4:   ACCELEROMETER MODULE   Final Report
(Draper (Charles Stark) Lab., Inc.)   43 p

Unclas
00/35   25127

SEP 5 1973

JM4

Charles S. Draper Laboratories, Inc.
Attn: John Pulcini, Security Officer
68 Albany Street
Cambridge, Massachusetts 02139

Subject: Declassification of Report R-746, SIRU Development - Final
           Report, Volume IV, Accelerometer Module (U), May, 1973,
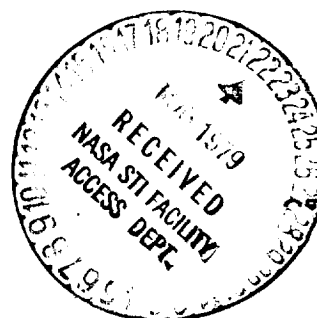   Contract NAS 9-8242

By letter dated August 1, 1973, the Strategic Systems Project Office,
Department of the Navy, approved the declassification of M.I.T. Report
R-743, Strapdown System Performance Optimization Test Evaluations.
Their approval was based on the fact that the report did not contain
any reference to the FBM Program.

Subject report has been reviewed and since it is a report on the
same technology already reviewed and declassified by the U. S. Navy,
and since it also does not contain any reference to the FBM Program,
it is felt that the above letter of August 1, 1973 provides sufficient
authority for the declassification of subject report.

Classification markings on subject report will be changed to
Unclassified and this letter may be cited as the authority for the
declassification action. Mr. Jerold P. Gilmore of your organization
should be notified of this action.

Gene L. Benjamin
Security Classification Officer

bcc:
EG/R. Chilton
EG5/W. Swingle
EG5/M. E. Jones
BC73/T. Lapko

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION
LYNDON B. JOHNSON SPACE CENTER
HOUSTON, TEXAS   77058

SEP 5 1973

REPLY TO
ATTN OF: JM4

TO: EG5/ Inertial-Optical Branch
            Attn: Malcolm E. Jones
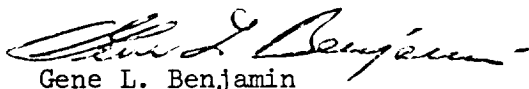
FROM: JM4/Security Classification Officer

SUBJECT: Request for Security Classification Review –
            MIT Report R-746, SIRU Development-Final Report, Volume IV,
            Accelerometer Module (U), May 1973, NAS 9-8242

Reference is made to your memorandum EG5-73-87, dated August 13, 1973
requesting a security classification review of subject document.

On August 1, 1973 the Strategic Systems Project Office, Department of
the Navy, approved the declassification of MIT Report R-743, Strapdown
System Performance Optimization Test Evaluations. Their letter stated
that there was no objection to the declassification of the report
since it did not contain any reference to the FBM Program.

Subject report has been reviewed and since it is a report on the same
technology already reviewed and declassified by the U. S. Navy, and since
it also does not contain any reference to the FBM Program, it is felt
that the above letter of August 1, 1973 provides sufficient authority
for the declassification of subject report.

Classification markings on subject report will be changed to Unclassified
and this memorandum may be cited as the authority for the declassification
action. M.I.T. will be notified of this action by separate letter.

Gene L. Benjamin

Encl: Ltr. dtd. 8/1/73

cc:
EG/R. Chilton
EG5/W. Swingle
BC73/T. Lapko

DEPARTMENT OF THE NAVY
STRATEGIC SYSTEMS PROJECT OFFICE
WASHINGTON, D. C. 20390

IN REPLY REFER TO

SP2020-RMJ:mlj
5510

AUG 1 1973

From: Director, Strategic Systems Projects
To: National Aeronautics and Space Administration,
       Lyndon B. Johnson Space Center, Houston, Texas 77058
       (Gene L. Benjamin)

Subj: Request for Security Classification Review

Ref: (a) NASA ltr JM 4 of 14 March 1973

1. This Office has reviewed enclosure (1) to reference (a)
for possible declassification action as requested by
reference (a) and has no objection to its declassification.
This evaluation is based upon the fact that there is no
reference to the FBM Program.

R.H. WERTHEIM
By direction

ACKNOWLEDGEMENT

The successful development of the SIRU system to its present state of hardware, software and analytical maturity results from the dedicated efforts of many people from the NASA L.B. Johnson Space Center and the C.S. Draper Laboratory to synthesize, design, fabricate and test a redundant body mounted inertial system employing state-of-the-art redundancy management techniques.

The technical and historical material presented in this volume of the SIRU Development Final Report was to a large extent contributed by the people who performed the original design and evaluation tasks. The major contribution by the authors has been in the collection, composition, direction and editing control of assembled material.

Special mention is due to the following for major contributions pertaining to their area of interest

Richard McKern	Arthur Boyce
Howard Musoff	David Brown
Siegbert Katz	Martin Landey
Julius Feldman	Thomas Shuck
David Swanson	

and to Jerold Gilmore and Robert Booth whose knowledge and assistance have been invaluable.

The work performed by Stephen Helfant with Linda Willy and Angela Desmond in editing and preparing the document for publication deserves meritorious recognition and heartiest thanks go to the Apollo Publications Group with special mention to Ellen Hurley.

The publication of this report does not constitute approval by the National Aeronautics and Space Administration of the findings or the conclusions contained therein. It is published only for the exchange and stimulation of ideas.

R-746

SIRU DEVELOPMENT – FINAL REPORT
VOLUME IV
ACCELEROMETER MODULE (U)

by

George Bukow
Roscoe Cooper

May 1973

Charles Stark Draper Laboratory
Massachusetts Institute of Technology
Cambridge, Massachusetts
02139

APPROVED: _____ Date: 5/25/73
J. P. GILMORE

APPROVED: _____ Date: 30 May 73
N. E. SEARS

APPROVED: _____ Date: 30 May 73
D. G. HOAG

NATIONAL SECURITY INFORMATION
Unauthorized Disclosure
Sanction

Pages 27, 28 and A-1 are CONFIDENTIAL.

All remaining pages are UNCLASSIFIED.

CLASSIFICATION CHANGE
To ___ UNCLASSIFIED
By authority of JSC Security Class, Officer
Changed by A. Benjamin Date 9-5-73

R-746

SIRU DEVELOPMENT FINAL REPORT

ABSTRACT

This report presents a complete description of the development and initial evaluation of the Strapdown Inertial Reference Unit (SIRU) system sponsored by the NASA Johnson Space Center under Contract NAS9-8242.

The SIRU configuration is a modular inertial subsystem with hardware and software features that achieve fault tolerant operational capabilities. The SIRU redundant hardware design is formulated about a six gyro and six accelerometer instrument module package. The modules are mounted in this package so that their measurement input axes form a unique symmetrical pattern that corresponds to the array of perpendiculars to the faces of a regular dodecahedron. This six axes array provides redundant independent sensing and the symmetry enables the formulation of an optimal software redundant data processing structure with self-contained fault detection and isolation (FDI) capabilities.

This report consists of four volumes.

Volume I, System Development, documents the system mechanization with the analytic formulation of the FDI and processing structure; the hardware redundancy design and the individual modularity features; the computational structure and facilities; and the initial subsystem evaluation results.

Volume II, Gyro Module, is devoted specifically to the Gyro Module, the inertial instrument and its digital strapdown torque-to-balance loop, the mechanical, thermal, and electronic design and function, test procedures and test equipment and performance results and analysis.

Volume III, Software, documents the basic SIRU software coding system used in the DDP-516 computer. The documentation covers the instrument compensation software, reorganizational and FDI processing, and the inertial attitude and velocity algorithm routines as well as servicing, input/output, etc. software.

Volume IV, Accelerometer Module, is devoted specifically to the Accelerometer Module, the inertial instrument and its digital strapdown torque-to-balance loop, the mechanical, thermal and electronic design and function and performance results and analysis, as it differs from the Gyro Module.

In addition to this report, SIRU Utilization Report R-747, has been issued documenting analyses, software and evaluation activities in the application of advanced statistical FDI algorithms, calibration and alignment techniques to the SIRU system.

April 1973

TABLE OF CONTENTS

LIST OF ILLUSTRATIONS AND TABLES

DICTIONARY OF TERMS

AC	Alternating Current
A/D	Analogue to Digital
ADIA	Acceleration-Dependent Gyro Drift Due to Acceleration Along the Input Axis
ADOA	Acceleration-Dependent Gyro Drift Due to Acceleration Along the Output Axis
ADSRA	Acceleration-Dependent Gyro Drift Due to Acceleration Along the Spin Reference Axis
CSDL	Charles Stark Draper Laboratory
DC	Direct Current
EA	Electronics Assembly
GSE	Ground Support Equipment
IA	Input Axis
INT	Interrogate Pulse
IRIG	Inertial Reference Integrating Gyro
+LDFF	Positive Level Detect Flip-Flop
MTBF	Mean-Time-Between Failures
NBD	Normal Bias Drift
OA	Output Axis
PIPA	Pulsed Integrating Pendulous Accelerometer
PMT	Permanent Magnet Torquer
PPM	Part Per Million
PTE	Pulse Torque Electronics
PVR	Precision Voltage Reference
RIP	Redundant Instrument Package
SA	Spin Axis
SF	Scale Factor
SG	Signal Generator
SIRU	Strapdown Inertial Reference Unit
SRA	Spin Reference Axis
TG	Torque Generator
TMSFF	Torque Motor Set Flip-Flop
TSRFF	Torque Switch Reset Flip-Flop

1.0 Introduction

Volume IV of the SIRU Development Final Report describes the design and performance features of the accelerometer module. Volume I provides an overview of all aspects of the SIRU Development program including mechanization, hardware, software, and reliability assessment. Volume II describes the design and performance features of the gyro module. Volume III consists of a detailed description of the system software including assembly listings and load maps.

1.1 System Description

A brief description of the SIRU system is provided here as an aid in associating the function of the accelerometer module with the other system elements.

The redundant Strapdown Inertial Reference Unit (SIRU) contains design features developed to provide an optimal combination of reliability and maintainability in a desirable size and weight configuration. Reliability results from the geometric redundancy afforded by a unique arrangement of six gyroscope and accelerometer pairs. Each pair is oriented such that their input axes (IAs) correspond to the array of normals to the faces of the dodecahedron, lie in the orthogonal planes of the structure referenced triad, and are displaced from the triad axes by a unique spherical angle (approx 31.7°).

This symmetry yields optimal redundant data processing with minimal error propagation. Software routines, by means of instrument output comparisons, permit failure isolation for up to two of the six instruments of each type and detection for a third failure. The reliability resulting from this design feature is compared to other redundant arrangements in Fig. 1.1. Maintainability results from the fault isolation capability and the replaceable modularized packaging arrangement made possible by the strapdown configuration. The Redundant Instrument Package (RIP) consists of a mounting and alignment structure to which the six gyroscope and six accelerometer modules are mounted. The assembled RIP is shown in Fig. 1.2. Each instrument module consists of a prealigned gyroscope or accelerometer packaged with its normalizing and calibrating electronics as an interchangeable sealed unit. Access to each module for inspection, servicing or replacement is available at the front of the RIP. Size and weight characteristics, even in this development model, compare favorably with alternate redundant systems. The RIP occupies a volume of 1754 cubic inches, weighs 63 pounds and requires 183 watts of power.

1
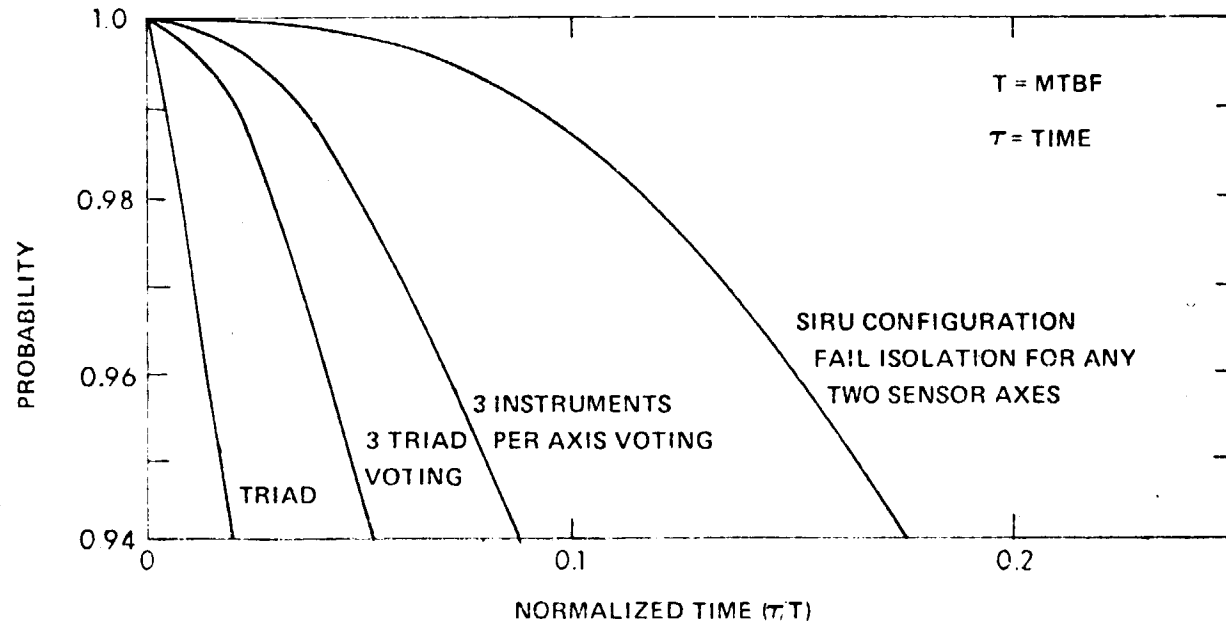
Fig. 1.1 MISSION SUCCESS PROBABILITY

SIRU INSTRUMENT PACKAGE
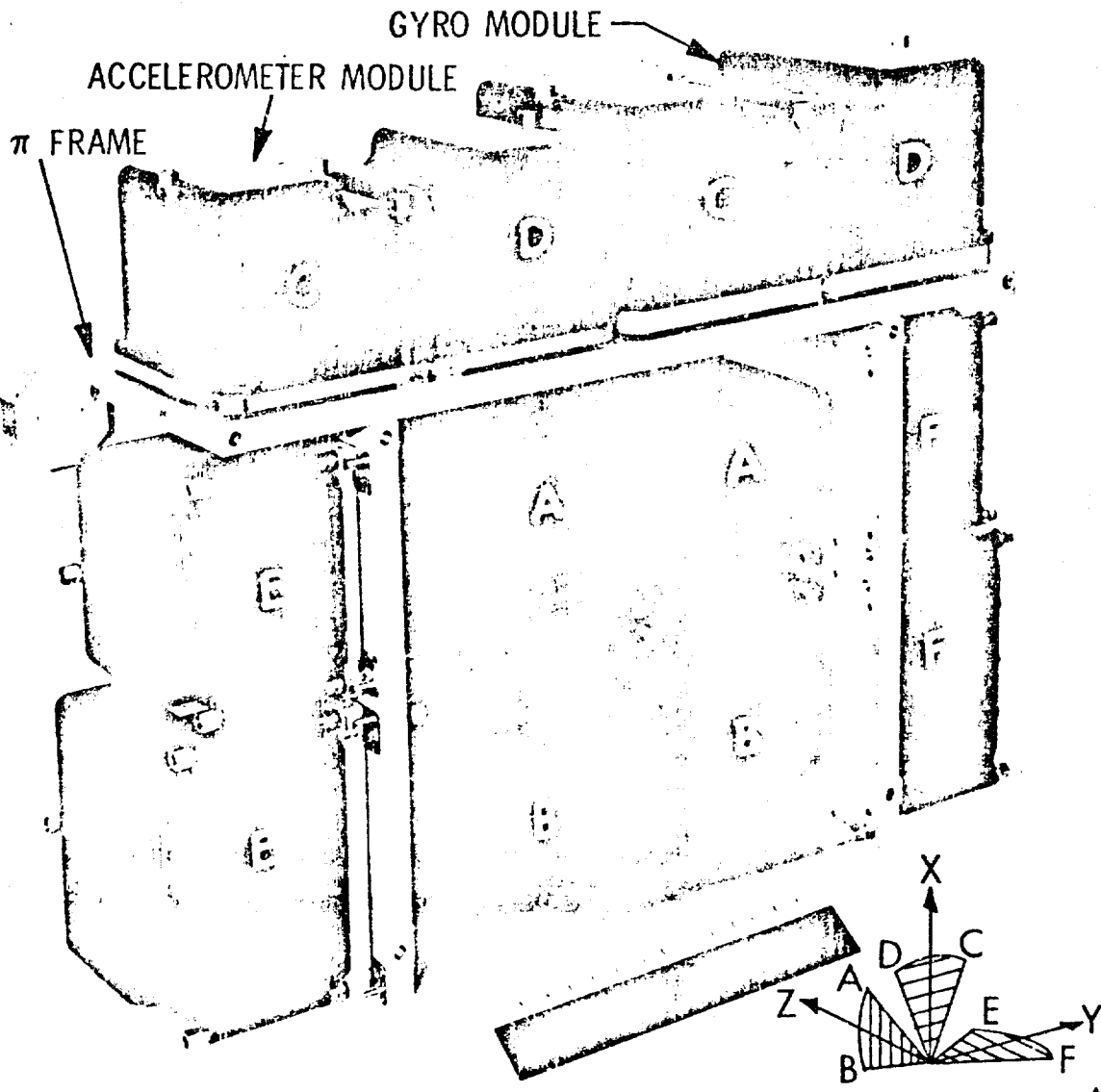
Fig. 1.2 SIRU Redundant Instrument Package

1.2   Accelerometer Module

The appearance and location of the accelerometer modules are shown in Fig. 1.2. These modules contain the specific force sensor with the associated pulse torque electronics, temperature controller and support electronics. The sensor is mechanically aligned in relation to the module mounting pads and all elements are normalized so that each module presents, within the tolerance specified, an identical interface with the SIRU system. General characteristics of the accelerometer module are shown in Table 1.1.

The design, operation, testing and performance of the accelerometer and its circuit elements are described in the following sections. The presentation is divided into four sections.

1.   Technical Description

This section provides a brief description of the design and operation of the accelerometer module to the extent that it differs from the gyro module as described in Volume II.

2.   Accelerometer Reliability and Production History

This section provides a summary of the production and reliability history of the accelerometers used in the SIRU development program.

3.   Accelerometer Test

This section describes the test routines performed in support of the accelerometer modules.

4.   Accelerometer Performance

This section presents instrument performance summaries developed from the program performance data.

4

TABLE 1.1

Accelerometer Module/PIPA Characteristics

PIPA MODULE

1.	Dimensions	4.3" x 3.9" x 3.6"
2.	Volume	58.4 in^3
3.	Weight	1170 gm
4.	Power	9 watts

PIPA

1. PHYSICAL DESCRIPTION

a)	Length	2.1 in
b)	Diameter	1.6 in
c)	Weight	354 gm

2. CONFIGURATION

a)	Signal Generator Type	Microsyn
b)	Torque Generator Type	Permanent Magnet
c)	Pendulum Support	Floated and Magnetic Suspension

3. PENDULOSITY   1 gm cm

4. OPERATING TEMPERATURE $130^\circ F$

5. TORQUE PARAMETERS

a)	Mode	Pulsed-Ternary
b)	Interrogation Rate	4800 pps
c)	Maximum Torque Rebalance Capability	19.0 g's

6. POWER

a)	Signal Generator	0.04 watts
b)	Torque Generator	0.75 watts
c)	Magnetic Suspension	0.6 watts

2.0   Accelerometer Module—Technical Description

The function of the accelerometer module is to sense the component of acceleration being applied along its IA and deliver as its output a sequence of weighted pulses which defines the magnitude and sign of the acceleration. The action is accomplished by closing a ternary loop around the accelerometer by means of precision current pulses to the accelerometer torquer. The general specification requirements for the accelerometer module including scale factor and bias parameters, input and output power and signal characteristics and tolerances, thermal limitations and connector pin designations are provided in Appendix A.

Modularized inertial component assemblies were incorporated in the SIRU system to meet the requirement for in-flight maintenance. The modules are configured mechanically, thermally, and electrically to make replacement as simple and straightforward as possible. To accomplish a removal it is only necessary to loosen three screws conveniently located on the module, disengage a single multi-pole connector and lift the module from the π-frame. Replacement reverses the procedure. This capability for simple in-flight replacement depends on the prealigned normalized condition of each module, the accuracy of the remount alignment provision, the rugged construction of the assembly, the accuracy and stability of the prealignment operation and the self-calibration features of the SIRU software.

A functional block diagram of the accelerometer module is shown in Fig. 2.1. A family tree diagram identifying drawings and specifications covering the major subassemblies is provided in Table 2.1.

The accelerometer module consists of the following components:

1.   SIRU accelerometer (16 PM PIP Mod B)
2.   Accelerometer Pulse Torque Electronics (PTE)
3.   8 Volt Power Supply
4.   Temperature Controller
5.   AC Calibration Module
6.   Line Driver Module

The location of these components in the accelerometer module is shown in Fig. 2.2. A description of the function and principal features of each component as it differs from the corresponding gyro module component follows:
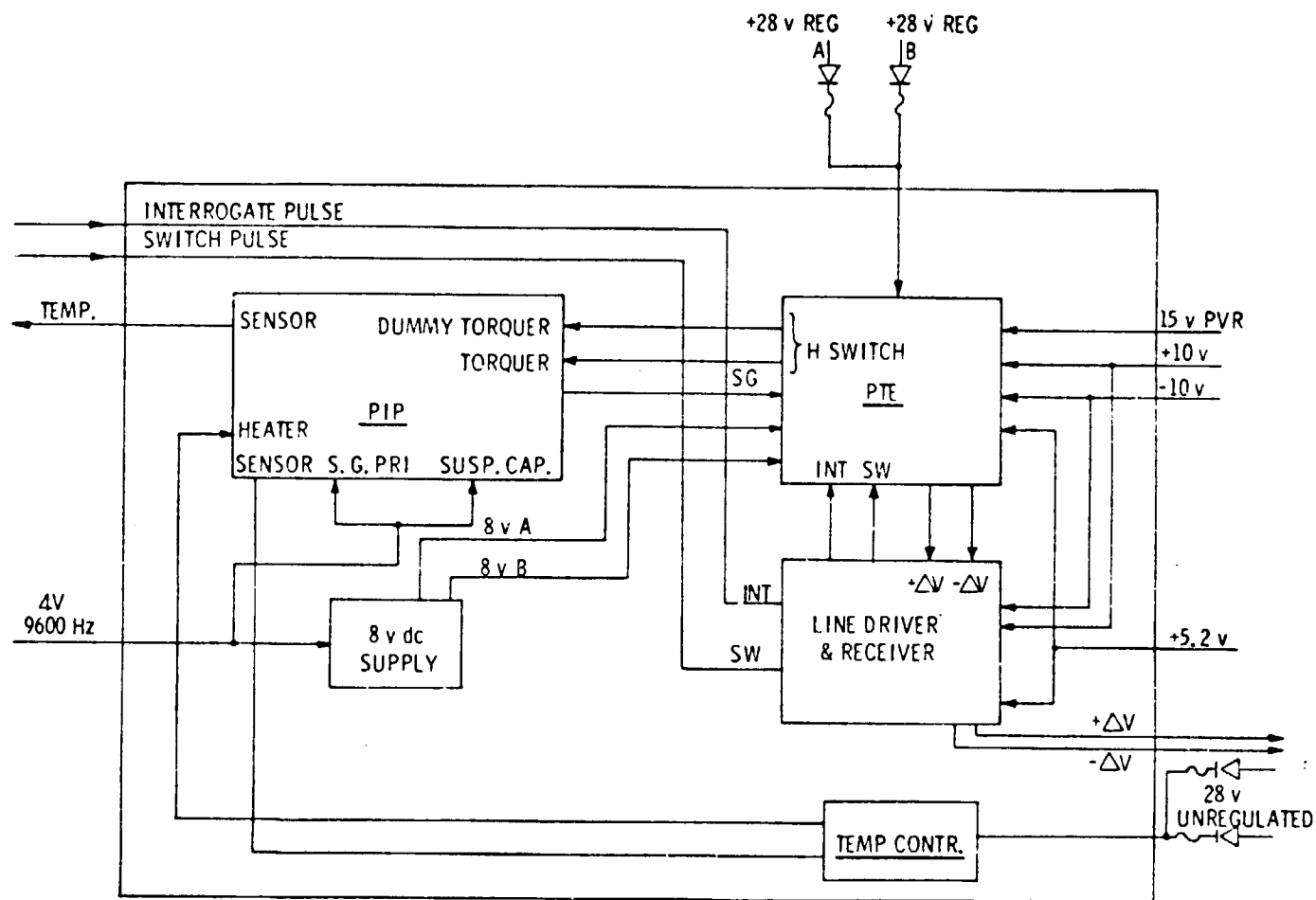
7

Fig. 2.1 SIRU PIPA Block Diagram.

TABLE 2.1

ACCELEROMETER MODULE FAMILY TREE

PIPA MODULE ASSY 2300005	PIPA MODULE SCD 2300098

HOUSING ASSY 2300014

TITLE	PART NO	QTY
BASE PLATE	2300010	1
SPACER INS	2300012	4
MTG BLOCK	2300011	1
INSERT THD	MS21208-C0410	10
INSERT THD	MS21208-C0810	1
INSERT THD	MS21208-F1-10	1
INSERT THD	MS21209-C0415	4
INSERT HELICOIL	1185-02CN-0086	8
INSERT HELICOIL	3585-02CN-0129	15
PIN DOWEL	MS16555-602	1
PIN DOWEL	MS16555-625	2
SCREW F.H.	1000106-16	2
SCREW CAP	MS21295-13	2
COMP. SILICON	1008954	A/R
SCREW B.H.	2-56 x 3/16 LG	6
SCREW B.H. NYLON	6-32 x 1/4 LG	2
WASH FLAT NYLON	#2	6
WASH FLAT NYLON	#3	2

ALIGN RING	2300023	1
INSERT THD	MS21209-C0410	4

GSE HEATER ASSY 2300073

TITLE	PART NO	QTY
HTR PLATE	2300037	1
HTR & SENSOR		1
STANDOFF SEALECTRO	FT-MM-SSL	4
PAD PROT	2300080-1	1
INSERT THD	MS21209-C0815	1
PAD PROT	2300081-1	1
INSERT THD	MS21209-C0815	1
PAD PROT	2300082-1	1
INSERT THD	MS21209-C0815	1

TITLE	PART NO	QTY
SCREW WEDGE	2300028	2
WASHER	2300103	3
SPACER	2300104	1
WIRE CLAMP	2300107	1
STANDOFF	2300083	2
CONN GASKET	2300013	1
COMP. SILICON	1008954	A/R
LOCK O-SEAL PARKER	800-030-2	6
O-RING PARKER	2-16	1

COVER ASSY 2300102

TITLE	PART NO	QTY
COVER	2300030	1
CAPT MTG SCRE	2300074-2	1
MTG SCREW	2300075-R	2
CONICAL BUSH	2300019	2
SPRING LEE	L00220-3-SS	3

TITLE	PART NO	QTY
16 PM PIP	2822000	1
PEM	2640558	1
PWR SUPPLY	2304017	1
LINE DRIVE & RCVR	2300056	1
TEMP CONTR	2304021	1
PWR TSTR SOL (TRDN)	2N3752	1
THERMO	2300081	1

HARNESS ASSY

CONNECTOR ASSY 2300096

TITLE	PART NO	QTY
CONN ADAPTER	2300100	1
CONN CANNON (MDM-S15)	25693	1
INSERT HELICOIL	3585-02CN	6
EPOXY	ND100226-II	A/R

6

TEMPERATURE
CONTROLLER

POWER
TRANSISTOR

PTE MODULE

LINE DRIVER
MODULE

16 PM PIP
(including temperature
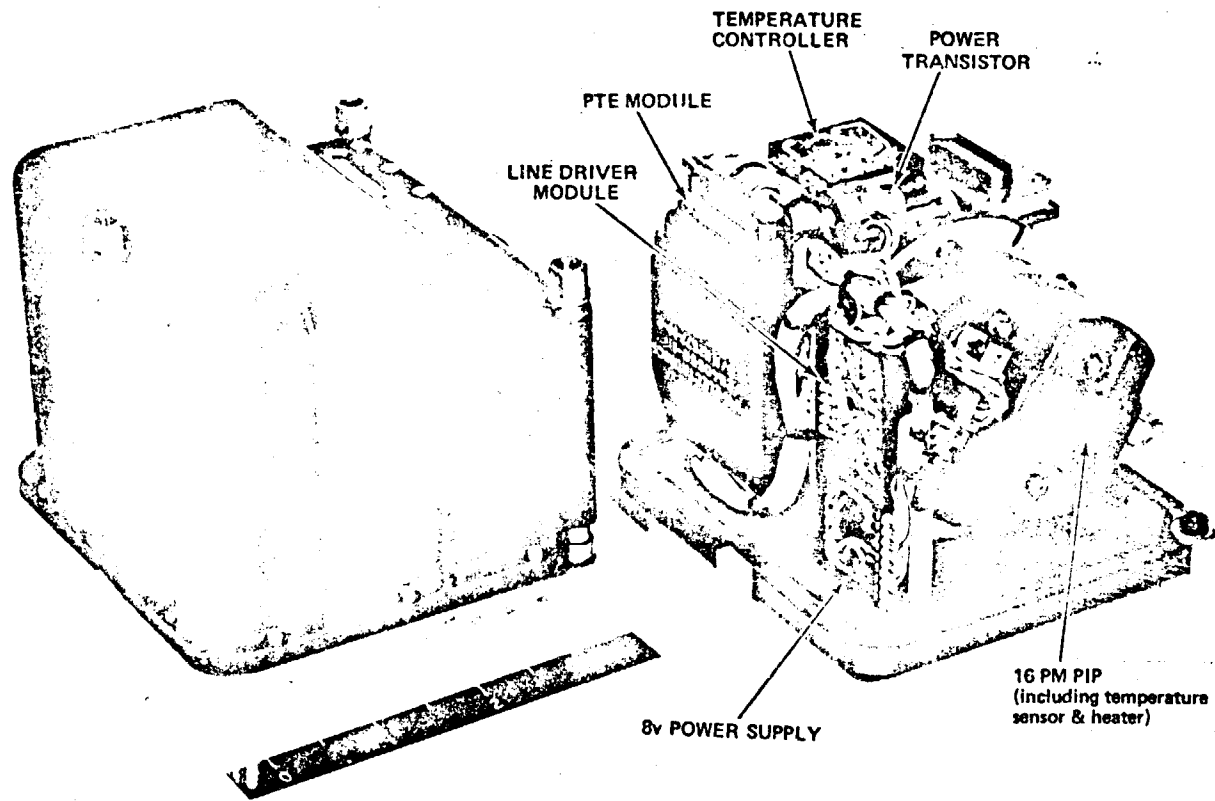sensor & heater)

8v POWER SUPPLY

Fig. 2.2 Accelerometer Module

1.   SIRU Accelerometer (16 PM PIP Mod B)

General Description

The SIRU accelerometer is a 16 PM PIP (Permanent Magnet Pulsed Integrating Pendulum). It is a high performance, single degree-of-freedom, floated, specific force integrating sensor. The instrument consists of a pendulous float magnetically suspended in a viscous fluid, signal generator and torque generator microsyns, and associated electronics and calibration modules.

Figure 2.3 provides a line schematic of the 16 PM PIP. The pendulous float is a solid beryllium cylinder with a built-in mass unbalance. At normal operating temperature the float is neutrally buoyant. A high density pendulous mass is shown mounted on the periphery of the float and extending into a small groove in the damping block. The width of the groove allows maximum rotation of the float of $\pm 1^\circ$ of arc.

Ferrite rotors are mounted at each end of the float, supporting the magnetic suspension and microsyn functions. The magnetic suspension stators are positioned opposite the inside portions of the rotors forming a part of a coaxial structure with the torque generator (TG) on one end and with the signal generator (SG) on the opposite end of the instrument. Radial and axial centering is produced by action of the magnetic field on the inner surface of the tapered rotor.

The signal generator employs a twelve-pole "E" type microsyn stator concentrically mounted to a one piece beryllium end housing and encapsulated in an epoxy compound.

The TG permanent magnet stator is a composite Alnico V cast magnet. Two flex leads are used to carry the torque current to eight air core coils mounted on the rotor. The torque produced is directly proportional to the torque current.

A thermal and magnetic shroud encloses the body of the instrument to reduce environmental effects.

Pulse Torque-to-Balance Operation

The 16 PM PIP was designed to operate in a closed digital loop in which the pendulous torque about the output axis (OA), caused by a component of acceleration along the IA of the PIP, is opposed by a torque generated by the TG.

TO TORQUER

SG OUTPUT
VOLTAGE

FLOAT

PM CORE

RETURN PATH
TORQUER

SUSPENSION CORE

SG MICROSYN

SG SUSPENSION

PULSED
RESTRAINING
TORQUE

OA

ACCELERATION
DEPENDENT
INPUT TORQUE

PENDULOUS
MASS

PENDULUM
REFERENCE AXIS

IA

AMPLIFIER, SHAPING,
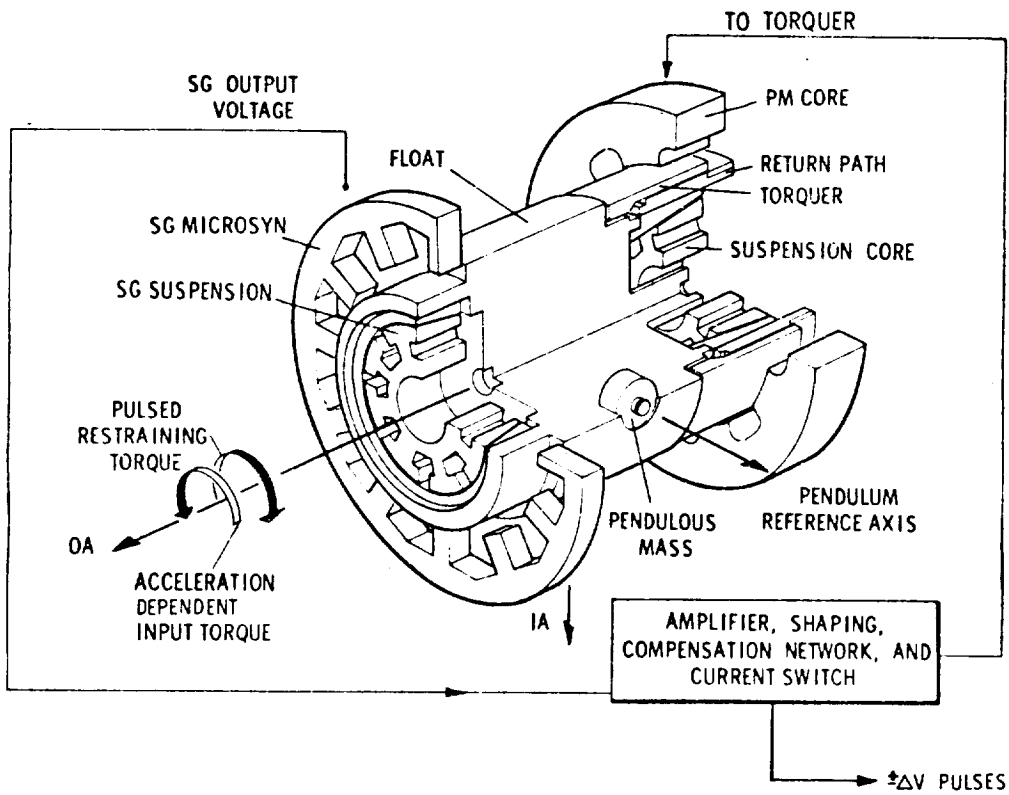COMPENSATION NETWORK, AND
CURRENT SWITCH

$\pm \Delta V$ PULSES

Fig. 2.3 Line Schematic of the 16 PM PIP

12

Referring to Fig. 2.3 and considering the float as a torque summing member and neglecting any inaccuracy torques, the torques acting on the float can be expressed as:

$$I \frac{d^2A}{dt^2} + C \frac{dA}{dt} + m\ell \, a_{(in)} \pm M_{(tg)} = 0 \tag{1}$$

where:

$I \dfrac{d^2A}{dt^2}$	=	the torque due to inertia of the float
I	=	moment of inertia of the float about OA
A	=	angle of rotation of the float about OA
$C \dfrac{dA}{dt}$	=	the viscous damping torque about OA
C	=	damping coefficient
$m\ell \, a_{(in)}$	=	input acceleration torque
$m\ell$	=	pendulosity of float
a_{in}	=	component of acceleration input along IA
$M_{(tg)}$	=	restraining torque provided by the torque generator.

Integrating Eq. (1):

$$I \frac{dA}{dt} + CA = m\ell \, v_{(in)} + \int_{0}^{t} \pm M_{(tg)} \, dt \tag{2}$$

where:

$$v_{(in)} = \text{component of velocity along IA}$$

With the rotation of the float kept close to the null position, the terms on the left side of Eq. 2 are small compared to the terms on the right side. Therefore:

$$v_{(in)} = \frac{1}{m\ell} \int_{0}^{t} \pm M_{(tg)} \, dt \tag{3}$$

Since the feedback torque supplied by the torque generator (TG) is determined at discrete intervals determined by the clock frequency:

$$v_{(in)} = \left[\frac{1}{m\ell} \int_{0}^{t_{(s)}} + M_{(tg)} \, dt + \int_{t_{(s)}}^{2t_{(s)}} \pm M_{(tg)} \, dt \ldots \right] \tag{4}$$

where:

$$t_{(s)} = \text{sampling time (time between clock pulses)}$$

$$v_{(in)} = \sum \pm \frac{M_{(tg)} t_{(s)}}{m\ell} \tag{5}$$

As indicated in Eq. 3 and Eq. 4, the input velocity to the 16 PM PIP is reduced to digital information and can be computed by counting the pulses of feedback torque and multiplying by the constant, $M_{(tg)} t_s/m\ell$. Therefore, the velocity input as indicated by the 16 PM PIP is:

$$v_{(ind)} = \frac{M_{(tg)} t_{(s)}}{m\ell} \left[\frac{N^{(+)} - N^{(-)}}{N^{(+)} + N^{(0)} + N^{(-)}} \right] \tag{6}$$

where:

$v_{(ind)}$ = indicated velocity input

$N^{(+)}$ = number of positive torque pulses in a given time period

$N^{(-)}$ = number of negative torque pulses in a given time period

$N^{(0)}$ = number of zero torque pulses in a given time period

The change in indicated velocity input is:

$$\Delta v_{(ind)} = \frac{M_{(tg)} t_{(s)}}{m\ell} \left[N^{(+)} - N^{(-)} \right] \tag{7}$$

2. Accelerometer Pulse Torque Electronics

The accelerometer PTE is basically identical with its gyro equivalent in the SIRU system. The detailed description of its operation is presented in Chapter 3 of Volume I and again in Volume II, and is therefore not repeated here. A list of the electrical interface requirements for the accelerometer module is provided in Table 2.2. The accelerometer PTE is a ternary torque-to-balance loop and its output pulse weight, scale factor corresponds to approximately 4 cm/sec with a range compatible with a 19g input.

3. 8 Volt Power Supply

This component is identical with its gyro counterpart and its description is covered in the gyro module, Volume II.

Table 2.2 Accelerometer Module/PIPA Electrical Interface Requirements

I. POWER REQUIREMENTS

A. Input Voltages (Nominal DC)

	Source Level	Load (Max.)	Ripple
1.	28.0 Vdc ±0.3 Vdc	100 ma	0.07 Vrms
2.	15.000 Vdc ±0.008 Vdc	11 ma	0.002 Vrms
3.	-10.0 Vdc ±0.5 Vdc	25 ma	0.140 Vrms
4.	+10.0 Vdc ±0.5 Vdc	25 ma	0.140 Vrms
5.	+5.25 Vdc ±0.25 Vdc	140 ma	0.1 Vrms
6.	+28 Vdc ±3 Vdc	0.75 A	0.5 Vrms

B. Input Voltages AC

1. 9600 Hz, 4.0 Vrms ±1%, 1.6 Watts max. Harmonic content <2%;
sinewave synchronized to interrogator pulse train

II. INPUT SIGNALS

A. Interrogate pulse 4.5 ±0.5 Vdc pulse amplitude, 4 μsec pulse width.
4 Kpps repetition rate.

B. Switch pulse pair 4.5 ±0.5 Vdc pulse amplitude, 0.4 μsec pulse width.
Pulse spacing 13 μsec, 4.8 Kpps repetition rate.

1. Reset pulse lags INTERROGATE pulse by 2 μsec ±1/2 μsec.

III. OUTPUT SIGNAL REQUIREMENTS

A. + ΔV; +5 Vdc pulse amplitude, 2 μsec pulse width typical

B. - ΔV; +5 Vdc pulse amplitude, 2 μsec pulse width typical

15

4.   Temperature Controller

The principle features of the accelerometer temperature controller are identical with those of the gyro module temperature controller. The temperature control circuit, see Fig. 2.4, consists of a current regulator, temperature bridge and feedback amplifier. The proportional temperature controller employs a balanced bridge circuit in which two of the elements are the temperature sensors wrapped around the body of the accelerometer. The bridge circuit is excited by a constant current source. A feature of the controller is the use of two integrated circuit amplifiers, a Fairchild A727 differential preamplifier and a A741 operational amplifier. The use of the A727, which has self-contained substrate temperature control, reduces the equivalent input stage drift to less than 1 v/$^{\circ}$C. A novel feature of the circuit is the use of a temperature sensor in the amplifier feedback compensation network (sensor #3 on schematic). The sensor circuit is padded to operate at a nominal temperature of 130.0°F ±1.6°F. Control accuracy is ±0.1°F. The 2N375? control transistor is mounted on the accelerometer alignment block, thereby utilizing the power dissipated in the transistor as control heat, linearizing the control action and increasing the control system efficiency.

The control heater located on the accelerometer mounting seat dissipates a maximum of 2.9 watts. A supplementary heater is the "dummy" torquer heater which is connected to the torquer circuit. Power is dumped into this heater by the ternary torque loop when zero torque is commanded. This scheme reduces thermal gradients in the accelerometer.

A separate ground support equipment (GSE) heater and sensor assembly is mounted on the accelerometer alignment block. This assembly operates during warmup. A safety thermostat is mounted on the aluminum mounting block. It serves to open the unregulated 28 vdc power line at a temperature below that at which recalibration of the accelerometer would be required.

5.   AC Calibration Module

The ac calibration module is built into a cap attached to the accelerometer and is procured as an integral part of the instrument. The module contains the suspension capacitors required for the passive magnetic suspension system. In addition the module contains the SG phasing resistor, a SG quadrature compensation network, suspension current monitoring resistors and a swamping resistor to prevent an excessive suspension current from saturating the stator iron, resulting in
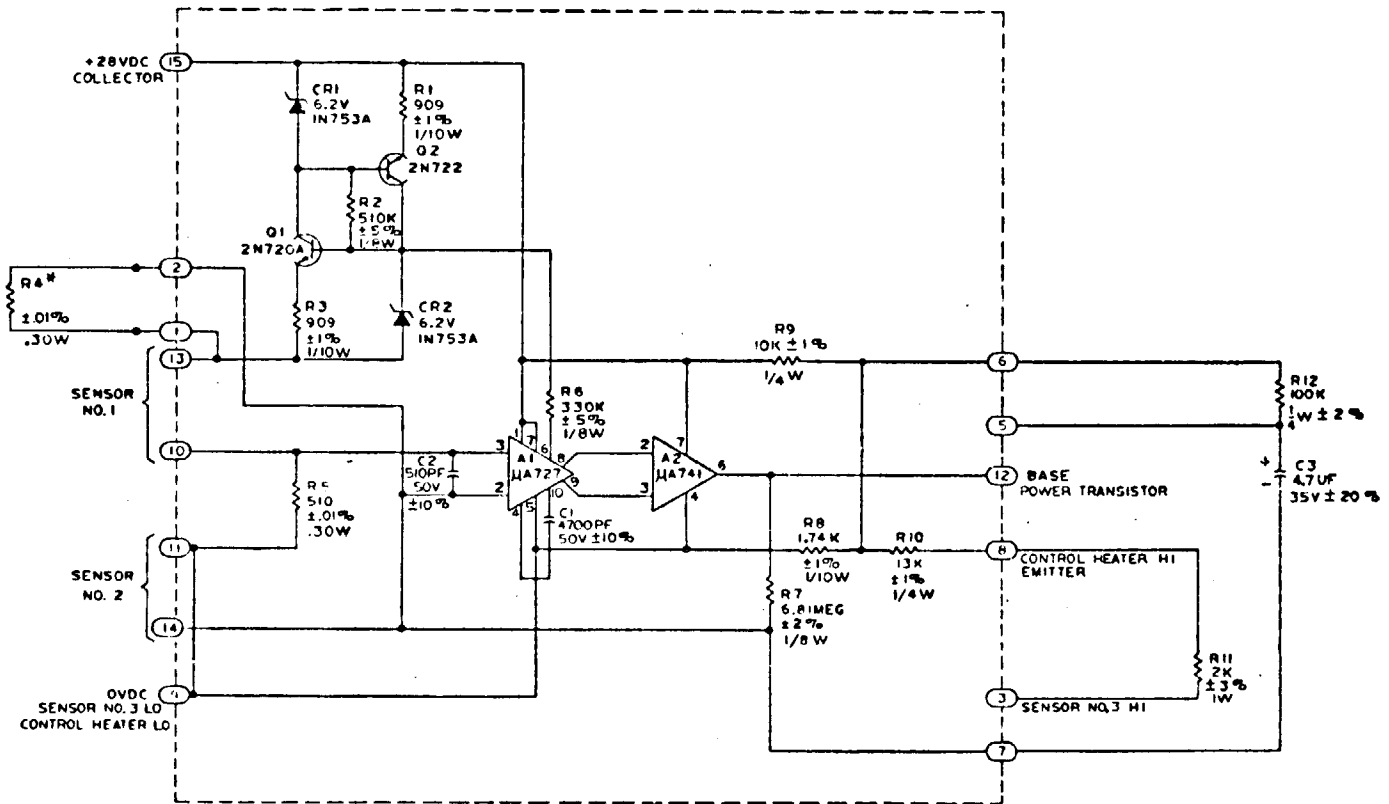
*R4 = Selected at assembly

Fig. 2.4   Accelerometer Module Temperature Controller Schematic

suspension instability. An RC tuning network for the dc torquer coil is also located in the module. All other normalizing components for the accelerometer are located in the accelerometer PTE.

6.   Line Driver Module

The line driver module contains the pulse line receivers and drivers used to assure that the incoming pulses are of the proper length, height and rise time after transmission and that the outgoing pulses are properly prepared for transmission to the multiplexer. Fig. 2.5 is a Data Pulse Driver schematic . It shows how the timing pulse triggers the blocking oscillator to produce a 2.3 microsecond pulse at the multiplexer gate. In the gyro module these functions are included in the gyro PTE.
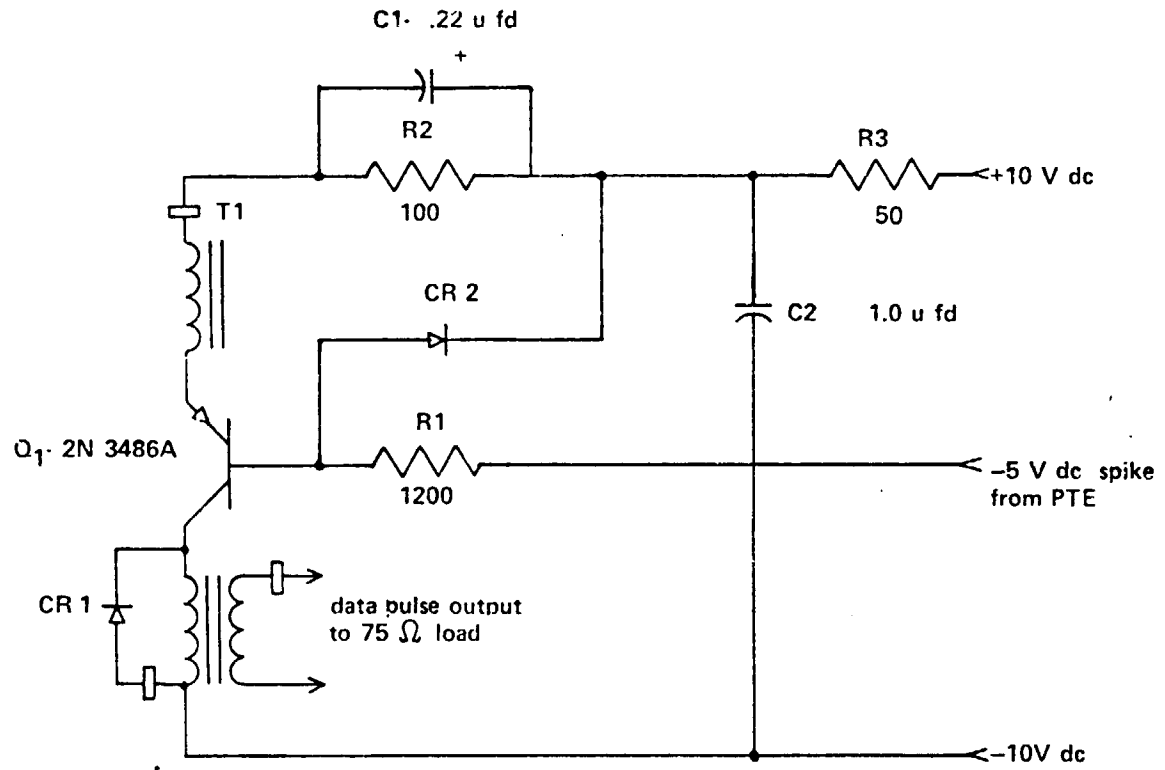
Fig. 2.5 Data Pulse Drivers

3.0   Sensor Reliability and Production History

The accelerometers used in the SIRU program were purchased directly from the Navy and were delivered from the manufacturing sources developed for the Poseidon program.

SIRU experience with this instrument has been very satisfactory; no instrument failures recorded in a total of 147,800 operating hours over a total period of 405 instrument - months. The number of operating hours for each accelerometer exceeds 24,000.

One electronics failure occurred in an accelerometer module during the 139,800 hours of system operation resulting in an observed MTBF of 139,800 hours and at 90% confidence level, 35,800 hours. The electronic failure in the module was a transistor in the temperature controller.

Three of the accelerometers were made by Honeywell, Florida, Nos. 5008, 2001 and 5006. One unit, BNC 10-15 is a Bendix built instrument and the two remaining units were built at MIT.

4.0   Accelerometer Test

Accelerometer tests can be divided into three classifications:

a)   Accelerometer Acceptance Tests
b)   Accelerometer Calibration Tests
c)   Module Calibration Tests

Each of these types of tests are described briefly in the following paragraphs.

Instrument Acceptance Tests

These tests are performed at the manufacturers' test laboratories and are repeated in part as an incoming inspection test to verify the integrity of the instrument. The tests include resistance and continuity, a float freedom test (to determine the unimpeded mobility of the moving elements), determination of signal generator sensitivity, float centering ratio, suspension current and phasing, temperature sensor padding requirements and such other tests as experience may dictate are necessary to insure that the instrument will meet the system requirements.

Accelerometer Calibration Tests

After completion of the initial acceptance tests the accelerometer is mated to a set of PTE.

The individual tests include:

a.   Torquer tuning — an RC network is placed in parallel with the accelerometer torquer to tune it resistively.

b.   Scale factor set (magnetization and stabilization) — the permanent magnet is magnetized and then stabilized at the required operating point.

c.   Scale factor equalization — the plus to minus scale factor difference is reduced to a minimum by adjusting the bias shunt resistors.

d.   Bias determination

e.   Bias and scale factor stability—parameter stability measured across a four hour test period.

Special tests to insure proper operation of the electronics include:

a. Leakage check—insure acceptably small transistor leakage current flow through the torquer during periods of no torquing.

b. Voltage and temperature sensitivity—verify acceptably small changes in instrument scale factor across voltage and temperature changes.

A final test performed at this stage is the accelerometer alignment. In this test the instrument is aligned such that the IA has the required orientation relative to the mounting flange.

Module Calibration Tests

Scale Factor and Bias

Because of the configuration constraints imposed by operation of the accelerometer within the SIRU module not all accelerometer parameters could be measured within the module. The bias of the accelerometer was, therefore, assumed to be equal to that measured during the accelerometer calibration tests. Using this assumed value of bias, the minus scale factor was determined from data taken at minus 1g input. To check scale factor equality, an approximate plus scale factor was obtained by using an input of $g \sin \alpha$, where α is the SIRU angle (31.7°).

By monitoring the stability of the minus 1g data, the joint bias plus scale factor stability could be determined; i.e., a given variation in 1g data could be ascribed to bias or scale factor instability or to some combination of the two.

Leakage Check

The transistor leakage currents flowing through the torquer are measured as in the accelerometer calibration tests to insure acceptably small errors.

A summary of calibration and performance tests for the accelerometer is shown in Table 4.1.

The alignment of the accelerometer within the SIRU module is accomplished as part of the module calibration tests. The required IA orientation at the dodecahedron angle, α, is established at this time. See Fig. 4.1. The alignment orientation of the input axis relative to the perpendicular reference plane shown in the figure is also determined. Optical checks and closed loop measurements are used to verify the inertial orientations obtained. The measured misalignment data is supplied to the SIRU system and becomes a basis for compensating the output values. Error analysis of the alignment technique shows that it has an overall one sigma uncertainty of 2.24 sec.

Table 4.1: PIPA Test Summary

CALIBRATION TESTS

1. Torquer Tuning
2. Scale Factor Set (Magnetization and Stabilization)
3. Scale Factor Equalization
4. Bias Determination
5. Bias and Scale Factor Stability
6. Leakage Check
7. Scale Factor Temperature Sensitivity
8. Scale Factor Voltage Sensitivity
9. Alignment

PERFORMANCE TESTS (IN SIRU MODULE)

1. Scale Factor
2. Bias and Scale Factor Stability
3. Leakage Check
4. Alignment

PLANE ⊥ TO BOTH
MOUNTING PLANE AND
REFERENCE AZIMUTH

PLANE OF
BASE MOUNTING PADS

MODULE COVER

OA

PRA
TG
OA
IA

IA

α

α = 31° 43' 2.8"

REFERENCE AZIMUTH (DEFINED BY
ALIGNING PINS)

TORQUE
ELECTRONICS
MODULE

TEMPERATURE CONTROL
MODULE

LINE DRIVER
MODULE

8V POWER SUPPLY
MODULE

ALIGNING
RING

16 PM PIP

AZIMUTH INTERFACE
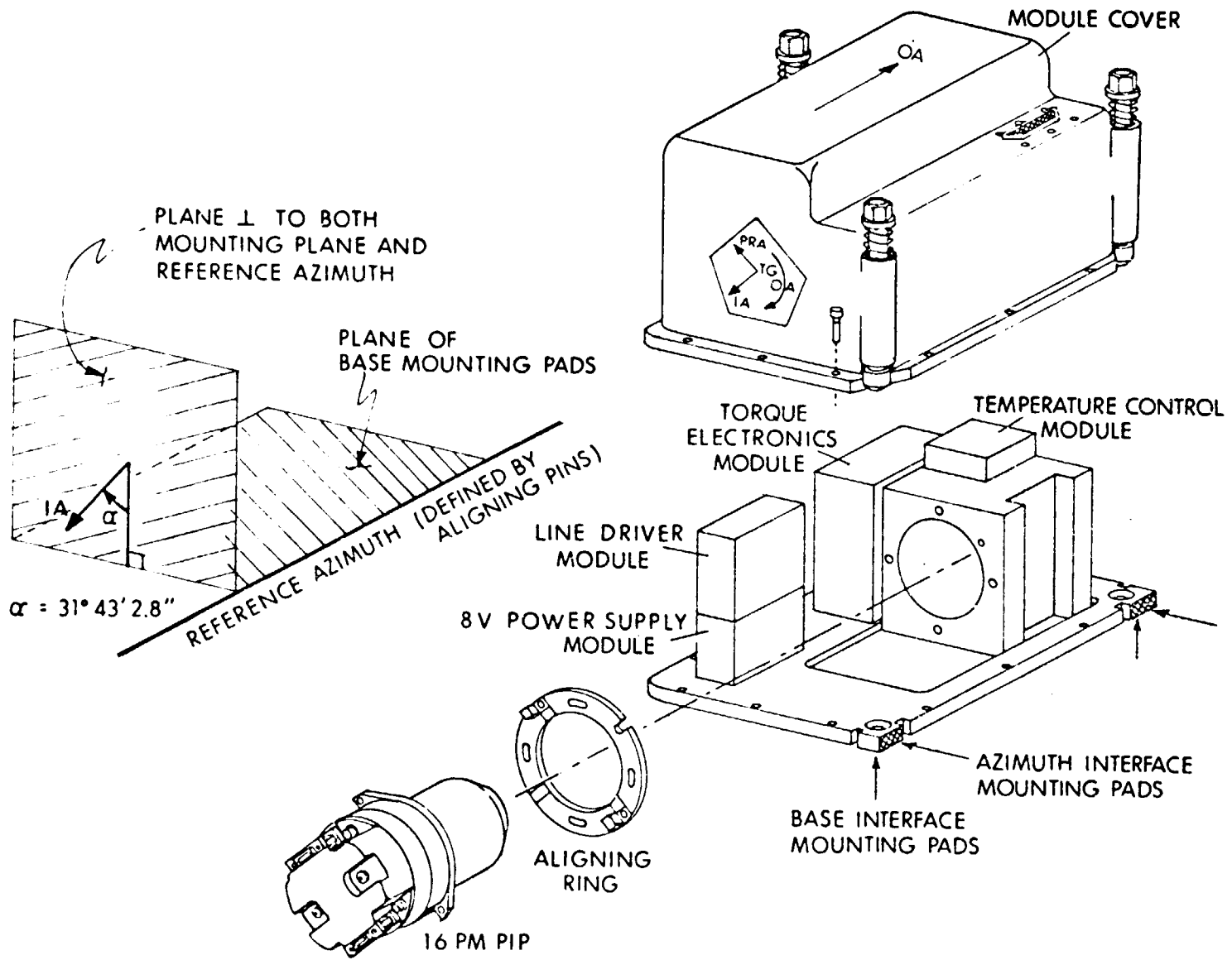MOUNTING PADS

BASE INTERFACE
MOUNTING PADS

Fig. 4.1 SIRU Accelerometer Module Assembly Alignment Orientation

5.0   Accelerometer Data (U)

(U)   Complete records of the test results obtained on the accelerometers. both in and out of modules, are maintained.

(U)   The data from these records are analyzed periodically to provide a statistical measure of the performance achieved. Figure 5.1 shows the latest presentation of this data for pendulous and output axes misalignments, scale factor and bias obtained across remounting, cooldowns and test repetitions. The change in misalignment angles, scale factor and bias were tabulated and an rms average calculated for the sample size to show the effect of module remounting (Column 1) and of cooldown (Column 2). The larger sample size of the cooldown data results because all installed instruments are affected by a system cooldown whereas remounting affects only individual instruments. The tabulation of standard deviations (Column 3) for the same parameters is derived from one to six months of calibration test results
(U) chosen to exclude all interposing cooldowns or remounts.

(U)   The results show that misalignment angles are affected most strongly by remounting approximately 13 sec compared to about 6 sec for cooldown and 2 sec for uninterrupted operation. Scale factor and bias appear to be equally affected by remounting and cooldown. This is to be expected as the environmental impact on the instrument is nearly the same in each case (all power off).

(U)   Table 5.1 is included to show that the performance of the accelerometer modules is not significantly affected by operation in different orientations. The data shows the average sigma of the stability data applicable to each instrument in five of the six test positions. These test positions are defined in Fig. 5.2.

(C) TABLE 5.1 (U)

PIPAS
AVERAGE SIGMA OF THE STABILITY DATA*
OCTOBER 23, 1970 TO JULY 29, 1971 (U)

AXIS	PIPA	POS #1	N	POS #2	N	POS #3	N	POS #4	N	POS #6	N
A	S/N 5008	.0029	8	.0016	11	.0033	3	.0024	4	.0010	7
B	S/N 0020	.0029	8	.0025	11	.0046	3	.0015	4	.0023	7
C	S/N 2001	.0014	8	.0011	11	.0021	3	.0018	4	.0014	7
D	S/N 5006	.0020	8	.0031	11	.0015	3	.0012	4	.0026	7
E	S/N BNC-10-15	.0019	7	.0019	11	.0017	3	.0013	4	.0016	7
F	S/N 0015	.0025	8	.0016	11	.0009	2	.0007	4	.0011	7

* cm/sec^2

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27
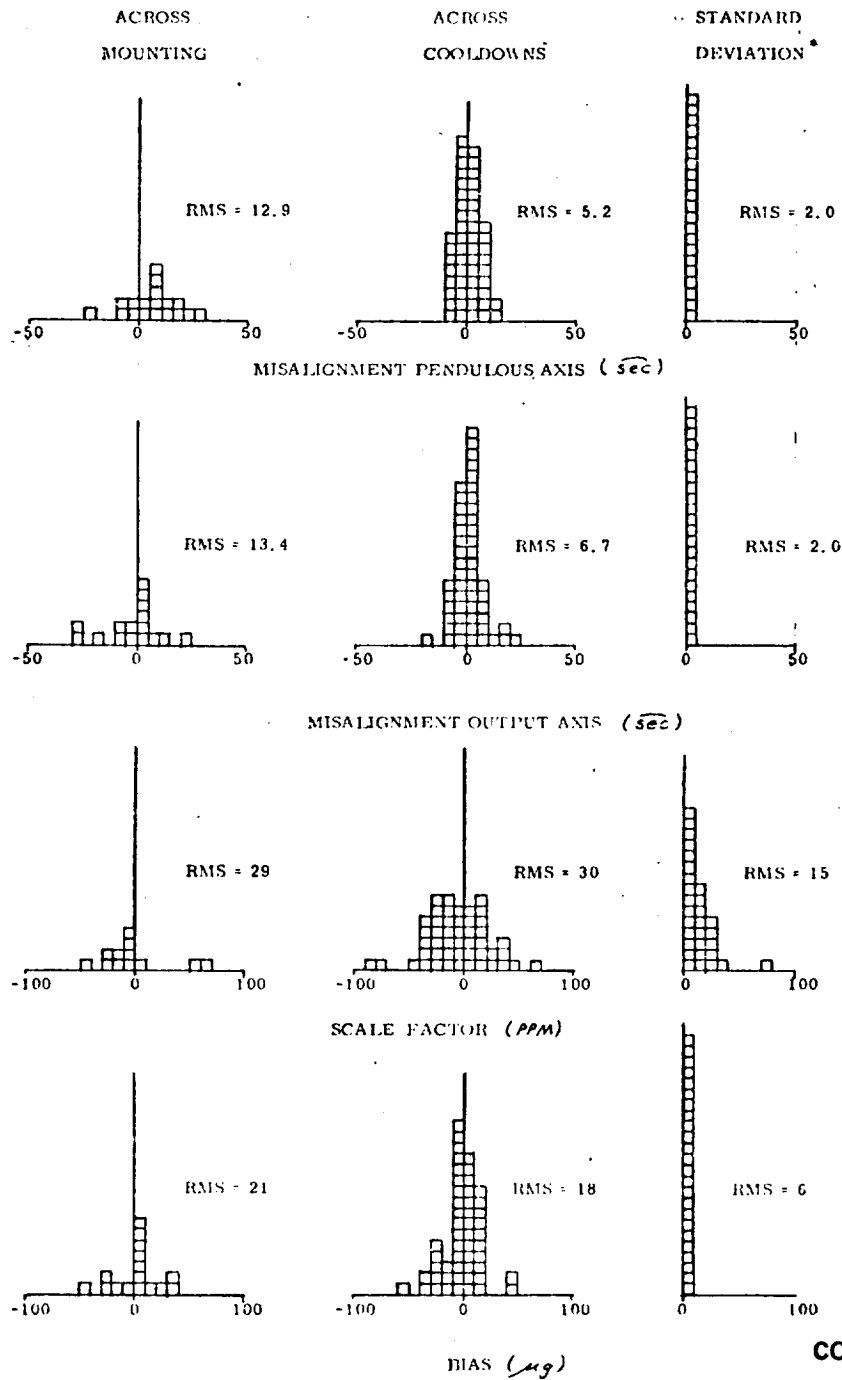
(C) Fig. 5.1 Accelerometer Performance Data (U)

RA1 = ROT. Axis 32" Table
RA2 = ROT. Axis 16" Table
TA1 = TRUN. Axis 32" Table
TA2 = TRUN. Axis 16" Table

1 — Table Position
RA1=0°
RA2=180°
TA1=0°
TA2=90°

4 — Table Position
RA1=270°
RA2=270°
TA1=0°
TA2=90°

2 — Table Position
RA1=0°
RA2=0°
TA1=0°
TA2=90°

5 — Table Position
RA1=0°
RA2=270°
TA1=90°
TA2=90°

3 — Table Position
RA1=90°
RA2=90°
TA1=0°
TA2=90°

6 — Table Position
RA1=90°
RA2=0°
TA1=0°
TA2=0°
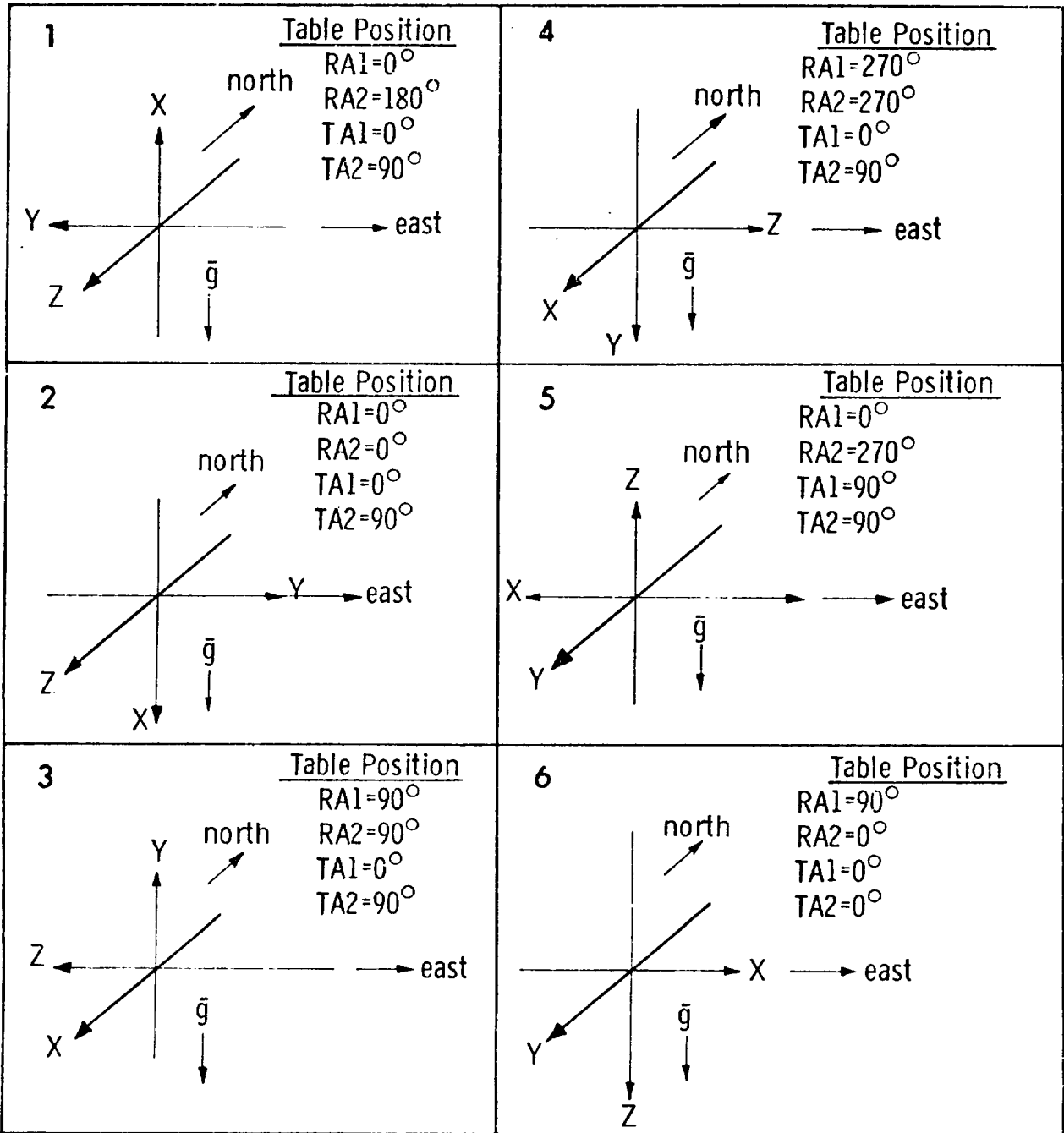
Note : Positions 2, 4 & 6 are the Basic Positions for Rate Testing

Fig. 5.2 Gyro and Accelerometer Static Calibration Positions

29

APPENDIX A
ACCELEROMETER MODULE PARAMETERS (U)

(U) 1.0   Introduction

The principle parameters of the accelerometer module as implemented for the SIRU system are summarized in this appendix. They represent performance consistent with the goals contained in the original NASA Statement of Work and subsequent cost effective design tradeoffs.

(C) 2.0   Module Performance—Nominal in the system with no cooldowns or remounting

Scale Factor Stability−3 sigma   30 ppm
Bias Stability−3 sigma $.018 \ cm/sec^2$ ppm
Misalignment−3 sigma   6 sec

(U) 3.0   Operational Characteristics

(U) 3.1   Power Supply Characteristics

DC	Source Level	Load (Max)	Ripple
1.	28.0 vdc ± 0.3 vdc	100 ma	$0.07 \ v_{rms}$
2.	15.000 vdc ± 0.008 vdc	11 ma	$0.002 \ v_{rms}$
3.	-10.0 vdc ± 0.5 vdc	25 ma	$0.140 \ v_{rms}$
4.	10.0 vdc ± 0.5 vdc	25 ma	$0.140 \ v_{rms}$
5.	5.25 vdc ± 0.25 vdc	140 ma	$0.1 \ v_{rms}$
6.	28 vdc ± 3 vdc	750 ma	$0.5 \ v_{rms}$

b.   AC

1.   9600 Hz, 4.0 v_{rms} ± 1%, 1.6 watts, maximum harmonic content <2%. Sine wave synchronized to interrogator pulse train.

A.1

3.2 Timing Pulse Characteristics

Interrogate pulse

Amplitude	4.5 ± 0.5 vdc
Width	4 microseconds
Repetition Rate	4.8 kpps

Switch pulse pair

Amplitude	4.5 ± 0.5 vdc
Width	0.4 microseconds
Spacing	13 microseconds
Repetition Rate	4.8 kpps

Lag of reset pulse to interrogate pulse 2 microseconds $\pm 1/2$ microseconds

3.3 Output Signal Requirements

ΔV pulses 5 vdc amplitude, 2 microseconds width

3.4 Monitoring Line Identification

1. PVR power test point
2. Single ended SG monitor point—400 mv/milliradian rms about OA at 9600 Hz.
3. Scale factor resistance test point
4. Accelerometer temperature sensor #4—500 ohms $\pm$ 0.15 ohms at operating temperature ($+00226$ ohms/ohm/$^{\circ}$F).
5. DC amplifier test point.

3.5 Auxiliary Input Requirements

1. 0 to 28 vdc at 0 to 0.4 amps (available for adjustable fixed heat when used with GSE only).
2. Frequency and Timing Accuracy and Stability—All ac input voltage frequencies and input signal repetition rates are derived from a clock whose basic frequency is 3.6864000 mega Hz $\pm$ 1 part in 10^{8} with a stability of $\pm$ 3 parts in 10^{7}/week.

A2

4.0 Accelerometer Module Connector — Pin Identification

Pin Identification	SIRU Accelerometer Module Connector
1.	+ Delta V Hi
2.	+ Delta V Lo
3.	Interrogate Pulse Hi
4.	Interrogate Pulse Lo
5.	GSE Sensor Hi
6.	GSE Sensor Lo
7.	Spare
8.	Structure Ground
9.	Accelerometer Sensor Hi
10.	Monitor Point
11.	Monitor Point
12.	Spare
13.	Spare
14.	9600 Hz Hi
15.	+28 vdc Regulated
16.	+28 vdc regulated Return
17.	Spare
18.	+15 vdc PVR Hi
19.	Shield Ground
20.	Shield Ground
21.	Shield Ground
22.	Shield Ground
23.	GSE Heater Lo
24.	Spare
25.	Spare
26.	Accelerometer Sensor Lo
27.	Monitor Point
28.	Monitor Point
29.	Signal Generator Monitor Return
30.	Spare
31.	Spare
32.	9600 Hz Lo
33.	-10 vdc

34.	+5 vdc
35.	+15 V PVR Lo
36.	-Delta V Hi
37.	-Delta V Lo
38.	Switch Pulse Hi
39.	Switch Pulse Lo
40.	GSE Heater Hi
41.	Spare
42.	+28 vdc Unregulated
43.	0 vdc
44.	Shield
45.	Shield
46.	Signal Generator Monitor Hi
47.	Spare
48.	Spare
49.	+5 vdc
50.	0 vdc
51.	+10 vdc

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