NASA Technical Paper 1108

An Active Nutation Damper for Spacecraft

Richard A. Abercrombie and Thomas W. Flatley

DECEMBER 1977

NASA

NASA Technical Paper 1108

An Active Nutation Damper for Spacecraft

Richard A. Abercrombie and Thomas W. Flatley
Goddard Space Flight Center
Greenbelt, Maryland

National Aeronautics
and Space Administration

**Scientific and Technical
Information Office**

1977

This document makes use of international units according to the Systeme International d'Unites (SI). In certain cases, utility requires the retention of other systems of units in addition to the SI units. The conventional units stated in parentheses following the computed SI equivalents are the basis of the measurements and calculations reported.

CONTENTS

NOTATION

A	System transverse moment of inertia (including flywheel)
a	Angular accelerometer output
C	System spin moment of inertia (including flywheel)
H	System angular momentum
I	Flywheel moment of inertia
ω_i	System angular velocity components, i = 1, 2, 3
ω	System transverse angular velocity = $\sqrt{\omega_1^2 + \omega_2^2}$
Ω	System spin angular velocity = ω_3
σ	Flywheel relative angular velocity
σ_0	Maximum motor speed
λ	Body nutation frequency
θ	System nutation angle

AN ACTIVE NUTATION DAMPER FOR SPACECRAFT

Richard A. Abercrombie and Thomas W. Flatley
Goddard Space Flight Center
Greenbelt, Maryland

INTRODUCTION

An active nutation damper was developed to combat nutational instability of spinning spacecraft, particularly for spacecraft that use long coast periods during a transfer orbit prior to firing an apogee kick motor (AKM).

This active damper was first used with the Laser Geodynamic Satellite (Lageos) which is a 410.9 kg (906 lb), 0.609 m (2 ft) diameter sphere launched into a near-circular, near-polar orbit on May 4, 1976. The purpose of the satellite is to demonstrate space techniques that will contribute to the development and validation of predictive models for ocean surface conditions, ocean circulation, and the alleviation of earthquake hazard. The satellite is tracked by measuring laser beam reflections from a set of 426 corner reflectors covering its surface.

The Lageos had an unfavorable moment of inertia ratio in its transfer orbit and was thus nutationally unstable. Uncertainties in the estimation of the energy dissipation characteristic of the Lageos assembly during the long transfer orbit, particularly within the rubbery solid propellant of the AKM, dictated the use of a device to reduce any nutational coning that might occur because of this instability. Thus, the Lageos Active Nutation Damper (LAND) was developed for this specific purpose.

SYSTEM DESCRIPTION

The active nutation damper system consists primarily of an angular accelerometer, a dc-motor-driven flywheel, and associated electronics. All components are mounted in a single cubical box with the accelerometer input axis perpendicular to the motor/flywheel axis of rotation. On the spacecraft, these axes must also be perpendicular to the nominal spin axis (figure 1). Since the angular accelerometer is insensitive to translational motion and the relative orientation of the accelerometer and motor in the box are fixed, no other position or alignment requirements exist. That is, the damper unit may be mounted in any position, provided that the plane of the accelerometer/motor is normal to the spacecraft spin axis and, for phasing, that the proper end of the housing is up. Thus, the angular accelerometer has an alignment advantage compared to the precise alignment requirements necessary when

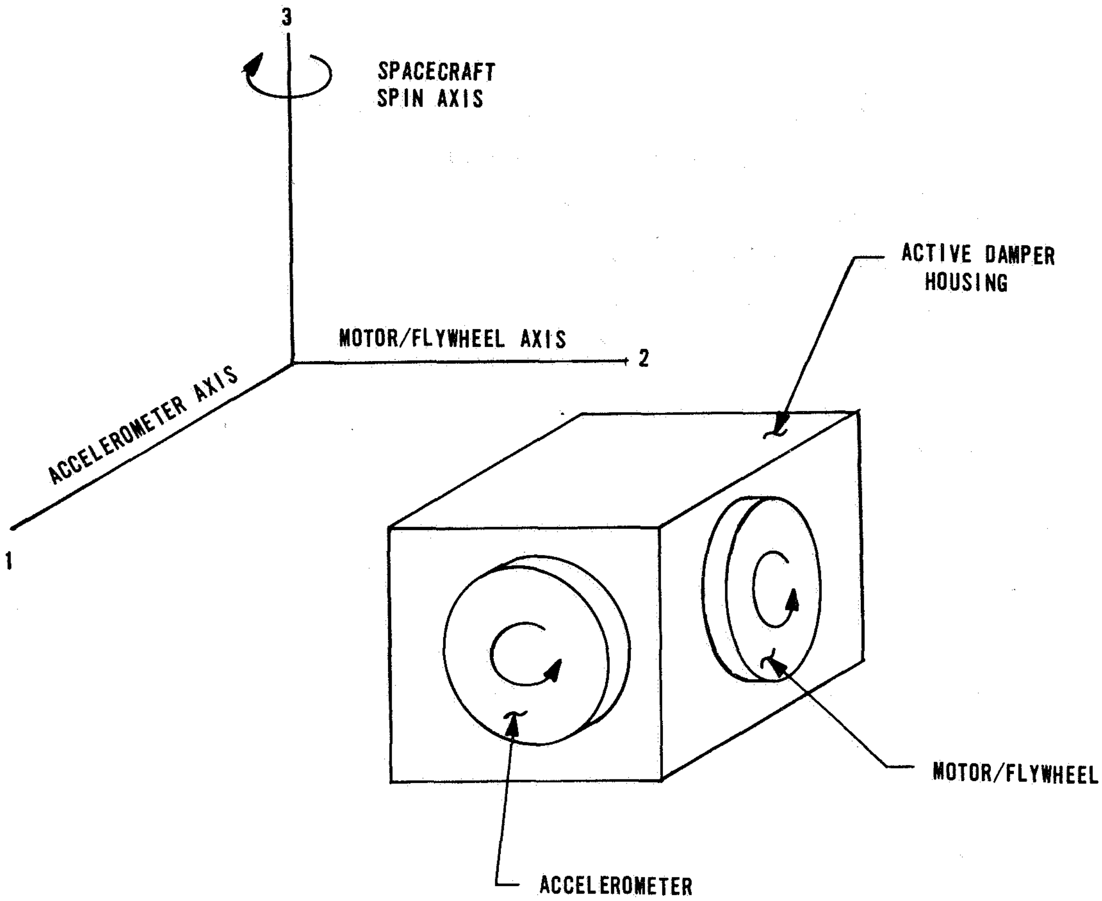

Figure 1. Active nutation damper configuration.

using linear accelerometers or gyros. It should be noted that the availability of angular accelerometers, space qualified or not, is very limited. Accelerometer problems revealed during the test program will be discussed in the section, "Test Program."

Performance Analysis

Although the device described above could be used for nutation control in a wide variety of spacecraft applications, for clarity, only the symmetric rigid body single spin case will be addressed here. Consider a 1-2-3 righ-handed coordinate system defined and illustrated in figure 1.

Let the system angular velocity and angular momentum vectors' components in body coordinates be given by $(\omega_1, \omega_2, \omega_3)$ and $(A\omega_1, A\omega_2 + I\sigma, C\omega_3)$, respectively. The exact Euler equations for the system then become:

$$A\dot{\omega}_1 + (C-A)\,\omega_3\,\omega_2 = I\,\sigma\,\omega_3$$

$$A\dot{\omega}_2 - (C-A)\,\omega_3\,\omega_1 = -\,I\,\dot{\sigma}$$

$$C\dot{\omega}_3 = -\,I\,\sigma\,\omega_1$$

The well-known zeroth order (that is with I = 0) solution of this set of equations is:

$$\omega_1 = \omega \cos \lambda\, t$$

$$\omega_2 = \omega \sin \lambda\, t$$

$$\omega_3 = \Omega$$

where

$$\lambda = \left(\frac{C}{A} - 1\right)\Omega$$

Now, in terms of the angular momentum H and the nutation angle θ,

$$C\omega_3 = H \cos\theta \text{ (exactly)}$$

Substituting this into the third Euler equation above produces

$$H\,\dot{\theta}\,\sin\theta = I\,\sigma\,\omega_1 \text{ (exactly)}$$

Substituting now for ω_1 with its zeroth order solution (with $A\omega \approx H \sin\theta$), we have

$$\dot{\theta} \approx \frac{I}{A}\,\sigma \cos\lambda\, t$$

Now, if we have a motor which runs at a maximum speed of $\pm\sigma_0$, optimum nutation damping will obviously be achieved if we drive the motor such that

$$\sigma = -\,\sigma_0 \operatorname{Sgn}(\cos\lambda\, t)$$

If we do this, since the maximum average value of $\cos\lambda\, t$ over one half of a nutation cycle is $2/\pi$, the maximum achievable nutation decay rate will be

$$\dot{\theta}_{opt} = -\,\frac{2}{\pi}\,\frac{I}{A}\,\sigma_o$$

Implementation

Recalling that the angular accelerometer input axis was aligned with the 1-axis (figure 1), it will measure $\dot{\omega}_1$, that is

$$a = \dot{\omega}_1 \approx -\,\omega\lambda \sin\lambda\, t$$

Since we want the sign of the motor speed opposite to the sign of cos λ t, figure 2 shows that optimum motor switching should occur at the peaks of the accelerometer output.

In practice, digital electronic circuitry is used to divide the nutation period into eight parts. Using positive-going zero crossings of the accelerometer signal as a reference, it drives the motor positive for one fourth of a nutation cycle starting at one eighth of the period, then off for a quarter of a cycle and negative for a quarter cycle. Figure 3 shows this logic schematically and illustrates qualitatively the actual flywheel speed achieved relative to the optimum.

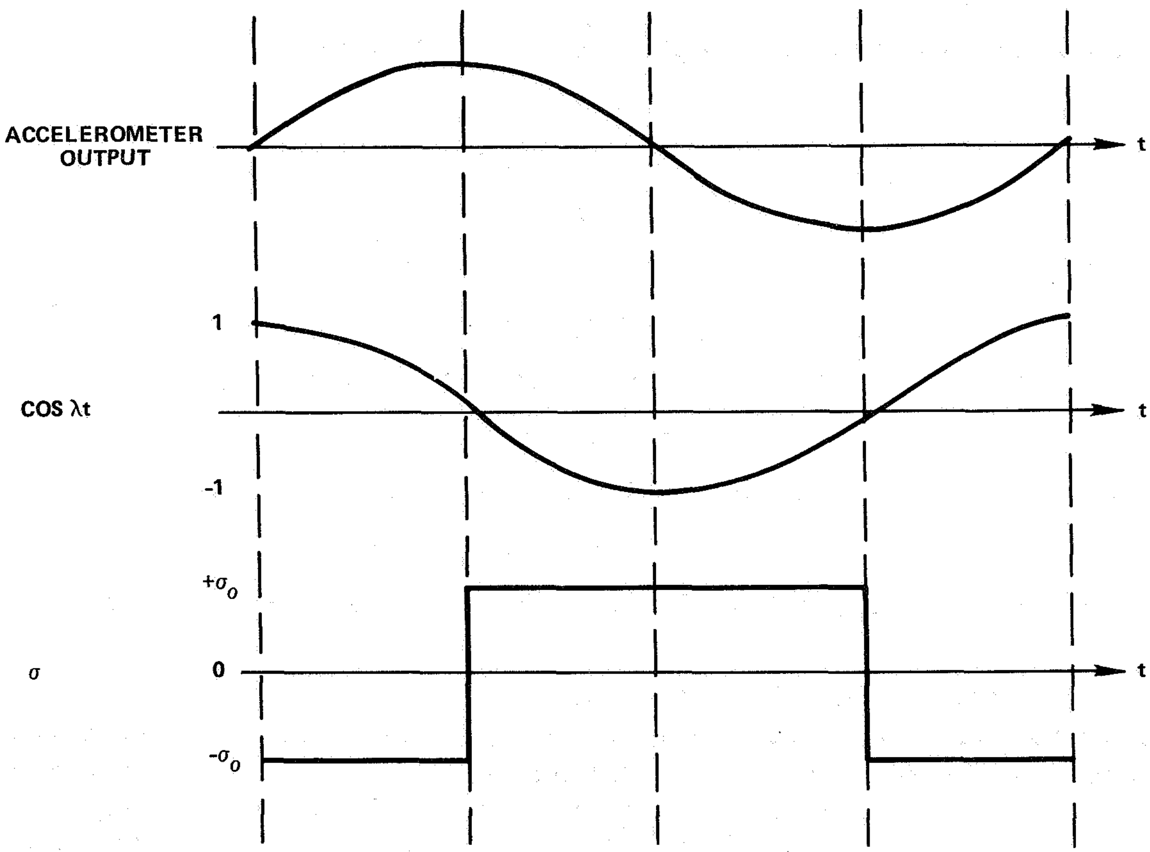

Figure 2. Optimum motor speed control.

GENERAL DESIGN DETAILS

Figure 4 illustrates the overall dimensions of the damper assembly and locates its components. The assembly includes the power converter, the accelerometer, the reaction wheel, and the associated electronics. The dc/dc regulated converter is designed to put out ± 15 V with inputs ranging from 24 to 32 V. The converter output will power the accelerometer and the control electronics. The angular accelerometer is operated within a ± 15-V input and will give a ± 5-V functional output. Full-scale output represents an input acceleration of 0.5 rad/s^2.

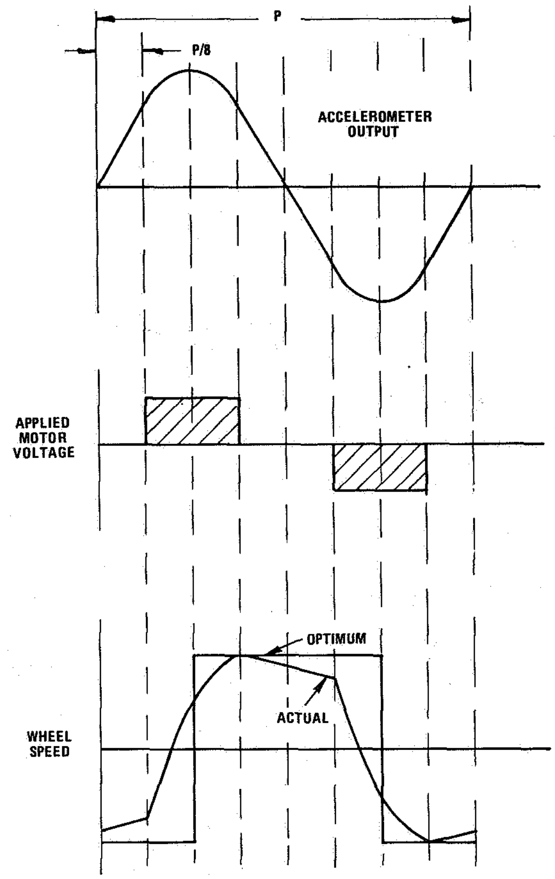

Figure 3. Motor voltage/accelerometer output curves.

The control electronics measure the period of the nutation signal, using this information to properly phase the reaction wheel drive to reduce the spacecraft nutation. The reaction wheel is made up of a 28-Vdc torque motor rotor and a stainless steel flywheel. This unit is mounted on preloaded, duplex, back-to-back, paired bearings directly to the housing at right angles to the accelerometer. The motor is energized by suppressed-contact relays driven by the control electronics. A wiring diagram of the LAND system is shown in figure 5. All power inputs and outputs are isolated through the use of diodes. Relay K4 can latch the system either to internal power furnished by the system battery or external power. This relay can be activated to provide power to the 28-V bus that furnishes power to the converter, the accelerometer, and the electronics. Power will not be furnished to relays K1 and K2 until relay K3 is activated. Thus, the system, with the exception of the reaction wheel, may be turned on before launch. However, the reaction wheel will be powered only after the K3 relay contacts close.

By providing accelerometer and battery telemetry throughout launch, and delaying reaction wheel operation until needed, valuable acceleration data can be telemetered while circumventing excessive battery drain. The failure of relay K4 to power the 28-V bus will result in the loss

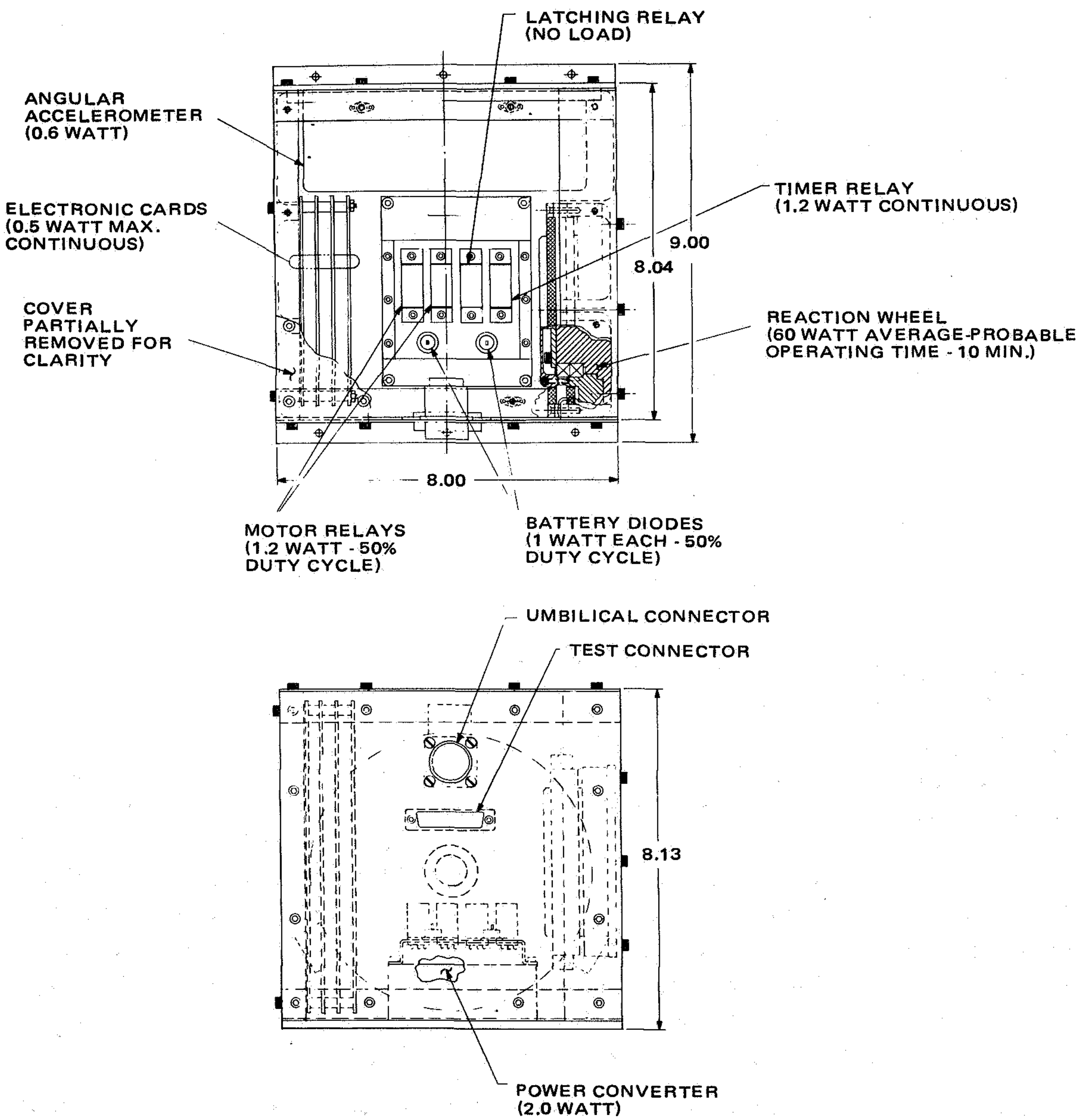

Figure 4. Lageos active nutation damper package.

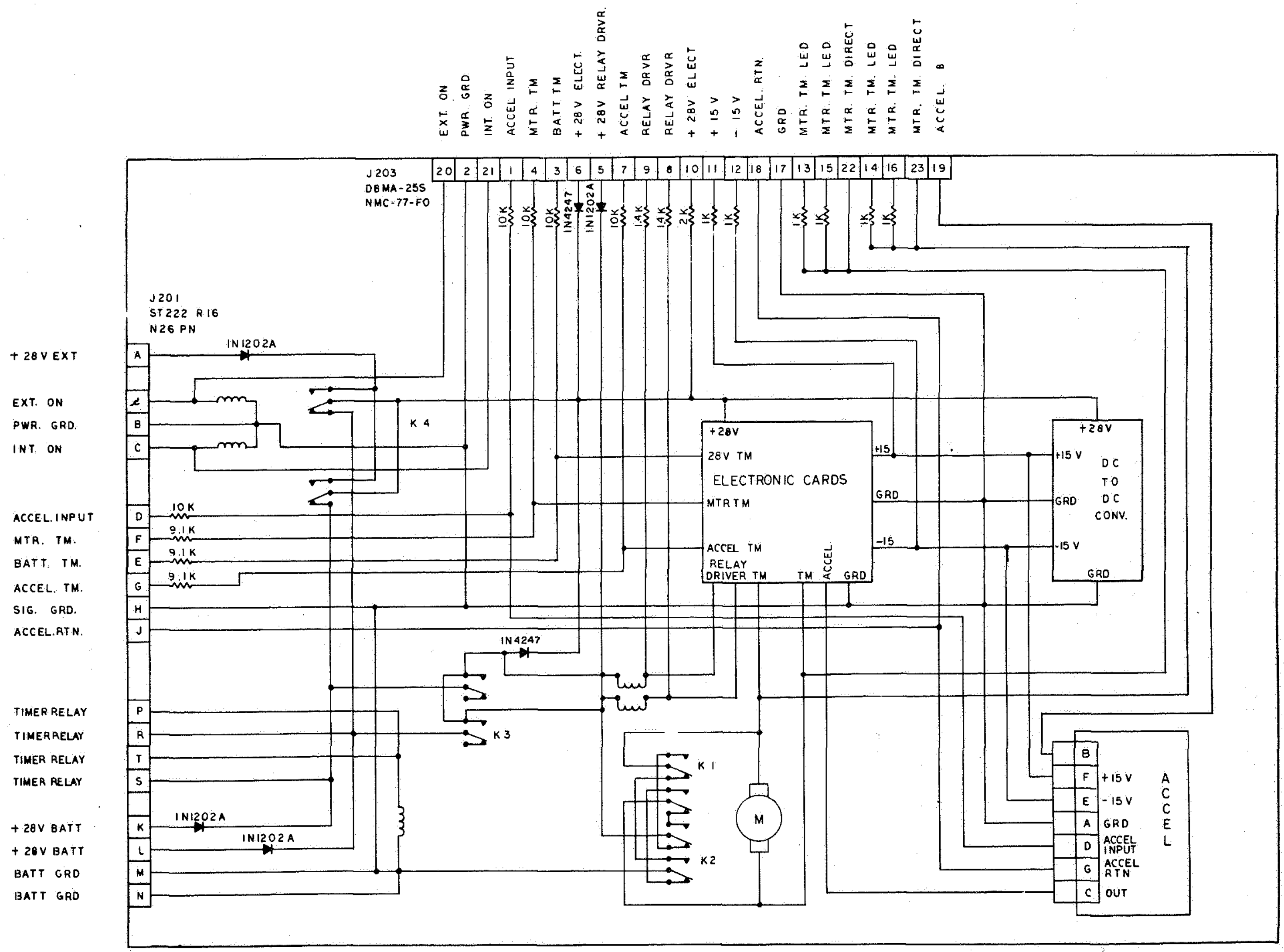

Figure 5. LAND wiring diagram.

of all system outputs until relay K3 is activated, at which time the system will become fully operable. The failure of relay K3 to power the motor driving relays, K1 and K2, will result in loss of the nutation damping capabilities of the system.

System Power

The system requires a 28-V motor voltage source with a dc to dc converter to furnish ± 15 V required by the electronics and the accelerometer. The system will require 2 W of power to drive all components except the torque motor. When the system is damping (dc torque motor operating) the load requirement is 35 W.

Telemetry

The telemetry signals range from 0 to +5 V. The signals are buffered with resistors and limited by Zener diodes.

Test Connector

The electronics assembly contains a test connector that can be used to power the electronics, stimulate the angular accelerometer, and observe the analog telemetry. Access to the electronics must be available through the spacecraft umbilical connector.

Circuit Operation (figures 6 and 7)

The accelerometer signal is amplified, filtered, and fed to zero-crossing and threshold detectors. When the signal exceeds a preset threshold, the zero-crossing detector output is enabled and used to measure the nutation period. For a timing diagram, refer to figures 8 and 9. The timing pulses for the system are obtained from a 1.5-kHz oscillator. At the end of the measurement cycle, the up-counter (figure 6) clock is disabled, and its information is divided by eight and transferred to the holding register. The holding register is updated every other period when the accelerometer signal exceeds the threshold, and will retain the measurement of the last period when the accelerometer signal drops below the threshold.

At the positive zero-crossing, the information in the holding register is transferred to the down-counter. The counter is clocked at the oscillator frequency until it reaches zero count. At this point, a pulse is produced by a one-shot and used to reload the down-counter and to advance the decade-counter-decoder. This pulse represents 45 degrees of nutation phase travel from the previous zero crossing. The CW1 output of the decade-counter goes high and causes the phasing circuitry to produce an output to drive the motor in the clockwise (CW) direction. The down-counter is again clocked to a zero count. This occurs at a 90-degree angle from the zero crossing. The one-shot pulse again reloads the down-counter and advances the decade-counter-decoder. The CW2 output of the counter decoder goes high and the phasing circuit keeps driving the motor in the CW direction. This action occurs eight times per period, causing the decade-counter-decoder to go through its CW1, CW2, and CCW1, and CCW2 states to drive the motor in the CW direction from 45 to 135 degrees and in the

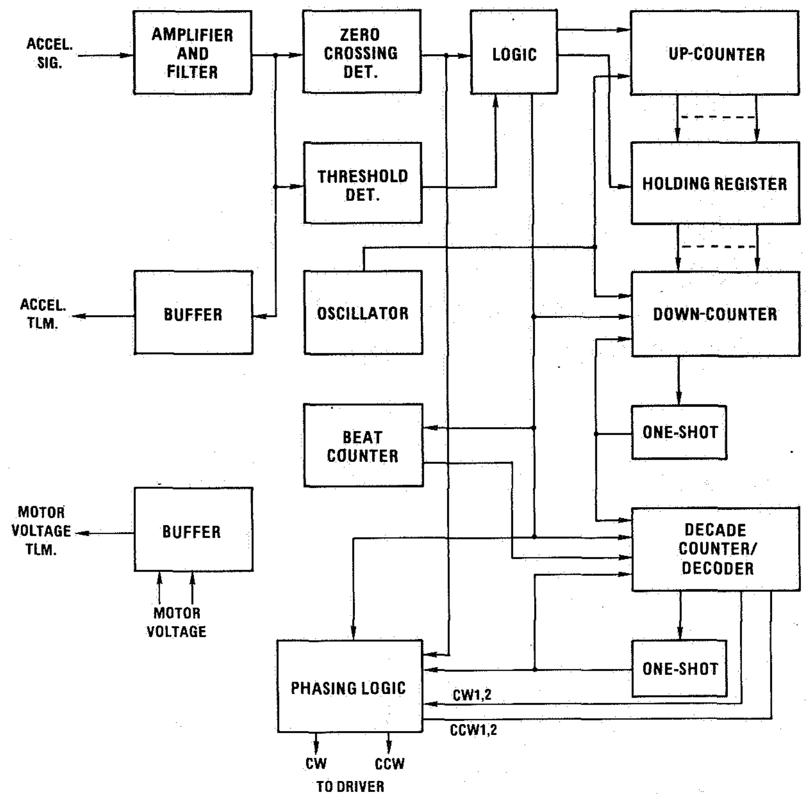

Figure 6. Electronics block diagram.

counter-clockwise (CCW) direction from 225 to 315 degrees. The decade-counter-decoder is reset at the positive zero crossing.

The beat counter is used to develop a number of CW and CCW motor pulses after the accelerometer signal is below the preset threshold (beat mode). The beat counter technique will allow the system to drive the nutation to some angle less than that which is controlled by the threshold voltage. The beat counter is preset to count at every zero crossing following a threshold pulse, and is clocked down by one at the end of every CCW2 pulse from the decade-counter-decoder.

When the accelerometer signal is below the threshold (beat mode), the zero-crossing detector is disabled. The up-counter will not take a new period measurement and the holding register retains the count from the last zero crossing. The down-counter and one-shot continue producing the 45-degree pulses, and the same action occurs in the decade counter as before, except that it uses its eighth state, 360 degrees, to reset itself. This occurs approximately where the positive zero crossing pulse would have been. At the end of the CCW2 pulse, the beat counter is decreased by one until it reaches zero and then holds the system reset. The next zero crossing pulse after a threshold pulse reinitiates the system.

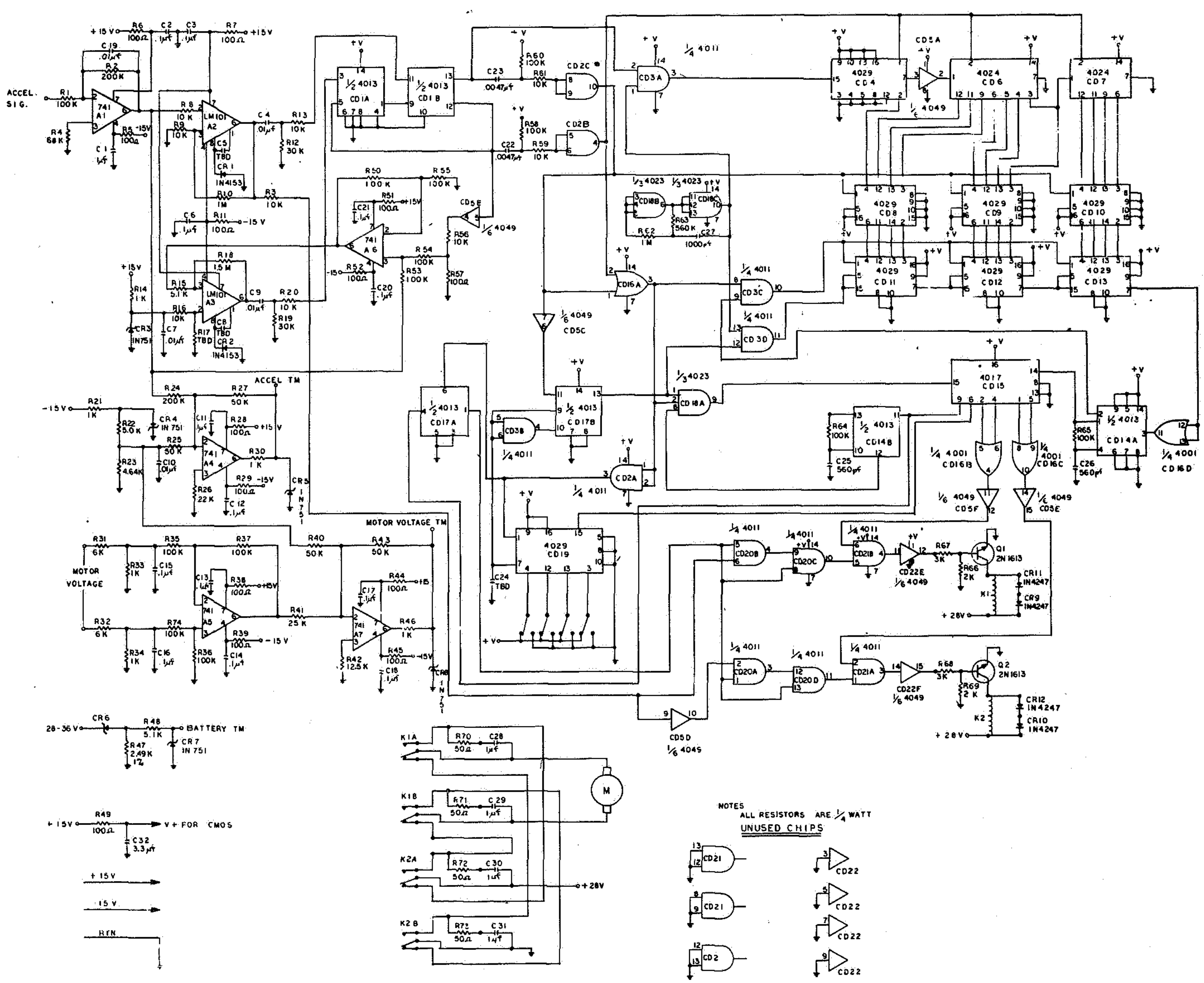

Figure 7. LAND control electronics schematic.

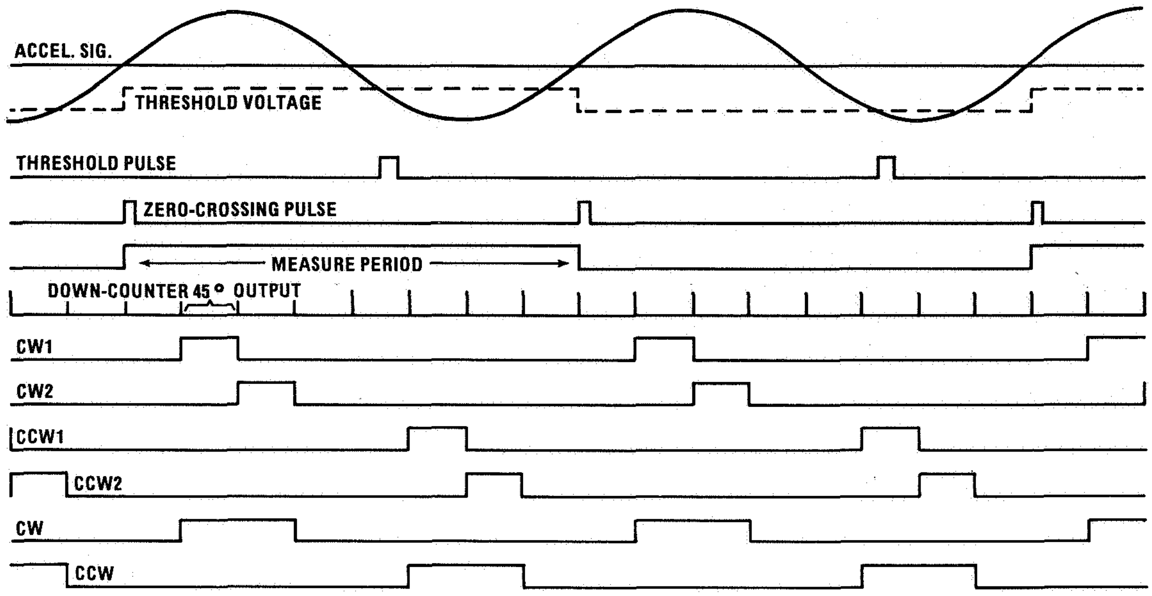

Figure 8. Timing diagram.

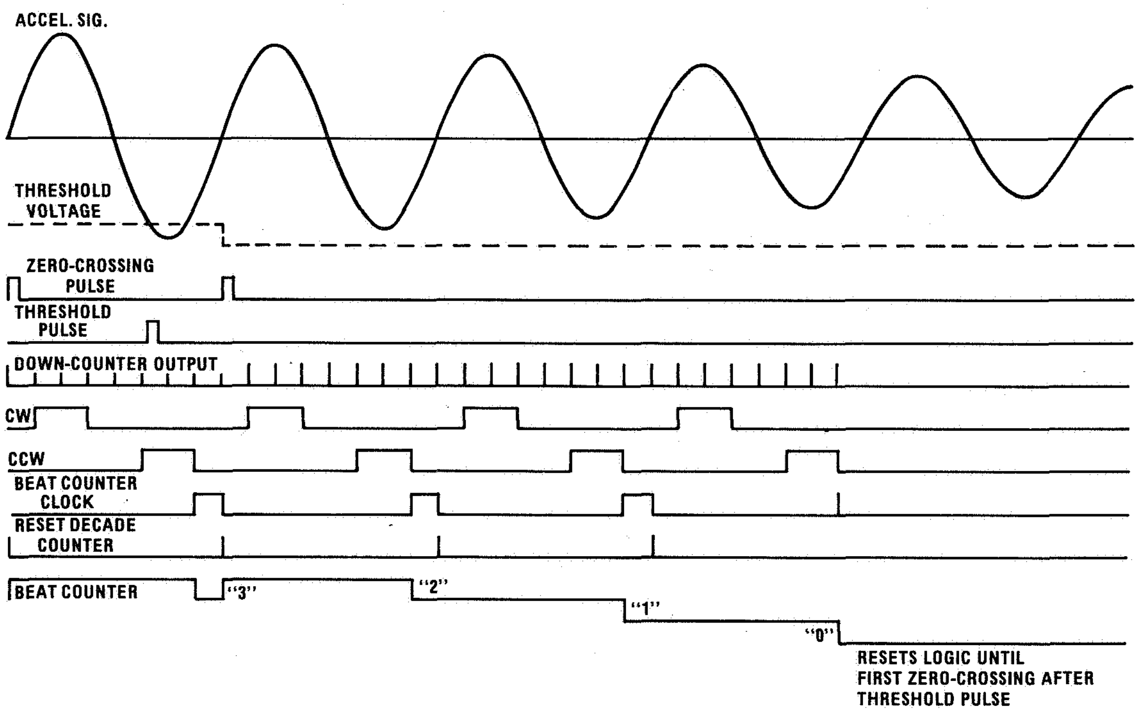

Figure 9. Timing diagram showing beat counter.

Additional logic is implemented to the system so that it cannot develop pulses that are out of phase from the accelerometer signal. This is done by gating the CW and CCW pulses with the zero-crossing detector output. Because of the uncertainty of the zero-crossing pulses during the beat mode, the gating is removed and the system allowed to operate without phasing from the zero-crossing detector. This occurs during the beat mode. The low level CW and CCW pulses are amplified by transistors to drive the relays that apply the +28 V to the motor. The relay contacts are wired in such a manner as not to short the 28-V bus to ground if both relays ever become energized at the same time. The accelerometer signal, motor voltage, and battery voltage are conditioned for 0 to +5 V for telemetry.

Mechanical

The active nutation damper assembly interfaces mechanically with the spacecraft through a mounting bracket. The bracket performs two distinct functions; namely, it rigidly attaches and transfers the torque loads from the active nutation damper assembly to the spacecraft, and it positions the assembly to a specified orientation. The active nutation damper package (including reaction wheel, angular accelerometer, and electronics) is basically a 20.3-cm (8-in) cubical box, weighing approximately 7.5 kg (16.6 lbs). Mounting attachment is provided by two integral flanges at the base of the housing. The mechanical design was divided into three main areas: the reaction wheel, housing/structure, and component packaging.

The reaction wheel incorporates a flywheel driven by a frameless, dc, permanent magnet torque motor (figure 10) with the rotor mounted to the flywheel, and the stator mounted to the housing. The flywheel and rotor are supported by duplexed/angular contact bearings with the following attributes:

- Consistent preload regardless of environment
- Preload accurately established by bearing manufacturer
- Nonlinear force/displacement characteristics with high reliability
- Greater rigidity under moment loading
- Accurate, rigid rotor positioning to assure balance stability

The bearings are lubricated with Krytox to reduce friction and wear between moving parts, to dissipate heat, and to prevent corrosion of critical surfaces.

Additionally, the bearing and lubrication are protected from contamination by a labyrinth seal. The housing is a composite structure that provides rigid mounting surfaces for components, component protection from mechanical damage, alignment of components, electrical and thermal conductive paths, and thermal coating on the outside surfaces for thermal integrity.

The packaging concept optimizes the component location and position to achieve accessibility, load and weight distribution, to reduce load impact due to vibration, and to give a favorable center-of-mass location.

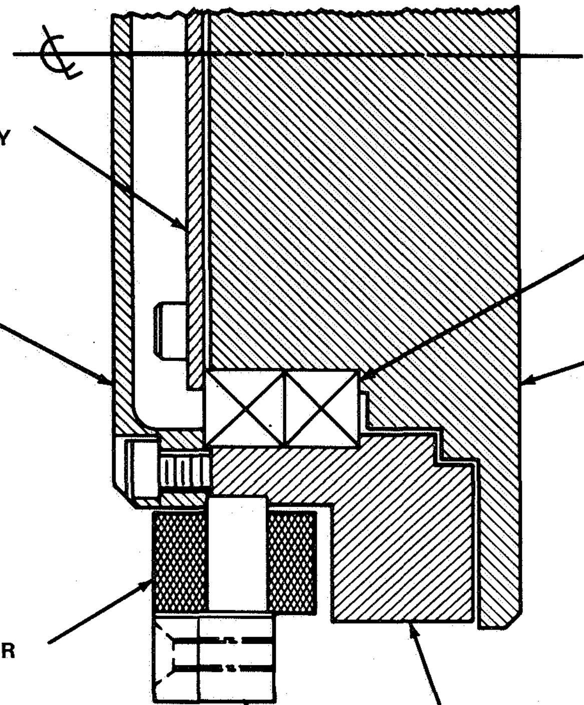

Figure 10. Motor/bearing assembly.

TEST PROGRAM

The LAND system was subjected to a test program to generate performance data and to prove its capability of meeting the Lageos flight requirements. Engineering tests were run on the breadboard unit to prove the electronic design. Performance tests of the complete unit were conducted before and after vibration, EMI, and thermal vacuum tests. Two complete LAND units were constructed. One unit was environmentally qualified at Flight Prototype levels to be used as a flight spare. The other unit was tested at Flight Acceptance levels, and was the flight unit.

Mechanical Stimulation Test

All major components were subjected to preassembly performance checks. The accelerometers were mechanically stimulated using a single-axis air-bearing table mounted on a seismic block. Four large arms, equally spaced from each other, were secured to the floating portion of the air-bearing assembly. Cables were attached to the ends of opposing arms, then passed over pulleys and attached to weights (figure 11). Thus, if the whole floating arrangement were deflected a few degrees and then released, it would oscillate at varying

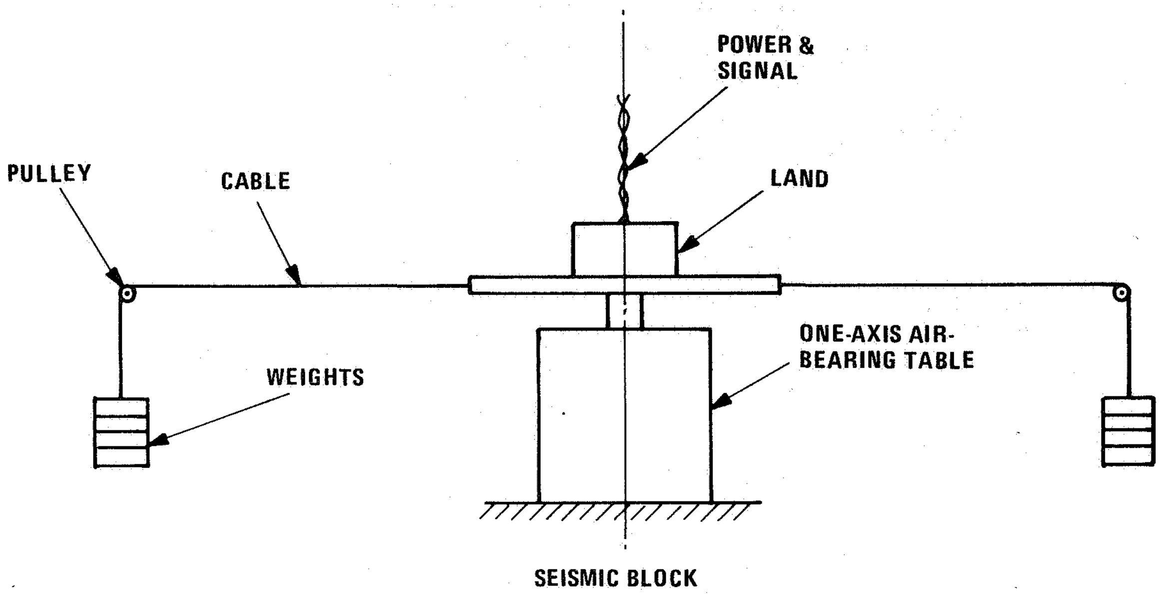

Figure 11. Physical stimulation test setup.

frequencies depending on the quantity of equal weights applied to the opposing arms. Weights were added until a frequency of 1.3 Hz (the calculated Lageos nutation frequency) was reached. The large mass of this arrangement allowed the table to oscillate at a specific frequency fairly constantly for a short period of time. The complete system was placed on a seismic block to effectively isolate the sensitive accelerometer from various vibrations in the building. With the LAND unit mounted to the center of this arrangement and powered up through a connector, a functional test of the accelerometer, reaction wheel, threshold level, and phasing was conducted visually and recorded as the table was oscillated. This test revealed that movement of wires carrying a 10-MHz accelerometer oscillator signal produced a noise level that exceeded the threshold level of the system. This problem was solved by shortening the cable between the electronics and the sensing unit of the accelerometer, conformal coating all wires carrying this 10-MHz signal so they could not move, and filtering all accelerometer inputs and outputs with RC networks.

Gas-Bearing Test

The active nutation damper package was evaluated and proven on a 3-axis gas-bearing simulator (figure 12) that duplicated the Lageos critical flight dynamics. The spin rate, and the spin and transverse inertias of the simulator were made to be equal to that of the Lageos spacecraft in transfer orbit. Testing was conducted under vacuum in a dynamic test chamber. Nutation was induced in the simulator and both the flight and back-up LAND units were activated for full-scale performance tests. These tests verified that the LAND system would reduce nutation at the predicted rate of 1 degree per minute.

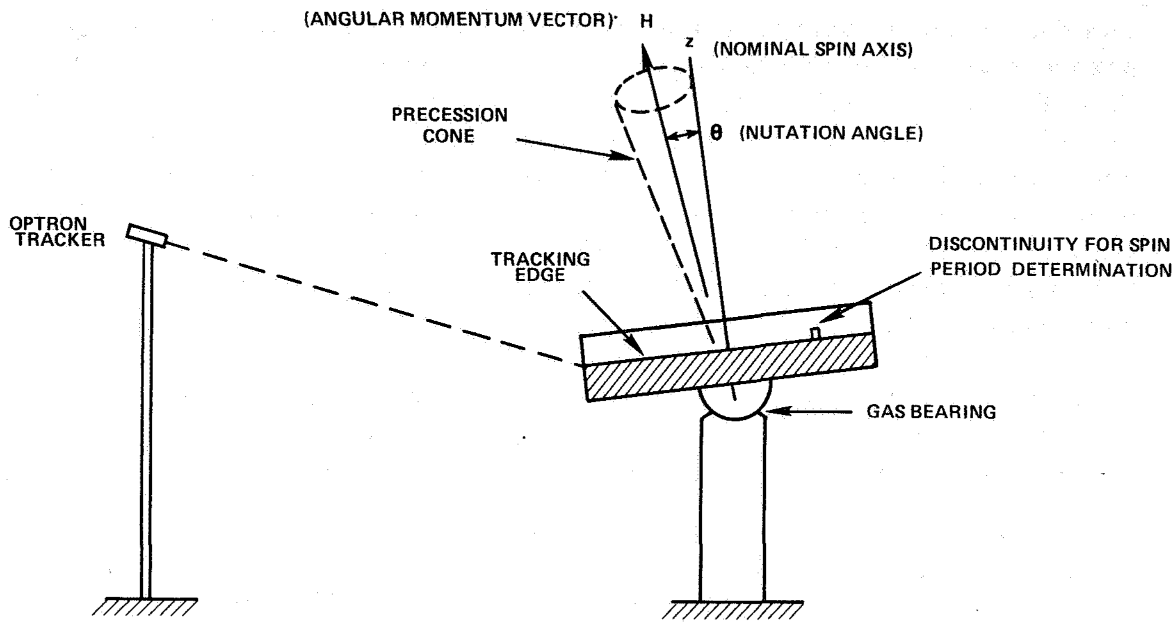

Figure 12. Optron attitude sensing.

Failure Analysis

In general, there were many single point failures that would have caused the LAND system to fail and not supply damping. One way to have eliminated these failures would have been to use a redundant system with a command capability to switch from one system to the other. This approach was not considered, because it would have doubled the weight, and because a command system was not available. In order to avoid single point failures, an extensive testing and quality control program was instituted. The established philosophy for failures in the LAND system was to accept single point failures if they resulted in reduced performance, no performance, or small one-shot nutation impulses (that is, less than 1 arc minute). Any single point failure that could have resulted in a phasing error of greater than ± 90 degrees would have caused a nutation buildup on the spacecraft, which would be considered totally unacceptable. The system was designed so that there were no known single point failures that would cause nutational buildup. The failure analysis was conducted by addressing each of six assemblies in the LAND system and presenting ways in which failed outputs could have affected the LAND performance. The LAND system was designed against any failure mode that would cause the nutation angle to increase and possibly cause a mission failure. This type of failure is specifically addressed in this analysis. There was no known way a failure (including mechanical or electrical failure) could have caused the accelerometer output to become greater than 90 degrees out of phase with the input. The electronics were designed so that all failures would cause either no output or a saturated output. If no output occurred, the LAND system would have ceased to operate. This would have also occurred with a saturated output, since the signal is ac-coupled on the electronics assembly. Mechanical failures in the accelerometer, such as broken connections, would have caused no output or a saturated output. If any oil had leaked out, the system would have acted normally until an air bubble (caused by the leak) moved to the sensing area, where the surface tension would have tended to pull the accelerometer sensor paddle to one side, producing a saturated output. Accelerometer failures can yield only zero output, plus or minus saturated output or reduced gain. If the bearings failed while the motor was running at high speed, the wheel momentum would have been transferred to the spacecraft. Since the wheel inertia was small (0.0027 kg-m^2 (0.002 slug-ft^2)) compared to the Lageos 163 kg-m^2 (120 slug-ft^2), the disturbance would have been less than 1 arc minute of nutation. If the motor failed, the LAND would either have ceased to provide damping or would have damped at a slower rate depending on the type of failure. Total motor failure obviously results in no damping and partial failure (slower motor rates) will simply reduce the damping efficiency but still provide proper damping. Inertia wheel and motor failures can yield either a one shot impulse of nutation (less than 1 arc minute), no nutation damping, or reduced damping.

A failure in the dc/dc converter that supplies the ± 15 V to the electronics and accelerometer would have resulted in no voltage drive to the motor since there would have been no accelerometer output or signal processing in the electronics. This would have resulted in no damping.

Battery Analysis

If the battery had supplied no voltage or a low voltage, the dc/dc converter would have ceased to operate and the drive voltage would not have been supplied to the wheel. This would have resulted in no damping.

A failure to the telemetry conditioning electronics would have resulted in no telemetry data being supplied. This would not have affected the damping performance.

The electronics assembly was designed against any single point failure that would cause a nutation buildup. Since nutation buildup can only result from an out-of-phase condition, protective circuitry (see figure 13) was added to eliminate any improper phase drive to the motor. This circuit permitted drive signals to the wheel only when the accelerometer phasing (Z) is proper with respect to the wheel drive signals (CD 5E and CD 5F). Thus, any failure ahead of this circuit, when coupled with the drive circuitry, would not have permitted an out-of-phase drive.

The only known failure in the electronics that could have caused phasing errors in excess of 90 degrees would have been a false period in excess of twice the true period stored in the holding register. Complete protection against this failure was provided by the phasing protection circuit. However, double protection was provided for Lageos by the logic circuitry, not recognizing periods in excess of 1.5 s.

In summary, while there were many single point failures that could have caused no drive or saturation drive to the motor, there were no known single or double point failures that could have resulted in phasing errors in excess of plus or minus 90 degrees.

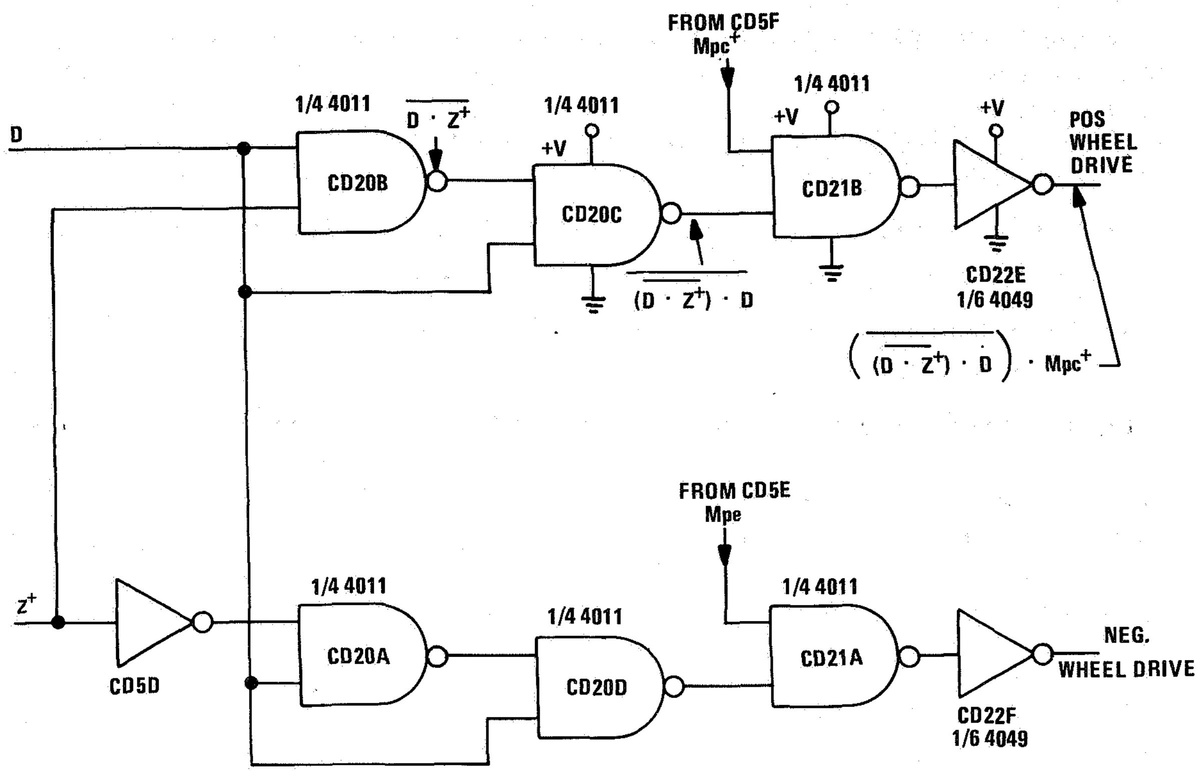

Figure 13. Phasing protection circuit of LAND control electronics.

FLIGHT PERFORMANCE

The Lageos spacecraft was successfully launched May 4, 1976. The LAND system was turned on just before launch except for power to the motor driven flywheel. The angular accelerometer and electronics were powered up before launch as a functional check and to provide accelerometer telemetry data during the launch phase. The reaction wheel was furnished power through a timing switch closure that occurred shortly after third stage separation, at which point the long coast (4500 s) transfer orbit started. Telemetry indicated that the LAND system's motor/flywheel was activated as the timing switch closed. The nutation at the beginning of the long coast period was 0.6 degrees, which was greater than the 0.38 degrees threshold of the logic circuitry. Thus, the LAND's motor turned on and it operated for a period of approximately 20 s, reducing nutation to 0.25 degrees. This performance verified the nominal preflight prediction of 1.0 degree per minute for the nutation control capability of the damper. The balance of the long coast period was completed without sufficient nutation growth to restart the LAND system.

CONCLUDING REMARKS

The most significant features of this development program may be summarized as follows:

- This was the first time an angular accelerometer has been used for sensing spacecraft nutation.
- This was the first time an active nutation damper made use of internal torquing to control nutational coning.
- The flight capability of this active nutation damping system has been proven by the Lageos launch.
- This damper design is particularly suitable to those spacecraft without gas control systems that require long coast transfer orbits.
- This system can easily be adapted to fire jets for gas control of nutational coning.

ACKNOWLEDGMENTS

Credit is due to the following members of the Stabilization and Control Branch of Goddard Space Flight Center: Walter Squillari, the Electronics Design Engineer; Robert Shelley, the Mechanical Design Engineer; and to Henry Hoffman and James Donohue for their conceptual design of this damper system.

Goddard Space Flight Center
National Aeronautics and Space Administration
Greenbelt, Maryland October 1977

1. Report No. TP 1108	2. Government Accession No.	3. Recipient's Catalog No.
4. Title and Subtitle An Active Nutation Damper for Spacecraft		5. Report Date December 1977
		6. Performing Organization Code 712
7. Author(s) Richard A. Abercrombie and Thomas W. Flatley		8. Performing Organization Report No. G 7702 F-23
9. Performing Organization Name and Address Goddard Space Flight Center Greenbelt, Maryland 20771		10. Work Unit No.
		11. Contract or Grant No.
12. Sponsoring Agency Name and Address National Aeronautics and Space Administration Washington, D.C. 20546		13. Type of Report and Period Covered Technical Paper
		14. Sponsoring Agency Code
15. Supplementary Notes		

16. Abstract

An active nutation damping device, consisting of an angular accelerometer, a dc-motor-driven flywheel, and associated electronics, has been developed for spacecraft use. This damping system was used on the Lageos spacecraft, launched May 4, 1976, to control nutation buildup during the long coast period (approximately 75 minutes) after the third stage separation.

Of many electrical and mechanical design choices, an angular rather than linear accelerometer offers some advantages. There were, however, some problems in adapting the angular accelerometer to spacecraft use.

The damper package was evaluated and proven on a three-axis gas-bearing simulator that duplicated the Lageos spacecraft critical flight dynamics. In addition, a failure analysis of the damper assembly was performed.

Performance of the damper during the Lageos flight has confirmed the preflight evaluation and analysis.

17. Key Words (Selected by Author(s))	18. Distribution Statement
Active nutation damper, Nutation control	Unclassified–Unlimited Cat. 15

19. Security Classif. (of this report)	20. Security Classif. (of this page)	21. No. of Pages	22. Price*
Unclassified	Unclassified	26	$4.50

*For sale by the National Technical Information Service, Springfield, Virginia 22161

NASA- Langley, 1977