

TECHNICAL REPORT ON A PORTABLE GRAVITY METER PLATFORM
AND FIRST TEST RESULTS(U) WOODS HOLE OCEANOGRAPHIC
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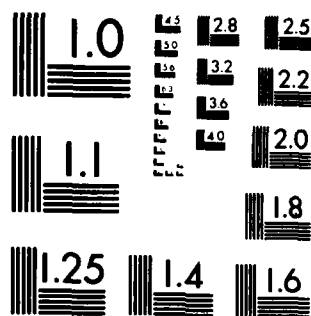
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REPORT DOCUMENTATION PAGE		READ INSTRUCTIONS BEFORE COMPLETING FORM
1. REPORT NUMBER WHOI-83-4	2. GOVT ACCESSION NO. AD-A124697	3. RECIPIENT'S CATALOG NUMBER
4. TITLE (and Subtitle) TECHNICAL REPORT ON A PORTABLE GRAVITY METER PLATFORM AND FIRST TEST RESULTS		5. TYPE OF REPORT & PERIOD COVERED Technical
		6. PERFORMING ORG. REPORT NUMBER WHOI-83-4
7. AUTHOR(s) Robert Goldsborough, Edward K. Scheer and Carl Bowin		8. CONTRACT OR GRANT NUMBER(s) N00014-82-C-0019; NR 083-004
9. PERFORMING ORGANIZATION NAME AND ADDRESS Woods Hole Oceanographic Institution Woods Hole, MA 02543		10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS NR 083-004
11. CONTROLLING OFFICE NAME AND ADDRESS NORDA/National Space Technology Laboratory Bay St. Louis, MS 39529		12. REPORT DATE January 1983
		13. NUMBER OF PAGES 25
14. MONITORING AGENCY NAME & ADDRESS (if different from Controlling Office)		15. SECURITY CLASS. (of this report) Unclassified
		15a. DECLASSIFICATION/DOWNGRADING SCHEDULE
16. DISTRIBUTION STATEMENT (of this Report) Approved for public release; distribution unlimited.		
17. DISTRIBUTION STATEMENT (of the abstract entered in Block 20, if different from Report)		
18. SUPPLEMENTARY NOTES This report should be cited as: Woods Hole Oceanog. Inst. Tech. Rept. WHOI-83-4.		
19. KEY WORDS (Continue on reverse side if necessary and identify by block number) 1. Gravity meter 2. Stable platform 3. Digital signal processing		
20. ABSTRACT (Continue on reverse side if necessary and identify by block number) See reverse side.		

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This report describes the new portable platform and gravity meter system which has been assembled at the Woods Hole Oceanographic Institution. It consists of three functionally distinct parts.

The first of these is a recently developed gyro-stabilized two-axis platform. This platform has been designed to carry the vibrating string accelerometer (VSA) and its associated oven assembly as the gravity sensor. The new platform represents a major reduction in both size and weight over other platforms suitable for gravity measurement. The second major part of this system is a new gravity readout which interfaces with the VSA, processes the VSA output, and prepares the resulting filtered acceleration data for output to the acquisition system. The readout has been designed to allow flexible use of the gravity system on a variety of vehicles, including ships, submarines and aircraft. The third part of this new meter is the data acquisition system. It consists of a microprocessor interfaced to a Kennedy 9-track tape drive. Both the platform and the readout are connected to the microprocessor.

Results are presented from Endeavor cruise 88 that demonstrate the ability of the platform to stabilize the gravity meter and for the gravity system to produce raw data with a resolution of 48 milligals at a sampling rate of 10 Hz. Digital signal processing techniques which were used to filter the data and extract the gravity signal with a resolution of 0.48 milligals are also discussed.



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TECHNICAL REPORT ON A PORTABLE GRAVITY METER PLATFORM
AND FIRST TEST RESULTS

by

Robert G. Goldsborough, Edward K. Scheer
and Carl Bowin

WOODS HOLE OCEANOGRAPHIC INSTITUTION
Woods Hole, Massachusetts 02543

January 1983

TECHNICAL REPORT

*Prepared for the Office of Naval Research under
Contract N00014-82-C-0019; NR 083-004.*

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ABSTRACT

This report describes the new portable platform and gravity meter system which has been assembled at the Woods Hole Oceanographic Institution. It consists of three functionally distinct parts.

The first of these is a recently developed gyro-stabilized two-axis platform. This platform has been designed to carry the vibrating string accelerometer (VSA) and its associated oven assembly as the gravity sensor. The new platform represents a major reduction in both size and weight over other platforms suitable for gravity measurement. The second major part of this system is a new gravity readout which interfaces with the VSA, processes the VSA output, and prepares the resulting filtered acceleration data for output to the acquisition system. The readout has been designed to allow flexible use of the gravity system on a variety of vehicles, including ships, submarines and aircraft. The third part of this new meter is the data acquisition system. It consists of a microprocessor interfaced to a Kennedy 9-track tape drive. Both the platform and the readout are connected to the microprocessor.

Results are presented from Endeavor cruise 88 that demonstrate the ability of the platform to stabilize the gravity meter and for the gravity system to produce raw data with a resolution of 48 milligals at a sampling rate of 10 Hz. Digital signal processing techniques which were used to filter the data and extract the gravity signal with a resolution of 0.48 milligals are also discussed.

SYSTEM DESIGN OBJECTIVES

Primary design objective for the new gravity platform is to provide a small two-axis stable table which can be installed in a variety of vehicles and which will carry the existing VSA gravity sensor. The range of vehicles that is considered acceptable for gravity work includes surface ships, submarines and airplanes. To take advantage of the opportunity provided by such a selection, it is necessary that the system be easily portable. Since some of these vehicles will have little space to devote to additional instrumentation, the platform shall be as small and compact as possible.

The platform should maintain level with sufficient accuracy that gravity data can be resolved to 1 milligal while the system is in operation on a sur-

face ship in moderate seas. The stable platform inertial data, which consists of the instantaneous accelerometer outputs and the integrated accelerations, or inertial velocities, are provided as outputs for subsequent analysis of the vehicle's dynamic motion. Gimbal angle resolvers provide output of pitch and roll data.

Data input to the platform are speed, heading and latitude. Because it is anticipated that the stable platform will be used in airplanes, it must be capable of handling speeds of several hundred knots as well as the more leisurely pace of the surface ship or submarine.

We were fortunate to have received from the Charles Stark Draper Laboratories (CSDL) two engineering models of the Apollo inertial navigation platform. These were given to us as a source of gyros and accelerometers and other parts that could be fit into our design. From these Apollo navigators we obtained two gyros, two accelerometers and four torque motorbearing assemblies with sliprings. Using these parts and the design goals stated above, we developed the design for the small stable table.

Platform Description

The platform that was designed to meet these requirements is depicted in simplified schematic form in figure 1. This figure shows only one axis of the two, since they are identical. The electronics and the computer are mounted separately from the gimbals, to which they are connected by a 10 ft. cable.

Because the Apollo accelerometers are pulse-torqued, it was decided that the best approach for the electronic design would be to use a digital control loop. Included within the loop would be a small computer. In this way, data from accelerometers and navigation devices would be used to calculate directly the torquing rates applied to the gyros. Software would replace the mechanical or electrical integrators that have been traditionally used, and the system could be easily adapted to different configurations.

Consultation for this design was provided by A. Gulovson from CSDL. With his help, we developed the platform operating requirements and the digital control loop concept. Based on his past experiences with inertial navigation systems and his associations with the people who were involved with the Apollo system, he was able to provide us with circuit diagrams and operating

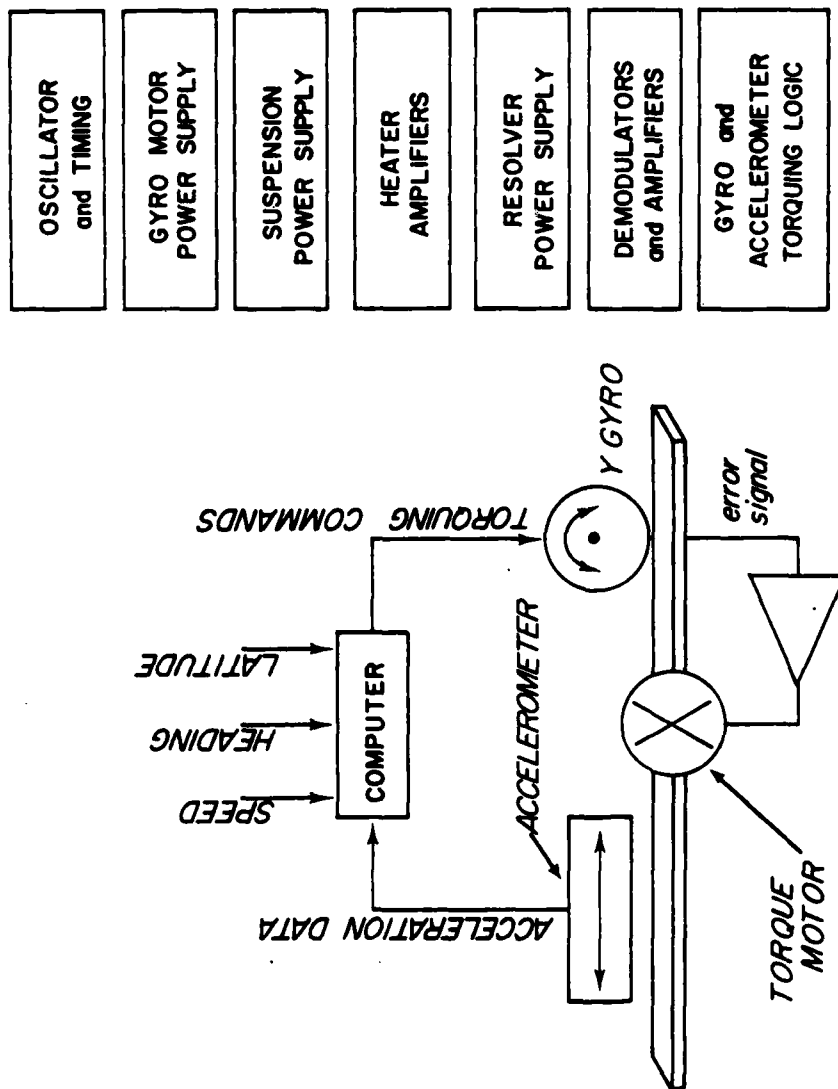


Figure 1 Stable Platform, the Major Functional Units. This very simplified schematic diagram shows the two primary control loops: 1) the gimbal stabilization loop and 2) the vertical erection loop.

procedures for the major portions of the system. These include:

- 1) Gyro and accelerometer torquing loop
- 2) Demodulators and servo amplifiers
- 3) Resolver demodulators
- 4) Moding logic
- 5) Heater control circuits
- 6) Oscillator and timing circuits
- 7) AC power supplies

In addition to the circuit diagrams and the Apollo specification drawings, Gulovson provided us with a computer program which he used to test the concept of the digital control loop. Within this program were the algorithms and equations which we included in our real-time computer program.

MAJOR SYSTEM COMPONENTS AND OPERATION

The central elements of an inertial platform are the accelerometers and gyros. These components determine the maximum performance which can be attained from the system. The gyro is used for platform position control, while the accelerometer is used for vertical reference. These instruments are mounted on the stable member, which is in turn supported by a gimbaled system.

The short-term vertical reference is provided by the Inertial Rate Integrating Gyro. The unit consists of a float, or housing, for the gyro motor, a signal generator which indicates float position relative to a null point, and a torquing mechanism which can rotate the float about the input axis. The float is heated to 135 degrees F. and maintained at this temperature so that it is neutrally buoyant within a fluid filled case. It is loosely held near the center of the case by an electro-magnetic suspension system. A two-phase motor at the center of the float turns the gyro wheel at 24000 rpm. Position of the float about a null point is sensed by the signal generator which has output of 11.8 millivolts/micro-radian. A torquing command signal may be input to the gyro to rotate it about its input axis in order to compensate for such things as gyro drift, earth rate and velocity.

The long-term vertical reference is provided by the Pulse Integrating Pendulous Accelerometer (PIP). This has a heated float element similar to that of the gyro. The float is weighted and suspended, creating a pendulum

which rotates freely about one axis. When the PIP is accelerated, the float rotates by an amount proportional to the acceleration. This rotation away from the null point is sensed by the signal generator, with the phase of the signal indicating on which side of the null the pendulum has moved. The phase information from the signal generator is amplified and output to a torque generator attached to the float. Utilizing this data, the torque generator returns the float to the null point. Thus, as continuous pulses of current flow into the torque generator, the float is kept hovering about zero. These pulses, when summed, represent the amount of restoring force required to maintain the float at null. This is directly proportional to the acceleration along the sensitive axis of the instrument.

Gimbal Rings

The stable member of the gravity platform is held within the framework of a two-axis gimbal system. This stable member is made from a 0.5 inch hardened aluminium plate approximately 12 X 14 inches, with a cutout to allow the VSA oven to be suspended through it. The gyros are mounted in a two-piece fixture that places one above and one below the aluminium plate. The accelerometers are housed in a one-piece block and also mounted above and below the plate. Symmetry and distribution of mass in the platform design have been maintained to keep the center of mass as close as possible to the axis center. Preamplifier circuit cards for the temperature sensors and the signal generators are mounted in edge connectors near each instrument.

The stable member is supported by a pair of torque motor assemblies. The weight is carried by stub shafts riding in a set of bearings. These bearings transfer the load to the outer case of the torque motor. A face plate is fastened to the inner end of the stub shafts and this provides the mounting surface for the stable member. The outer cases of the torque motors are mounted in fixtures that are integral components of the gimbal rings. Thus, the inner ring consists of two loops of formed aluminium tubing which interconnects the fixtures for holding the torque-motors. An outer ring made from three loops of tubing plus the torque-motor housings provides support for the inner ring. The outer ring is shock-mounted and attached to a baseplate and support structure. Pitch-axis control is provided by rotation of the

stable member on the torque motor axis inside the inner ring. The roll-axis pivots on the axis of the torquers fastened to the outer gimbal ring. Both axes can rotate through 360 degrees.

Besides supplying structural support between the two gimbal rings and the stable member, the torquer assemblies provide for monitoring of the gimbal angle and for the passage of electrical signals between rings. Each unit also contains a DC torque motor used to maintain the position of the gimbal controlled when an external force acts to rotate it out of alignment. Each pair of torquer assemblies has a 16X and a 1X resolver for angle readout and manual gimbal control in the "standby mode." The 1X resolvers are connected to a 12-bit synchro-to-digital converter so that the pitch and roll angles are available to the data acquisition system with a resolution of 8.5 arc-minutes. The center of each assembly contains a slipring unit with 48 individual circuits. All electrical signals, including shields and ground pass to the stable member through the sliprings.

Platform Concepts

There are two major control loops within the stable platform system. The first of these is for gimbal stabilization. This loop connects the output from the signal generator of each gyro to demodulators and amplifiers which drive the torque motors on the roll and pitch platform axis. Since the gyro is mounted rigidly to the platform, the loop is closed through mechanical coupling between them. If the platform is rotated by some outside force, the motion is sensed by the gyro as a misalignment between the float and its null point. The signal generator output drives the torque motors restoring the platform to its prior position. This loop has sufficient speed to maintain very tight coupling between the gimbals and the gyro. Platform errors due to the stabilization loop are less than 15 arc-seconds.

The second major loop is the Vertical Erection Loop. This feedback system senses the local vertical, and torques the gyros to align with a plane which is perpendicular to it. In operation, data from the accelerometers are processed in the computer, along with navigation information so that a level plane is maintained by the generation of gyro torquing rates which compensate for the earth's rotation and for vehicle translation and acceleration.

In the new gravity platform, the Vertical Erection Loop is a digital system. A computer with a real time data processing program (Fig. 2) is continuously being updated with acceleration, speed, heading, and latitude. With these data, gyro torquing rates are calculated. These rate numbers are then converted to the pulse trains which are input directly to the gyro torquing electronics. The accelerometers are sampled every 5 milliseconds. A new torque command is issued to each gyro at the same time. The acceleration samples are summed for one second to generate the average acceleration value for the one second interval. This value becomes the current input to the navigation subroutine (NAV79). Speed, heading, and latitude from the vehicle's sensors are updated as available. NAV79 converts the accelerations to velocities, filters these velocities in a lag/lead network and adds a correction for earth rate. The results of these calculations are scaled to produce the correct torquing rate for each gyro.

Systems can be designed which will theoretically indicate the vertical despite movements of the system in any fashion about the earth's surface. However, if an error in the vertical indication, or an initial offset, is introduced, these theoretical systems will oscillate indefinitely at a period of close to 84 minutes. Schuler first demonstrated this fact for a compound pendulum in 1923. The same is true for all modern stable table designs. The 84 minute period is determined by purely physical quantities: G , earth gravity, and R , earth radius. Since errors can never be eliminated in real systems, in order to prevent continuous oscillation, insensitivity to vehicle motion must be sacrificed. A damping filter is included in most designs which effectively increases the natural frequency of the instrument above the Schuler frequency. Normally, this damping is small so that the system remains fairly insensitive to motion, but oscillations die out with time. In some situations, the natural frequency is increased to the point that the period of damped oscillation is on the order of a few minutes. The latter type of filter is used particularly at startup time when it is desired to have a system aligned with the local vertical in a short amount of time. If a system continues to operate in a highly damped "startup mode", it will go off level when a change in velocity occurs, but the instrument will recover in a comparatively short amount of time. When the primary purpose of a system is

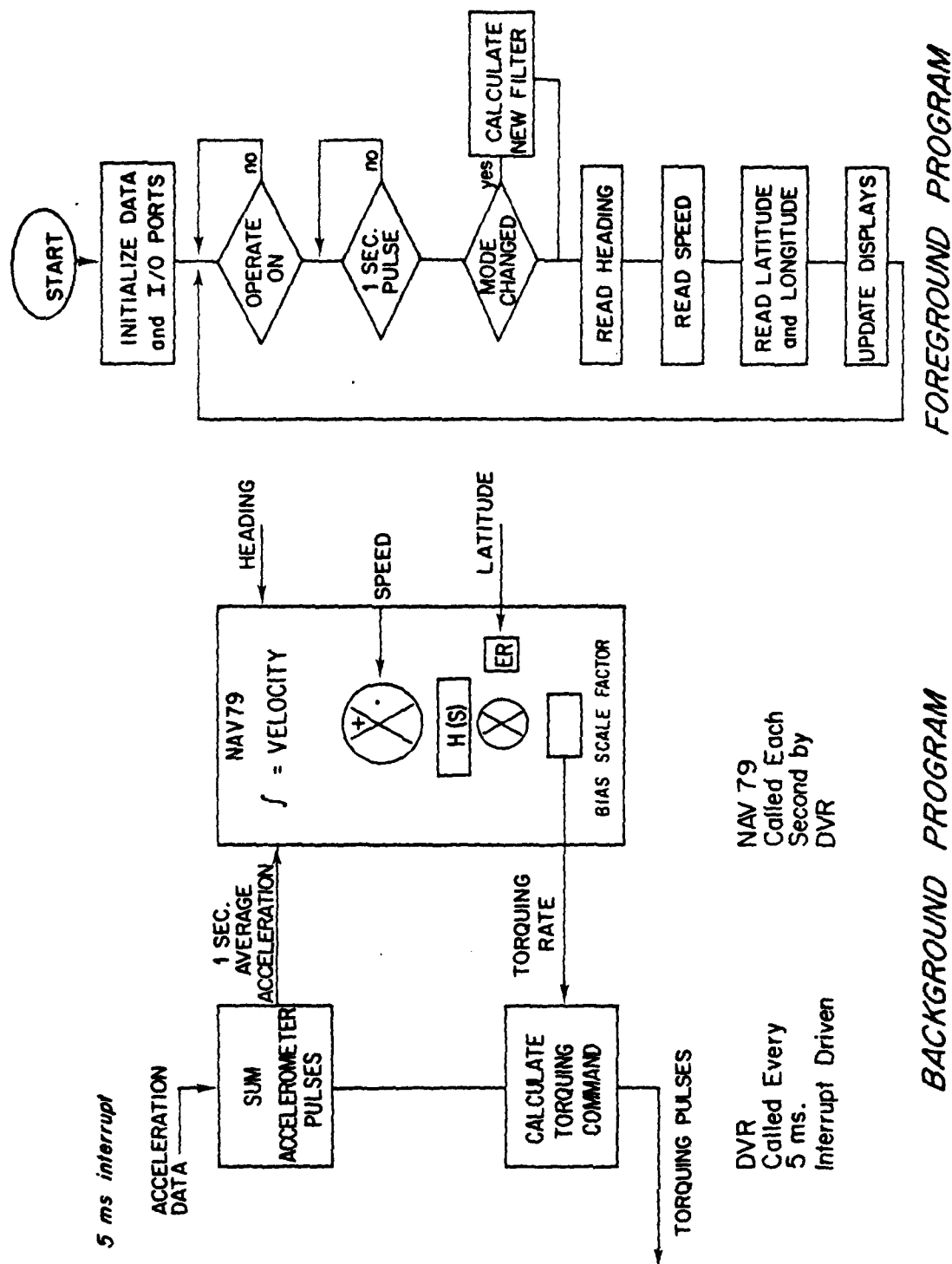


Figure 2 The Real Time Computer Program. The background program provides acceleration data and outputs gyro torquing commands every 5 ms.; every second a new torquing rate is calculated. The foreground program monitors the operational mode of the platform, provides navigation information, updates the displays and communicates with the data link.

the measurement of the vertical gravity component, there is a basic tradeoff between the desire for insensitivity to vehicle motion, and the need for quick recovery from an off-level state. In the present design, damping is controlled by a digital filter. Its characteristics can be modified by the operator, thereby allowing for experimentation with the tuning and damping applied to the gyro torquing loops. It is anticipated that the platform can be adjusted for best performance, depending on the particular vehicle.

A digital computer inside the loop of an inertial system is not a new idea. The usual implementation has been to use counting circuits and adders to emulate the functions of an analog computer. Analog computers were necessary to perform the multiple integrations and summations for conversion of accelerations into distance and to maintain the proper gyro torquing rates. However, the microprocessor offers new opportunities for performing these tasks. In this system, the integrations and filtering are performed using digital signal processing techniques. The result is that good control is maintained over the performance of the system. The software is easily modified or adapted to interface with specific navigation sensors or environments.

The Microcomputer System

It was desired to keep the on-board microcomputer system as simple as possible, in order to avoid major computer hardware development work. A board-level system was selected to allow flexibility in hardware configuration yet provide us with well-defined operational equipment. It was also necessary to maintain software compatibility with a microcomputer to be used for software development.

The microcomputer selected for use in the platform electronics consists of a collection of Standard (STD) Bus microprocessor components manufactured by the Mostek Corporation. This set includes a Z-80 CPU card, 32k RAM memory card, 3 parallel I/O cards, 1 serial I/O card, and one card with a rudimentary operating system in ROM plus a TTY port. The I/O boards interface the microcomputer system to the gyro-torquing electronics, accelerometers, and other sensors and displays which make up the platform electronics. The TTY port on the ROM card is connected to a larger computer system.

It is the interface to the larger computer system which lends flexibility and programming ease to the platform computer. The larger system is also a Z-80 CPU, running under a CP/M operating system. With this configuration, software modules can be developed using the higher-level languages and programming aids available for the CP/M system. These can be linked to modules written in the Z-80 assembly language and the complete program loaded to form a memory image of the desired computer program for the platform. Then, using a program written for the purpose, plus the absolute loader in the Mostek ROM, the memory image is down-loaded into the RAM in the platform computer where it is executed. This arrangement has been very helpful with software development, allowing for quick turnaround in the debugging process.

The computer-to-computer link allows for convenient changes to the software. It is through this mechanism that the operational response of the platform can be reconfigured to test new ideas or to match performance to different vehicles.

Additionally, it was discovered that this link was the solution to platform data-acquisition. By modifying the FORTRAN library drivers, a WRITE statement was made to transmit data up the link to the CP/M computer. This bi-directional link provides the ability to record and display in real time any of the numerical results of NAV79 or the data input to it. From these exchanges of information, the behavior of the platform can be analyzed, with modifications made to system constants and damping parameters while the platform is operating.

CRUISE RESULTS

The first sea trials for the new stable platform-gravity meter system have been completed on Endeavor, cruise 88. This cruise was one of a series for the Warm Core Rings Experiment, at the edge of the Gulf Stream. We worked in cooperation with T. Joyce of the Physical Oceanography department, who provided us with space on the Endeavor and access to the Loran navigation and gyro heading data which is collected by his Acoustic Profiler of Ocean Current (APOC) system. These data were available to us in real time on the SAIL loop (Serial ASCII Interface Loop), which interconnected the current profiler with the various sensors. The stable platform was connected to the SAIL loop as a listening device.

The first three days of the cruise were used to complete an initial software system for data acquisition. Concurrently, the stable platform computer was being interfaced to the ship's doppler speed equipment. On August 6, the platform was operated for the first time at sea.

The gimbal servos became unstable immediately, oscillating about the null point. This condition was determined to be caused by two factors: 1) the temperature of the platform was slightly higher and more uniform than it had been in the laboratory, since the gimbals were now covered by a plastic housing, and 2) vibrations were present. The elevated temperature raised the frequency response of the gyros, increasing the gain bandwidth product. The vibration provided a mechanical high-frequency input. The increased high-frequency response from the gyros changed the gain-phase relationship, lowering the phase margin of this tuned feedback system, and causing an instability at higher frequencies. The noise and vibration provided inputs in the frequency range where the loop was not unstable. This loop was probably marginally unstable during tests in the lab, although this was not observed. The gimble servos were made to function adequately by removing the cover and adjusting the overall gain of the servo amplifiers. This was only a temporary fix, and the system needs to be retuned by changing the gain and phase delay of the servo amplifiers.

It was observed that while in the "navigate mode" there was insufficient damping, so that the platform oscillated at the Schuler period, see fig 3. However, the oscillations did die out over time.

In the "fast erect mode" the system is much more responsive. The inertial velocities are accurate within 0.5 kts of the rough estimates of ship's speed. In this mode, the integral of the acceleration data tracks velocity data input from the Doppler speed meter. In effect, the closed loop error signal becomes the difference between integrated acceleration and velocity data. However, the platform remains very nearly level over the long term, since the integral of the acceleration is finite, and the deviation from velocity is small. A profile of "fast erect" response is shown in figure 4. It can be seen from the figure that there is a one to one correspondence between the velocity vectors derived from the Doppler speed meter (resolved with the gyro compass) and the velocity vectors generated by integrating the data from the two accelerometers.

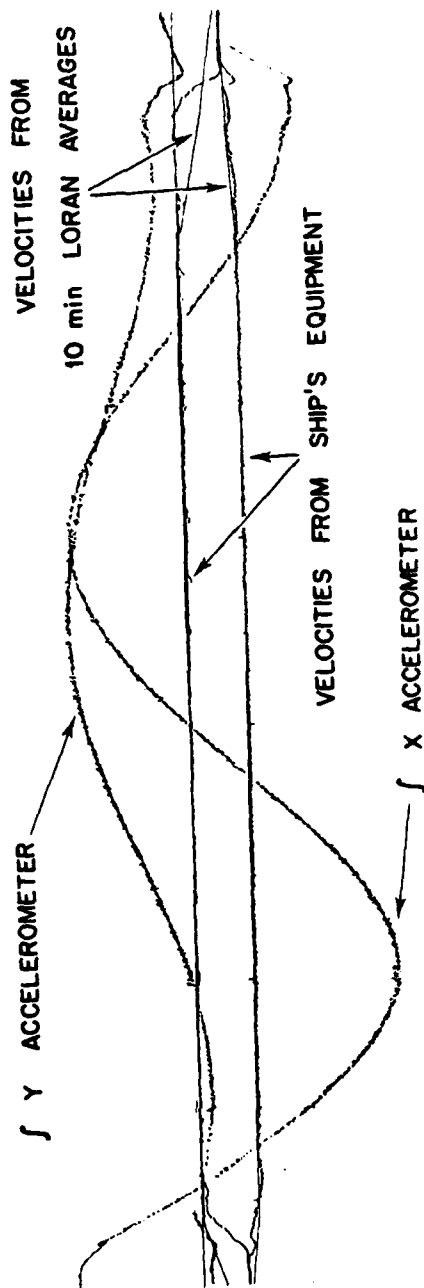


Figure 3 Inertial Velocity Navigate Mode. The summed acceleration data shows that the platform is oscillating around vertical. The period is just under the 84.4 second Schuler rate. The time axis is approximately 100 minutes.

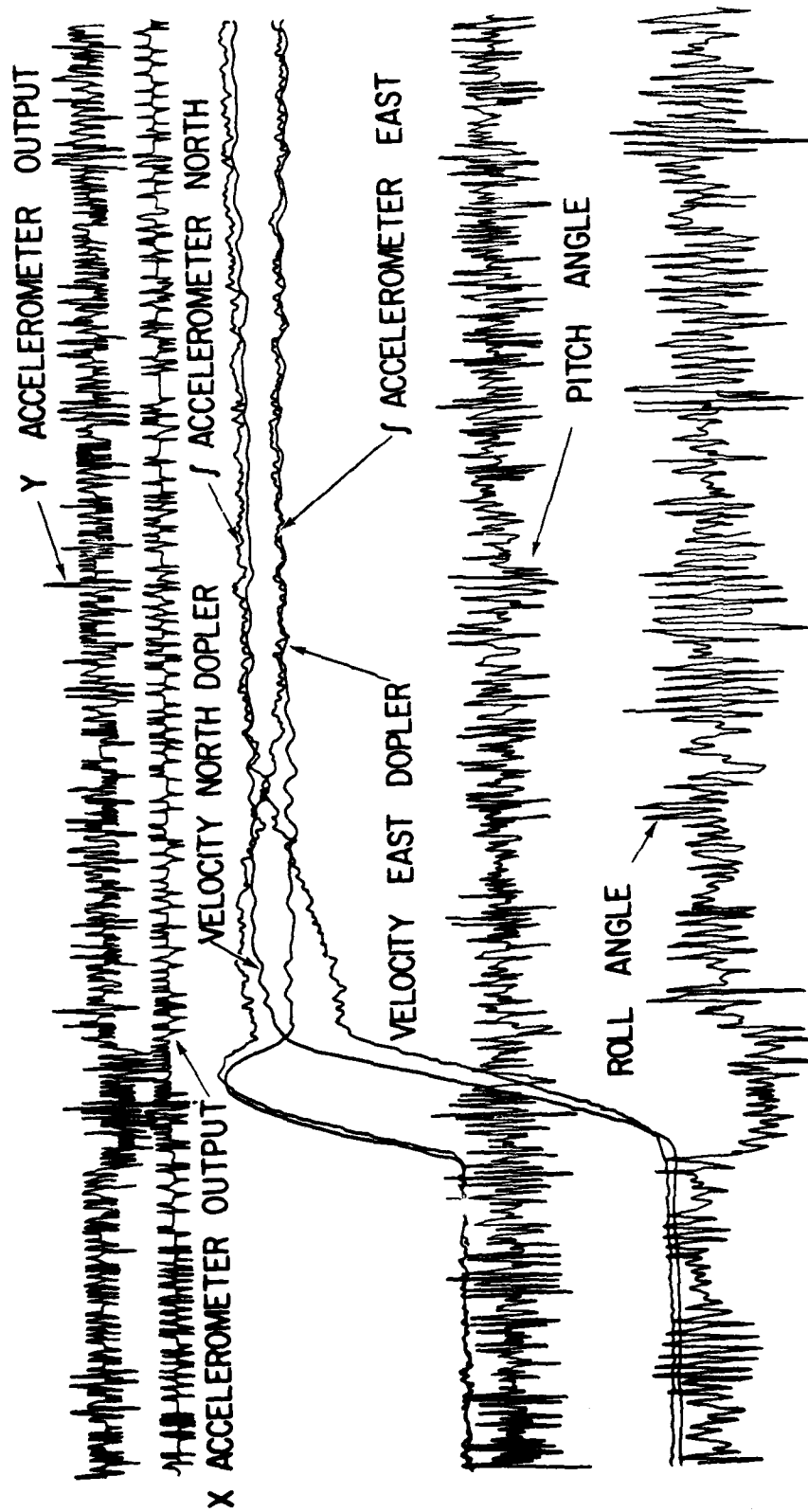


Figure 4 Inertial Velocity Quick Erect Mode. It is seen that the integrated accelerations match closely with the speed and heading data. The abrupt shift is a course change. The length of the plot is 20 minutes.

An error in estimation of the bandwidth of the ship's heave resulted in a phase-lock loop design for the gravity readout having insufficient dynamic range to remain in lock for normal sea states. Therefore, vertical acceleration data were obtained only for short periods of time during calm seas. Data were obtained directly from the vertical sensor using a frequency counter in order to correctly estimate the range for the redesign of the phase-locked loop.

The gravity meter data recorded during a brief calm period have been reduced using numerical analysis techniques to be discussed below.

Data acquisition programs were developed for recording the inertial data and dynamic motion of the ship as sensed by the gyro-stabilized platform. These time-series data were merged with the frequency counts from the gravity readout and the resultant time series was recorded on nine-track magnetic tape. Twenty tapes were obtained. The data include platform behavior in the "fast erect mode" and in the "navigate mode." They also include performance for various damping parameters. Recordings of LORAN, speed and heading, and vertical acceleration are also available for analysis. Information during one XBT star was recorded for subsequent comparison with the APOC data.

Processing of VSA data from New Platform

Data from the Vibrating String Accelerometer, which is used as the gravity sensor in the system (Bowin et al, 1972), is encoded as a pair of narrow band signals which are brought out to a readout unit for preliminary processing. The difference in frequency between this pair of signals is proportional to the acceleration experienced by the VSA along its input axis. This axis is aligned to the local vertical by the platform. The difference frequency is on the order of $f_d = 65$ Hertz, when the VSA is static with its input axis along the vertical. A rough measure of its scale factor is then $G/65$ or about 15000 milligals/Hz, where G is the normal, average vertical gravity component (980000 milligals).

The difference frequency is obtained in the readout by applying both VSA signals to a dual balanced mixer which, in effect, multiplies the two inputs and generates an output made up of sum and difference frequency components. The sum component is subsequently filtered out with an analog low pass filter

(LPF). In the present application, in which typical vertical accelerations will be no more than .3G, the signal at the output of the LPF is a narrow band signal centered at f_d Hz. The problem of obtaining vertical acceleration and gravity information from this output is thus essentially a problem in narrowband FM demodulation.

The information encoded in the modulating frequency is obtained by counting zero crossings, a simple technique which can readily be used for narrowband FM (Stark and Tuteur, 1979). The application of digital signal processing techniques to data in which information is encoded in the zero crossings of a signal is not a problem often encountered in the related literature. One aspect of the problem is that the fundamental sampling rate of the information varies with the timing of the zero crossings. If an estimate of the instantaneous frequency is obtained by taking the reciprocal of the time between two crossings, then results will be available at an irregular rate. On the other hand, if we count N crossings during an interval of time T , thereby maintaining a constant sample rate, the frequency estimate, N/T , is an average of instantaneous frequency during time T . In addition, the error of the estimate will be plus or minus one count, or $\pm 1/T$.

In the present readout crossings are counted to insure a uniform sampling rate and the interval T is kept as small (.1 second) as possible in order to minimize the amount of averaging, while still maintaining compatibility with the maximum data rate capability of the acquisition computer. The $\pm 1/T$ error problem is handled with the use of a phase lock loop (PLL) circuit (Gardner, 1979) that multiplies the difference frequency by a factor of 3200, reducing the scale factor of the acceleration and gravity information to $(15000/3200)$ or about 4.8 milligal/Hz. The output of the PLL is counted in a specially designed frequency counter incorporated in the readout; the resulting counts are made available to the acquisition system. In this way, the $1/T$ (10 Hz at $T=.1\text{sec}$) error, with the reduced scale factor, is decreased from $(15000 \times (1/T))$ to $(4.8 \times (1/T))$, or about 48 milligals/data point.

Clearly, this 48 milligal error (at a 10 Hz sample rate) is in itself unacceptable. The frequency counter in the readout, however, is designed so that no counts are missed between adjacent counting intervals. This enables the data to be processed such that measurement error is reduced in a way unique to systems in which information is encoded using frequency. Unlike

conventional acquisition systems (where information is available in a sampled voltage, and errors in measurement are statistically independent), the sum of M data points in the present system will still retain an ambiguity of only plus or minus one count so that the effective error is reduced to $1/MT$. Sampling at 10 Hz enables the system to measure vehicle accelerations to a resolution of 48 milligals with a minimum of averaging, while still allowing measurement to an accuracy of $48/M$ milligals with increased averaging. The averaging implemented by summing counts is a low pass filter with an approximate cutoff at $1/MT$ Hz. In the processing of data from the test cruise, a value of $M=100$ was used so that the effective filter cutoff was $1/(100 \times .1)$ or .1 Hz. with an error of $48/100$ or .48 milligal. Since the signal of interest, vertical gravity, will appear in frequency bands far below .1 Hz in both sea and air vehicles, the averaging does not affect required performance.

Along with multiplication of the difference frequency, the PLL can also provide analog filtering of the information encoded in the FM modulation. In previous seagoing systems (Bowin et al, 1972), the main bulk of low pass filtering necessary for obtaining gravity from the VSA data was done in the PLL, with a cutoff frequency of .003 Hz. The raw gravity signal was then available in real time. In the present readout, since the system is designed with airborne gravity measurement in mind, a minimum of filtering is done in the PLL, so that more precise digital filtering techniques can be applied to the data and so that more information is available concerning vehicle accelerations. Since airplanes will travel at higher speeds, the frequency band containing desired gravity signals will extend above .003 Hz and will overlap bands in which vehicle accelerations are prevalent. Using Kalman filtering techniques, a precise ancillary navigation time series together with the VSA data can separate these accelerations from the gravity signal, and Eotvos corrections can also be performed. By setting the PLL analog filter cutoff at 1 Hz, so that negligible frequency components appear beyond 5 Hz (in keeping with the Nyquist criterion for a 10 Hz. sampling rate) all frequency components of both gravity and vehicle accelerations below 1 Hz are passed, and the present system should be well designed for use in aircraft.

In the test cruise, unfortunately, a major component of the PLL had inadequate dynamic range for maintaining phase lock for accelerations above .05G,

while the actual sea state accelerations in the passband of the PLL filter were on the order of .1G. A simple component replacement was all that was needed to solve the problem, but the part was unavailable on the cruise. One of the data tapes, however, was obtained during a period of relatively calm seas; a report follows on the processing techniques applied to this data set.

Processing Sequence

Figure 5 is an illustration of about 9 minutes of raw data obtained from the readout. As mentioned above, the data was sampled at 10 Hz. with an initial resolution of 48 milligals/count, so that the overall vertical span of the chart represents about .1 G or 100000 milligals. The first minute or so of data illustrates the characteristics of the data when the loop was out of lock, and the time when lock occurred is denoted. This point occurred immediately after a course change, so that the vessel was riding more smoothly and lock was obtainable. In Figure 6, about 80 seconds of a horizontally expanded section of locked data is shown which details the accelerations due to sea state as measured by the VSA. Again, the total vertical scale encompasses a range of about .1G, the resolution is 48 milligal, and we observe that the average period of wave motion was about 5 seconds (.2 Hz).

The first step in processing this data involved the use of a "moving average" operation which simply replaced each point in the data by the sum of 100 points about it. In this way, as we have explained, resolution was increased to about .48 milligals/count, and an effective filtering of the data at a cutoff of about .1 Hz was a byproduct. This "filter" can be viewed as a finite impulse response (FIR) filter with 100 coefficients, all of which are unity. At this point, the output rate of this filter was still at 10 Hz.

The actual implementation of this operation was done in the frequency domain, to obtain increased computational efficiency. Data was taken in 3000 point segments, an FFT was applied, the product of the result and the FFT of the FIR coefficients was formed, and an inverse transform to this product was computed and combined with results from other segments using the "overlap/add method" (Oppenheim and Schaffer, 1975).

Since these data were obtained at sea the gravity signal was in a very low frequency band and corrections for vertical motions of the vessel were

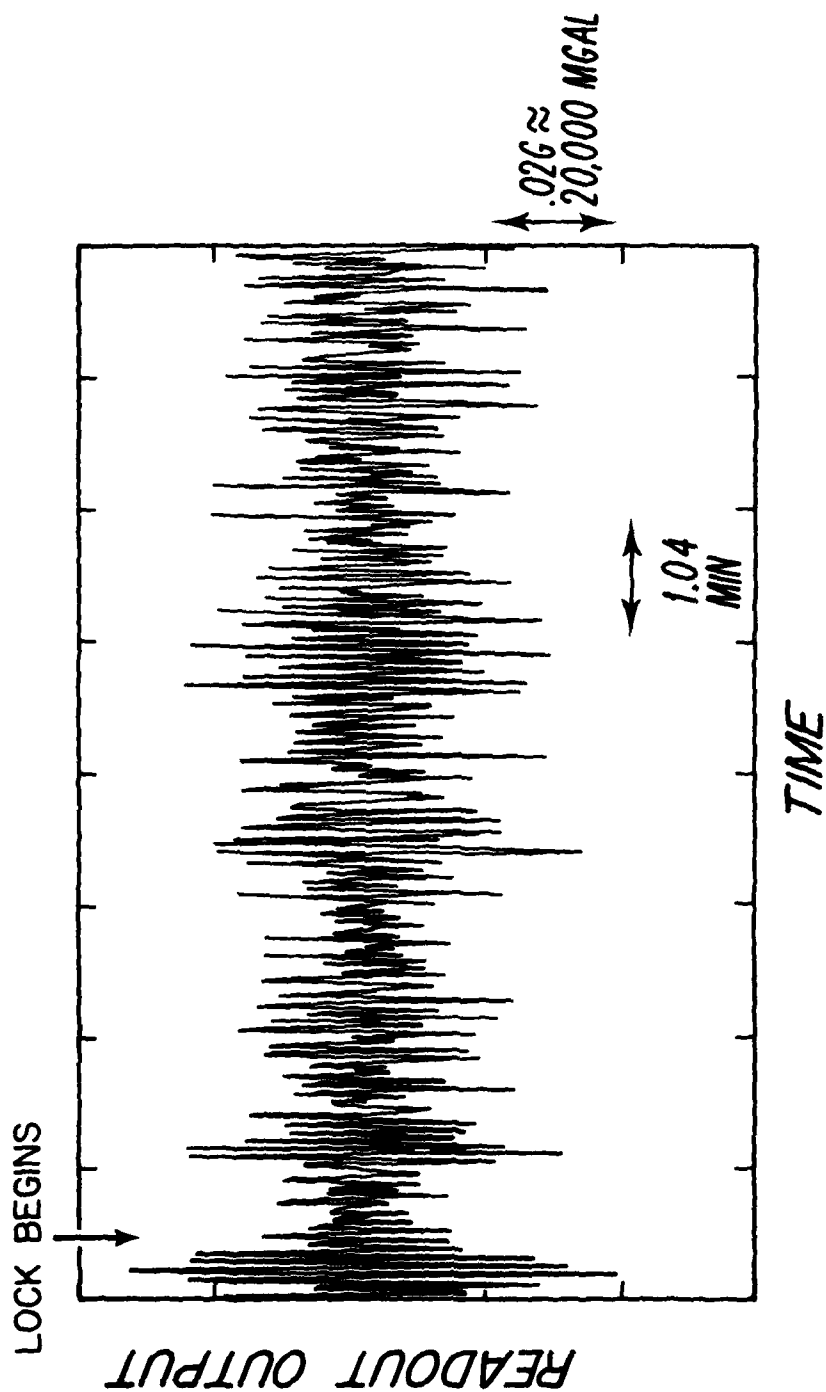


Figure 5 Total Acceleration from VSA Gravity Meter System. This profile represents about 9 minutes of data. The vertical span represents about 100,000 milligal. The phase lock loop was out of lock during the first minute.

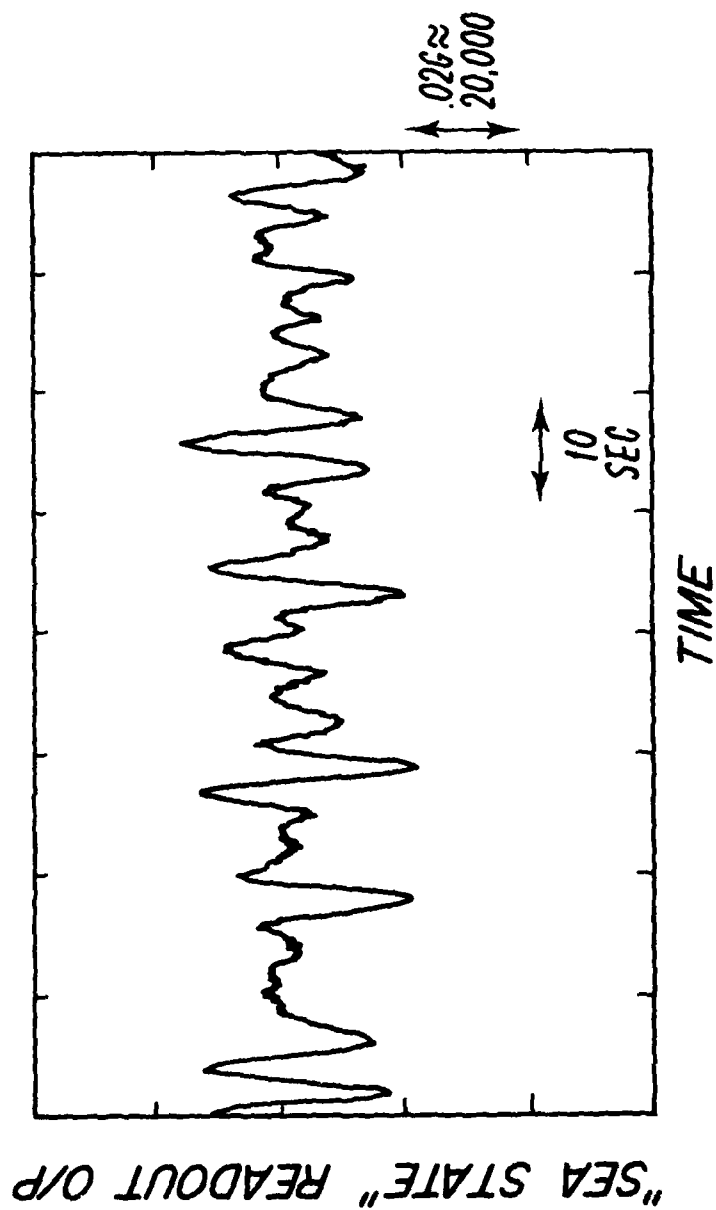


Figure 6 Total acceleration from VSA gravity meter system showing details of accelerations due to sea state. The vertical span represents about 100,000 milligal, horizontal span about 80 seconds. Data are expanded from locked portion of record shown in Figure 1.

unnecessary (they average to zero over long time periods). The large volume of data (about 165000 data points for 4.5 hours for a distance covered of about 100 km) was unnecessary, and a decimation of the data by a factor of 100 (i.e. a new data rate of 10 sec) was desired. Before this was done, however, a second low pass filtering operation was performed so that the resulting decimated signal would satisfy Nyquist criteria (Crochiere and Rabiner, 1981). A FIR filter was desired since linear phase characteristics would insure preservation of waveforms such as the gravity signal that are within the passband. 305 filter coefficients were calculated with an algorithm that maximizes flatness in the passband (Parks and McClellan, 1972) with a -35 db stopband beyond .05 Hz. This filter was again implemented with the overlap/add technique. After selecting one out of every hundred points of the output of this filter, the data set was in a more manageable size, and a final 50 coefficient filter with an effective cutoff at .005 Hz. was used for the final raw gravity result.

Figure 7 illustrates 4.5 hours of processed raw gravity data obtained with these techniques. The vertical scale now encompasses a total span of 400 milligals or .00041G. There are two time periods in which data is obviously invalid. Figure 8 is a profile of the east component of ship velocity during this time period, and we see that the patches of invalid data occur immediately before and after significant changes in the vessel's course. In the quieter sections of Figure 7, abrupt changes in level are seen to occur at times which also correspond to changes in east velocity, an indication of the presence of the Eotvos effect on gravity measurements. An Eotvos correction was applied to the raw gravity, using the east velocity, and the platform latitude data available on the initial data tapes. The results are shown in Fig. 9, in which we observe that the step changes have been removed by the corrections. The good quality of the results of the Eotvos correction, which were based on navigation data from an independent source, confirms that the processed data is indeed a profile or free-air gravity.

We have shown that the raw VSA data obtained with the new platform and PLL characteristics, is capable of measuring sea state accelerations to an accuracy of 48 milligals (.00005G). This capability is required for work aboard aircraft in tandem with a second set of acceleration data obtained from

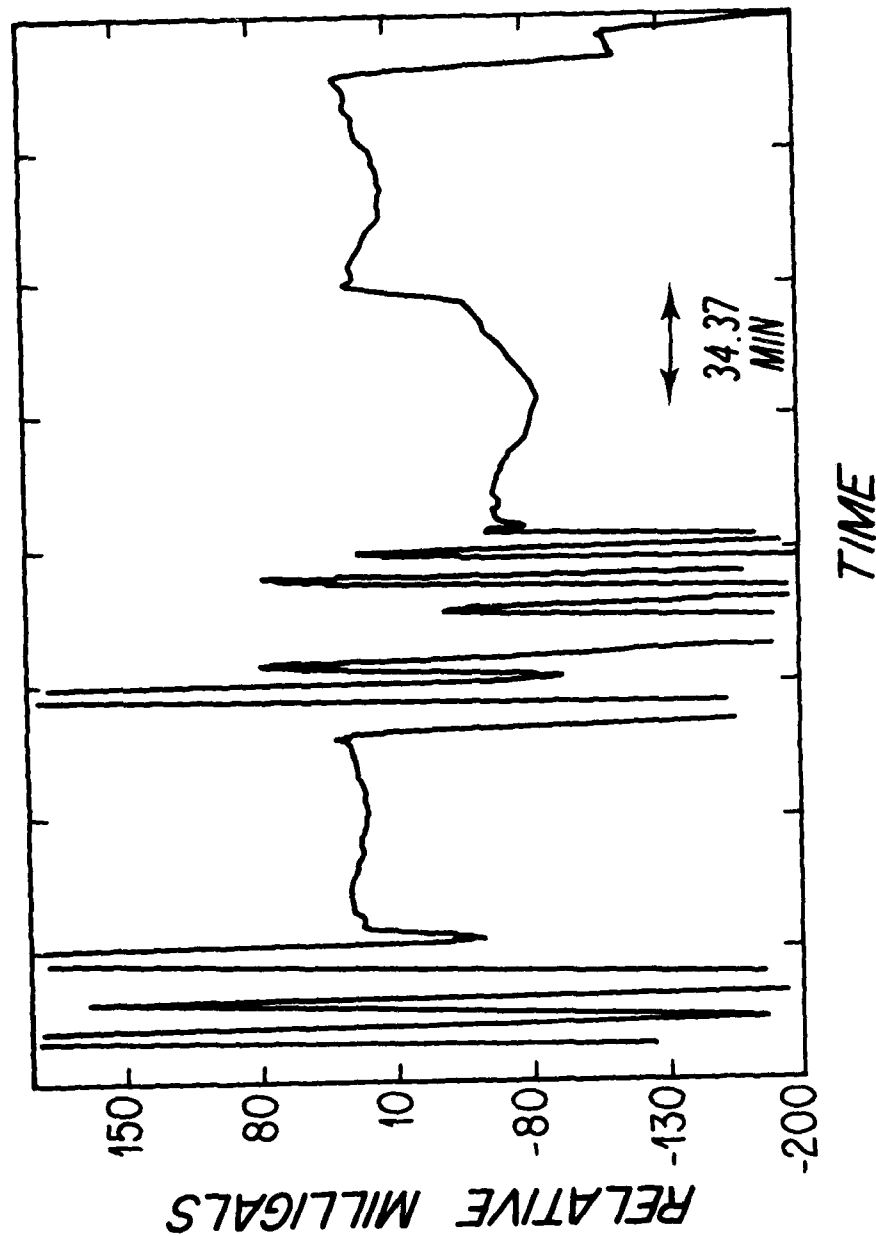


Figure 7 Filtered total acceleration from VSA gravity meter system. See text for description of filtering procedures. Horizontal axis is equivalent to 4.5 hours, vertical range is 400 milligals. Portions of profile with large short-period oscillations are where system was out of phase lock.

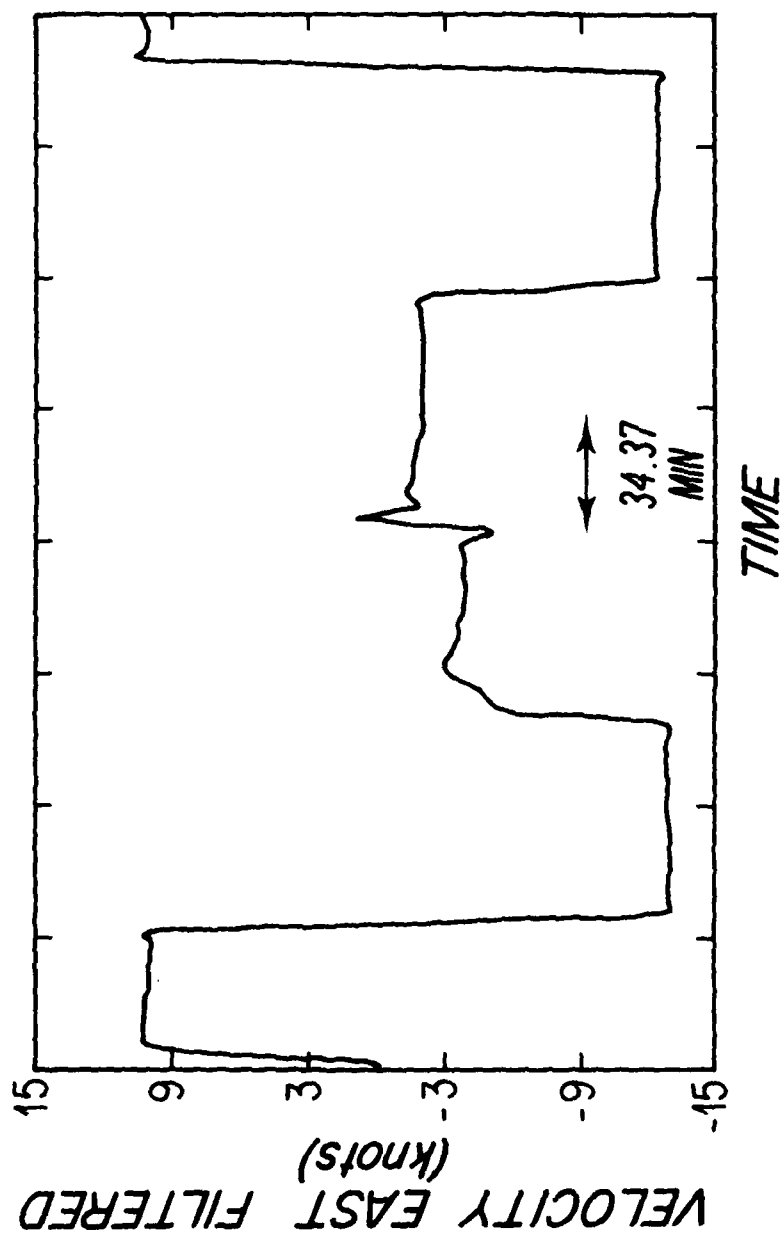


Figure 8 East component of ship velocity. Display is for the same time period shown in Figure 7. Course changes occurred at prominent "step" changes in velocity east.

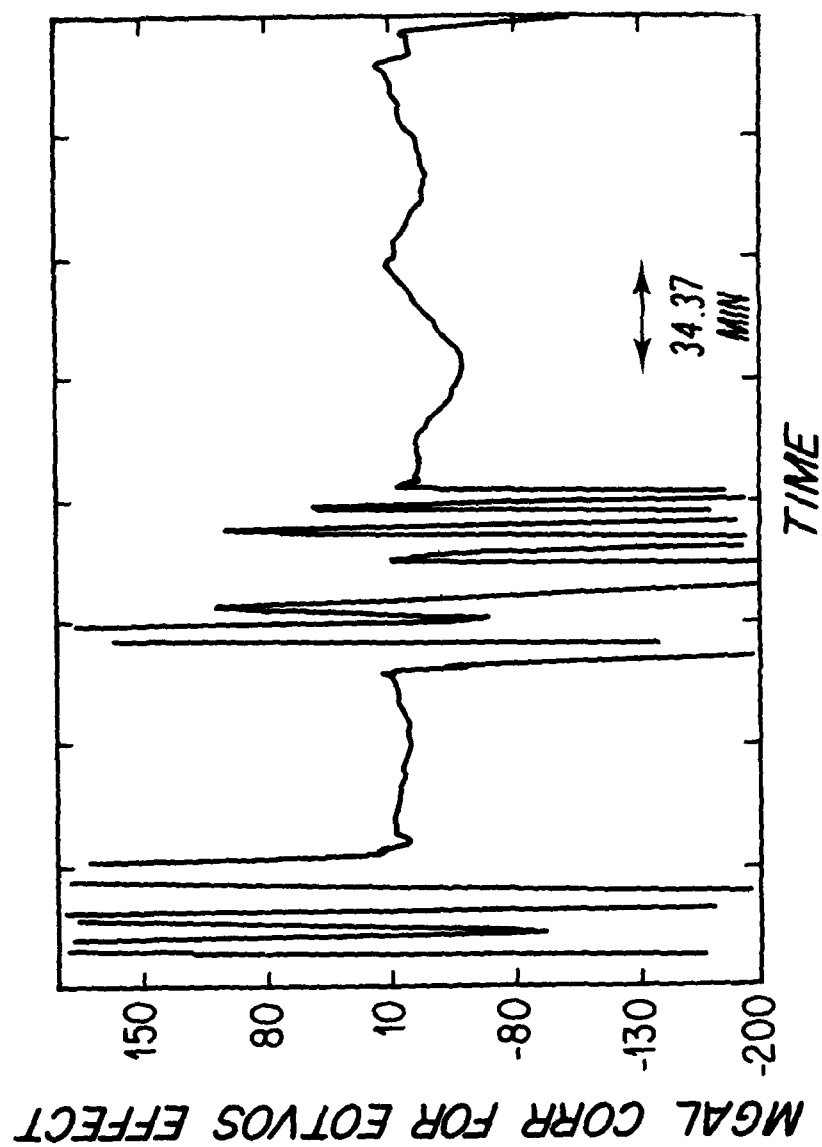


Figure 9 Filtered acceleration data summed with Eotvos correction estimated from velocity east. Same scales as for figure 7. Note that the discontinuities at course changes in figure 7 are not evident here.

a precise navigation stream, so that gravity data could be sorted out in certain frequency bands. At the same time, after suitable processing, accelerations in frequency bands near DC (such as longer wavelength gravity components) may be measured to an accuracy of at least .48 milligal.

A second test cruise is planned for late January, 1983. In order to obtain a complete accurate gravity profile for the entire length of the cruise, based on the results mentioned above, we are concentrating on the following problems:

- 1) Adjust frequency response in servo amplifiers
for better performance
- 2) Improve the platform temperature regulation
- 3) Add an error handling routine to platform computer
- 4) Calibrate the gyros and accelerometers
- 5) Improve the "navigate mode" algorithm
- 6) Redesign the phase-lock loop

Acknowledgements

We would like to express our sincere appreciation to many people for their help, expertise and encouragement that made this project a reality: Art Gulovsen answered our frequent questions, shared with us his knowledge of inertial platforms, detailed circuit drawings and obtained the Apollo platforms for our use. We want to thank Jerry Dean whose prior experimentation with fabrication techniques for small gimbal rings paved the way for his mechanical design of the gimbals for this platform. Without his methods, a platform such as this would not have been practical. And to Ted Spencer, a true craftsman in the machine shop, who was able to make his old equipment hold very tight tolerances. We thank Julie Milligan and Karen Hall for their critical assistance, and Terry Joyce for providing an opportunity to test the platform at sea on the ENDEAVOR.

This project has been supported by the Department of the Navy, Office of Naval Research under contract No. N00014-82-C-0019 NR 083-004.

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