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# CHARLES STARK DRAPER LABORATORY

MASSACHUSETTS INSTITUTE OF TECHNOLOGY

CAMBRIDGE, MASSACHUSETTS, 02139

E-2603

# A TRAVERSE GRAVIMETER FOR THE LUNAR SURFACE

by

Glenn Mamon

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E-2603

# A TRAVERSE GRAVIMETER FOR THE LUNAR SURFACE


## ABSTRACT

A semi-automatic, self-levelling lunar gravimeter has been designed for the purpose of measuring gravity at predetermined stops along the route of a Lunar Rover Vehicle to obtain a gravity profile. The Traverse Gravimeter is completely self-contained and is powered by an internal battery. The gravity sensor is a vibrating string accelerometer (VSA) which is enclosed in a precision oven. Gravity data are obtained by initiating a measurement. After the gravimeter has levelled, the VSA difference frequency is counted down and a gate is generated to enable a crystal-controlled clock to a BCD counter. The BCD counter stores the data which are a measurement of gravity. These data, displayed upon command by the astronaut, are transmitted by voice back to earth.

It is expected that the accuracy of the gravimeter will be better than one milligal. Low power, light weight, reliability, and simplicity of operation are major considerations in the design of the gravimeter.



by Glenn Mamon


August 1971

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# A TRAVERSE GRAVIMETER FOR THE LUNAR SURFACE

## 1. Introduction

The traverse gravimeter will be used to obtain a profile of gravity at various points on the lunar surface. The profile will be used to reveal information related to density variations in the moon's subsurface. The gravimeter will be transported to the lunar surface on the Lunar Module descent stage of APOLLO 17. After the Lunar Module has landed, the gravimeter will be deployed on the lunar surface and initial measurements will be made in the vicinity of the Lunar Module. The gravimeter will then be mounted on the Lunar Roving Vehicle (LRV), and gravitational measurements will be made at various points where the LRV is stopped. The duration of a lunar excursion is about 6 to 7 hours, and it is hoped that approximately 20 measurements can be obtained during each of three traverses.

The gravity sensor employed is a vibrating string accelerometer (VSA). VSA's have been previously used with great success in sea gravimeters. Wing (Ref. 1) describes a sea gravimeter in detail and gives a thorough presentation of the principles of VSA's. The VSA has been used in several types of inertial systems for space and aircraft systems. Excellent results have been obtained in gyrocompassing and navigational modes of operation. The VSA's low power, small size and accuracy make it an ideal candidate for use in a lunar gravimeter.

To obtain accuracy, the VSA must be temperature controlled. The VSA is, therefore, mounted in a precision oven. The precision oven, which is enclosed by an outer oven, forms part of an inner gimbal. A two-gimbal system is provided for levelling in two axes. The levelling system contains two-axis pendulums as the level sensors. The gimbals are driven by stepper motors which in turn drive gear trains. A phase-locked loop is provided to filter the VSA signal. The control logic detects when the system is level and permits the measurement of the VSA difference frequency. This measurement is stored and displayed on a visual readout upon command. The display consists of nine numerical digits. The first seven display the gravity reading: the last two display the oven temperature and the status of temperature alarms. Figure 1 shows a cutaway view of the instrument.

The gravimeter is 20 inches high, 11 inches wide and 9.75 inches deep, and weighs about 25 pounds. It is enclosed in a multilayered insulating blanket which provides thermal protection. An outline drawing is shown in Figure 2.

A heat radiator located at the top of the unit provides the primary means of heat expulsion. The radiator, as well as the display panel, is protected from the lunar environment by hinged metal covers.

There is a folding handle on top of the gravimeter. Cam latches on the sides of the handles secure the gravimeter to the LRV pallet when the handle is pressed down toward the rear of the unit.

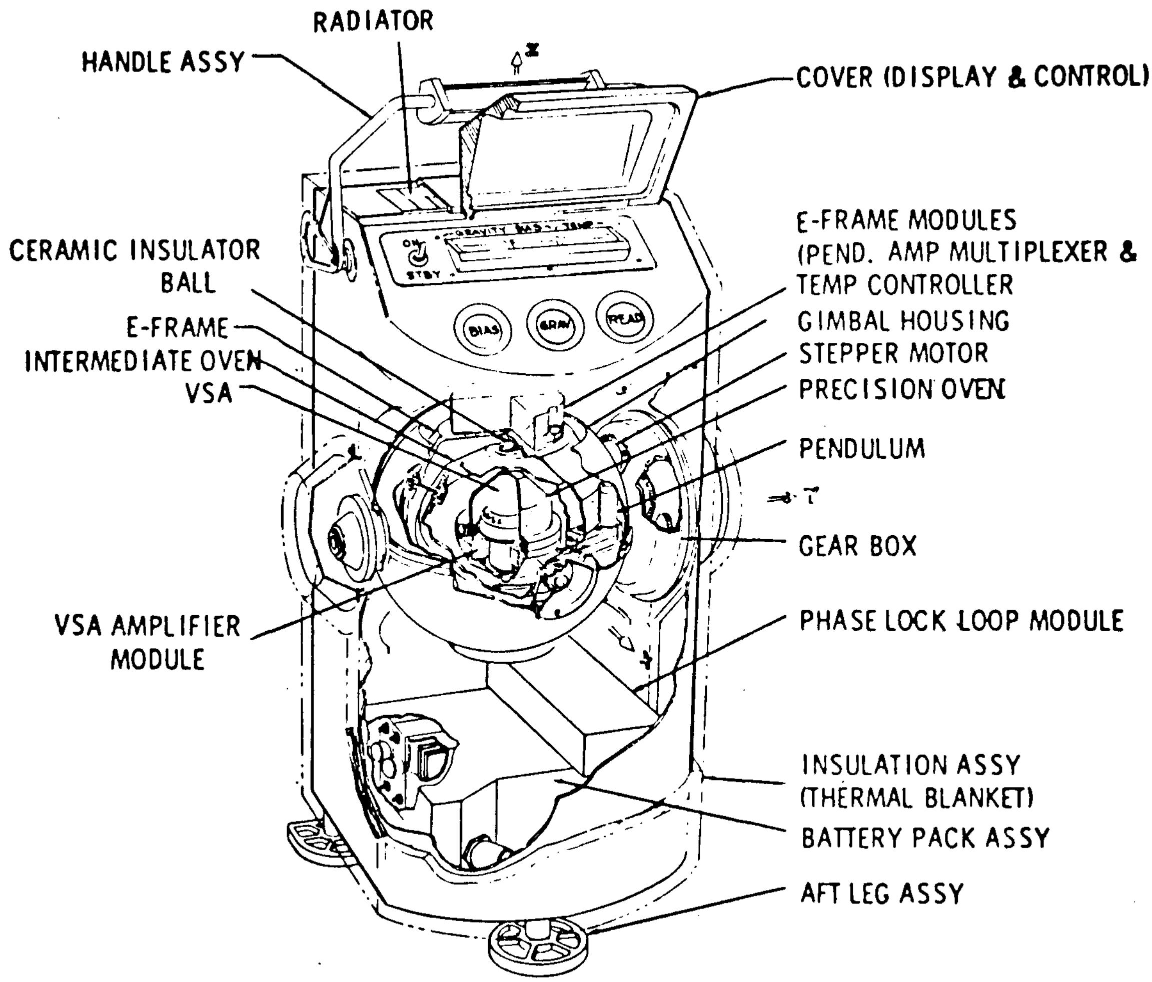


Fig. 1 Traverse gravimeter - cutaway view.

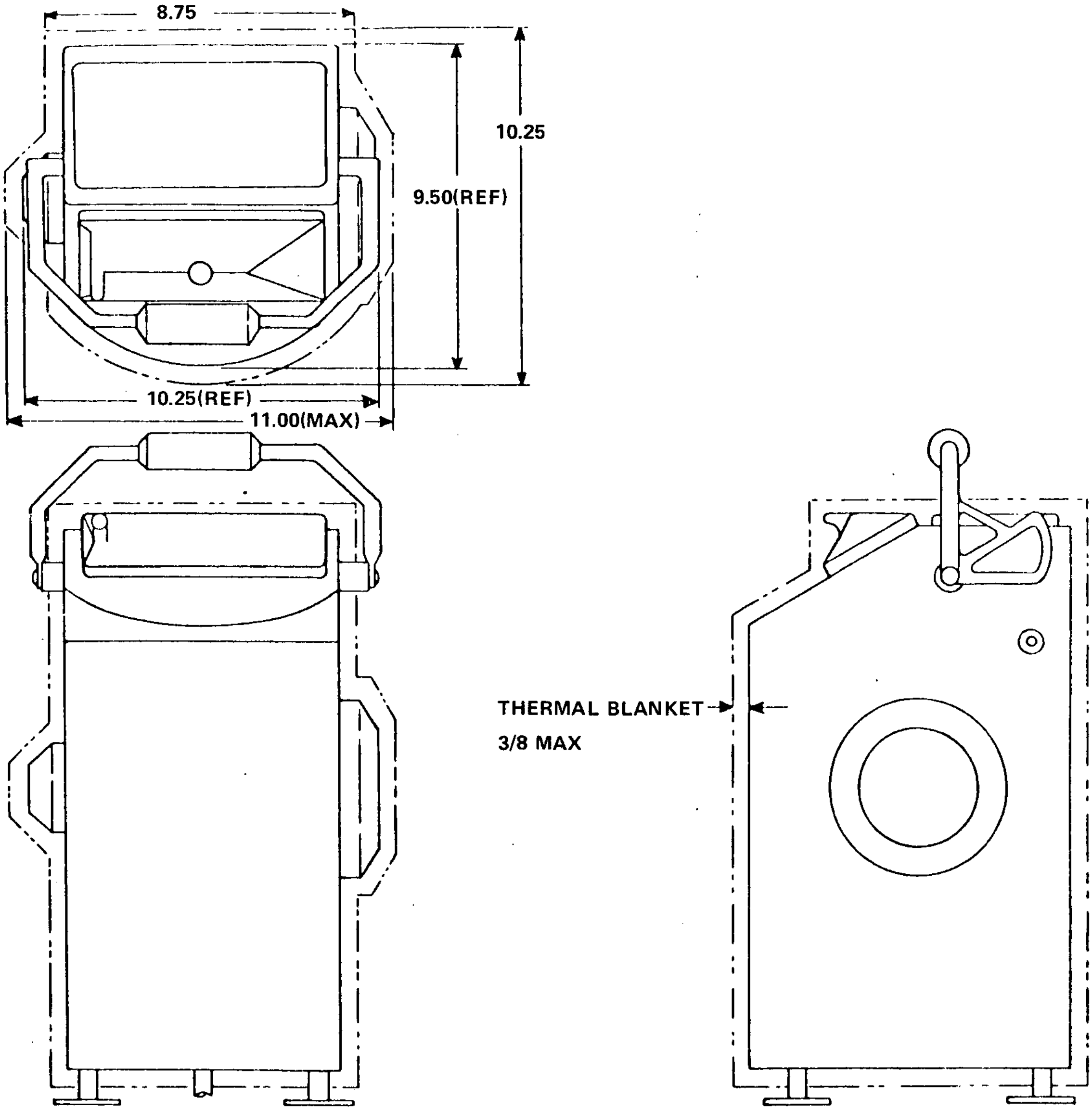


Fig. 2 Traverse gravimeter - outline drawing.

## 2. Functional Description

The traverse gravimeter is capable of providing a gravity measurement in either an upright or an inverted orientation. The provision for measuring gravity in both orientations has been included so that the VSA bias may be updated on the moon. Upon initiation of a measurement, the gravimeter seeks level in two axes. After settling to level, the difference frequency of the VSA is counted down and a gate is generated that is inversely proportional to the difference frequency. The width of this gate is then measured by counting a precision clock train. A seven-decade BCD counter serves the dual purpose of counter and storage register. The contents of this register are then transferred to a visual numeric display from which the astronaut relays the data back to earth by voice.

### 2.1 Modes of Operation

The sequential steps that occur in taking a gravity measurement are best displayed in Fig. 3, Gravimeter Sequencing. The gravimeter has five modes of operation: Standby, On, Gravity, Bias and Display. A toggle switch permits selection of the Standby or On modes. In the Standby position, used during translunar flight until deployment on the lunar surface, power is applied only to the VSA oscillator amplifiers which are mounted with the VSA in a controlled oven, and to the temperature controller for the oven. Since this mode is of long duration, every effort was made to minimize power dissipation in this mode. The VSA oscillator amplifiers consume only 30 milliwatts. An oven with a high thermal resistance is used to minimize the average power delivered to the heater.

When the gravimeter reaches the moon's surface, the Standby/On switch is placed in the On mode. In this mode, power is enabled to a small portion of the logic to permit proper initialization when taking a gravity measurement. Also, the BCD counter and associated logic is enabled to permit the storage of the last gravity reading taken, and to make it available for display. The crystal oscillator that is used to supply the stable clock for the gravity measurement is also energized in this mode, to permit

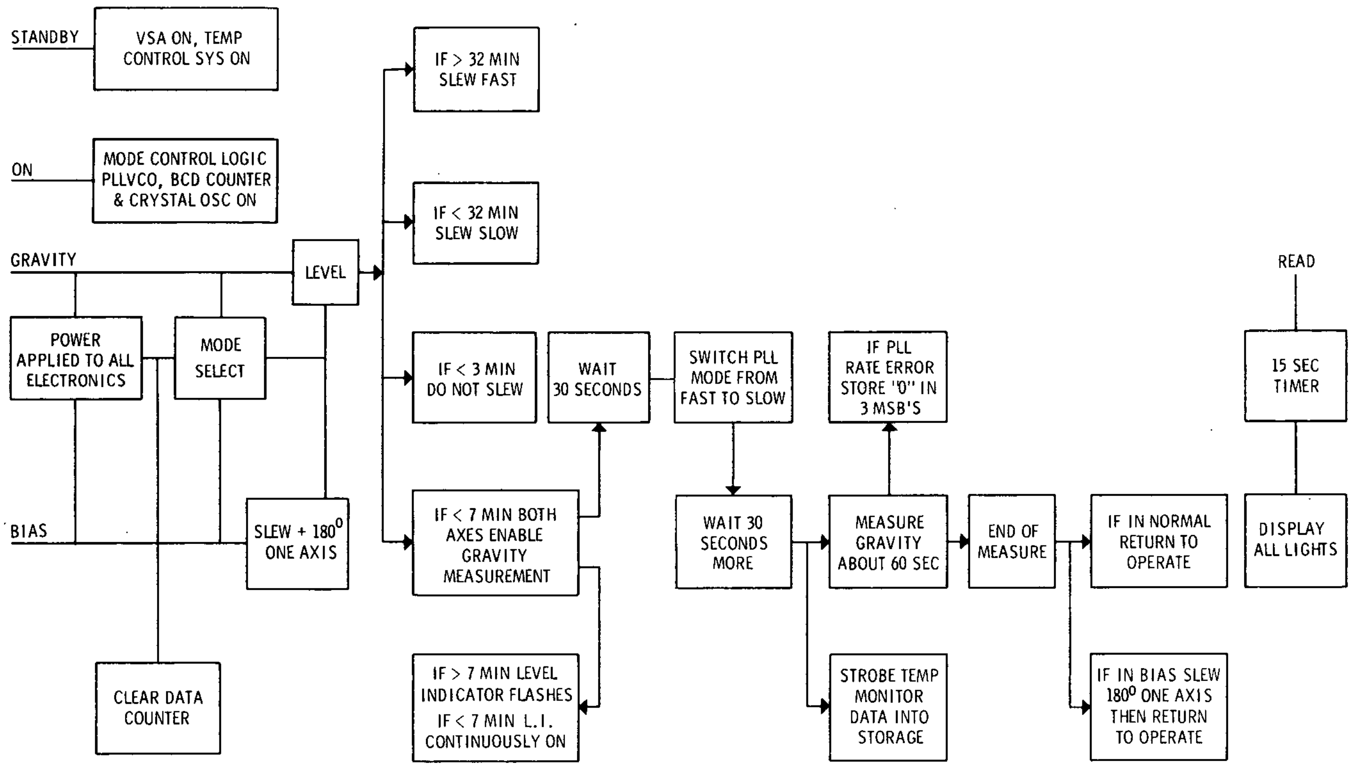


Fig. 3 Gravimeter sequencing.

thermal transients to settle out so that the oscillator drift may be minimized.

The gravimeter is maintained in the On position for the duration of a lunar excursion. When the Gravity pushbutton is depressed, power is supplied to all the circuitry. Automatic levelling begins. After the gimbal assembly has settled at a level position, a gravity reading is taken and the data are stored in the BCD counter. When the gravity measurement is completed, the instrument automatically reverts to the On mode of operation. As soon as the gravity mode is initiated an incandescent indicator located on the display panel cover is energized. A flashing light informs the operator that the system is levelling. When the light is on, but not flashing, the system has completed levelling and is in the process of taking a reading. When the indicator turns off, the measurement is complete, the system is back in the On mode, and a new gravity measurement has been stored and is ready for display.

Before and after each traverse, it is desired to perform a bias measurement to calibrate the VSA. By depressing the Bias pushbutton, the gravimeter tests for level in the normal position and is then rotated 180 degrees in one axis. When rotation is complete, fine levelling as in the normal position is accomplished. A gravity reading is taken and the gravimeter automatically slews back to the normal position.

Depressing the Display button will always present the value of the last gravity reading taken in either the Gravity or Bias modes. The display remains energized for about 15 seconds in order to minimize power consumption.

## 2.2 Major Electronic Modules

The VSA amplifiers which process the string outputs are located in the precision oven around the VSA (refer to Fig. 1). The E-frame around the inner gimbal contains the pendulum amplifier - demodulators which amplify the signals from the level sensors. The temperature controller for the precision oven and a multiplexer are also mounted on the E-frame. The demodulated pendulum signals and a temperature monitor signal from the temperature controller are time-shared in the multiplexer. The output of the multiplexer drives an analog to digital converter which is packaged with the display and control logic. The logic contains the timing circuitry and control functions for automatic levelling and displaying a gravity reading. A phase-locked loop module provides filtering of the VSA difference frequency. The phase-locked loop is a two-mode subsystem having a wideband acquisition mode and a narrowband tracking mode. Timing references are obtained from a crystal oscillator. Power supplies for the various modules obtain their raw power from an internal 7.5-volt battery.

## 2.3 Vibrating String Accelerometer

The vibrating string accelerometer with its oscillator-amplifiers is shown in Figure 4. The VSA consists ideally of a pair of single vibrating strings back to back. Separate, but equal masses, joined by a soft isolating spring, are suspended by identical berylium copper strings. The difference frequency between the two strings is a nearly linear indication of gravity.

$$\Delta f = f_1 - f_2 = K_0 + K_1 g + K_2 g^2 + K_3 g^3 + \ldots$$

The scale factor, $K_1$, is normally about 128 Hz/g. The bias $K_0$ will vary from one accelerometer to another and will usually lie in the range of 3 to 15 Hz. The stability of the scale factor is greater than that of the bias and will be calibrated on earth. The bias will be periodically updated on the moon before and after each traverse.

Each vibrating string passes through a magnetic field. The driving force of the string is furnished by an oscillator amplifier whose output is a current through the vibrating string and whose input is the back EMF created by the motion of the string in its magnetic field. The natural frequency of oscillation of each string is nominally about 9.5 kHz. The output voltage signal of each oscillator amplifier is voltage limited to provide a constant current source to drive the string.

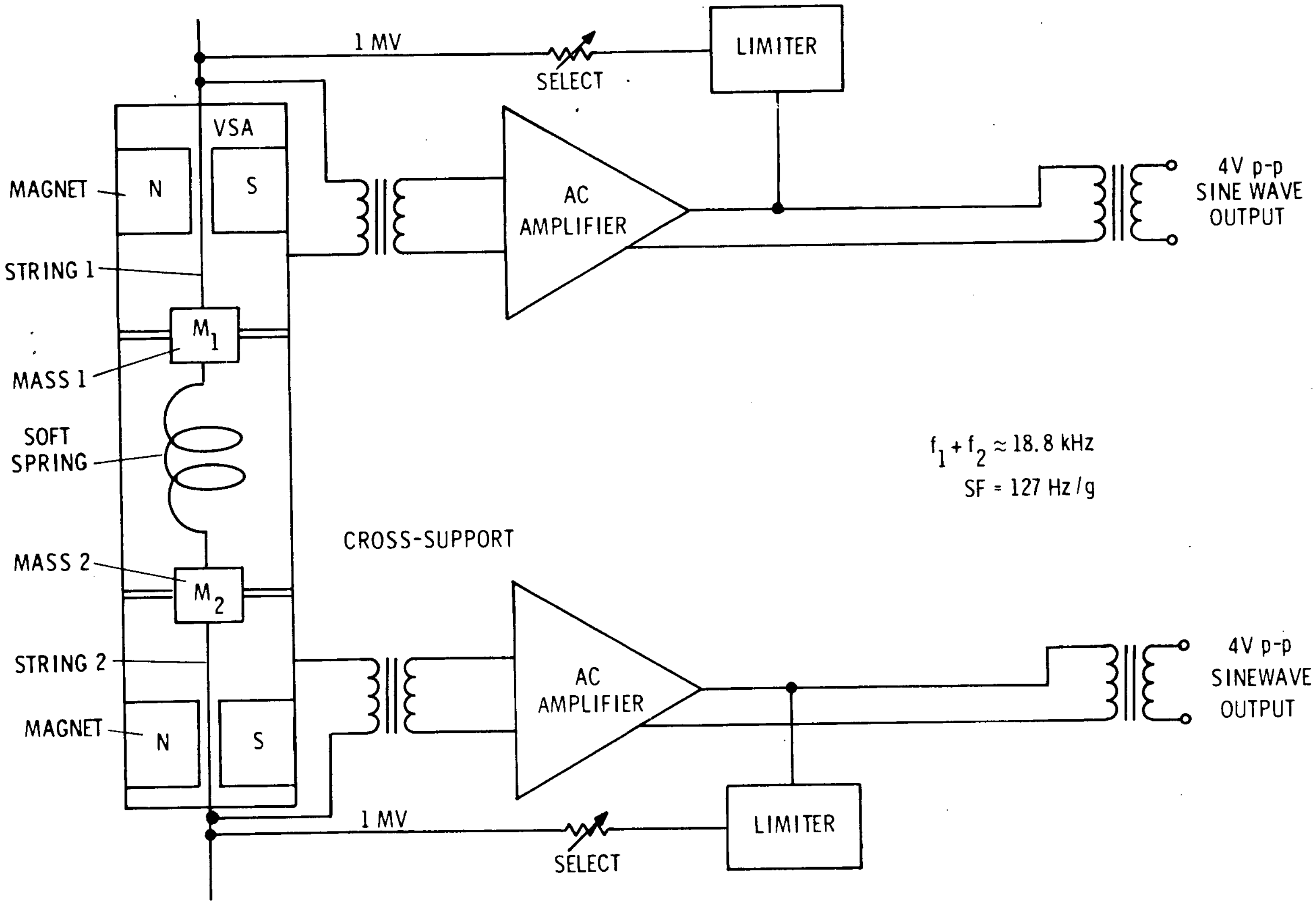


Fig. 4 Vibrating string accelerometer.

The processing of the VSA string outputs is shown in the simplified block diagram of Figure 5. The outputs of the VSA amplifiers are fed to the phase-locked loop filter where the two strings are mixed. The output of the mixer is filtered to obtain the difference frequency and attenuate the sum frequency. The difference frequency is the signal to which the phase-locked filter is locked. The purpose of the phase-locked loop is to act as a narrowband filter to attenuate the possible residual vibrations of the Lunar Roving Vehicle which might occur when taking a measurement.

## 2.4 Gravity Measurement Technique

The VSA difference frequency is approximately 20 Hz on the moon. It is desired to quantize this signal to approximately one part in $10^7$. If zero crossings of the difference frequency were counted, it would take an extremely long time. It is much simpler to perform a period measurement. The method for doing this is explained in the following paragraphs.

There are really two timing clocks in the data readout. One is the 4-MHz crystal oscillator; the other is the VSA difference frequency. Binary countdowns from the 4-MHz oscillator provide the timing for the A/D encoder, the motor drive electronics, power supply synchronization, level light flasher and, above all, the gravity measurement itself. The 4-MHz oscillator is a temperature compensated crystal oscillator (TCXO) with an accuracy of 2.5 parts in $10^7$. Although frequencies as high as 4 MHz are not used in the gravimeter, 4 MHz was chosen based on the superior performance of crystals at this frequency. The VSA difference frequency acts as a clock to generate the gate during which time gravity is actually measured. The gate generator logic selects a fixed number of cycles of the VSA difference at the appropriate time. The number of cycles selected is chosen to provide a gate width of approximately one minute. In order to keep the gravity measurement time approximately the same in all measurement modes, the number of cycles selected differs in the various modes. As shown in the chart of Figure 6,

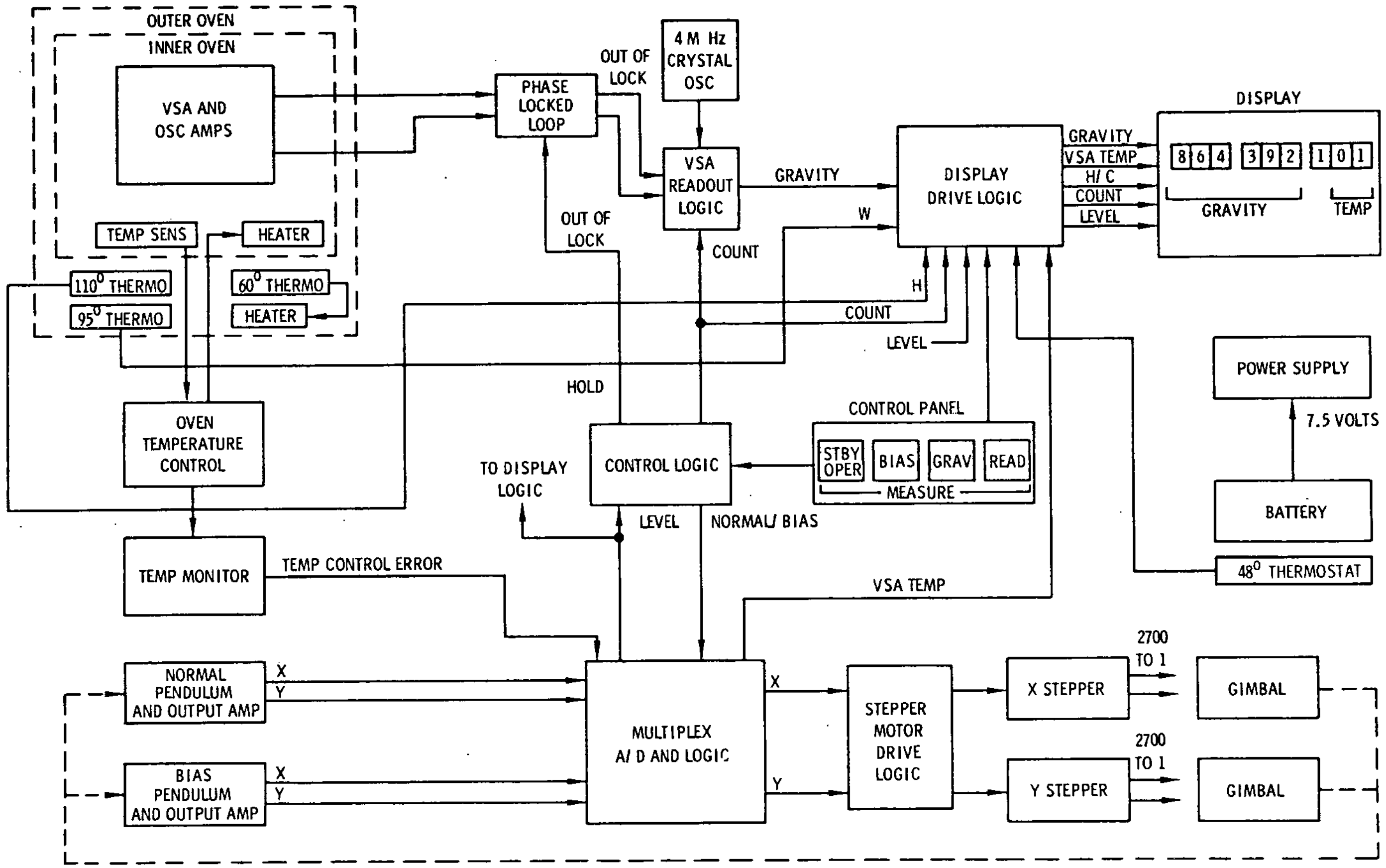


Fig. 5 Traverse gravimeter - functional block diagram.

| Mode | VSA Bias | VSA Diff. Freq. | Number of Counts | Quantization | Gravity Measurement Time | Total Time after Level | PLL Hold Time |
|---|---|---|---|---|---|---|---|
| Moon-Normal | 3 hz | 24.1 hz | $7.95 \times 10^6$ | .024 mgal | 63.7 sec | 147.9 sec | 42.1 sec |
| | 7 hz | 28.1 hz | $6.81 \times 10^6$ | .0315 mgal | 54.5 sec | 126.5 sec | 36.0 sec |
| | 14 hz | 35.1 hz | $5.48 \times 10^6$ | .0493 mgal | 43.7 sec | 101.5 sec | 28.9 sec |
| Moon-Bias | 3 hz | 18.1 hz | $2.65 \times 10^6$ | .0525 mgal | 21.2 sec | 49.2 sec | N/A |
| | 7 hz | 14.1 hz | $3.41 \times 10^6$ | .0317 mgal | 27.2 sec | 63.0 sec | N/A |
| | 14 hz | 7.1 hz | $6.86 \times 10^6$ | .00795 mgal | 54.0 sec | 125.0 sec | N/A |
| Earth-Normal | 3 hz | 130.0 hz | $8.75 \times 10^6$ | .117 mgal | 70.0 sec | 162.0 sec | 46.7 sec |
| | 7 hz | 134.0 hz | $8.62 \times 10^6$ | .122 mgal | 69.0 sec | 160.0 sec | 46.0 sec |
| | 14 hz | 141.0 hz | $8.15 \times 10^6$ | .136 mgal | 65.2 sec | 152.0 sec | 43.5 sec |
| Earth-Bias | 3 hz | 124.0 hz | $9.30 \times 10^6$ | .106 mgal | 74.5 sec | 172.0 sec | N/A |
| | 7 hz | 120.0 hz | $9.55 \times 10^6$ | .099 mgal | 76.5 sec | 177.0 sec | N/A |
| | 14 hz | 113.0 hz | $10.20 \times 10^{6*}$ | .087 mgal | 81.5 sec | 188.0 sec | N/A |

* Overflow - Max. Bias so as not to overflow on earth = 12.4 hz

Gravity Measurement $TG = \frac{1536}{\Delta f}$ Moon-Normal

$= \frac{384}{\Delta f}$ Moon-Bias

$= \frac{9216}{\Delta f}$ Earth

Clock frequency = 125 khz

$$\text{Quantization} = \frac{1}{N}\left(\frac{K_0}{K_1} + g\right)$$

N = Number of Counts
$K_0$ = Bias
$K_1$ = Scale Factor

Fig. 6 Gravimeter timing.

the relationship between the gravity measurement gate width, $T_G$, and the difference frequency, $\Delta f$, is 1536 in the Moon-Gravity mode, 384 in the Moon-Bias mode and 9216 in both of the earth measurement modes.

The logic that generates the gravity measurement gate is prevented from doing so, however, until the system has levelled in both axes within ±7 arc minutes. The gate generator logic tests that the system is not only level but also has stayed level for at least 10 to 15 seconds. If the system is oscillating and a non-level signal is obtained, the gate generator timing is recycled and a gravity measurement is not performed. Once this level settling time has passed, the gravimeter goes on to perform the gravity measurement. The VSA difference frequency is used as the clock for this level test. The nominal 20-Hz frequency is fed to a fixed number of binary countdown stages. The output of this divider chain is fed to two more dividers. These two dividers are arranged as a two-bit shift register. These two flip-flops have as their clear signal the 7 arc minute level signal obtained by processing the pendulum signals through an A/D encoder. Since the flip-flops are held to zero by the clear signal until the system is level, this register can be used as a time delay circuit. By checking the states of the flip-flops, the amount of time that has passed since the system has levelled can be measured in terms of the clock frequency driving this shift register. This clock, of course, is merely a scaled VSA difference frequency.

Approximately one minute is allowed before the gravity measurement gate is actually generated. After the system has levelled, the phase-locked loop filter is switched to a narrowband tracking mode. This occurs about 30 seconds before the generation of the gravity measurement gate. Once the level test circuit indicates a level status, a fixed number of cycles of the VSA difference frequency is counted, before gravity counting begins. The gravity measurement gate width is approximately one minute. The clock used to measure the width of this gate is 125 kHz derived from the precision 4 MHz oscillator. As seen in Figure 6, this provides a quantization of less than 0.1 mgal on the moon and only a little more than 0.1 mgal on earth. Figure 6 also shows the settling time after level before a gravity measurement is performed as well as the phase-locked loop hold time (the amount of time allowed for the phase-locked loop to settle in the narrowband mode before gravity counting begins). Cases are shown for the possible range of biases that may occur for different VSA's; any one particular VSA will have a relatively constant bias and the gravity measurement times will be constant for successive measurements. Figure 6 also indicates that the quantization is not merely a function of the displayed number and the full-scaled value. The fact that the displayed number consists of a relatively large bias that is considered constant must be taken into consideration. If the bias were zero, then the quantization would be simply $\frac{g}{N}$ where N is the displayed number and g is the full-scale value (980 gals on earth; 162 gals on the moon). Since the function being measured consists of a variable ($K_1 g$) and a constant ($K_o$), the actual quantization in milligals is $\frac{g}{N}\left(\frac{K_o + K_1 g}{K_1 g}\right)$ or $\frac{1}{N}\left(\frac{K_o}{K_1} + g\right)$.

## 2.5 Automatic Levelling System

Referring back to Figure 5, the seven-arc minute level indication that permits a gravity measurement to be performed comes from the levelling section. There are two pendulums in the gravimeter. Each one is a two-axis device. One pendulum is used in the normal orientation and the other in the bias mode. The pendulums are excited with an ac supply. The pendulum output signals are first normalized for scale factor, adjusted for phase shift and trimmed for quadrature rejection before they are amplified, demodulated, buffered, and then multiplexed and sent to an A/D encoder. (In addition to the pendulum signals, the temperature monitor is also fed to the A/D encoder). The outputs of the A/D encoder are strobed into storage flip-flops, and then decoded to provide the information to the stepper motor-gear train assemblies to drive the gimbals. The A/D provides four states of information about the

X and Y axes of the pendulums: polarity, which determines the direction to slew the gimbals, thresholds at ±32 arc minutes, ±7 arc minutes and ±3 arc minutes. The gimbal gear train ratio is 2700:1 so that each $90^{\circ}$ step command to the stepper motor drives the gimbal 2 arc minutes. Above ±32 arc minutes, the stepper motors are slewed at a fast clock rate of 122 arc minutes per second; below ±32 arc minutes, a slow rate of 7.6 arc minutes per second is used. Below ±3 arc minutes the motors are not slewed at all, and power is removed from the stepper motors. The plus and minus three arc minute deadband is well within the ±7-minute threshold at which a gravity reading is enabled. With the proper damping fluid in the pendulum, the gimbals respond to a 15-degree step in less than 20 seconds with only one overshoot.

## 2.6 Multiplexer and A/D Encoder

The multiplexer and A/D encoder are shown in Figure 7. The A/D is a 4-bit successive approximation encoder. The pendulum signals are scaled at one-arc-minute-per-bit, so that full-scale output from the A/D is the ±7 arc minute information. Polarity is obtained from the sign bit and the ±3-arc-minute deadband is determined by proper combinatorial logic. Thrity-two arc minute information for switching between the fast and slow levelling modes is obtained by using two level comparators, one at +32 arc minutes and the other at -32 arc minutes. The output of the multiplexer feeds both comparators as well as the A/D, and the logic strobes the data out at the appropriate time to separate the information for the two gimbal axes.

The encoder sampling rate is 244 Hz/channel which is higher than the fastest slew rate of the gimbal (61 pulses per second). The stepper motor driver consists of a two-bit shift register. The clock to this register is either the fast or slow clock. Below 3 arc minutes the clock is inhibited. The outputs of the two flip-flops in the shift register are gated to provide the 4 phases for driving the stepper motor windings. The stepper

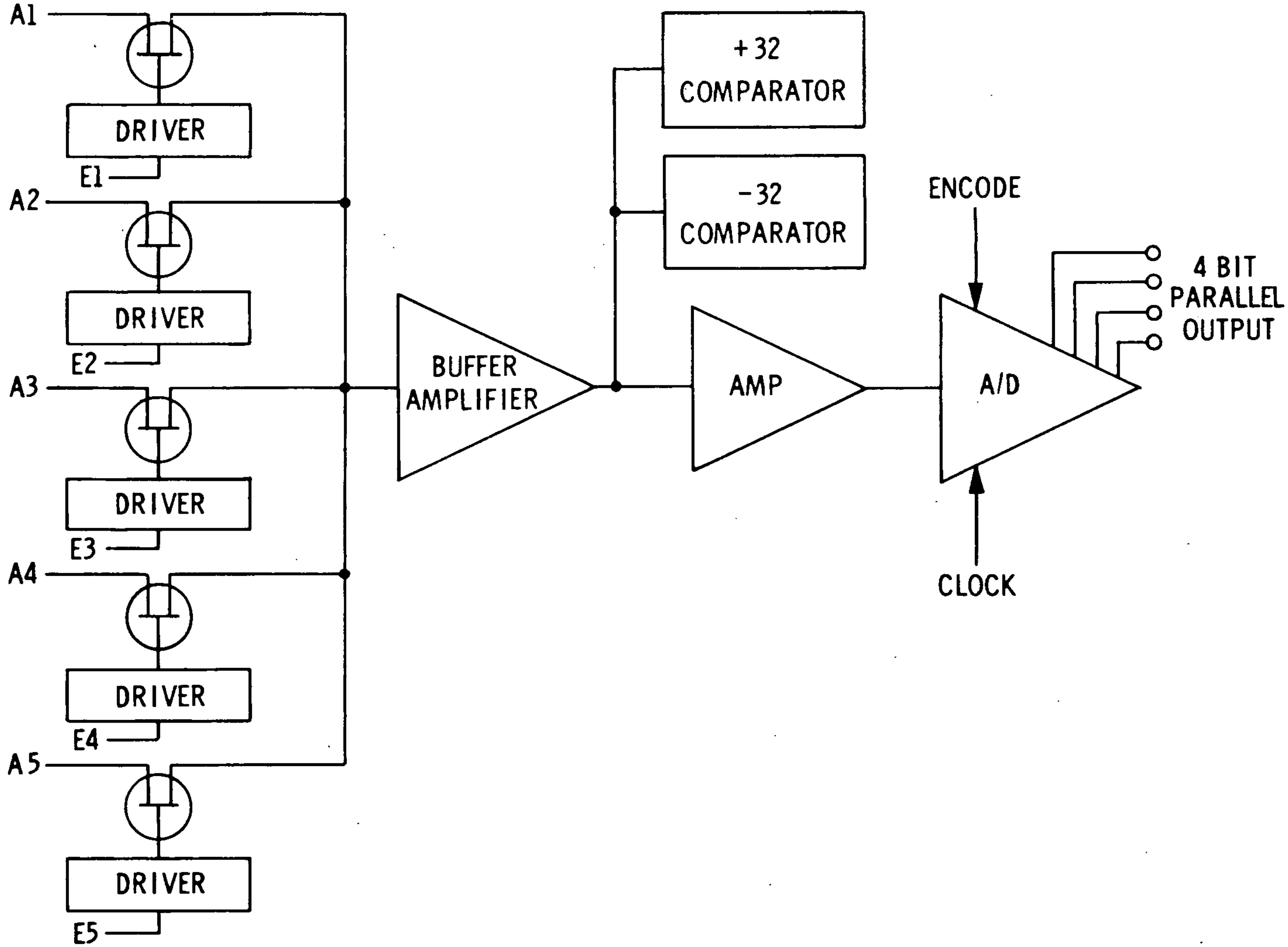


Fig. 7 Multiplexer and A/D encoder.

motor is driven either clockwise or counterclockwise, depending on the polarity information from the pendulum. The temperature monitor signal that also is fed to the A/D is scaled to $0.01^{\circ}C$ per bit. Therefore, temperature information up to $\pm 0.07^{\circ}C$ is obtained. This temperature information is strobed at the time a gravity measurement is made and then transferred to the display along with the gravity information.

## 2.7 The Phase-Locked Loop Filter

Possible vibration resonances that might be experienced on the LRV are believed to be at frequencies of one Hz and higher. The VSA difference frequency, as was mentioned before, will be approximately 20 Hz on the moon and will vary with gravity. To filter this signal by conventional methods, a very narrow bandpass filter would have to be built and its center frequency would have to track the VSA difference frequency. By using a phase-locked loop, the problems of a very narrow bandpass tracking filter are eliminated and a low pass filter in the loop provides the required filtering. Vibrations applied to the VSA will appear as frequency modulation on the string frequencies. Most phase-locked loops are designed to track the frequency modulation components on a fixed carrier signal. In this case, it is desired that the loop attenuate the modulation and produce only the carrier. In other words, the average value of the VSA difference frequency over a period of time is sought. Gravity information is contained in only the very low frequency bandwidth of the phase-locked loop.

Providing a narrowband low pass filter in the loop requires a very low closed-loop gain in order for the loop to be stable. A low gain loop provides a very small lock-in bandwidth. In order to acquire the signal in a relatively short period of time, the phase-locked loop was designed with two modes: a wide band mode for acquiring the signal and a narrowband mode for filtering the VSA signal.

The phase-locked loop is shown in Figure 8. The VSA string frequencies are mixed and filtered. A ring diode demodulator is used as the mixer and a low pass filter allows the difference frequency to pass through, but attenuates the sum frequency (approximately 19 KHz) to below 1 mv. The filtered sine wave feeds a zero-crossover detector to provide a square wave compatible with logic. (The divide-by-six circuit shown merely scales the difference frequency for earth measurements to be approximately 20 Hz.)

The wideband filter feeds a Sample and Hold circuit. The narrowband signal is summed with the output of the S & H circuit into the voltage controlled oscillator (VCO). In the wideband mode, the gain of the narrowband loop is so small that it has very little effect on the summation signal to the VCO. Some time after the gravimeter has levelled, but about 30 seconds before the gravity measurement begins, the phase-locked loop is switched from the wideband mode to the narrowband mode. At this time, the S & H circuit holds the sampled voltage into the VCO. The narrowband loop now takes over. The purpose of the Sample and Hold Circuit is to determine the approximate bias voltage the VCO requires at the time of a measurement. The narrowband filter provides the remainder of this voltage. The capture range of the wideband loop is about 3 Hz. The narrowband loop provides in excess of 40 dB attenuation at one Hz. This is achieved by using a two-pole Butterworth filter as the low pass filter. The closed-loop response of the narrowband loop is that of a third-order system $\frac{0.68}{s^3 + 2.1s^2 + 1.1s + 0.68}$ The Bode plot of this loop is shown in Figure 9.

## 2.8 Temperature Control

A proportional plus derivative temperature controller maintains the precision oven to within $\pm 0.01^\circ C$. The precision inner oven contains the sensors and heaters as well as the VSA and its amplifiers. The sensors are two thermistors located in opposite arms of a 4-arm bridge. The bridge is excited by

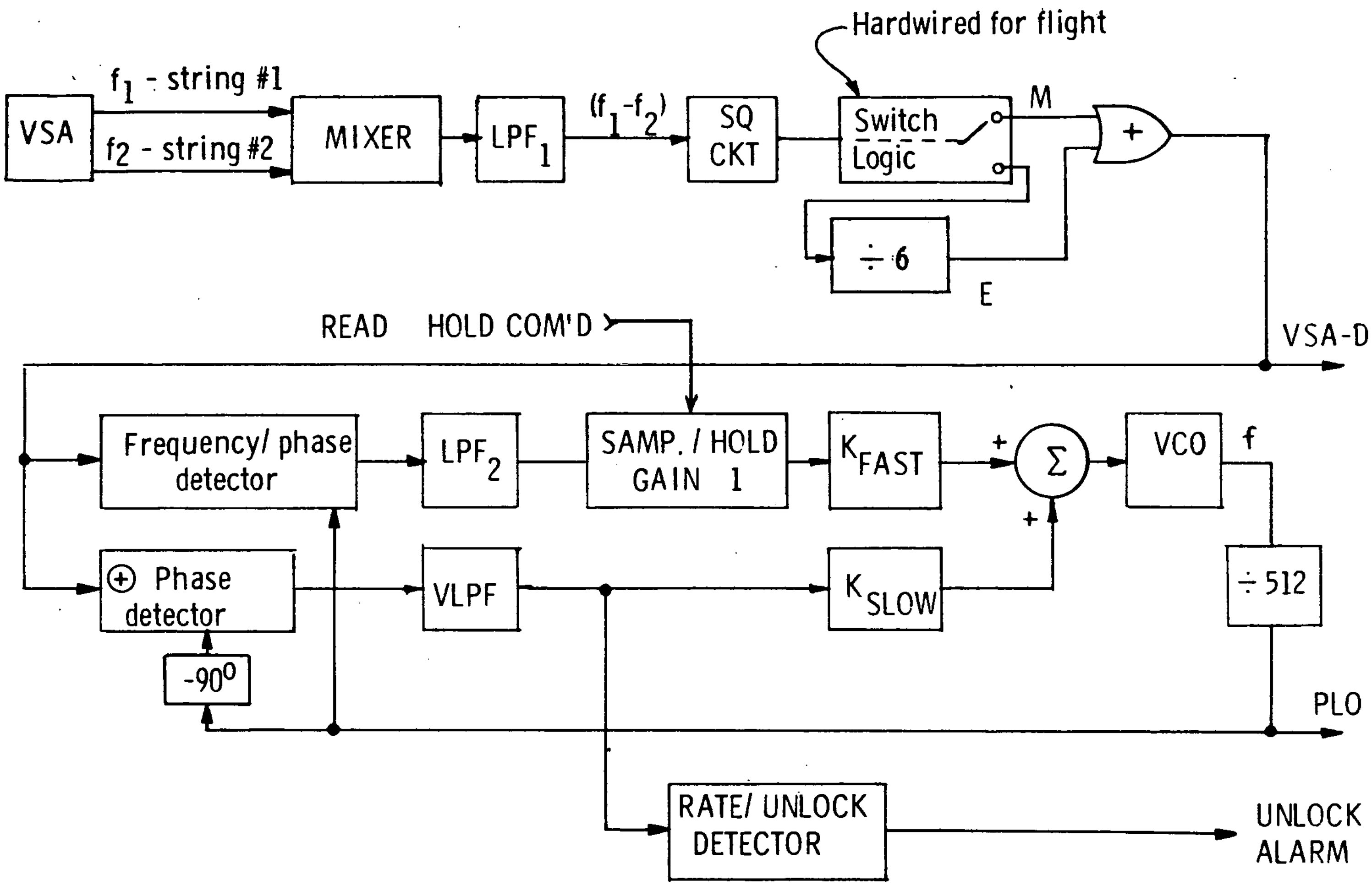


Fig. 8 Phase-locked loop - block diagram.

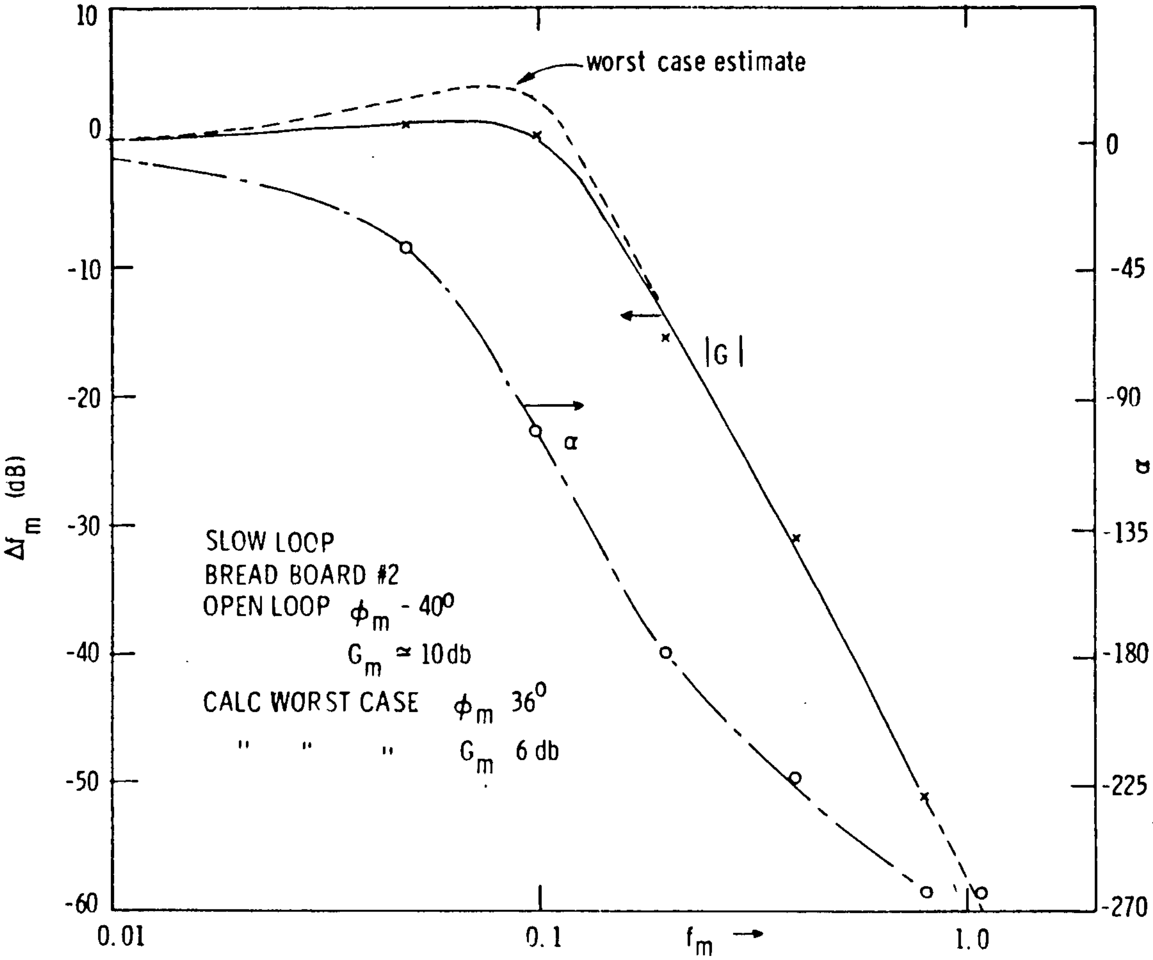


Fig. 9 Phase-locked loop - Bode plot.

a regulated low voltage ac supply. The excitation is kept low and regulated to minimize the effects of self-heating. The bridge provides an output of about 18 mv per degree F to the temperature controller (See Figure 10). The bridge signal is amplified in a high-gain preamplifier. By providing most of the gain ac, the problem of dc offset and drift is minimized.

After ac amplification, the bridge error signal is demodulated in a standard diode ring phase sensitive demodulator. The demodulated signal is buffered and scaled to a sensitivity of 50 mv/0.01$^{\circ}$C. The buffered signal is the temperature monitor signal that is sent to the multiplexed A/D converter to provide information on the temperature controller. The demodulated output is also sent to the proportional plus derivative stage which provides the drive for the heaters. The time constant of this stage is adjusted to match the natural frequency of the whole system, which in turn is determined by the system gain and the time lag between heater and sensor.

The output stage consists of 4 transistors physically located on the precision oven structure. Thus, the heat of these transistors is utilized to heat the structure. Heater resistance, half in the four transistors' collectors and half in the emitters, is distributed to make the transistors' gains less critical, and also to provide a uniform heat distribution to minimize temperature gradients.

## 2.9 Power Supply

In order to minimize power consumption, all analog circuits are operated from plus and minus five volts. Low-power TTL is used for the logic circuits operating at +5 volts. The only exceptions are the crystal oscillator which needs +12 volts, the stepper motor which requires +28 volts, and the LED display which requires +4 volts. The high power consumers which are the stepper motors, and the display are energized only when required. Thus, the average power is kept down by minimizing the duty cycle. A chart of the system's voltage requirements is shown in Figure 11.

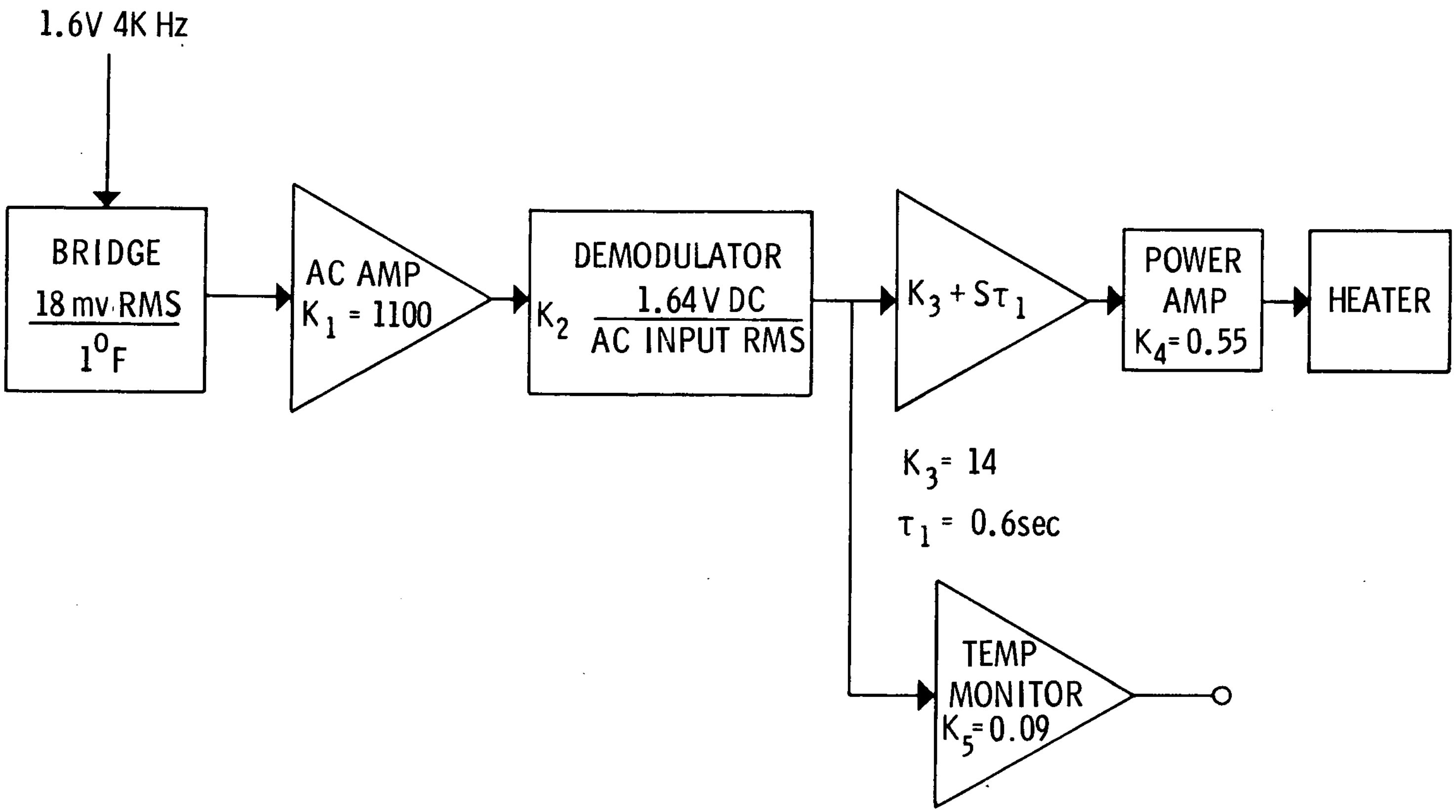


Fig. 10 Temperature controller.

| MODE | VOLTAGE | CURRENT | REGULATION |
|---|---|---|---|
| STANDBY | +5Vdc STBY | 5 ma | ± 0.2 % |
| | -5Vdc STBY | 5 ma | ± 0.2 % |
| | 4kHz 1.6 V | 2 ma | ± 1 % |
| | 4kHz 2 V | 2 ma | ± 1 % |
| | 4kHz 7.5 V | 0.5 ma | ± 1 % |
| OPERATE | +12 V | 5 ma | ± 5 % |
| | +5 LOGIC | 75 ma | ± 2 % |
| | +5 PLL | 20 ma | ± 0.2 % |
| NORMAL OR BIAS | +5 LOGIC | 1 Amp | ± 2 % |
| | -5 V MEASURE | 50 ma | ± 2 % |
| | +28Vdc | 0.4 Amp | UNREGULATED |
| DISPLAY | +4Vdc | 3 Amp | ± 5 % |

Fig. 11 System voltage requirements.

In the Standby mode, plus and minus five-volt supplies are provided for the VSA oscillator amplifiers and the temperature controller. The heater is supplied with current from the battery. Therefore, the load on these supplies is essentially constant throughout the mission. The tight regulation of 0.2% is required to minimize the voltage sensitivity of the VSA amplifiers, as well as to provide a constant thermal load in the oven. Changes in supply voltage result in phase-shift changes in the VSA amplifiers. A change in phase-shift between input and output will result in an apparent frequency change and produce gravity measurement errors.

The VSA amplifiers use the 725 operational amplifier. A closed-loop gain of 500 is required at 10 kHz, which is the natural frequency of oscillation of the VSA. In addition to maintaining a close voltage regulation, the pair of 725's selected for a particular VSA is matched for similar closed-loop responses.

To supply the temperature controller excitation and demodulator reference, a low power Colpitts oscillator is provided in the power supply. The oscillator drives a reference transformer that supplies the bridge excitation and demodulator reference, and also the pendulum excitation. Feedback is provided around the Colpitts oscillator to regulate the output to within ±1% over temperature excursions and with battery variations. As with the 5-volt standby supplies, the ac loads are practically constant. The Colpitts oscillator also feeds a sinewave amplifier which drives a fleapower chopper. The chopped signal is rectified and is fed to the -5-volt regulator. The plus and minus five-volt regulators are similar and use an integrated circuit regulator with low internal dissipation. A block diagram of the power supply is shown in Figure 12.

When switched to the On mode, the fleapower chopper output is enabled to a low-level chopper. This chopper contains the circuitry to supply the unregulated input to the +12-volt regulator for the crystal oscillator and the -5-volt regulator for the analog circuitry used in the gravity measurement modes. The -5 volt

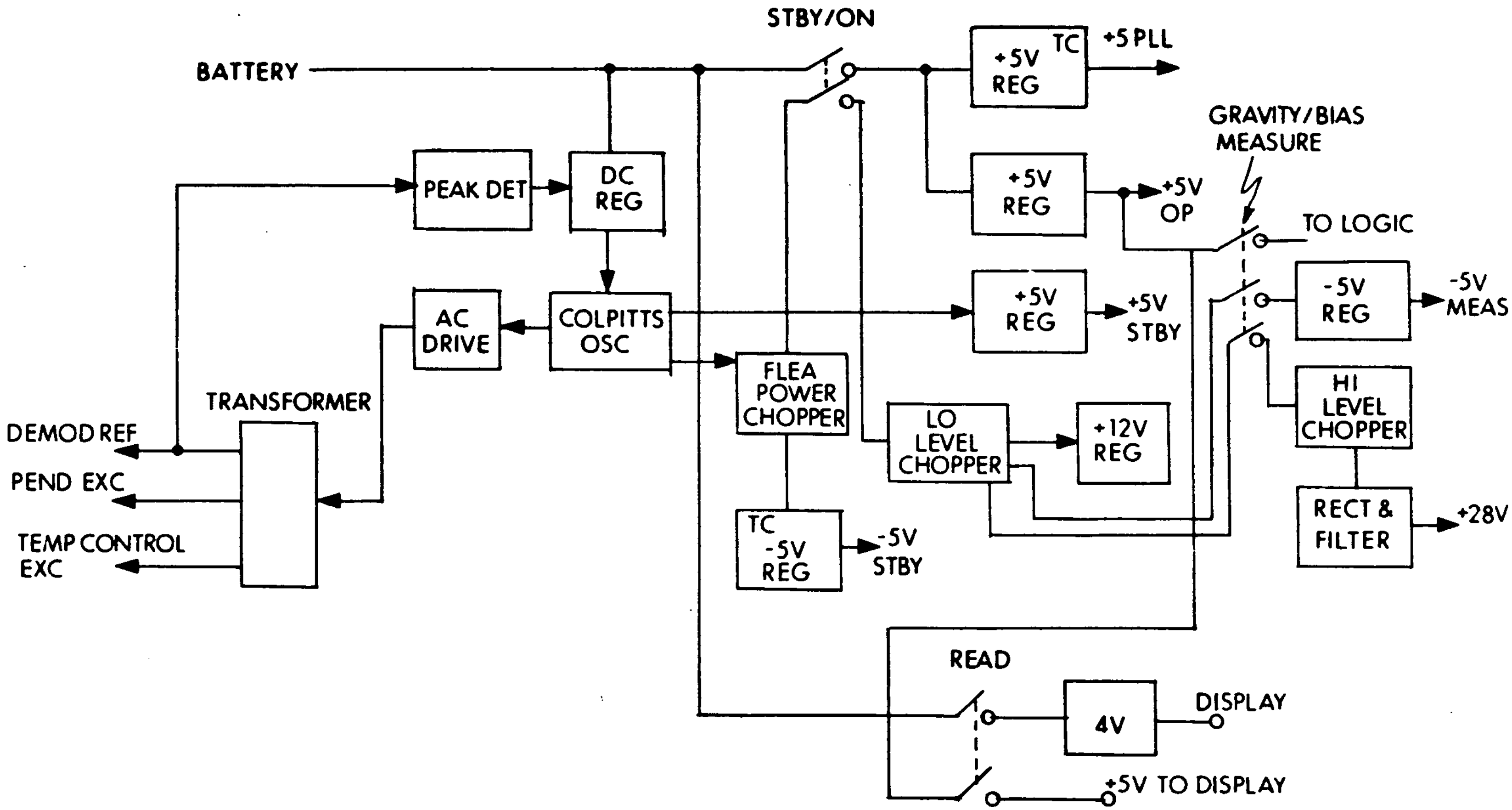


Fig. 12 Power supply - block diagram.

supply is not provided to these circuits in the On mode. In addition, two other +5 volt regulators are energized in the On mode. One regulator energizes the voltage controlled oscillator (VCO) in the phase-locked loop. The other provides logic power for the mode control logic and the BCD counter that stores the gravity measurement. The VCO supply is kept separate to provide isolation and to minimize the amount of load variation.

In the Gravity and Bias measurement modes all the other power supplies are turned on except for the light emitting diode (LED) display supply. The +5 volt logic supply is enabled to all the logic circuitry as well as the gimbal electronics and A/D converter. The -5 volt supply that is generated by the low-level chopper is supplied to the high-level chopper. This chopper produces 28 volts for the stepper motors.

The Display mode enables the 4-volt regulator to be turned on. This, in turn, drives the LED display. In addition, the +5 volt for the logic is provided to the LED display to energize the I. C. decoders that are integral with the display units.

To minimize the possibility of asynchronous noise, the 4 kHz AC supply is synchronized with a 3.906 kHz clock from the binary countdown during the measurement modes of operation.

## 2.10 Circuit Components

The number of types of components used was held to a minimum in order to provide standardization and ease of testing. Integrated circuits were used in both analog and digital functions. Discrete transistors are used in signal level conversion and power supply circuits.

The 4250 integrated-circuit-micropower-operational amplifier is used in most of the analog applications. The exceptions are the VSA amplifier and temperature controller bridge amplifier where the 725 is needed because of its higher gain bandwidth product. Also, a 108 is used in the Sample and Hold circuit of the phase-locked loop because of its low leakage characteristics.

The logic uses low power TTL. Approximately 100 flat packs mounted on multilayer boards are used. About 10 different types of devices of the 54L series of low power TTL are used Peak power drawn by the logic is less than one amp and is drawn only during the measurement modes.

The 111 integrated comparator is used in applications, such as the phase-locked loop rate detector, the A/D converter and zero-crossover circuits. Its low power, compatibility with TTL logic. and the use of plus and minus 5-volt supplies make this device attractive.

## 3. Conclusions

The electronic design features of a lunar traverse gravimeter have been described. The unique features are its almost completely automatic modes of operation and the use of an accurate low power vibrating string accelerometer as the gravity sensor. The instrument is capable of providing a gravity measurement in approximately 2 minutes after a gravity measurement is initiated by a pushbutton. Filtering of the Rover vibrations is provided by a phase-locked loop filter, in addition to the integration effects obtained by providing a gravity measurement period of about one minute.

A quantization in excess of 0.1 mgal is obtained on a visual display readout with an overall expected accuracy better than one milligal. The system can be levelled when the base of the instrument is within ±15 degrees of the horizontal.

The gravimeter is completely self-contained. An internal 7.5-volt battery provides up to 340 watt hours for all modes of operation over a 15-day period.

## References

1. C. G. Wing, "The MIT Vibrating String Surface Ship Gravimeter," Report No. DSR75162-1, September, 1969.

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