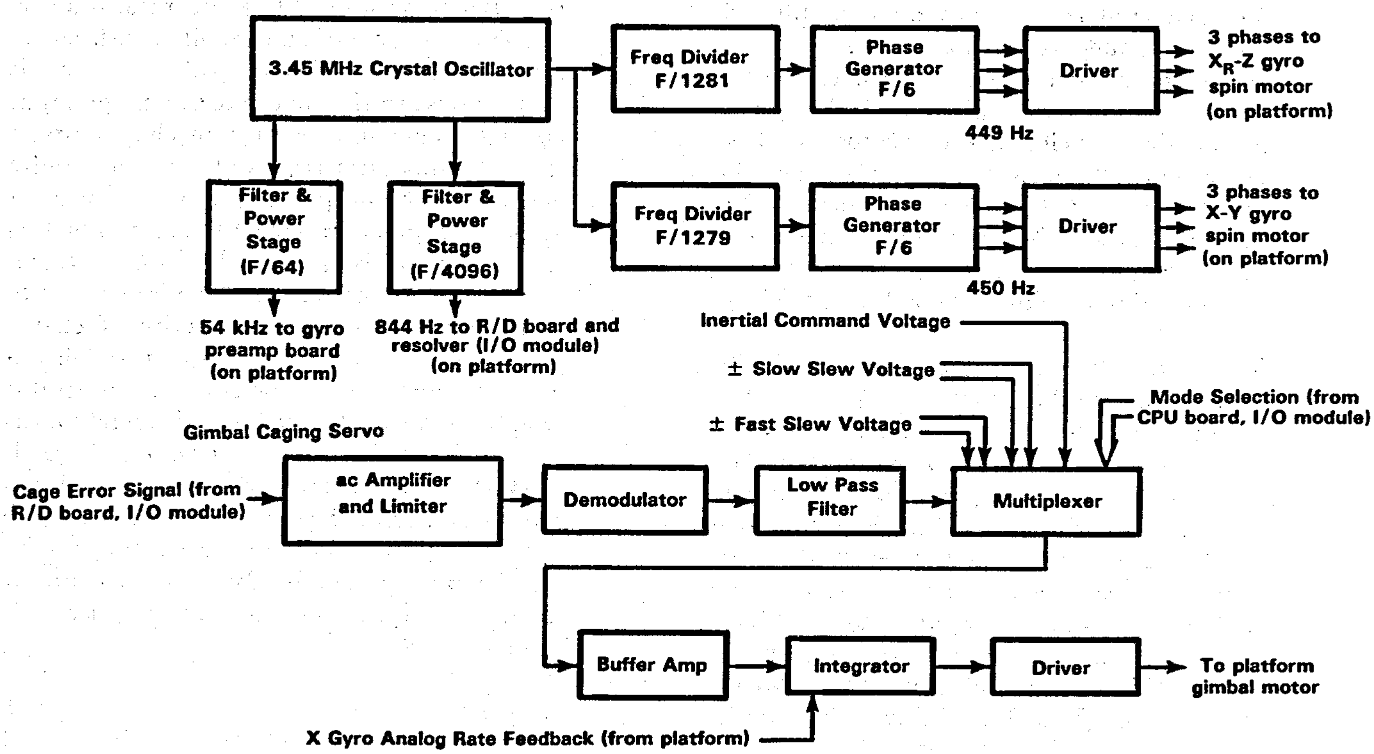


Figure A13. Power Converter's Inverter Board

The power supply board receives raw +28, -28, and +9.6-V power from the battery module and outputs +28, -28, +18, -18, and +5-Vdc. If the battery fails, no-go logic switches off the +28-V outputs which disables the gimbal motor drive and gyro torquer excitation and prevents the platform's gimbal motor from an uncontrolled spin-up that could damage the gyros.

The inverter board contains a 3.45-MHz crystal oscillator and a set of frequency dividers that produce ac signals at 54 kHz for the gyro pickoffs, 844 Hz for resolver excitation, and three phases of 450 Hz for the gyro spin-motor drives.

The gimbal caging servo is also located on the inverter board. A mode selection signal from the CPU board in the I/O module may command any one of six gimbal control states: inertial (the gimbal is inertially stabilized, as when WINS is navigating), slow or fast slew (in either direction), and caged. In the caged mode, the gimbal-caging servo loop rotates the gimbal to a predetermined position. A cage error signal, consisting of a voltage that represents the difference between the commanded and actual gimbal position, is filtered out, demodulated, integrated (with rate feedback from a gyro), and sent to the platform gimbal motor. The motor rotates the gimbal until the cage error signal is zero, that is, when the gimbal is at the commanded position. The gimbal resolver provides the gimbal's angular position measurement.

Gyro Servo and A/F Module

The gyro servo and A/F module contains the X-Y gyro servo board, the X_R-Z servo board (both of which are identical). It also contains the X-Y gyro A/F board, the X_R-Z gyro A/F board, and the X-Y accelerometer A/F board, all of which are identical.

- X-Y Gyro Servo Board—Each of the two gyros on the platform has two input axes: the X-axis being parallel to the gimbal axis of rotation, and the Y-axis being perpendicular. The X_R-axis of the X_R-Z gyro is redundant in the X direction. Each gyro contains a torquer that precesses the spinning wheel so that it follows rotations of the vehicle. The current to the torquer is nominally proportional to the angular rate about the gyro's input axis. A servo board for each gyro contains the circuitry that generates the proper current for the torquer. On the X-Y gyro servo board (Figure A14), the pickoff voltage (an ac signal proportional to the tilt of the wheel in response to an input rate) for each gyro axis is demodulated, filtered, integrated, and—through a voltage-to-current amplifier—it then produces a current in the cross-axis torquer. Simply stated, the X-axis pickoff signal excites the Y-axis torquer. Stability requires that the torquer-axis rate-signal be introduced at the integrator. This signal is the differentiated Y-axis pickoff voltage. The tilt of the gyro wheel, relative to the case, is maintained at nominal zero by this servo loop.

- X_R-Z Gyro A/F Board—Each gyro is served by an A/F converter board (Figure A15). The A/F circuitry from the gyro torquer converts the current for each axis into a pulse train, the frequency of which is proportional to input current. Since the current is proportional to angular rate, each pulse represents an increment of angle. These pulses go to the I/O module where they are accumulated and integrated into the data string that goes up the cable to the computer. The A/F circuitry contains an intergrator that receives the current from the gyro torquer. The integrator is a current-boosted, operational amplifier with capacitor feedback in which the voltage output is proportional to the time integral of the input current. When the voltage reaches a preset level, a comparator trips and turns on a pulse generator. The output of the pulse generator activates a precision current source, which is switched for a fixed interval into the integrator's input. As the torquer supplies current to the integrator, a precise quantity of charge from the capacitor is withdrawn through the current source. This prevents the integrator from becoming saturated and discretely measures the current from the torquer. The A/F converters for the accelerometers are similar to those of the gyro. The accelerometer's torquer current is porportional to acceleration and to the A/F pulse rate. Therefore, each A/F output pulse is proportional to an increment of velocity change.

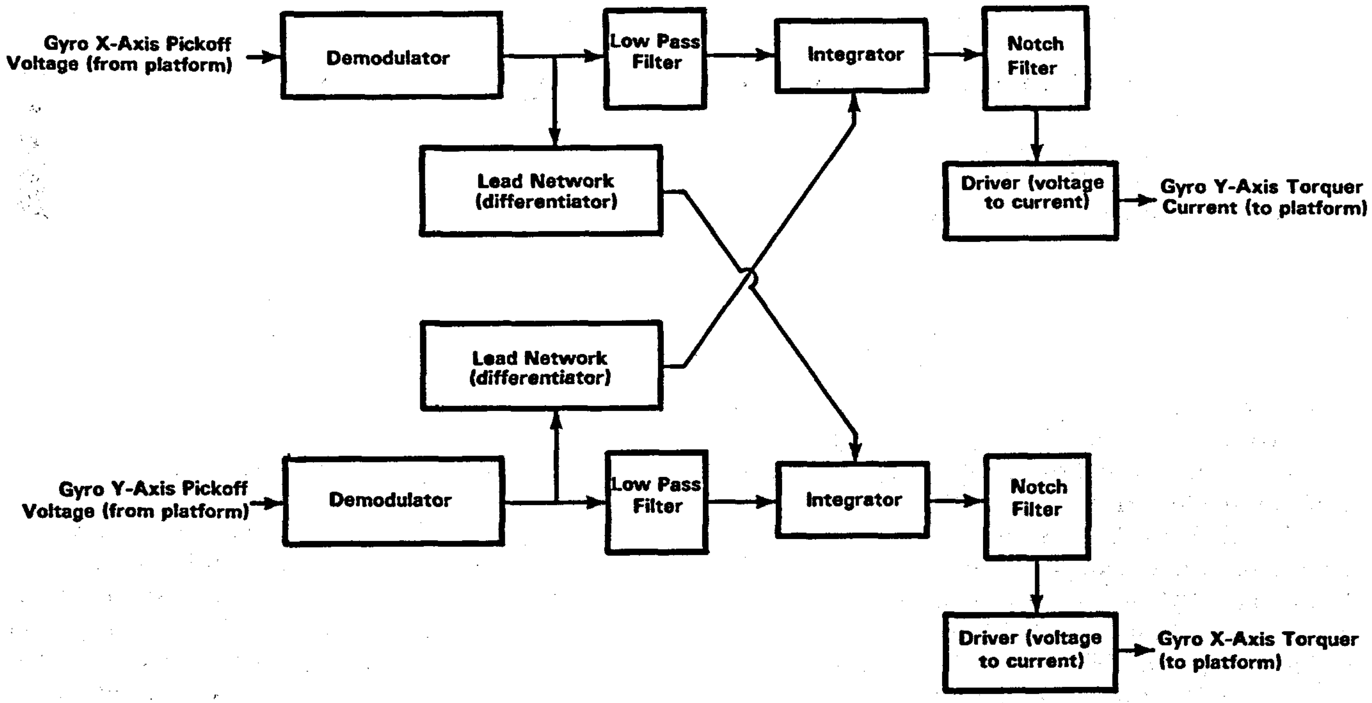


Figure A14. X-Y Gyro Servo Board

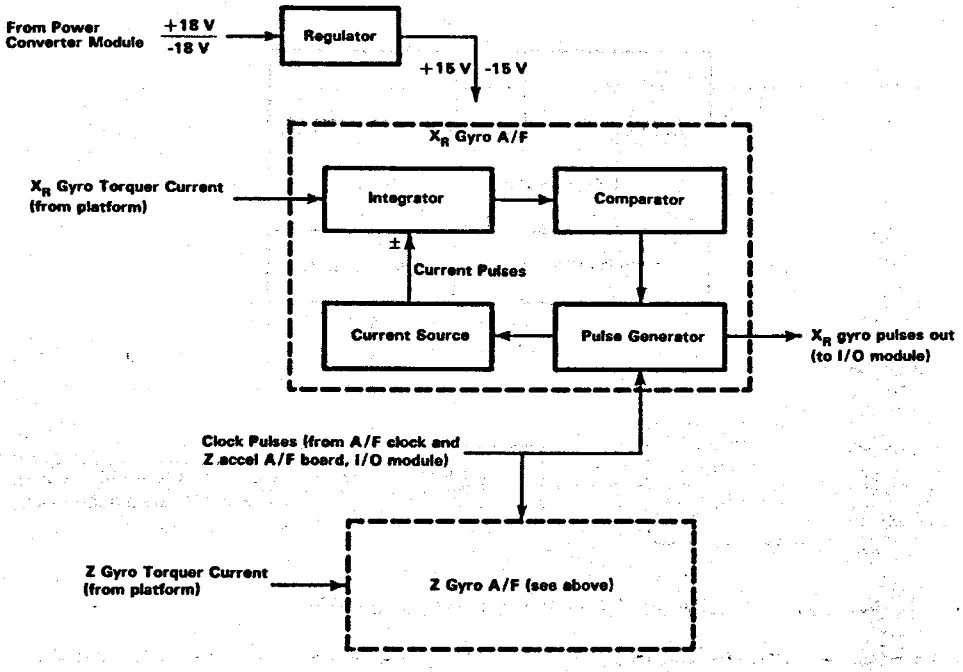


Figure A15. X_R-Z Gyro A/F Board

Input/Output Module

The I/O module contains an A/F clock and Z-axis accelerometer A/F board, an A/F counter board, a resolver-to-digital (R/D) board, a CPU board, and a line driver board.

- A/F Clock and Z-Axis Accelerometer A/F Board—A crystal oscillator in the A/F clock circuitry (Figure A16) produces a 2-MHz pulse frequency that is divided down to 65 kHz and passed to a waveform generator. The generator supplies several 65-kHz pulse trains of different phases and duty cycles, which are then used in generating and timing pulses in the A/Fs and in the timing and logic of the R/D board. The Z-axis accelerometer A/F circuitry is identical to the A/F circuitry described previously.
- A/F Counter Board—The seven (four gyros and three accelerometer) counters accumulate A/F pulses and periodically latch the accumulated totals onto the data bus to the CPU board (Figure A17). Each total represents the angle increment or velocity change occurring during the counting-time interval. The counter outputs are placed on the data bus sequentially according to commands from a CPU-controlled decoder.
- Resolver-to-Digital Board—The R/D board (Figure A18) contains an R/D converter that supplies an analog representation of the gimbal's angular rate and a digital representation of the gimbal's angular position. The converter sends the angular-rate signal, along with signals from temperature sensors located at various points within the system to an analog-to-digital (A/D) converter. The A/D output is fed to a Universal Asynchronous Receiver-Transmitter (UART) that arranges them into the proper format for transmission up the cable to the computer. Also supplied to the UART are the gimbal's digital angle data from the R/D, as well as A/F data from the A/F counter board, through the CPU board. These A/F data consist of output from the two gyros and the three accelerometers. In addition to assembling downhole data for transmission, the UART receives data and commands from above through the seven-conductor cable and via the CPU board.
- CPU Board—The CPU board (Figure A19) contains an 8-bit microprocessor or a central processing unit (CPU), programmable read only memory (PROM) and random access memory (RAM), latches, bus drivers, a decoder, and timing and control logic. The software of the microprocessor controls data handling within WINS. For example, the sequence and timing of the data on the UART bus are microprocessor-controlled, as is the order and rate at which the A/F counters are reset.

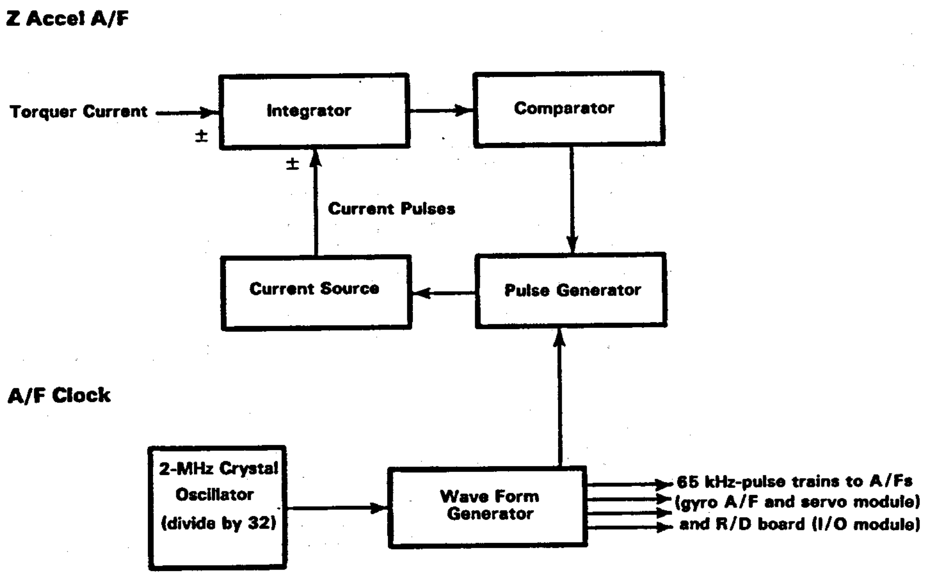


Figure A16. A/F Clock and Z Accelerometer A/F Board

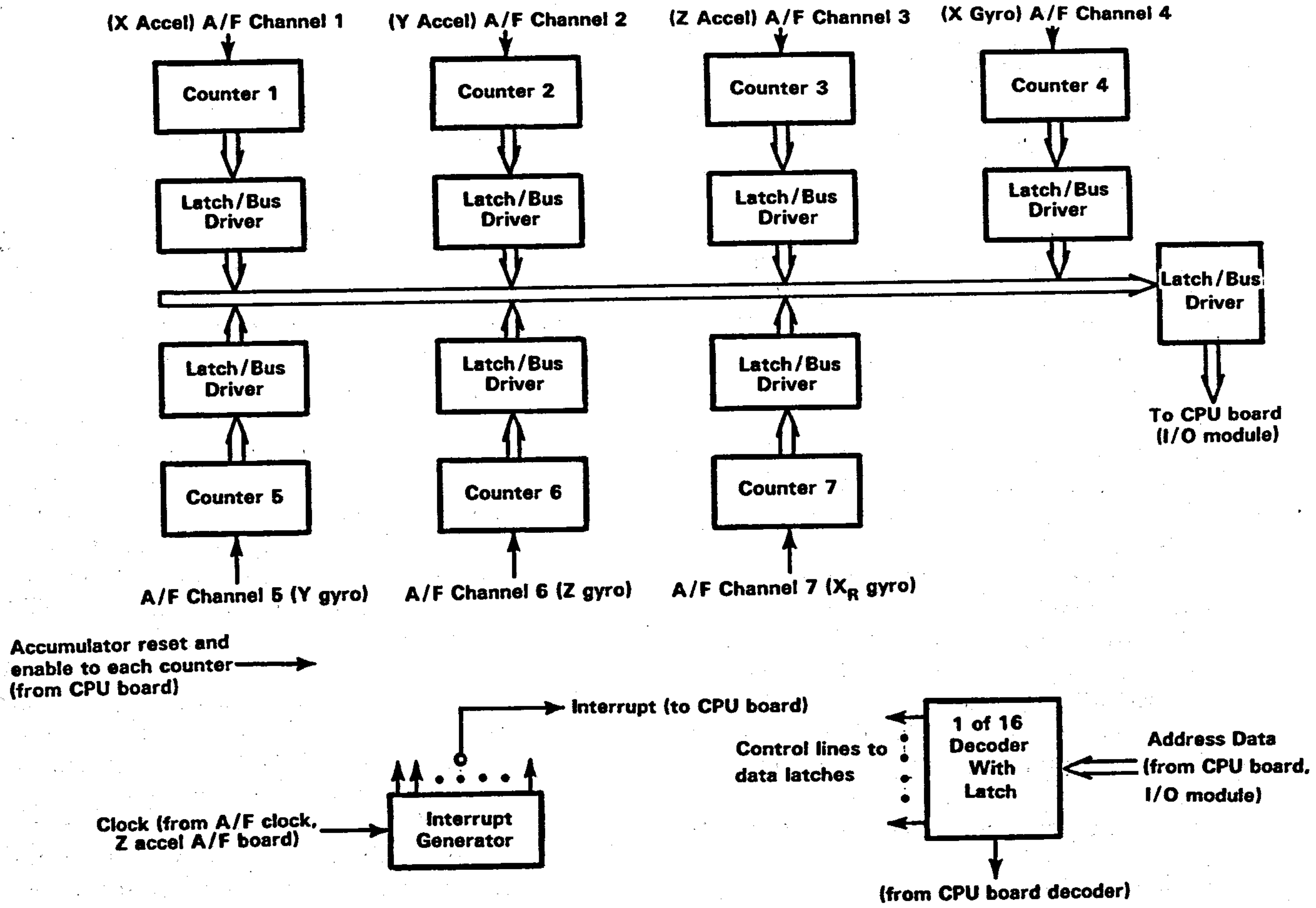


Figure A17. A/F Counter Board (I/O Module)

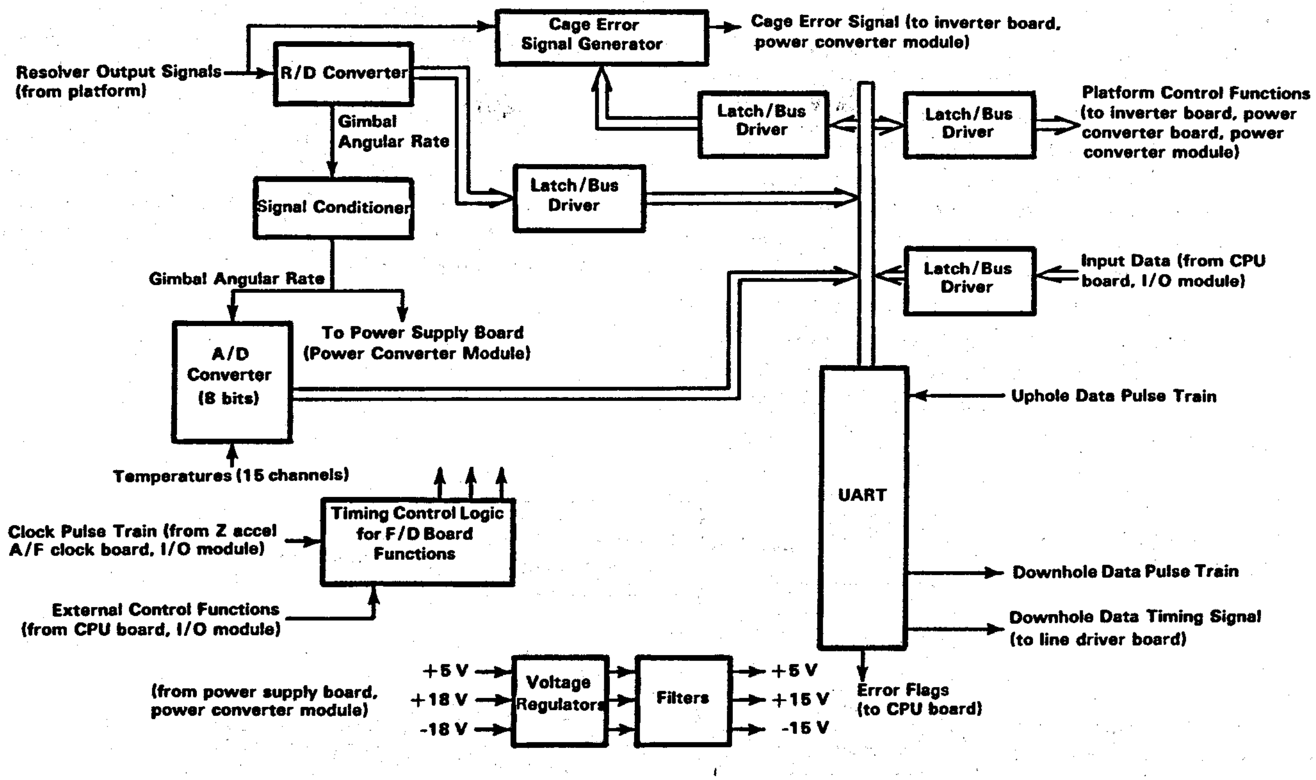


Figure A18. R/D Board (I/O Module)

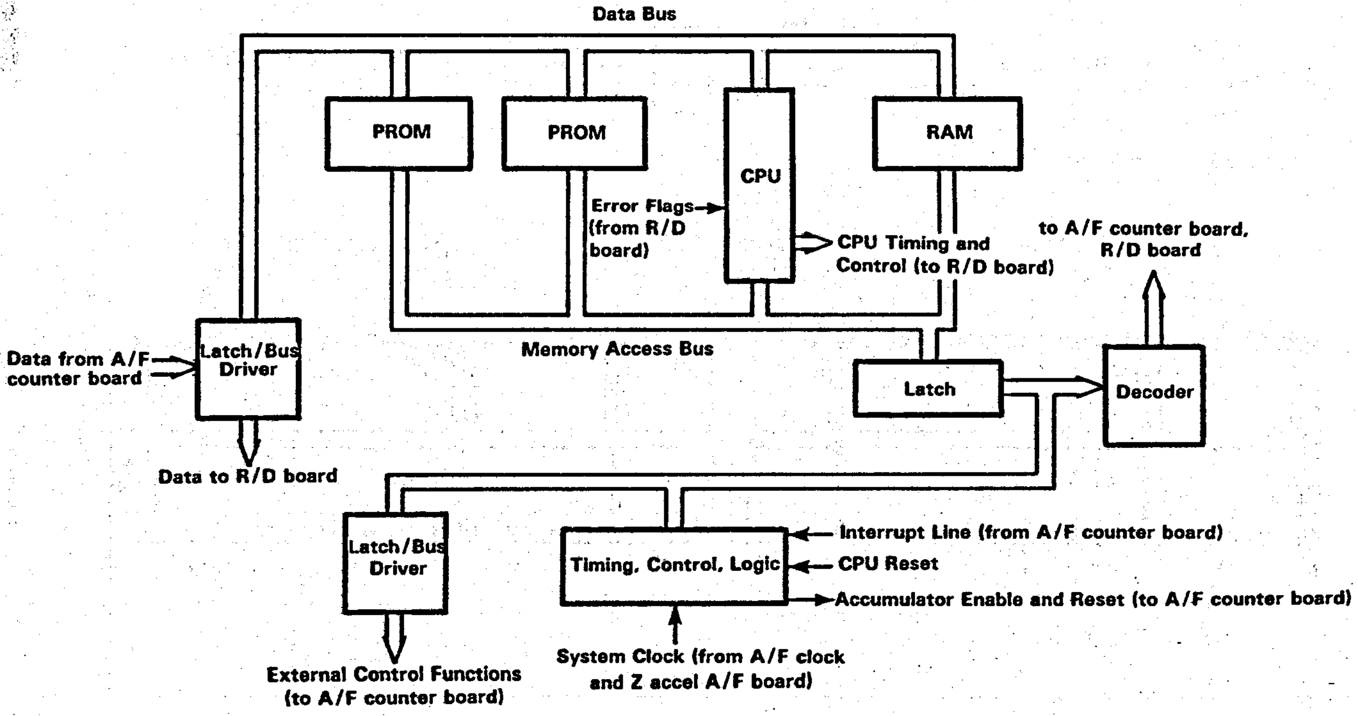


Figure A19. CPU Board

- Line Driver Board—Four of the seven conductors in the cable are used for data transmission: the uphole data-ready and data-lines, and the downhole data-ready and data-lines (Figure A20). The downhole data and ready lines are each put through a selectable inverter that provides proper pulse polarity. The inverters are followed by current sources which convert the voltage pulses to current pulses on the cable. Data from uphole is run through an optoisolator consisting of a photodiode and a photocell. By eliminating a direct electrical connection to the cable, the possibility of noise pickup is reduced.

- Battery Module—The battery module (Figure A2) contains 56 D-size, 1.2-V, 4-Ah, rechargable nickel-cadmium cells. The +28 and -28-V supplies each consist of 24 cells connected in series and the +9.6-V supply contains the remaining 8 cells. Estimated average power drain from each supply is about 1 A, so the battery module should be able to provide power for 4 h of tool operation.

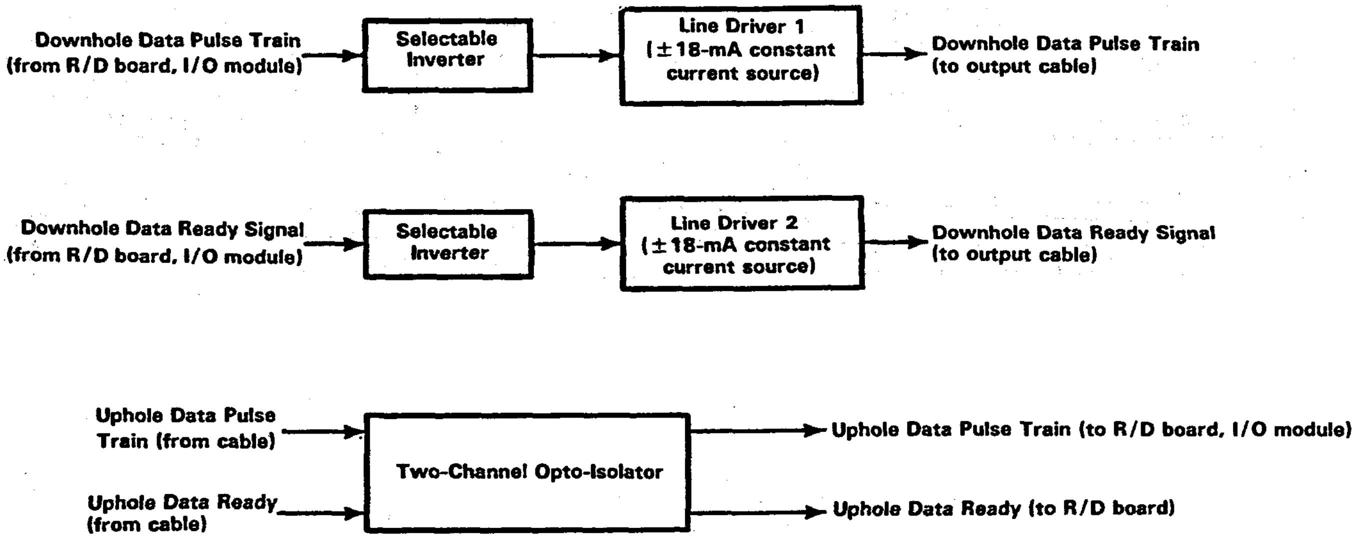


Figure A20. Line Driver Board

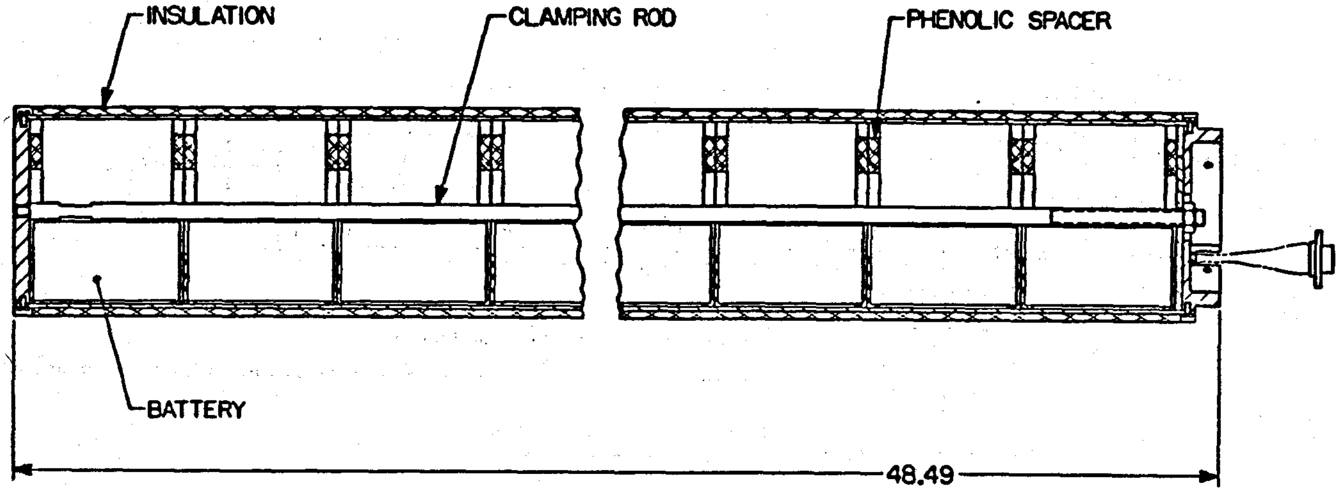


Figure A21. Battery Pack

Data Transmission

The data for a serial-data stream (or word) containing approximately 125 bits is transmitted uphole 32 times per second, for a data rate of 4 kb/s. Each word contains 20 bits for each of three gyro channels (the redundant X_R gyro channel is not sent), 10 bits each for each of the three accelerometer channels, 10 bits for resolver information, 10 bits for 1 or 2 of the 15 temperature channels, and 5 bits for spacing. Since one set of accelerometer or resolver data requires 20 bits, 2 cycles are needed to complete the transmission of data from these items. In summary, the gyro data-transmission rate is 32 Hz, accelerometer and gimbal resolver rate is 16 Hz, and complete temperature data are transmitted at 4 Hz. The gyro data rate is fastest because the attitude calculation rate is probably the limiting factor of navigation accuracy in a dynamic environment.

Dedicating 20 bits to each gyro or accelerometer channel is somewhat conservative because, at the full-scale A/F pulse rate of 65 kHz, only about 2000 pulses (2^{10} bits) are accumulated in 1/32 s. Since the UART operates with 8-bit words (+2 for overhead), 20 bits in the data stream are required to send 10 bits of data. If more efficient use of space were required, the data could be packed more densely, at the cost of some increase in complexity of microcomputer software.

A UART and line driver circuit similar to that in the I/O module will be used at the uphole end of the cable to send and receive signals.

The seven conductors of the cable are used for the following functions (battery power will be shut off if the system overheats or a catastrophic malfunction occurs):

Channel 1: data from uphole (uphole data)
2: spare
3: uphole common
4: data from downhole (downhole data)
5: downhole timing signal
6: downhole common
7: master power switch

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