R-826

FINAL REPORT

VOLUME II

STANDARDIZED STRAPDOWN INERTIAL COMPONENT MODULARITY STUDY

by

Julius Feldman

July 1974

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

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FINAL REPORT
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STANDARDIZED STRAPDOWN INERTIAL COMPONENT MODULARITY STUDY

ABSTRACT

To obtain cost effective strapdown navigation, guidance and stabilization systems to meet anticipated future needs a standardized modularized strapdown system concept is proposed. Three performance classes, high, medium and low, are suggested to meet the range of applications. Candidate inertial instruments are selected and analyzed for interface compatibility. Electronic packaging and processing, materials and thermal considerations applying to the three classes are discussed and recommendations advanced. Opportunities for automatic fault detection and redundancy are presented. The smallest gyro and accelerometer modules are projected as requiring a volume of 26 in^3 and 23.6 in^3, respectively. Corresponding power dissipation is projected as 5 watts and 2.6 watts, respectively.

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CHAPTER 1

INTRODUCTION

1.1 Task Identification and Description

Tasks 4, 5 and 6 (see Preface) of contract modification number 8 describe the Inertial System Strapdown Concept effort. The basis for determining the study requirements was developed from consideration of the history, current status and future applications of inertial guidance, navigation and control systems. Historically these inertial systems have been developed individually to meet the specific requirements of the manned space, booster, satellite or entry vehicle with which they were intended to function. Implementation of similar functions in the various systems have reflected the individual decisions made for each system. Standardization even at the lowest level was non-existent. For example, Table 1.1-I lists representative applications that have employed strapdown systems; sponsors, purpose and gyro types. This state of affairs can probably be considered normal for rapidly developing art, but the burgeoning number and variety of current and proposed system applications; space shuttle, scientific and observation satellites and guided vehicles of all kinds, make it increasingly evident that the possibility of a better long run approach needs to be explored.

Recognizing the broad spectrum of individual system performance requirements which might be specified and the cost constraints which are necessarily being applied, this study sought to determine the feasibility of creating a standard strapdown gyro and accelerometer module concept, with suitable performance and interface requirements, that would encompass the requirements for a wide variety of potential inertial system applications. A fundamental goal was to determine if a standardization approach that would enable the use of proprietary and non-proprietary vendor instrument sources on an interchangeable basis was possible. The competitive cost and logistic advantages inherent in such a potential are self-evident. Thus, as a first step, Task 4 calls for the identification of currently available production or developmental instruments that would be candidates for a standardized module design, their respective design and performance features, their mechanical, electrical and thermal interface and the prospects for application compatibility.

On the basis of the results of Task 4, the objective in Task 5 was to develop the concepts and ground rules which should apply to the module design, taking into account such elements as system applications, performance requirements, electronic design and packaging, thermal control requirements, integration level, design and acquisition costs and module size, weight and power requirements.

Table 1.1-I Strapdown Inertial Systems Deployment
Representative Milestones For Strapdown Systems*

Category	Mission (vehicle)	Sponsoring Agency/Gyro User	Function	Configuration (number)	Gyro Identification	Gyro Type[a]
Launch vehicles and boosters	Agena B	USAF/Lockheed	Guidance, Flight control	Strapdown (3)	Honeywell GG76	SDF-RI
			Guidance, Flight control	Strapdown (3)	2 Honeywell GG76 1 Honeywell GG87	SDF-RI
	Agena	USAF/Lockheed	Guidance, Flight control	Strapdown (3)	Kearfott 2564	SDF-RI
			Navigation, Guidance, Flight control	Strapdown (3)	Honeywell GG-334	SDF-RI
	Atlas (SLV-3A)	LeRC/Convair	Flight control, Stabilization	Strapdown (3) Strapdown (3)	Honeywell GG87 Nortronics GRH4T	SDF-RI SDF-rate
	Burner 2	USAF/Boeing	Guidance	Strapdown (3)	Honeywell GG-49	SDF-RI
	Centaur	LeRC/Convair	Guidance, Attitude reference	Platform (3)	Honeywell GG-49	SDF-RI
	Delta	NASA/Douglas	Guidance	Strapdown (3)	Hamilton Std. RI-1139E	SDF-R
	Saturn IB	MSFC/Chrysler	Guidance, Stabilization	Platform (3) Strapdown (9)	Bendix AB-5-K4 Nortronics GRH4T	SDF-DRI SDF-rate
	Saturn V	MSFC/Boeing	Stabilization, Guidance, Navigation	Strapdown (9) Platform (3)	Nortronics GRH4T Bendix AB-5-K8	SDF-rate SDF-DRI
	Scout	LaRC/LTV	Guidance, Stabilization	Strapdown (3) Strapdown (3)	Honeywell GG87	SDF-R SDF-rate
	Titan IIIB	USAF/Martin	Guidance	Strapdown (3) (wide angle)	Kearfott 2536	SDF-R
			Stabilization	Strapdown (5) (rate)	Kearfott 2536	SDF-RI
	Titan IIIC	USAF/Martin	Guidance Stabilization	Platform (3) Strapdown (5) (rate)	Delco 651C Kearfott 2536	SDF-R SDF-RI

[a]RI = rate-integrating; DRI = double rate-integrating.

*Table extracted from NASA-SP-8096 "Space Vehicle Gyroscope Sensor Applications" by William C. Hoffman and Walter M. Hollister

Table 1.1-I — (continued)

Category	Mission (vehicle)	Sponsoring Agency/Gyro User	Function	Configuration (number)	Gyro Identification	Gyro Type
Space-craft	Apollo CM	MSC/NAR	Navigation, Stabilization	Platform (3)	AC 25IRIG	SDF-RI
			Stabilization, Display	Strapdown (3) (wide angle or rate)	Honeywell GG248	SDF-RI
			Stabilization, Display	Strapdown (3) (rate)	Honeywell GG248	SDF-RI
			Stabilization	Strapdown (3)	Kearfott 2021	SDF-rate
	Apollo LM	MSC/Grumman	Navigation, Stabilization	Platform (3)	AC 25IRIG	SDF-RI
		MSC/TRW	Navigation, Stabilization	Strapdown (3)	Hamilton Std. RI-1139	SDF-RI
	ATM	MSFC	Pointing, Stabilization	Strapdown (3)	Kearfott 2519	SDF-RI
	Biosatellite	ARC/G.E.	Attitude reference, Stabilization	Strapdown	Honeywell JRT45	SDF-rate
	ERTS	GSFC/G.E.	Stabilization, Attitude reference,	Strapdown (1)	Kearfott 2564	SDF-RI
			Initial stabilization	Strapdown (1)	Nortronics GRH4	SDF-rate
	Explorer 31	GSFC/	Stabilization	Strapdown	Honeywell JRT45	SDF-rate
	Gemini	MSC/McDonnell	Stabilization	Strapdown (6)	Honeywell MS-133	SDF-rate
			Navigation	Platform (3)	Honeywell GG-8001	SDF-RI
	Lunar Orbiter	LaRC/Boeing	Attitude reference, Stabilization, Pointing	Strapdown (3)	Sperry SYG-1000 Kearfott 2564	SDF-RI SDF-RI
	Mariner	JPL	Stabilization, Attitude reference, Pointing	Strapdown (3)	Kearfott 2565	SDF-RI
	Mercury	MSC/McDonnell	Stabilization,	Strapdown (3)	Honeywell GG-79A	SDF-rate
			Attitude reference	Strapdown (2)	Honeywell GG-53	2DF-free
			Attitude, Rate display	Strapdown (3)	Honeywell MS-100	SDF-rate
	Nimbus	GSFC/G.E.	Stabilization, Attitude reference,	Strapdown (1)	Kearfott 2564	SDF-RI
			Initial stabilization	Strapdown (1)	Nortronics GRH4	SDF-rate
	OAO	GSFC/Grumman	Stabilization	Strapdown (3)	Honeywell JRT45	SDF-rate
			Attitude reference	Strapdown (3) Strapdown (3)	MIT 2FBG Kearfott 2564	SDF-RI SDF-RI
	OGO	GSFC/TRW	Stabilization	Strapdown (1)	Honeywell MS 130B1	SDF-rate

Table 1.1-I — (continued)

Category	Mission (vehicle)	Sponsoring Agency/Gyro User	Function	Configuration (number)	Gyro Identification	Gyro Type[a]
Space-craft						
	OGO	GSFC/TRW	Pointing	Strapdown (2)	Honeywell GG49	SDF-RI
	OSO	GSFC/Ball Bros.	Stabilization	Strapdown (1)	Bendix 25IRIG	SDF-RI
	OSO-3	GSFC/Hughes	Pointing	Strapdown (1)	Northrop GI-K7G	SDF-RI
	Ranger	JPL	Stabilization, Attitude reference, Pointing	Strapdown (3)	Honeywell GG49	SDF-RI
	Skylab workshop	MSFC/Douglas	Pointing, Stabilization	Strapdown (9)	Kearfott 2519	SDF-RI
	Surveyor	JPL/Hughes	Attitude reference, Stabilization	Strapdown (3)	Kearfott 2514	SDF-RI
	Viking Lander	LaRC/Martin	Inertial reference	Strapdown (4)	Hamilton Std. RI-1139S	SDF-RI
	Viking Orbiter	LaRC/JPL	Attitude reference, Stabilization, Pointing	Strapdown (6)	Kearfott 2565	SDF-RI
Entry vehicles	ASSET	USAF/ McDonnell	Stabilization, Flight termination, Guidance	Strapdown (3) Strapdown (1) Strapdown (3)	Honeywell Giannini 151D Honeywell	SDF-rate 2DF-free SDF-RI
	DynaSoar	USAF/Boeing	Guidance, Backup guidance	Platform (3) Strapdown (2)	Honeywell 8001 Bendix 19008	SDF-RI 2DF-free
	HL-10	FRC/Northrop	Stabilization	Strapdown	U.S. Time	SDF-rate
	M2-F2	FRC/Northrop	Stabilization	Strapdown	U.S. Time	SDF-rate
	M2-F3	FRC/Martin	Stabilization	Strapdown (9)	Nortronics GRH4T	SDF-rate
	PRIME	USAF/Martin	Guidance	Strapdown (3)	Honeywell GG87	SDF-RI
	X-15	FRC/No. American	Navigation, Stabilization	Platform (3) Strapdown (3)	Honeywell 8001 Nortronics GRH4T	SDF-RI SDF-rate
	X24A/ SV-5P	USAF-FRC/ Martin	Stabilization	Strapdown (9)	Nortronics GRH4T	SDF-rate

Table 1.1-I — (continued)

Category	Mission (vehicle)	Sponsoring Agency/Gyro User	Function	Configuration (number)	Gyro Identification	Gyro Type
Sounding rockets	Aerobee 150/170/350	GSFC/Ball Bros. (Strap III)	Pointing, Stabilization Fine pointing	Platform (2) Strapdown (3) Strapdown (2)	Conrac 34646H-04 VARO 1005435-01 Honeywell GG 87	2DF-free SDF-rate SDF-RI
	Aerobee	AFCRL/NRL/ Space General (Mark II)	Pointing, Stabilization	Platform (2) Strapdown (3)	Whittaker FM10G-2 U.S. Time Model 40	2DF-free SDF-rate
	Aerobee 150/170	Space General (Mark III)	Pointing	Strapdown (1) Strapdown (3)	Whittaker FM10G-2 U.S.Time Model 40	2DF-free SDF-rate
	Aerobee 150/170	Kitt Peak/ Ball Bros. (SPCS-1)	Pointing	Platform (3)	VARO	SDF-rate
	Aerobee 150/170 Nike-Tomahawk	Ball Bros. (SPCS-2)	Pointing, Stabilization	Strapdown (1)	Condor Pacific R8-93AA-1	SDF-rate
	Nike-Tomahawk Black Brandt III	GSFC/Space Vector Corp. (SPT)	Pointing	Platform (2)	Space Vector MARS I	2DF-free

Task 6 contemplates the creation of a design requirements document based on the results from Tasks 4 and 5 and to include preliminary design layouts of gyroscope and accelerometer modules incorporating these requirements.

The entire study is restricted to strapdown inertial systems, as indicated by the title, as opposed to gimbal inertial systems. This approach is dictated by two specific considerations which point to the strapdown (or body mounted) configuration as the proper approach to the modularization and standardization of inertial system design. These considerations are described in the following paragraphs.

1. Mounting arrangement. The strapdown configuration lends itself naturally to a convenient and accessible arrangement of interchangeable modules with built-in alignment features. To accomplish an equivalent degree of plug-in accessibility and interchangeability in a gimbal system is difficult if not impossible.

2. Performance. The strapdown system can, by proper choice of system elements, provide performance to fulfill the mission requirements of the bulk of current and future space applications. As illustrated in Table 1.1-I, strapdown implementations have been successfully used on

numerous space missions for attitude referencing, stabilization, pointing control and guidance. In addition, the strapdown system has inherent fine attitude and attitude rate resolution and is readily configured to be digital in nature while being less complex in electro-mechanical design features. It can be expected to demonstrate a substantial reliability improvement with maturing electronic and instrument designs.

CHAPTER 2

STANDARDIZED MODULARIZATION CONCEPT

2.1 Introduction

The basic modularity concept addressed in this study consists of a family of standardized, function oriented, prealigned and calibrated submodules which are capable of being assembled to form an inertial gyro or accelerometer sensor module, complete and self-contained, needing only an input power source and a digital timing or instruction word, and producing a digital word containing inertial data and module self-test status. Within this gyro or accelerometer module, each submodule performs a basic function (thermal control, excitation voltages, etc.) compatible with the instrument and with performance and range suitable for the system application requirements. The system would be configured by a suitable selection and integration of modules, dependent on the application function (e.g. attitude reference, guidance, etc.) and level of redundancy needed (e.g. a triad configured with three gyro modules or a fault tolerant implementation using six gyro modules).

As an example to show in general the content and arrangement of a typical instrument module, Fig. 2.1-1 presents a possible layout for a gyro module using a candidate 1.3 in. diam. gyroscope. The submodules plug into the module structure to provide wheel supply, pulse torque loop electronics, temperature control electronics, suspension excitation supply, signal generator excitation supply, input/output conditioning and clock/digital interface functions. Descriptions of the design and performance characteristics of these elements are provided in Section 3.0. The gyro is prenormalized to present a standard interface to the submodule electronics. The means employed to accomplish the standardization, and the instrument categories needed to cover the range of system applications are covered in Section 2.2.1.

2.2 Benefits from Standardized Modularization

The benefits which can be expected to result from a carefully planned and skillfully executed program of standardized modular construction can be identified in five principal categories. These categories are described below and the discussion indicates that substantial reductions in life cycle costs can be achieved with a minimum of system performance constraints.

Dimensions 3" x 3" x 3"
Weight 1.5 lbs.
Power 4.7 W

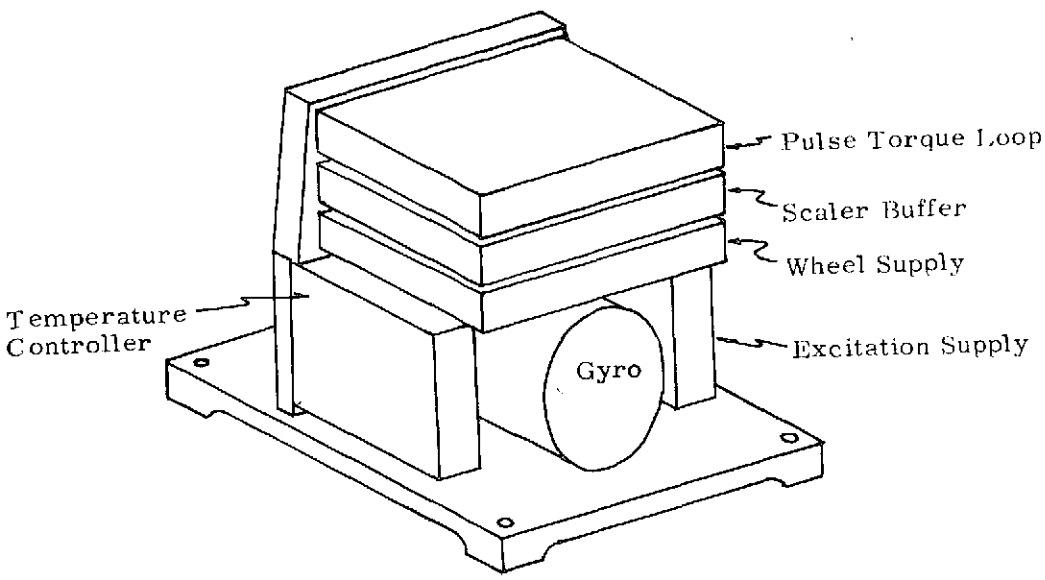

Fig. 2.1-1 Miniature Strapdown Gyro Module

2.2.1 Design and Development

This category contains the extra effort required to take into consideration the ranges of performance, the interface standardization, the interconnection problems, the environmental and reliability factors and all the other features which otherwise would only need be considered for a single set of system requirements.

The first step in the analysis of the design problem demanded a review of the system performance range requirements with the objective of defining a limited number of performance classes to cover the range of known and projected system applications. This effort resulted in the following breakdown.

a. Long duration guidance, navigation, or attitude reference functions, where updating is not possible or is very infrequent, requires an extremely stable gyroscope and its associated torque loop. Systems in this category require a state-of-the-art, high performance instrument and control loop technology. Some anticipated extremely high performance applications, such as for the Large Space Telescope, may even require additional development to achieve the required performance. This group represents the highest performance category.

b. Strapdown systems for aircraft navigation and satellite attitude reference applications, where periodic updating can be provided and where navigation performance between one and ten nautical miles per hour, or drift performance between 0.01^{o}/hr and 0.1^{o}/hr is sufficient, can draw from a broad technology base of available instruments and torque loop designs. A major portion of the anticipated system applications falls into this second group.

c. A third category, comprising short memory guidance or flight control system applications, can provide the necessary performance with modest requirements for instrument and control loop stability. This application would obtain its performance with navigation aided techniques such as DME or Loran. They can use low cost inertial components with drift performance between 0.1^{o}/hr and 1 deg/hr. There are many applications requiring low cost systems, such as remotely piloted vehicles, that fall into this third group.

It is apparent, therefore, that, although the highest performance module could probably meet the requirements for every application, it would not be cost effective in terms of size, weight, power, and reliability. It appears that three categories represent a minimum complement, namely high performance, moderate performance and low performance inertial instrument modules. These modules need not be three completely different designs. A reasonable level of common mechanical structure, electronic submodules and logic components can be expected. The major variation is predominantly determined by the instrument selected, as reflected in cost versus performance.

The quantity of modules to be built for each class has been postulated to reflect a level corresponding to an assumed DOD and NASA overall need. The recurring cost projections have been set at achievable values corresponding to the volume and performance needs. They are: high performance gyro modules ($50,000 to $91,000 per module)*, assuming on the order of 60 are built per year; moderate performance gyro or accelerometer modules ($10,000 to 22,000 per module), assuming 600 are built per year; and low performance gyro or accelerometer modules ($2,000 to 4,000), assuming 3,000 are built per year. The distribution of these costs are shown in Table 2.2-I. The designer will select electronics, components and packaging techniques to meet the performance and cost goals for each module class. To produce standardized modules would necessitate a non-recurring

*No accelerometers in this price range are included in the study, and thus only two classes of accelerometer modules are considered.

investment by the government in their design and development. The standardized module could be used in multiple applications by NASA and DOD agencies at the recurring costs shown in Table 2.2-I.

Table 2.2-I Module Cost Estimates (Recurring Costs Only)

PERFORMANCE	INSTRUMENT COST	MODULE COST RANGE	QUANTITY MODULES / YEAR
LOW	$ 500 - 1,000	$ 2,000 - 4,000	3,000
MODERATE	$ 6,000 - 12,000	$ 12,000 - 22,000	600
HIGH	$ 40,000 - 60,000	$ 60,000 - 91,000	60

THE MODULE COSTS HAVE BEEN ASSUMED DISTRIBUTED AS FOLLOWS:

	COST DISTRIBUTION of MODULE		
	LOW COST	MODERATE COST	HIGH PERF.
INERTIAL COMPONENT	$ 500 - 1,000	$ 6,000 - 12,000	$ 40,000 - 60,000
MECHANICAL HARDWARE	$ 100 - 200	$ 500 - 1,000	$ 2,000 - 3,000
ELECTRONIC FABRICATION	$ 400 - 800	$ 3,000 - 4,000	$ 5,000 - 8,000
TEST and ASSEMBLY	$ 600 - 1,200	$ 1,500 - 3,000	$ 8,000 - 12,000
ADMINISTRATION and PROFIT	$ 400 - 800	$ 1,000 - 2,000	$ 5,000 - 8,000

The second step in the study program required the identification of candidate strapdown inertial instruments and an assessment of the parameter incompatibilities which would have to be addressed in order to arrive at an interchangeable standardized desi gn. The proprietary, candidate inertial instruments shown in Table 2.2-II represent single degree-of-freedom gyros which have been manufactured and used in sufficient quantities over the last five to fifteen years to have acquired a history of successful operation and to have developed a mature design and manufacturing process. Most of these gyros are available with variations adapted to specific input voltages and frequencies so that standardization of some of these parameters would

Table 2.2-II Candidate SDF Gyros For a Modular Strapdown System

		PERFORMANCE										
		HIGH	MODERATE						LOW			
PARAMETER	UNITS	TGG	GG334A	18 Mod B	K7G-3K	2544 & 2546	13 IRIG	RI 1139D	GIG 6	IG-10	GG1111	1903HJ
Vendor		CSDL	Honeywell	CSDL	Northrop	Kearfott	CSDL	UAC	Northrop	US Time	Honeywell	Lear Seigler
Size (length x diameter)	inches	3.3 x 2.4	4.7 x 2.3	3.9 x 2.0	2.9 x 1.66	2.5 x 1.4	2.5 x 1.3	3.5 x 2.68	2.2 x 1.0	2.0 x .94	2.4 x 1.2	3.2 x 1.5
Weight	lbs	1.2	1.65	1.15	0.625	0.64	0.33	1.5	0.25	0.25	0.25	0.44
H/C S_{SG}	mV/mrad	48	8.0	4.3	10.0	2.7	0.8	14.0	12	100	10	20
Max Torque Rate (continuous)	rad/s	1/10	~1	~1	~1/4	~7/4	4.7	~5/6	~3/4	1/3	7	3
Angular Momentum	$gm\text{-}cm^2/s$	5×10^5	2×10^5	1.6×10^5	0.6×10^5	6×10^4	8.5×10^3	2.5×10^5	2.2×10^4	2.3×10^4	1.0×10^4	1.9×10^4
Time Constant	microseconds	750	450	330	1220	200	1000	270	< 2000	3000	1500	5000

not constitute a major obstacle. A similar table showing some candidate accelerometers, subdivided by system performance class is shown in Table 2.2-III. The two new CSDL instruments, the 13 IRIG and the 12 PIP, and the Kearfott 2544 strapdown gyro do not at this time represent mature design nor a production base. They have been included as candidates to facilitate design descriptions and estimates for miniaturized systems.

Table 2.2-III Candidate Accelerometers For a Modular Strapdown System

		PERFORMANCE							
		MODERATE					LOW		
PARAMETER	UNITS	4810	2401	16 PM PIP	12 PM PIP	GG177	QA116-17	4303	GG326
Vendor		Systron-Donner	Kearfott	CSDL	CSDL	Honeywell	Kistler	Systron-Donner	Honeywell
Size 1 x dia, or cube sides	inches	1 x 1.2 x 2	1.3 x 1.6 x 2	2.1 x 1.6	1.8 x 1.2	1.8 x 1.8	1.9 x 1.0	1.5 x .75	1.5 x 1 x 1
Weight	ounces	7	5	12	4	6	3	≈ 2	3
Range	g's	± 25	± 20	± 20	± 20	± 25	± 15	± 15	± 40

Tables 2.2-II and 2.2-III show the selected parameters of the candidate gyros and accelerometers. The distribution of weights and volumes for these instruments is shown in Figs. 2.2-1 and 2.2-2. It appears that two basic sizes of gyro modules and one size of accelerometer module would accommodate all of these instruments efficiently except for the GG334 and RI1139D units which would require a larger module and a less efficient layout.

To the extent that the principal characteristics of the inertial instruments, performance and size, determine the feasibility of the standardized modules, it appears from the study thus far that two, or at most three, module sizes with sufficient allowance for the electronic submodules required for operation, normalization and interface compatibility will satisfy the requirements for high, moderate and low performance systems. The proposed approach to the electronics design is covered in Section 3.0.

2.2.2 Producibility Benefits

Having completed the design and development of two or three versions of the standardized design to accommodate the sizes of the candidate instruments, the benefits to be accrued became apparent. Benefits show up first in producibility and are visible in the module and in the system. For the module we will have a maximum of three sizes of mostly identical structures with mounting provisions for standardized submodules to the extent that they are needed for a particular system or choice of instrument. A similar situation exists for submodules, although these will include a larger number of unique designs to provide for all of the necessary functions. The major source of producibility benefit comes from the manufacturing quantities involved as a result of standardization, making efficient tooling and automated assembly economically feasible. Continuing volume requirements will assure that an efficiently devised production effort operates effectively. At the system level, benefits accrue from the modular construction which reduces the system complexity to a primary structure containing routine accounting, control and display functions, and standardized, plug-in, prealigned and pretested, inertial instrument modules. Modules may be manufactured in-house or procured from multiple sources to preserve a competitive cost base and reduce the delays due to procurement factors. System testing and calibration is simplified by the use of the pretested, prealigned and precalibrated modules. Moreover, trouble shooting need consist only of substituting modules from stock. Failed units are returned to the component test level for verification. This picture contrasts sharply with the serial type fabrication and assembly procedures typical of gimbal systems and some current strapdown systems. Even the CSDL redundant dodecahedron, SIRU system is limited in the effectiveness of its modularity in comparison with the Standardized Modularized Concept System.

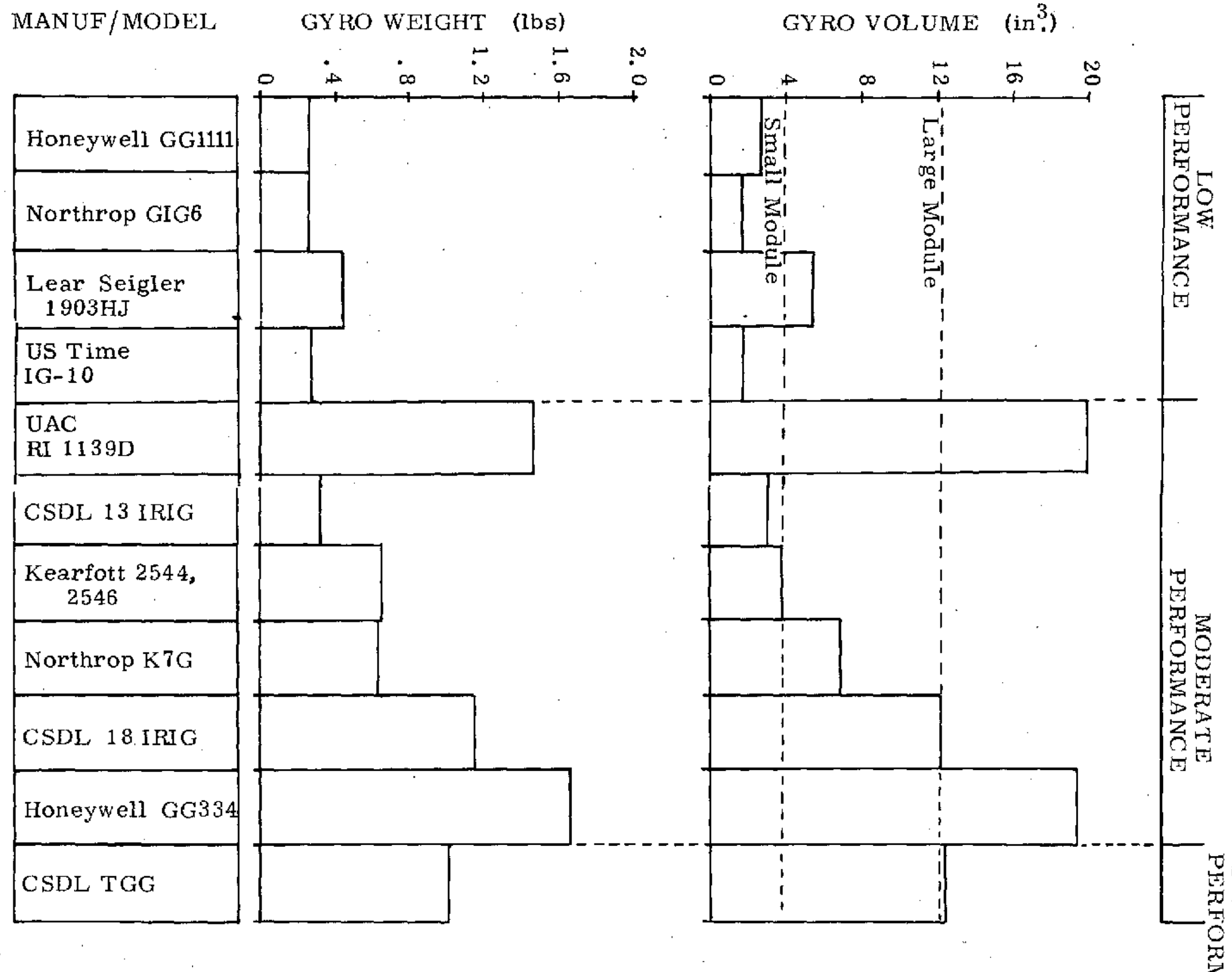

Fig. 2.2-1 Weight and Volume of Typical Strapdown Gyros

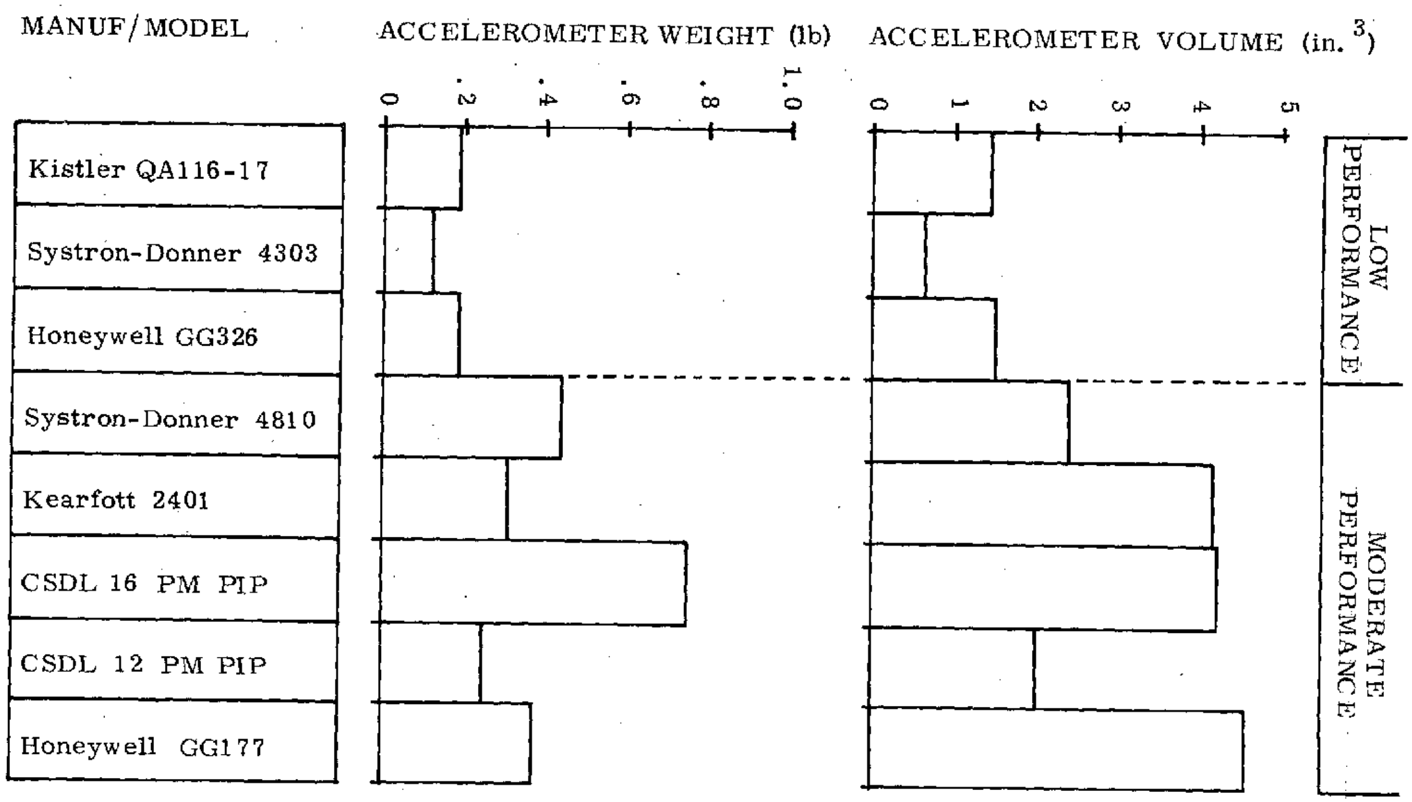

Fig. 2.2-2 Weight and Volume of Typical Strapdown Accelerometers

2.2.3 Maintainability Benefits

The cost effectiveness of the maintenance function is another benefit from the strapdown standardized modularized concept, both at the system operating level and at the module repair level. System maintenance, due to the convenience of the software failure, detection and isolation (FDI) and built-in test equipment (BITE), can be readily accomplished by flight line personnel by exchanging modules from a spares kit. The only further action required would be software calibration updates to introduce inertial instrument parameters, absolute biases, etc. It would probably not be cost effective to require an absolute hardware normalization range on all instruments. Automatic absolute calibration updates could be effected by incorporation of programmable read only memory (ROM) modules. The inertial sensor axes of the system thereby becomes a line replaceable unit with a mean time to replacement (MTTR) of less than 10 minutes by relatively unskilled personnel. This capability represents a significant improvement over present systems in which repairs involving inertial instruments generally require the removal of the whole inertial measurement unit (IMU) and its electronics rack. Replacement of the inertial element in a typical current system requires disassembly, reassembly, recalibration, and alignment of the IMU in the inertial navigation system (INS) rack before reinstalling it in the vehicle. Field experience with current gimbal systems having self-checking and failure identification features shows a significant percentage of false removals. The integrated functional nature of the gimbal implementation tends to make positive fault detection to a specific function difficult and in some cases impossible.

At the module repair level, maintenance can be effectively accomplished at intermediate support levels where electronic test equipment and spare submodules are available. The faulty plug-in submodule can be identified by automatic checkout equipment (ACE), rapidly disconnected and replaced. With the exception of the inertial components and their normalizing components, the submodules would be completely interchangeable without calibration or readjustment. This submodule interchangeability permits the repair of a module, with the exception of replacing an inertial component, to be accomplished at the intermediate (shop) maintenance level. Replacement of an inertial component, along with its normalizing components, or the repair of a failed submodule would be accomplished at the depot maintenance level where specialized personnel with manufacturing and test equipment is available.

Spares requirements are also affected by the multiple usage of standardized submodules. A relatively low percentage of operating spares can safely be maintained at the intermediate level only. Coordinating the procurement of spares between agencies is another possible source of savings in spares cost.

2.2.4 Reliability Benefits

Improved system reliability can be confidently expected to result from the standardized strapdown modular system concept.

Currently, each system, as delivered by its manufacturer, demonstrates over an extended period of time a certain level of reliability determined by its design and manufacture, environmental exposure and many other factors. Reliability improvements may be incorporated as the system matures, but are not generally transferable to other system designs. With the standardized strapdown modular system, not only can greater attention be devoted to increasing the reliability of each submodule, but also reliability data feedback can be implemented between system users and manufacturers to trigger design, manufacturing and test improvements which will be applicable to all systems in which the improved submodules are used. The larger quantity usage of individual submodules will result in a more accurate reliability assessment which permits the system design to specify the redundancy requirements on the basis of accurate reliability projections. Module reliability is achieved by choice of components, by the design of module and submodule interconnections, by the application of burn-in processes and by the efficiency of the test procedures employed. Failure analysis of generic design faults or weaknesses can be used to enable rapid design and production changes based on failure experience. Technical obsolescence in the submodules can be avoided by designs incorporating new technology but retaining identical interfaces. Procurement problems in obtaining components no longer stocked by suppliers is another troublesome aspect and with standardization can be overcome by the same approach of design modification with identical interfaces.

2.2.5 Compatibility Benefits

As has been described previously, module inputs and outputs are standardized to consist of 28 Vdc and a digital timing word for input and inertial data and a BITE or FDI word for output. This arrangement automatically provides a basis for compatibility with all systems developed from the standardized modules. By supplying the inertial information from one source, employing redundancy appropriate to the mission, and eliminating the independent inertial sensors from such systems as the flight control system, the attitude stabilization systems, load alleviation and mode stabilization systems, perhaps as many as 10 to 20 inertial instruments with their electronics, may be eliminated while at the same time providing improved performance and higher reliability. If a redundant dodecahedron array were used, integrated navigation, attitude reference and flight control sensing would be achieved using only 6 gyro and 6 accelerometer modules and yielding fail safe, fail safe, fail operational (FS, FS, FO) reliability. The dodecahedron configuration could be assembled using the standardized modules. The "dodecahedron" configuration is based on a unique, symmetrical, geometric arrangement in which the instruments sensing axes are arrayed to correspond to the angles that are made by the perpendiculars to the faces of a dodecahedron. This configuration was demonstrated in the SIRU* system. In the SIRU system, a modular axis approach was utilized in which instruments were packaged in prealigned modules and normalized with some of their electronics, although not as comprehensively as projected in the standardized module concept. Test results on the SIRU modules do serve, however, to demonstrate the feasibility of the modular approach. For example, the performance repeatability of the SIRU modules under various conditions, over several years of operation, has been impressive. Figures 2.2-3A and 2.2-3B summarize the stabilities of the CSDL SIRU modules, using the 18 IRIG Mod-B gyro, across remounting, cooldowns and repetitive tests. Figure 2.2-3A shows the bias drift (NBD) and g-sensitive drift (ADSRA, ADIA, and ADOA) stabilities. Figure 2.2-3B shows the major compliance (g^2), scale factor and input axis alignment stabilities that were obtained. Likewise, Fig. 2.2-4 summarizes the stability of the SIRU accelerometer modules, using the CSDL 16 PM PIP, across remounting, cooldown and repetitive tests. Alignment, scale factor and bias stability data are shown. These data indicate that, for the gyro/accelerometer module designs used, repeatability consistent with inertial grade performance was obtained with module interchangeability.

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*Design description, redundancy management, test results and reliability data of the SIRU system are covered in CSDL Report R746, Extension of the system to include statistical FDI, Self Calibration, Self Alignment and Local Level Navigation is presented in R747.

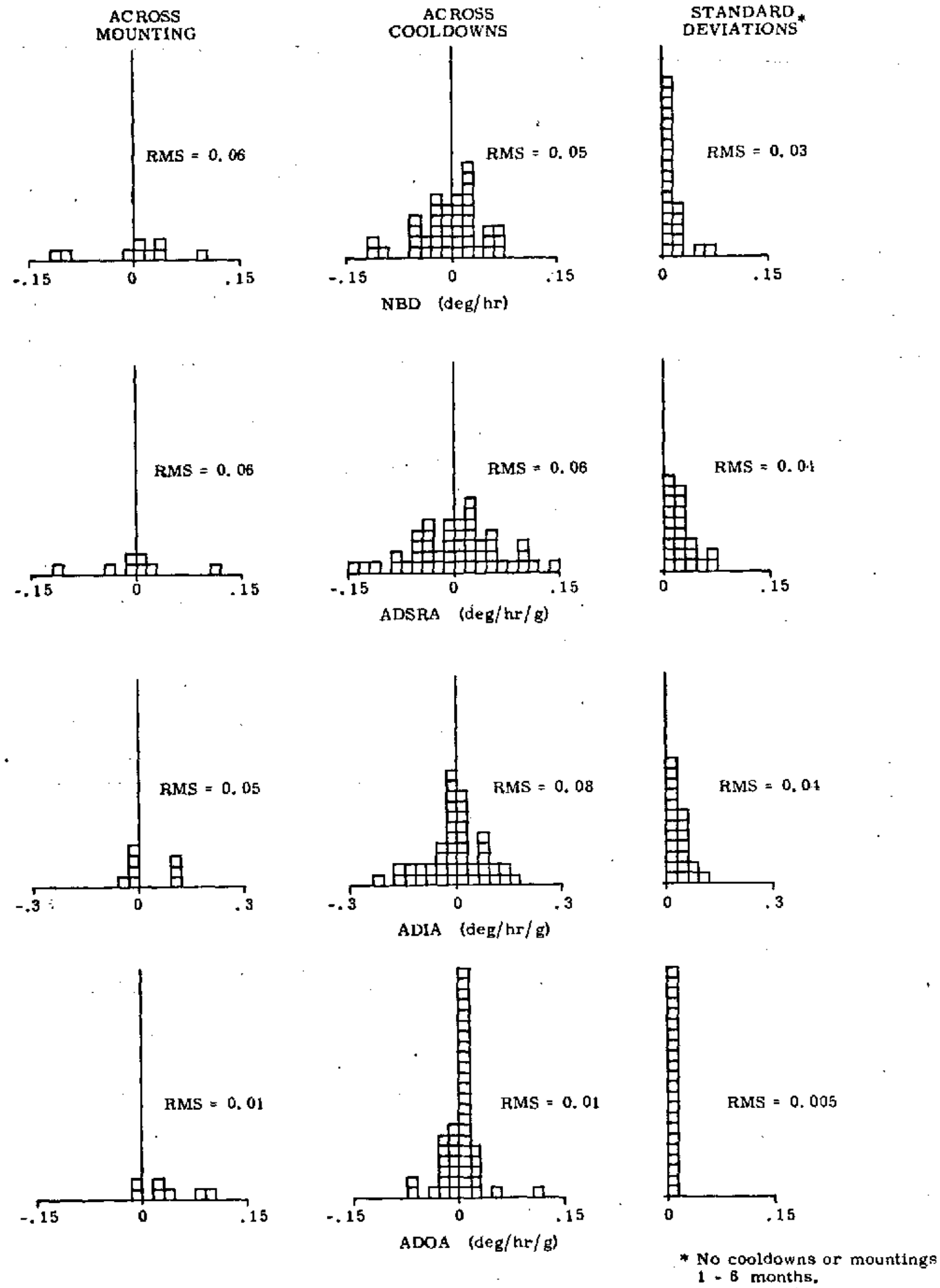


Fig. 2.2-3A Gyro Drift Performance-18 IRIG Mod B

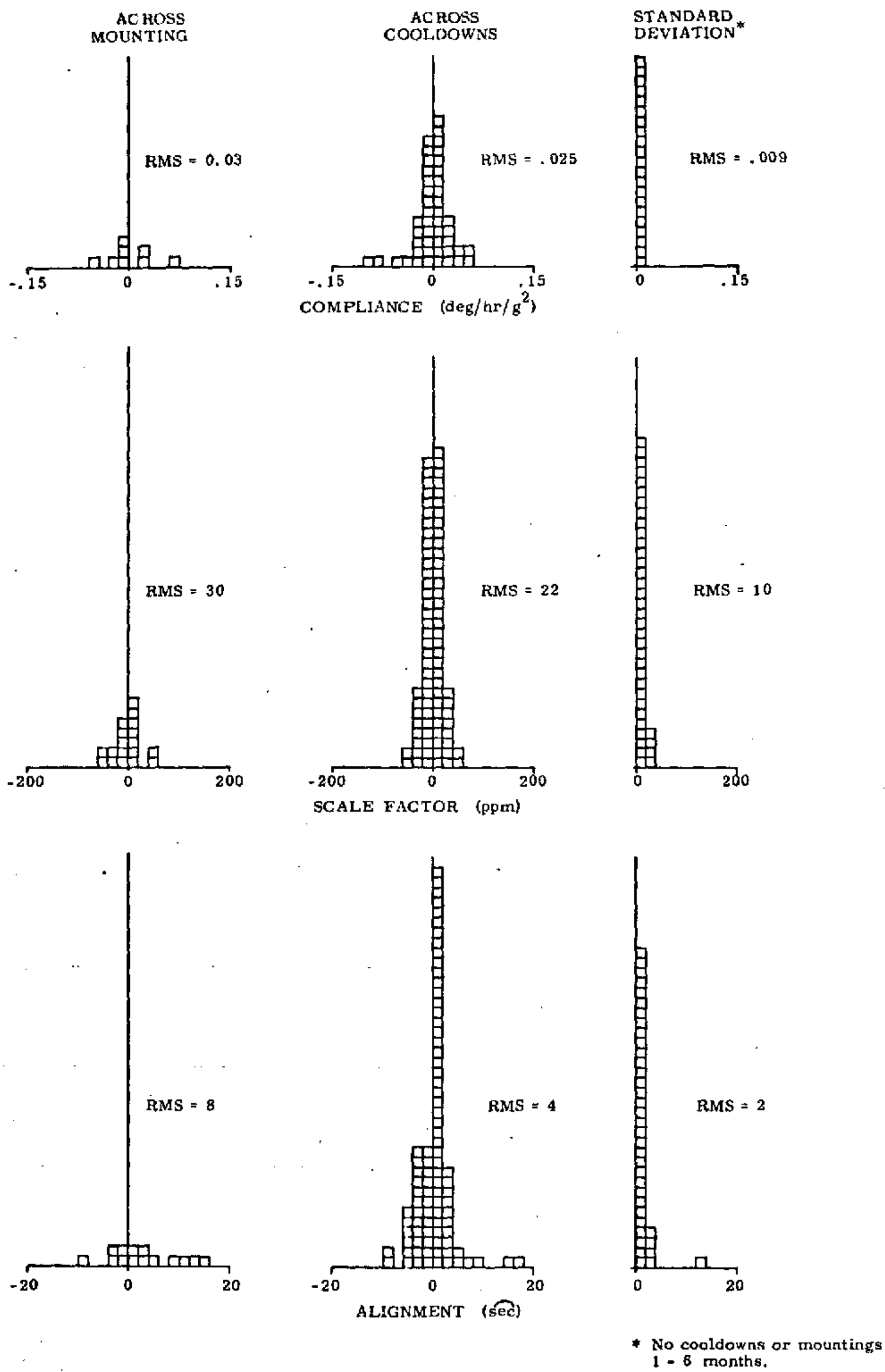


Fig. 2.2-3B Gyro Compliance, Scale Factor, and Alignment Data 18 IRIG Mod B Gyro

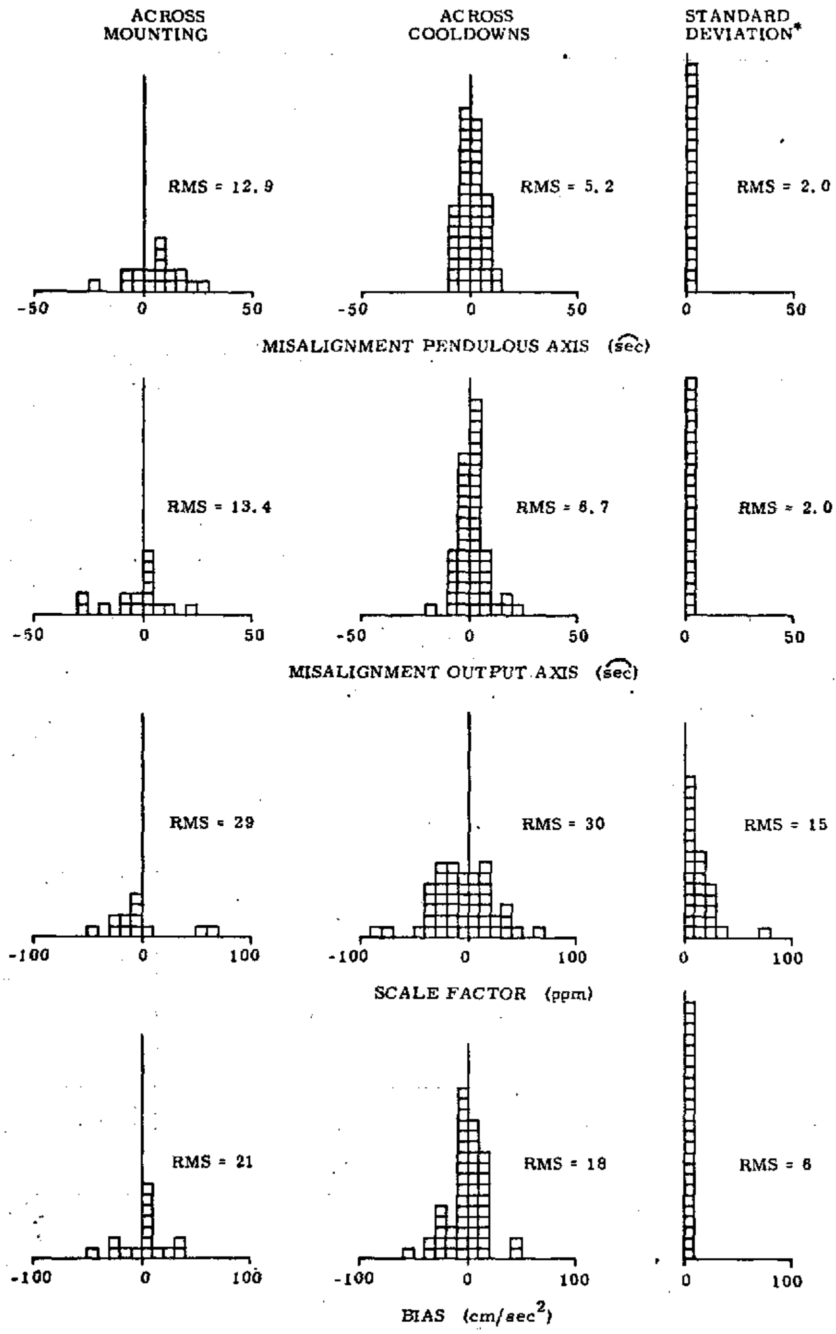


Fig. 2.2-4 Stability Data For 16 PM Accelerometer

CHAPTER 3

INSTRUMENT MODULE DESIGN STUDY

3.1 Introduction

The design study instituted to support the standardized, modularization concept consisted of two principal areas of investigation and analysis. These two areas are:

1. Comparison of candidate inertial instruments to define the relative performance capabilities of each instrument, the problems associated with providing a useful level of interchangeability and the possible constraints on the successful implementation of a modularized system;

2. Presentation of the design aspects of the submodules required to accommodate a wide variety of system performance parameters.

In order to constrain the study to manageable proportions, the candidate instruments were limited to mature examples of single-degree-of-freedom types with a reasonably broad production base and a recognized application history. This approach introduces some additional apparent incompatibilities because the identified instruments were designed for specific system configurations. However, it is reasonable to assume that many of the electrical parameters, such as wheel excitation, suspension and pickoff excitation, sensitivities and gains can be standardized without imposing any unacceptable burden on the instrument manufacturers. These changes should not significantly impact the basic instrument design or affect the basic reliability of the instrument.

Many of the support requirements for accelerometer modules are similar to the gyro module requirement. Although it can be argued that a combined gyro/accelerometer module is more cost effective, the added complexity and reduced flexibility of application resulted in a decision to retain only the independent configurations for this study. For example, many applications, space satellites, require only an attitude reference unit (ARU) or an ARU with a limited single axis burn velocity measurement capability.

3.2 Instrument Selection and Parameter Compatibility

The key parameters and performance requirements for the selected candidate instruments, divided into three performance classes, are tabulated in Tables 3.2-I and 3.2-II.

Table 3.2-I Performance Specifications For The Three Module Classes

	LOW PERFORMANCE MODULE	MODERATE PERFORMANCE MODULE	HIGH PERFORMANC MODULE
Max. Torquing Rate (rad/sec)	1	1	0.1
T.G. Current (mA)	170	140	150
S.G. Frequency (Hz)	4800	9600	6400
S.G. Voltage (V)	5	5	4.5
Suspension (V/Hz)	None	$\frac{8}{9600}$	$\frac{13.6}{12,800}$
Spin Motor			
Frequency (Hz)	1600	1600	1600
Phase	2	2 or 3	2
Voltage (V_{rms})	26	16	30
Power (W)	3	2.5	6
Temperature (^{o}F)	120	160	135
Required Stability:			
Temperature (^{o}F)	5	0.1	0.01
Frequency (ppm)	100	1	0.1
Motor Voltage (%)	5	1	0.01
Signal Gen. (%)	5	1	0.1
Suspension (%)	None	1	0.1
Torquer SF (ppm)			
Stability	100	10	1
Linearity	1000	100	10

Table 3.2-II Module Performance Goals

	PERFORMANCE CATEGORY		
	LOW	MODERATE	HIGH
Gyro Module			
Bias Drift Stability (1σ)			
1 week (^{o}/h)	3.0	0.03	<0.001
1 day (^{o}/h)	1.0	0.01	<0.001
1 hour (^{o}/h)	0.1	<0.01	<0.001
Scale Factor Stability (ppm)	100	10	1
Scale Factor Rate Linearity (0.1 to full rate) ppm	1000	100	10
Alignment Stability ($\widehat{sec}$)	100	10	<1
Maximum Torquing Range (rad/s)	> 1	> 1	0.1
Accelerometer Module			
Bias (μg)	1000	100	10
Scale Factor Stability (ppm)	100	10	1
Alignment Stability ($\widehat{sec}$)	100	10	<1
Maximum Acceleration Range (g)	20	20	5

The principal constraints on the module dimensions and weight appear to be instrument size and thermal control characteristics. Costs are affected if submodules are required to standardize different instrument interfaces. Analysis shows that one small module size could accommodate the low performance instruments and two of the smaller medium performance instruments. A larger size module would accommodate two moderate performance instruments and the high performance gyroscope. An even bigger module would be required for the Honeywell GG334 and United Aircraft RI1139D instruments. It appears that either two or perhaps three sizes of modules are required to utilize the candidate instruments.

The gyro and accelerometer performance level for each of the performance classes is shown in Table 3.2-II. The instruments in the moderate performance class are roughly two orders of magnitude better than those in the low performance class. Figure 3.2-1 shows the levels of short term, continuous operation, bias drift stability that are projected for the candidate gyros.

3.3 Submodule Support Requirements

Functions required to support the inertial instrument in the module are identified as submodules and for the purposes of this study are presumed to include some or all of the following:

1. input/output conditioning
2. clock and digital interface
3. temperature controller
4. pulse torque electronics
5. pulse torque power supply (high performance module only)
6. signal generator excitation
7. suspension excitation supply (for instruments with magnetic suspensions)
8. wheel supply (for gyro modules only)
9. precision reference voltage supply
10. 28 Vdc conditioner

This complement of submodule designs is aimed at supporting the four to seven wire interface, i.e. power in, data out. The data output is mechanized for data bus type communication with the computer. For all functions associated with the inertial component module, i.e. thermal control, dc regulation must be performed by electronics in the submodules.

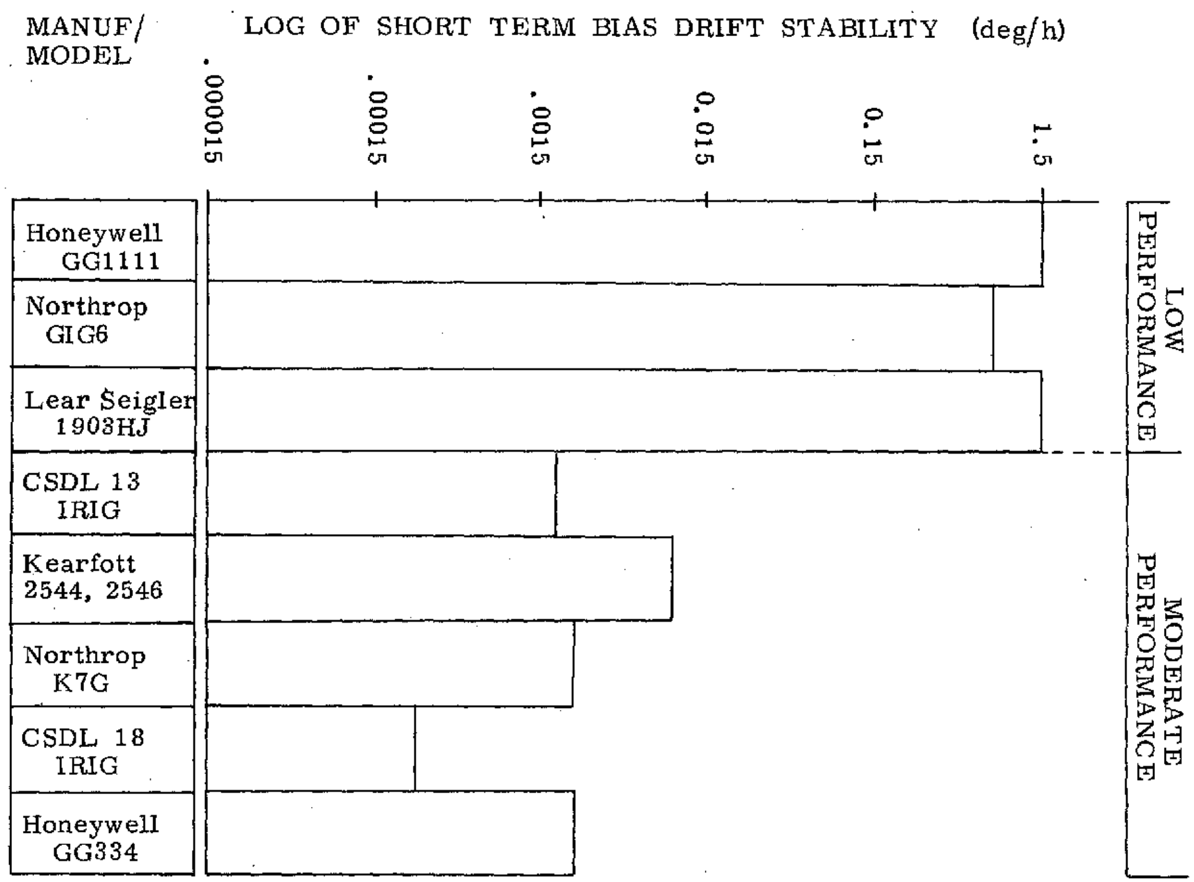


Fig. 3.2-1 Relative Short Term - Continuous Operation Bias Drift Stability

Each function is packaged as an independent, plug-in submodule with built-in self-test provisions. In this analysis transformer coupling of wheel and pickoff supplies are assumed although their bulk would be eliminated if the wheel phases and pickoff circuits could be made fully floated. Another set of submodules would be required in order to incorporate this option and it was not considered to be cost effective at this time.

Figures 3.3-1 through 3.3-3 show block diagrams of the three classes of gyro modules required to meet the supply stabilities and performance parameters shown in Table 3.2-II. The high performance block diagram represents a system providing the most stringent parameter control. Input 28 Vdc power is conditioned to 1%, a special pulse torque power supply is included, provision for individual temperature control of the PVR function has been made, zone temperature control is provided and wheel, suspension and pickoff excitations are delivered through transformer-coupled switch functions. The moderate performance module, Fig. 3.3-2, eliminates the special pulse torque power supply, simplifies the temperature control function to a single zone and no temperature control of the PVR function is required. The low performance module, Fig. 3.3-3 is similar in construction to the moderate module except that lower cost processing procedures can be employed, component screening would be reduced, and temperature and suspension control would be unlikely. The cost saving choices and processing will be described in later sections.

3.4 Submodule Design Features

This section describes in additional detail the design considerations, component selection and processing procedures applicable to the submodules to meet the specific requirements of high, moderate and low performance modules. These submodules are identified and presented as follows:

3.4.1 Input/Output Submodules

The input/output module receives data from, and sends data to the system computer. With the technology expected to be available in the late 1970's, this function could be performed with a microcomputer. However, the design described is presently being proposed by RCA to NASA for the Shuttle (NASA document MSC5144 Rev. A). As shown in Fig. 3.4-1, it uses Manchester Bi-phase, and because it contains its own clock information, it permits a two wire data output mechanization. The receiver/driver, the synchronization detector, the address decoder, and the cyclic error detector/encoder are incorporated in this RCA design using PMOS technology. Because PMOS has a limited temperature range, i.e. -20°C to 100°C,

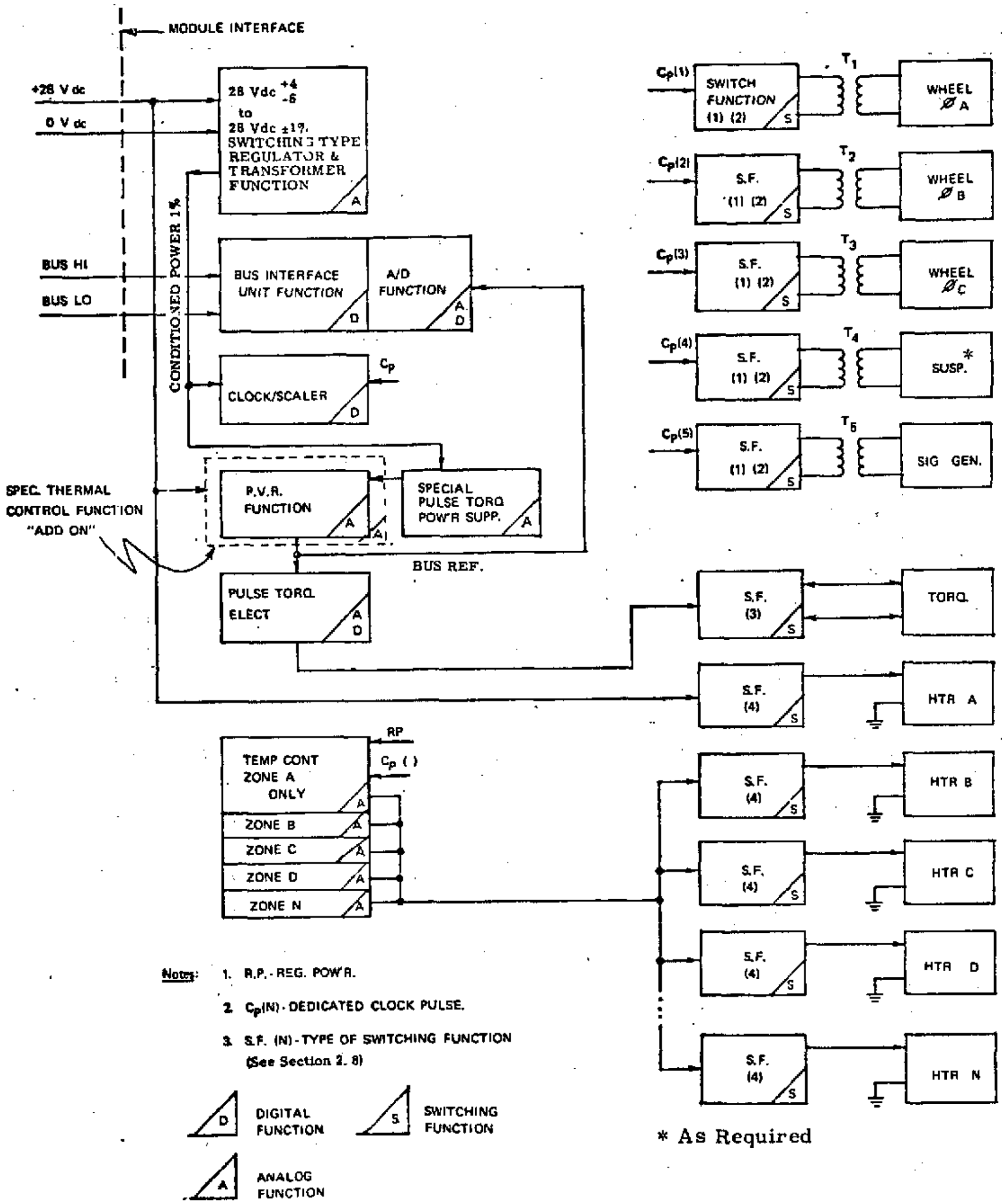
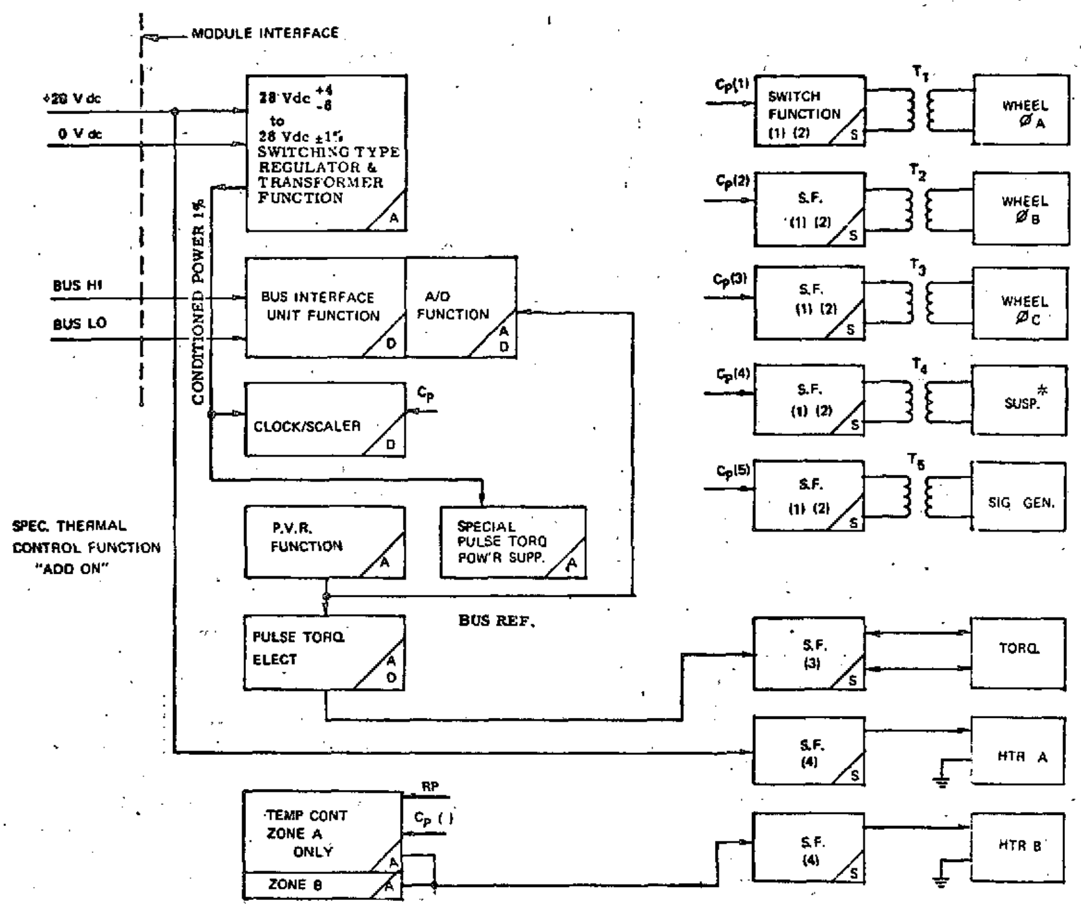


Fig. 3.3-1 Block Diagram of High Performance Strapdown Gyro Module



Notes: 1. R.P.- REG. POW'R.

2. C_p(N) - DEDICATED CLOCK PULSE.

3. S.F. (N) - TYPE OF SWITCHING FUNCTION (See Section 2. 8)

* As Required

D DIGITAL FUNCTION

S SWITCHING FUNCTION

A ANALOG FUNCTION

Fig. 3.3-2 Block Diagram of Moderate Performance Strapdown Gyro Module

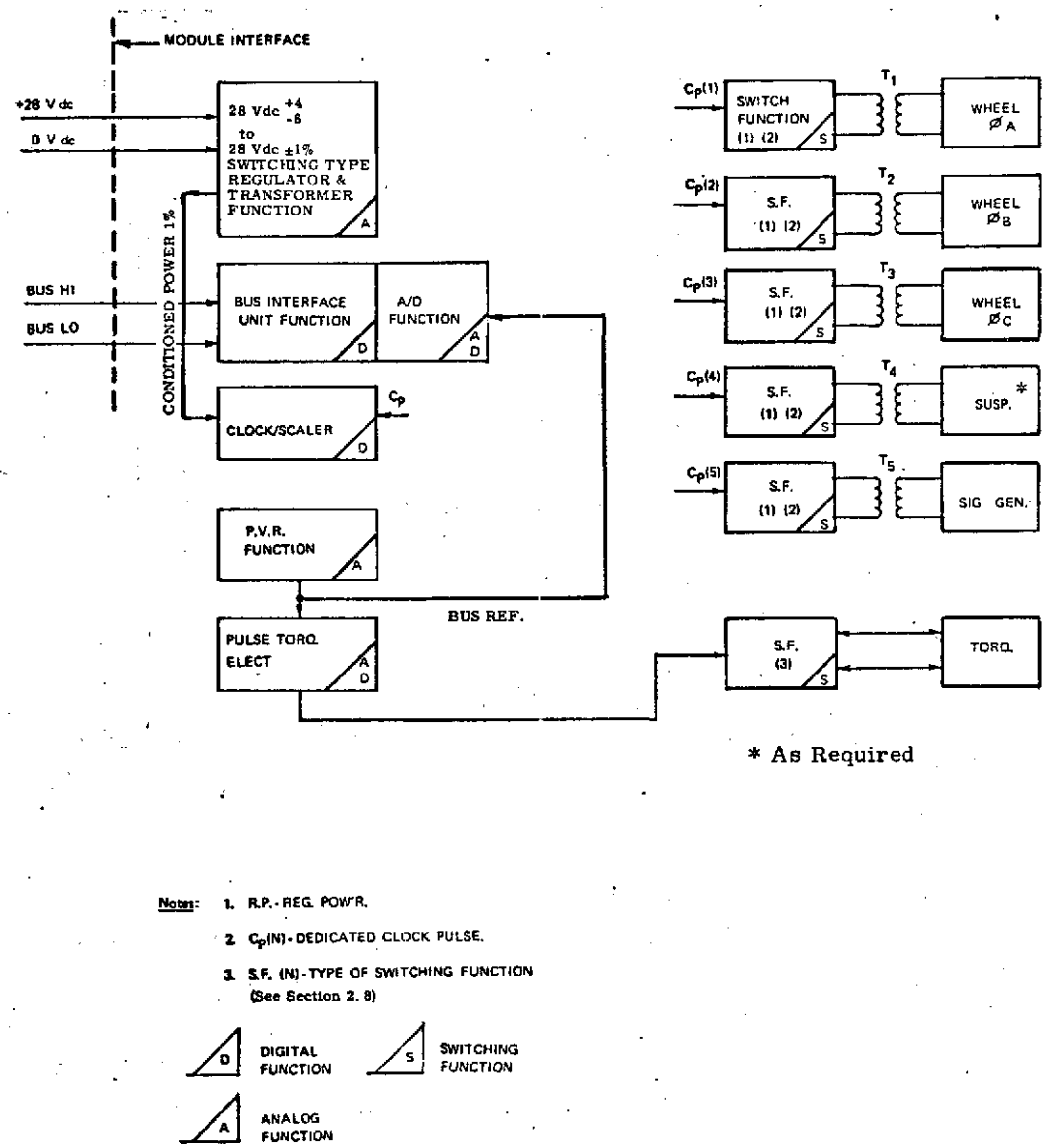
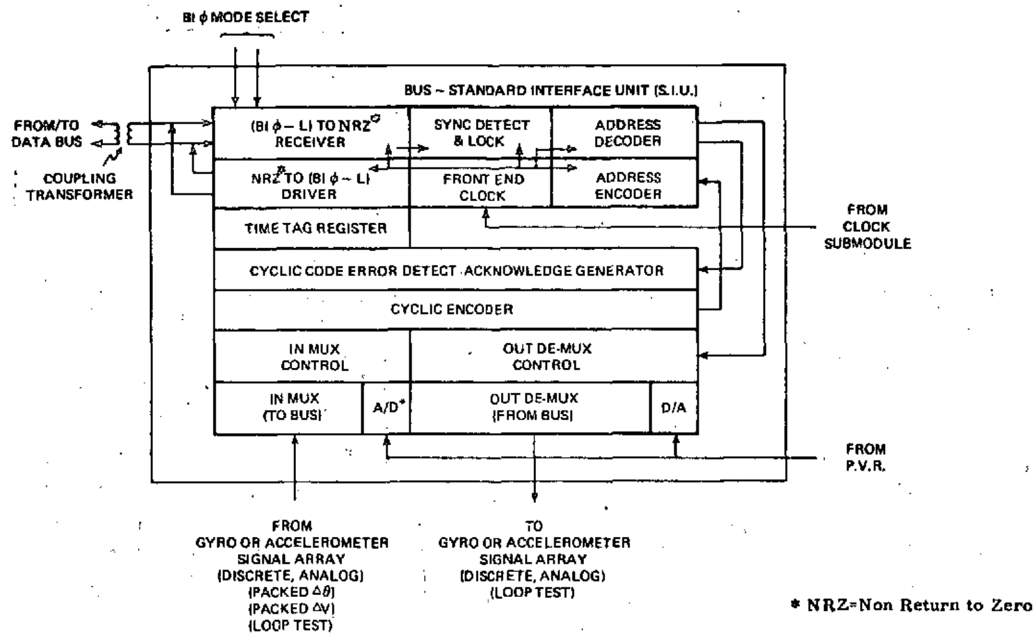


Fig. 3.3-3 Block Diagram of Low Performance Strapdown Gyro Module



Signal/message definition per NASA MSC 05144 Rev A Variant A per above, Variant B in/out mux-demux control and function separated and in another sub-module. (see Fig. 3.4-2)

Fig. 3.4-1 Input Output Submodule

modification to a CMOS low power design (also RCA technology) is preferred. The RCA design uses a 5 MHz bus frequency, although 1 MHz would be adequate for this application. Placing the input/output multiplexer-demultiplexer (Mux-deMux), with controls, in a separate submodule may give the input/output module greater flexibility. That option is shown in Fig. 3.4-2.

The synchronization detector/lock and front end clock shown in Fig. 3.4-1 detects a synchronization signal as a message and by using a combination of phase offset and lock, establishes that the message processing "front end" clock is synchronized to within 1/8 bit time to the bus and is locked to this "sync" for the total message and acknowledge duration; i.e., approximately 100 bits of message time. Accumulated skew between the bus clock and the gyro or accelerometer module clock does not exceed 3 nsec. in 100 bits. The skew specification accommodates 10 ppm blocks at both the sending computer and the receiving module.

The address decoder recognizes the module identification address and all subfield data addresses within the module. After decoding the module identification, the device enables all further address, cyclic, MUX or deMUX decoding. If, within

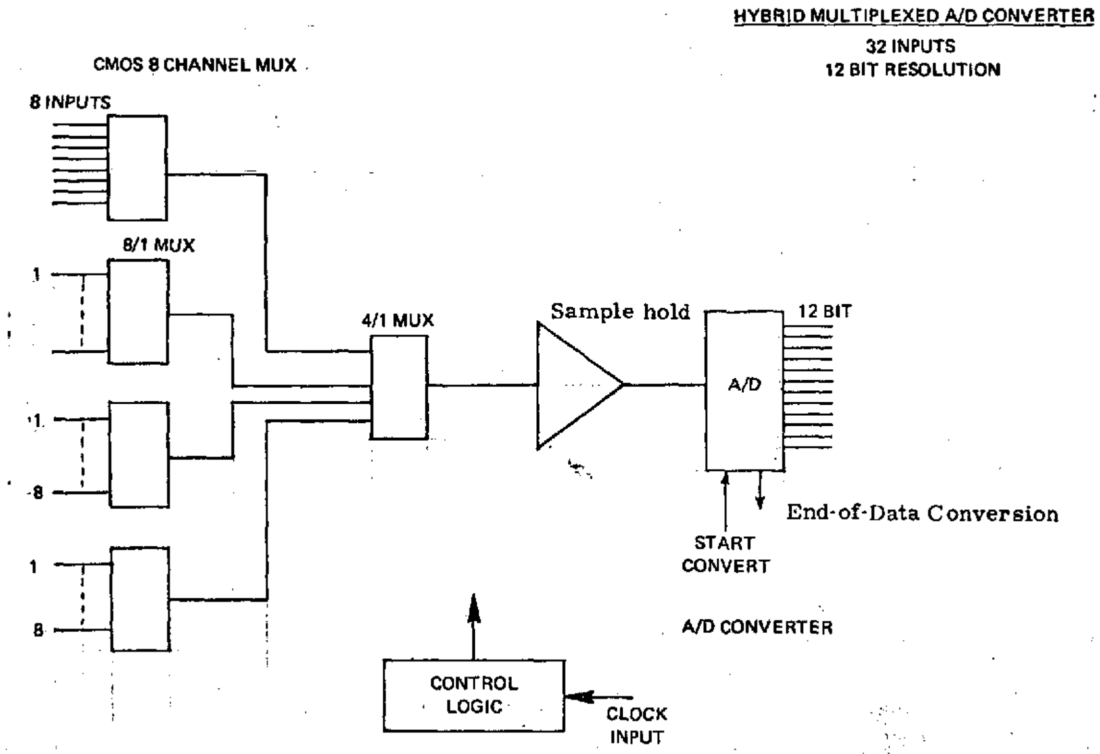


Fig. 3.4-2 Hybrid Multiplexed Anolog-to-Digital Converter

a certain number of message bits, it does not code "true", it puts all downstream functions to inhibit/clear/standby/"go to sleep" status, and awaits the next synchronization "alert". In addition, the decoder is capable of sensing a "time tag" message, identifies it, and upon completion of the error check, strobes the update time from the computer into its own time tag register, which then continues to count on the local clock oscillator. The "group" alert message may be used to set a group for either a synchronous local time update or a readout "N" clock times after the message.

The address encoder encodes all local address information in a message to the computer.

The time tag register is maintained closely synchronized with the computer by the decoded group alert message.

The cyclic coder/error detector looks for errors in the messages received and, when an error is detected, it inhibits action. It also forms a cyclic code addendum to the address encoder message. (A simpler parity check system could be used as an alternative).

The input/output control and multiplexer-demultiplexer processes data from the computer to the module and vice versa.

An analog-to-digital (A/D) converter, with part of the multiplexer section is shown in Fig. 3.4-2. Many self-contained A/D packages, some fully hybrid, are becoming available off-the-shelf. An A/D hybrid module for the B1 aircraft is currently going into production and could be used without alteration. CSDL is using similar devices in the Fly-by-Wire program for the NASA Langley Research Center.

The A/D section operates continuously in module testing. In flight it is required to respond with only one "page" of data per second. Therefore, the A/D power duty cycle may be 10% or less in actual flight.

3.4.2 General Purpose Clock Submodule

This submodule, shown in Fig. 3.4-3, contains an off-the-shelf crystal clock, a scaler set to provide any frequencies needed for the candidate gyros or accelerometers, and a ROM decoder which accepts a hardwire code (A, B, C, D) to call up the required set of frequencies on the appropriate lines.

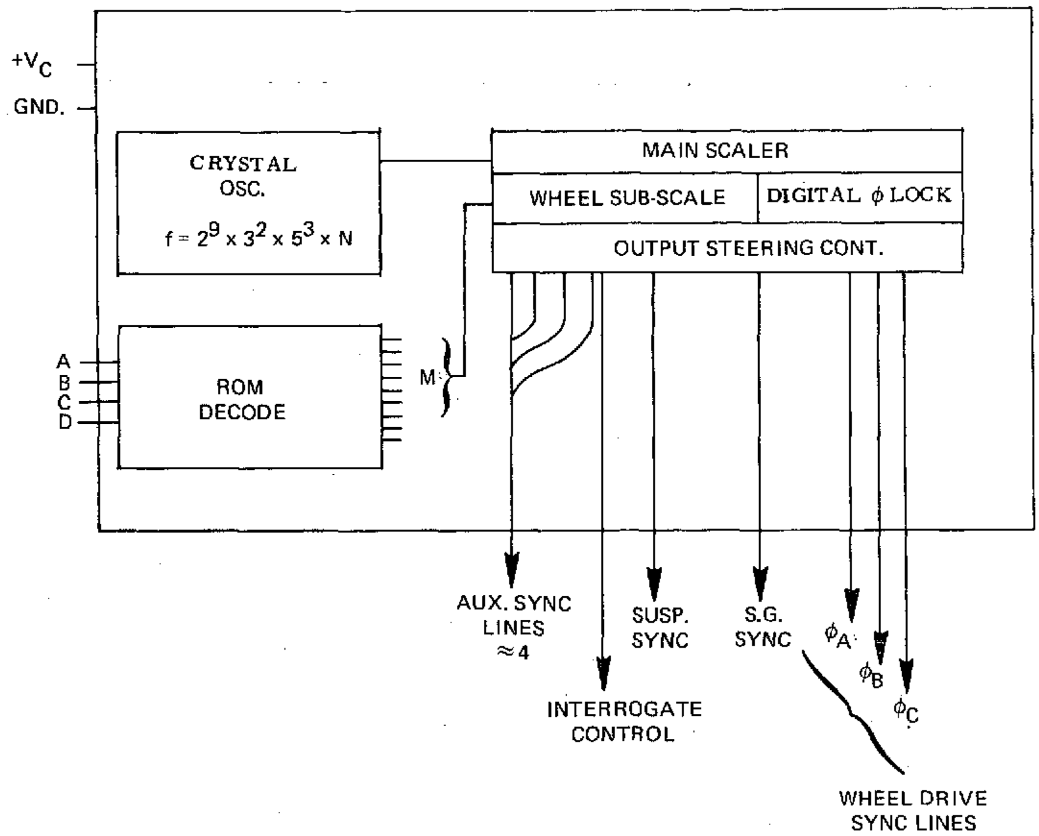
Without temperature control, the oscillator accuracy is nominally 10 ppm. This accuracy is sufficient for the low and moderate cost module. The oscillator performance is 1 ppm when temperature is controlled to plus or minus 10 degrees F. This requirement will be specified for the higher performance modules. The logic is essentially a dielectrically isolated CMOS, or SOS-SMOS, for operation at 1 MHz or higher. If cost savings result, bulk CMOS can be used for operation at less than 1 MHz.

Tables 3.4-I and 3.4-II show a preliminary breakdown of the typical frequencies that may be required from the general purpose clock and scaler.

The target power specification for the clock and scaler submodule is 100 mw.

3.4.3 Temperature Controller Submodules

For low performance modules a simple ON/OFF type controller is probably sufficient. This approach minimizes the power and volume required for the function. However, in the two higher classes of modules, range proportional control is necessary for set point accuracy and temperature stability. A pulse width modulated proportional controller or a digital controller is recommended. The peak start-up power to



A, B, C, D lines set up through the ROM appropriate output sync lines for up to 16 selections of gyros or accelerometer frequencies. Selection input field and auxiliary sync lines may be expanded if desired.

Fig. 3.4-3 General Purpose Clock and Scaling Module

some zone heaters can be as high as 30 watts which can create switching problems. Possible solutions and alternate temperature controller designs are discussed in Section 3.7.

The high performance candidate gyro can have as many as eight zones of temperature control; compared to one or two for typical instruments. This situation creates a volume efficiency problem or a redundancy opportunity for this submodule.

Table 3.4-I Candidate Frequencies For General Purpose Scalar Gyro Or Accelerometer Modules

DIGITALLY PHASE LOCKED WHEEL DRIVE FREQUENCIES			SUSP/SIGNAL GENERATOR DIGITALLY PHASE LOCKED TO WHEEL ϕ_A	INTERROGATE OR TORQUE SCALING FREQUENCIES	TEMPERATURE CONTROL
1ϕ (SPLIT) 400/800	2ϕ 400/800/1600	3ϕ 400/1200/2400	ALL WHEEL FREQUENCIES MAY BE OPTIONALLY USED - IN ADDITION THE FOLLOWING SHOULD BE AVAILABLE	ALL WHEEL SUSP. OR S.G. FREQ. MAY BE OPTIONALLY USED IN ADDITION	1
800/1600	800/1600/3200	800/2400/4800	12,800	102.4 (PWM ONLY)	10
1200/2400	1200/2400/4800	1200/3600/7200	25,600	204.8 (PWM ONLY)	30
1600/3200	1600/3200/6400	1600/4800/9600	28,800		50
			51,200		100
					200

3.4.4 Pulse Torque Electronics Submodule

A block diagram of the pulse torque electronic (PTE) submodule is shown in Fig. 3.4-4. This submodule will require major design effort to produce a loop capable of functioning with a variety of different gyros or accelerometers. Selectable components external to the main PTE hybrid package will be required to adjust gains, phasing, torquer current, etc., for the specific gyro or accelerometer.

For a given gyro rate capability, the torquer power will be directly proportional to the torquer resistance and angular momentum, and inversely proportional to the torquer sensitivity. The instrument designer generally tries to package as much torquer sensitivity per unit resistance in the available space alloted in the inertial component. This method of increasing rate capability is optimum because lowering the angular momentum will decrease torquer power, but at the sacrifice of drift stability. The same comments apply equally to accelerometers.

The relationship between equivalent input axis rate and torquer power is plotted for four gyros in Fig. 3.4-5. For a 60 deg/s rate input, the 18 IRIG Mod-B requires 3 watts of torquer power and the 13 IRIG requires less than 0.1 watt. For applications requiring high dynamic rates a low momentum instrument, such as the 13 IRIG, is

FREQUENCY (Hz)(1)	USED ON:	POWERS OF:		
		2	3	5
10	TEMPERATURE CONTROLLER	1	0	1
20	TEMPERATURE CONTROLLER	2	0	1
50	TEMPERATURE CONTROLLER	1	0	2
100	TEMPERATURE CONTROLLER	2	0	2
200	TEMPERATURE CONTROLLER	3	0	2
400	WHEEL DRIVE	4	0	2
800	WHEEL DRIVE	5	0	2
1000		3	0	3
1200	WHEEL DRIVE	4	1	2
1600	WHEEL DRIVE	6	0	2
2000	WHEEL DRIVE	4	0	3
2400	WHEEL DRIVE	5	1	2
3200	WHEEL DRIVE	7	0	2
3600	WHEEL DRIVE	4	2	2
4800	WHEEL DRIVE	6	1	2
6400	WHEEL DRIVE.	8	0	2
7200	WHEEL DRIVE	5	2	2 (2)
9600	WHEEL DRIVE	7	1	2 (3)
12,800	S. G.	9	0	2 (4)
1,000,000	BUS INTERROGATION	6	0	6

(1) Frequency = $2^X \cdot 3^Y \cdot 5^Z$

where,

X = powers of 2
Y = powers of 3
Z = powers of 5

(2) 9.0 MHz is required to attain a 7200 Hz symmetrical (square) wave.

i.e.

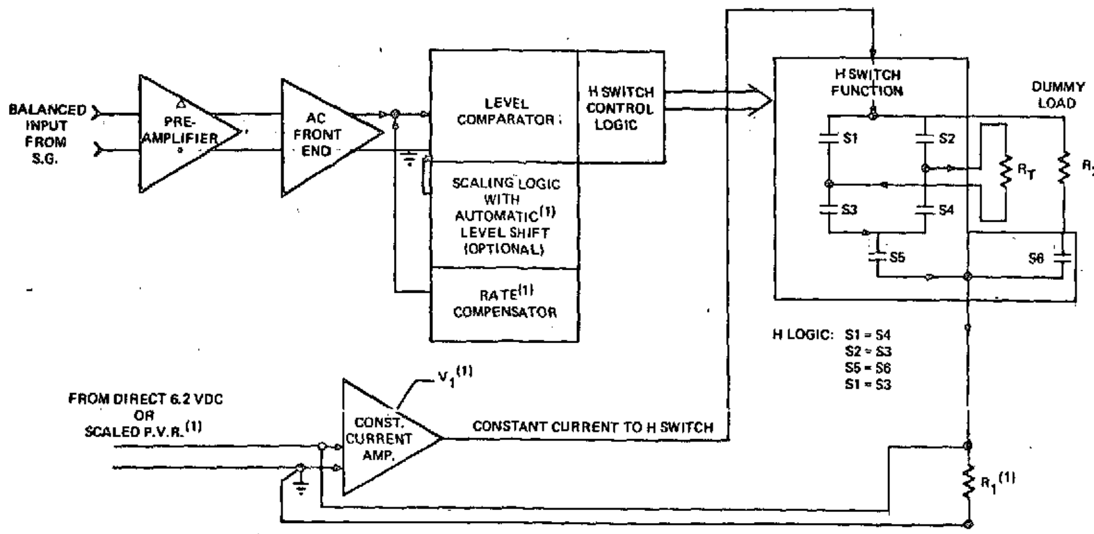
$$= \frac{9.0 \times 10^6}{7.2 \times 10^3} = 2 \times 5^4$$

Since 5^4 dividers are not symmetrical, a multiple of 2 is present for squaring. A 7200 Hz nonsymmetrical clock pulse can be derived from 4.5 MHz.

(3) A direct symmetrical divider for 9600 Hz, and all frequencies below it, would require a 36 MHz crystal. For a number of practical reasons, the crystal frequency should be close (within, say 20% of) to 10 MHz. Therefore, a 9600 Hz symmetrical square wave will be derived by frequency multiplier.

(4) A direct symmetrical divider for 12,800 Hz, and all frequencies below it, would require a 68 MHz crystal. Using a 10 MHz crystal, 12,800 Hz will be derived from 6400 Hz with a multiplier.

Table 3.4-II General Purpose Scalar For Gyro or Accelerometer Module



*May be alternatively located at accelerometer or gyro for reduced noise.

(1) Varies as a function of specific device and full scale range desired. Must be adjusted by simple change of external components.

Fig. 3.4-4 Functional Diagram of Pulse Torque Electronics

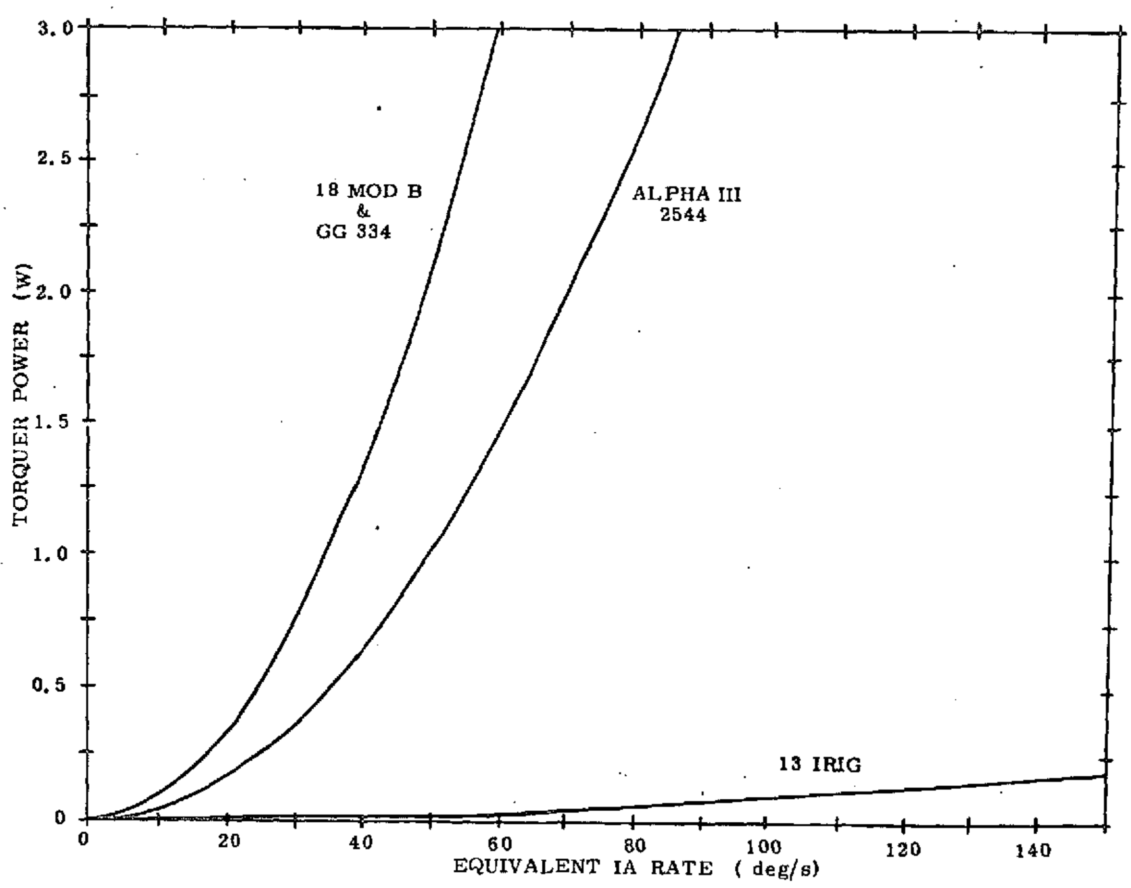


Fig. 3.4-5 Torquer Power vs Equivalent Input Axis Rate For Four Gyros

the only instrument available to meet that requirement. To obtain scale factor performance in the one ppm range, torquer power should not exceed 3 watts. This level of power dissipation in the available volume is commensurate with state of the art semiconductor circuit design. To obtain performance better than 1 ppm, power should be limited to the lowest possible level.

3.4.5 Pulse Torque Power Supply Submodule

The low and moderate performance modules will not require any additional voltage regulation. This submodule, therefore, will only be required in the high performance module, and will regulate the +15 Vdc for the precision voltage reference (PVR) and other required voltages to 0.01%. Series regulators of standard hybrid or IC design can be adapted to perform this function. The regulator will derive power from the 1% line pre-regulator, restricting the compliance range and resulting in an efficient design.

3.4.6 Precision Voltage Reference Submodule

A single, precision, voltage reference (PVR) submodule design, with selection, processing and external options to account for rising scale factor stability requirements, Fig. 3.4-6, will satisfy the requirements of the three classes of inertial instrument modules. Functionally, the PVR module contains;

1. A basic hybrid substrate design.
2. A basic array and interconnections for two Zener diodes, and fixed precision resistors.
3. A buffer amplifier to provide buffered reference(s) to the A/D and regulator functions.
4. An array of MSI Logic (or ROM) for mode/scaling control by digital inputs to provided terminals.
5. Terminal points for the connection of scaling resistors.

The submodule substrate is the same for the three classes of modules. The low performance module, requiring a scale factor stability of 100 ppm, will utilize the circuit elements with no burn-in or aging requirements, and good quality off-the-shelf diode chips will suffice. Resistors can be .01% and no temperature compensation is required.

Provision for scaling resistors to provide a low voltage alternative for those instruments requiring a low torquing current could be included as an external option.

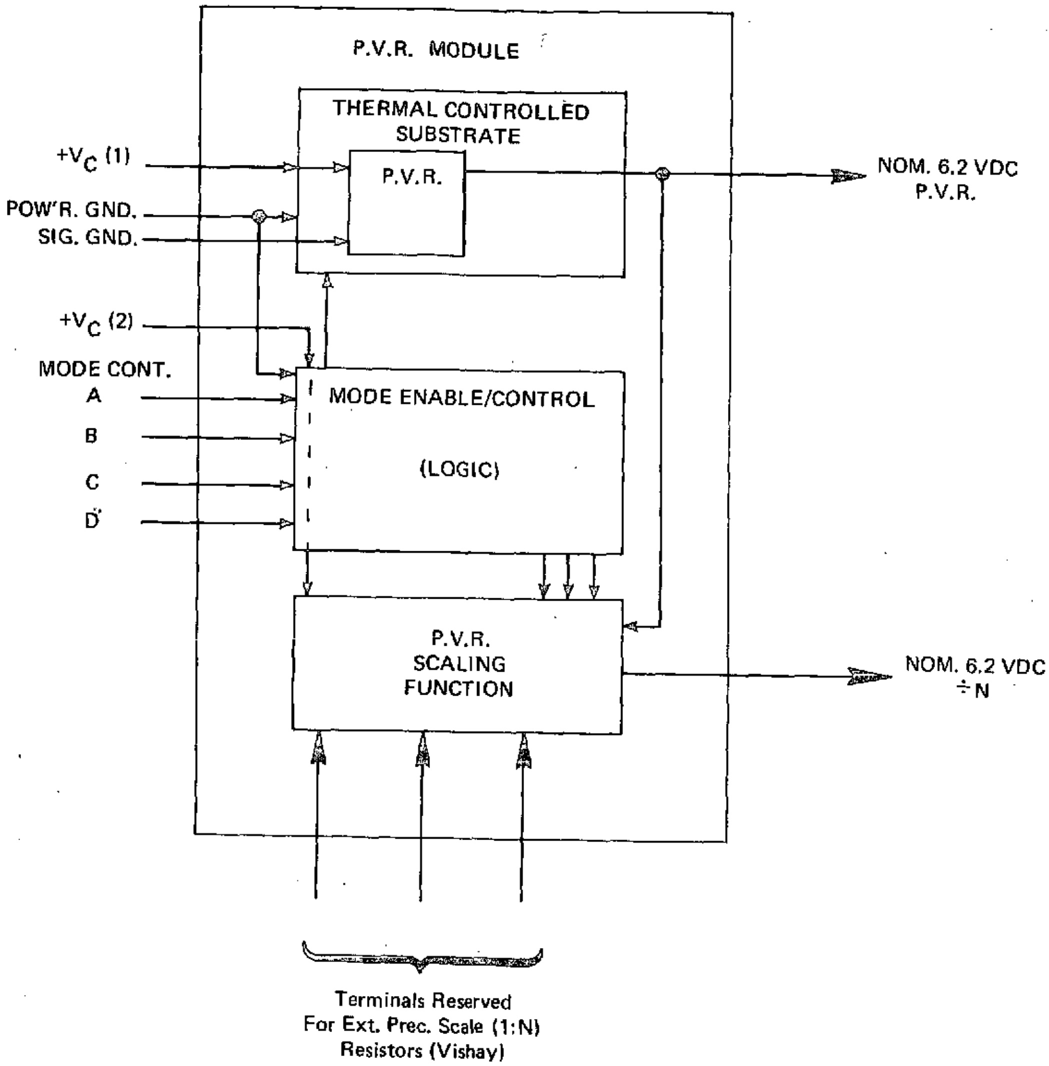


Fig. 3.4-6 Precision Reference Module

Also, the multi-level switching chips (logic and FETS) might not always be required for the low performance PVR submodule. This version includes a buffer amplifier(s) so that it can be used as a bus reference for a plurality of devices (gyros or accelerometers) and A/D encoders. This multiple usage contributes to lower cost.

The moderate performance module (providing a scale factor stability of 10 ppm) uses the same parts as the low performance module, but the burn-in and fine adjustment necessary to obtain the improved performance would be included. Multi-level switching FETs and control logic would be mounted on the substrate to accommodate optional uses as required.

The high performance module requires a scale factor stability of better than 1 ppm. This PVR submodule is essentially identical to the moderate performance PVR with the added requirement for independent temperature control by means of a wrap-around miniature oven (positive temperature coefficient semiconductor) or a substrate mountable, active, zone temperature controller located close to the PVR zener reference diodes.

3.4.7 Switch Drive Submodules

Four switch drive functions are conceptually shown in Fig. 3.4-7. A versatile, dual switch submodule will be employed in one of these four variations to accomplish all the switching functions. The four types of switches, types 1-4, are described as to function and operation as follows:

Type 1: This configuration is commonly used when driving a load that must be isolated thru a transformer and for direct ac switching regulators. The clock scaler module delivers a zero and 180° set of pulses that toggles Q_A and Q_B consecutively to generate a symmetrical square wave at the transformer secondary. Q_A and Q_B are transistor switches which may be mechanized as one or two pre-stage switches and associated resistors.

If both Q_A and Q_B are "off" for 60 electrical degrees in each half cycle, a 3 state symmetrical wave with 3rd harmonic suppression is generated. This wave has proven useful in reducing filter component size with certain ac loads and for general noise reduction.

Type 2: This type switch is essentially two type 1 switching functions driven with appropriate timing waves. When the ac load is floated, eliminating the need for transformer isolation, this switch is appropriate. Also, both symmetrical and non-symmetrical 3 state drives (+,0,-) or symmetrical and non-symmetrical 2 state drives (+,-) (+,0) (0,-) can be used. A single standard H (4 transistors) configuration could perform both type 1 and type 2 function but the effect on both volume and cost would be adverse.

Type 3: This switch type is specifically configured for use with pulse torque electronics. For the low performance modules and some of the moderate performance modules, this configuration as shown is adequate. However, some moderate and the high performance modules

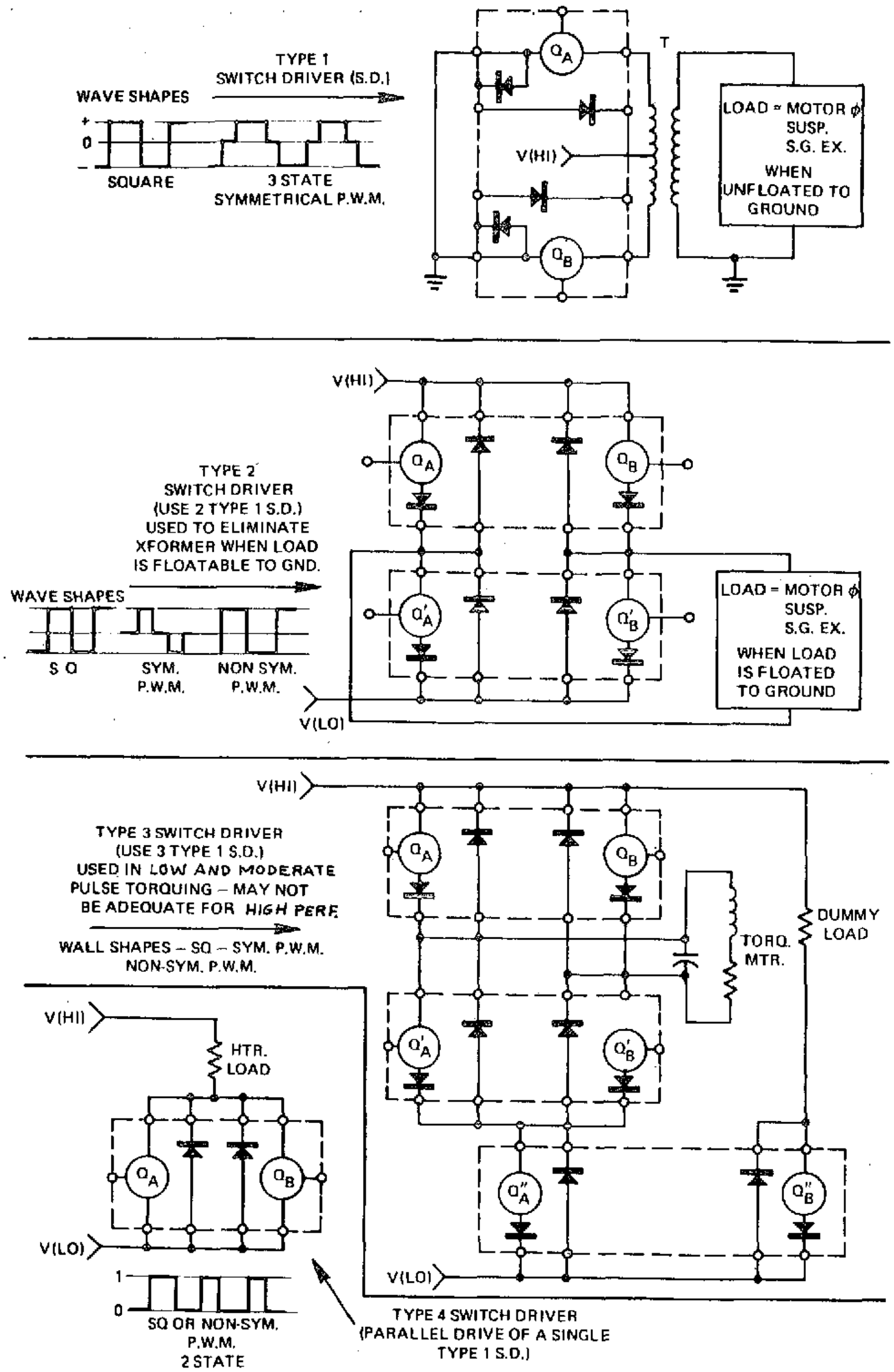


Fig. 3.4-7 Switch Drives

will probably require higher performance transistors. Otherwise, three type 1 switches are connected to produce a type 3 switch.

Type 4: This configuration is useful in temperature controllers for heater drive, i.e., drive up, then relaxation or cooling. Either Q_A or Q_B or both in parallel are implemented as required. Q_A and Q_B can also drive separate heaters for two-zone controls.

3.4.8 28 Vdc Power Conditioning Submodule

This device connects to the aircraft grade, 28 Vdc power, (or other 28 Vdc source) with a tolerance of -6 to +4 Vdc and regulates its output to 1%. This conditioned dc is thereby isolated from the 28 Vdc bus, and used for all module power except heater power (the heaters, because of their high start-up demand, use unconditioned 28 Vdc bus power). This submodule is essentially a switching regulator designed with a free running multivibrator on the input side to insure self-starting in the inertial instrument module.

Once the clock and scaler module is functioning, the regulator is synchronized by photo optic coupling to its normal conversion frequency. 25 to 50 kHz is the probable range of the synchronization frequency.

Secondary circuits with voltages less than 20 Vdc could employ Schotky diode rectifiers to obtain efficiencies as high as 70%. In applications where regulated prime power is available, this submodule could be eliminated with an attendant saving in volume and power requirements.

3.5 Module Volume and Power Estimates

3.5.1 Volume Estimates

Assuming dense hybrid packaging, volume estimates for the circuitry described in the previous section was performed. Packaging in this analysis was based on non radiation hardened designs. Electronic designs hardened for DOD type radiation application would require approximately 20% more volume. The pulse torque power supply (PTPS) and the power conditioning submodule are the largest submodules (each are 4.1 cubic inches) used in the strapdown inertial modules. For the following volume estimates, it was assumed that only one of these two submodules are used. This seems reasonable since: (1) the PTPS is only required in the high performance module and (2) power conditioning may be performed outside the module or (3) another power source which does not have to be conditioned may be available. The results are summarized in Table 3.5-I. This analysis shows a total of three possible module sizes.

1. A small gyro module with a volume of 25.9 cubic inches is predicted for gyros with a volume of less than 4 cubic inches. (These gyros include Timex, IG-10; Honeywell, GG1111; Northrup, GIG6; Lear-Siegler, 1903 HJ; CSDL, 13 IRIG and Kearfott 2544.)
2. A moderate size gyro module with a volume of 41.9 cubic inches is predicted for gyros with a volume of less than 12 cubic inches. (These gyros include Northrup, K7G, CSDL, 18 IRIG and CSDL, TGG.)
3. An accelerometer module with a volume of 21.6 cubic inches is predicted for instruments with a volume of less than three cubic inches. (These accelerometers include the Kearfott, 2401, CSDL, 16 PM PIP and Honeywell, GG177.)

These estimates are based on high density electronic packaging. To reduce costs, a less dense packaging technique might be appropriate. Trade-off studies of electronics size, reliability and costs were not performed for this study and are suggested for future investigations. The electronics and interconnections account for 17.9 cubic inches in the gyro module. Thus the gyro volumes (4 t o 12 cubic inches) do not appear to be an excessive percentage of the total module volume. Efforts to reduce gyro volume below the 4 cubic inch level will not significantly decrease the total strapdown module size.

Table 3.5-I Module Volumes (Cubic Inches)

	GYRO		ACCELEROMETER
	SMALL	MEDIUM	SMALL
Electronics	7.8	7.8	6.8
Interconnect	10.1	10.1	8.8
Gyro or Accelerometer	4	12	4.0
Mechanical Hardware	4	12	4.0
	25.9	41.9	23.6

TRIAD SYSTEM VOLUME

(3) Small Gyro Modules + (3) Accelerometer Modules 148.5 $in.^3$

(3) Medium Gyro Modules + (3) Accelerometer Modules 196.5 $in.^3$

3.5.2 Power Estimates

Table 3.5-II shows lower and upper limit power estimates for gyro and accelerometer modules and the contributing load from each submodule. Non-radiation hardened designs are assumed; hardened designs for DOD application require approximately 10% more power. The minimum gyro module load is 4.61 watts, and the minimum accelerometer module load is 2.61 watts. A triad gyro and accelerometer strapdown system using the small low angular momentum gyros

Table 3. 5-II Strapdown Module Power Estimates

	GYRO			ACCELEROMETER		
	Regulated Power		Unregulated Power	Regulated Power		Unregulated Power
Submodule	Minimum	Maximum		Minimum	Maximum	
Wheel supply	2.0	5.1				
Suspension	0	.40		0	.40	
S. G.	.21	.21		.21	.21	
Temp Controller	.2	.2	1.0 (2)	.2	.2	1.0 (2)
PVR	.1	.1		.1	.1	
A/D (1)	.2	.2		.2	.2	
I/O	.4	.4		.4	.4	
Clock/Scaler	.1	.1		.1	.1	
PTE	.3	5.0		.3	2.0	
PTPS	.1	2.0		.1	.80	
TOTAL	a) 3.61	a) 13.71	c) 1.0	a) 1.61	a) 4.41	c) 1.0
Regulator Loss (b)	1.08	4.11		.48	1.32	
Total Regulated (a + b)	4.69	17.82		2.09	5.73	
Total Regulated plus Unregulated (a + b + c)	5.69	18.82		3.09	6.73	
Total without Regulated Loss (a + c)	4.61	14.71		2.61	5.41	

and assuming power regulation is not needed would require 21.7 watts. The upper power requirement for a triad gyro and accelerometer system would be 76.6 watts if the high angular momentum gyros are used, less power efficient accelerometer modules are used, and the requirement that power regulation be performed in each inertial component module is invoked.

(1) The A/D device takes a peak power of 2 watts. By power mode control this device is full "ON" only 10% of the time in non-test or flight usage. During laboratory tests it may be full "ON."

(2) The heaters have a peak demand of 10 watts/zone at start-up. The average heater power requirement, after stabilization, of 1 watt can be further reduced by more exotic thermal control strategies but at an additional expense.

3.6 Submodule Materials and Processes

To achieve the performance, flexibility and reliability required for the functionalized module concept at low cost will depend to a large extent on the choice of effective materials and processes for the submodule fabrication. Hybrid substrates, component selection and attachment, deposition techniques, chip types, multilayer boards and connectors currently available or anticipated as mature technology in the next two to three years form the basis of the design study and comments on the more important elements are included in the following paragraphs.

1) Hybrid Substrates

For the present, the assumption is made that the materials selected will not be influenced by radiation levels. Radiation levels which would substantially degrade, temporarily or permanently, the materials identified are not anticipated.

Basic to the design and fabrication of hybrid circuitry is the method of semiconductor attachment. Of the many methods proposed and actually used, only two have gained wide acceptance. One is the familiar chip brazing followed by bonding using thermocompression with gold wire or ultrasonic with aluminum wire. Good chip brazing provides the best thermal transfer out of the chip. Epoxy bonding as a substitute for brazing has gained wide acceptance and offers several advantages. All of these operations tend to be tedious and repair is not facilitated. The second method uses a special chip with beam leads formed on it. The chip can be placed face down and all the leads bonded simultaneously. Conceivably, all the leads of all chips on one circuit could be bonded at once. The major drawbacks are the need for special chips and the lower power dissipation capability of the chip. We have chosen to use beam leads wherever possible and epoxy and wire bonded chips when beam leads are not available. Such techniques as spider bonding, evaporated connections, BLIP and planar coax, as possible means of avoiding chip processing problems, have not been considered in this study because these schemes have not yet passed into the pilot line or production stage and their use would pose a substantial risk.

2) Selection and Attachment of Components

The conductor area which mates with the semiconductors should be pure gold, either plated or fired, for good bonding. Solder does not bond well to gold; therefore, a second conductor material such as a platinum-gold alloy should be used where soldering is to be done. Only brazing and/or thermocompression bonding techniques should be used.

Thick film resistors are recommended down to 1% tolerance. For lower than 1% tolerance, photo etched metal film resistors (such as built by Vishay) should be used. They should be bonded in place and soldered or conductive epoxy connected. Small chip resistors (30 x 30 mils and 5 to 10 x 10^5 ohms) may be used in place of the thick film resistors. These are secured with adhesive and wire bonded.

Chip capacitors should be used in most applications. They should be connected in the circuit using solder or conductive epoxy. Small value capacitors may be silk screened, particularly if it is necessary to screen crossovers. The capacitors can then be made at the same time. Inductors should be mounted as discretes using epoxy to attach them to the substrate and solder or conductive epoxy to connect them into the circuit.

The package should be all alumina for strength and thermal conductivity, except for the kovar top, which is brazed or soldered in place. Leads should exit on approximately 50 mil centers. The maximum cavity size accommodates a 1 x 2 inch hybrid circuit. The hybrid circuit should be cemented in place in the package and connected to the input-output leads using wire bonding.

Since many square waves are used, considerable care in packaging to reduce noise is required. This reduction can be accomplished by spacing critical leads as far apart as possible and by the liberal use of ground planes in mother boards and on the backs and covers of hybrid packages. Lines on the mother board can be separated by separate ground lines where necessary.

The high power density caused by dense packaging requires that special attention be paid to the thermal design. Thermal problems can be solved by designing mechanical members, electrical connections, and connectors as adequate heat paths in preference to the introduction of additional material for this function.

3) Size Estimates of Hybrid Circuits

Table 3.6-I shows the sizes of components used in calculating the total areas necessary for hybrid circuits. These areas are estimated conservatively to allow for alternate production techniques and to encourage high yields. More dense packaging might allow a reduction in size of up to 50% but at a substantial increase in price, and with added problems in assembly and possibly reduced reliability. Components such as inductors are sized on an individual basis. They are normally approximated by using twice the square of the diameter or twice the major area of the component.

The hybrid circuit is contained in a hermetic package to prevent deterioration from the atmosphere with time. The maximum circuit thickness is normally 0.125 in. The dimension of the thickest component determines the thickness of the package. A rugged top and bottom, adding .075 in, is necessary because of the anticipated large size of the substrate (about 1 in x 2 in). The wall of the package adds .075 in to the sides of the package and the wall. Package internal input/output pads add .125 in to each side where leads exit.

Two principal approaches for interconnecting the packaged hybrid circuits are to connect the hybrid to a PC card mounted on a header and plugged into a mother board system, or to provide each hybrid circuit with an edge card type connection instead of leads. The second approach reduces the volume considerably but introduces problems in providing adequate thermal paths in the assembly. In addition to the packaging volume required for interconnecting a hybrid board into a submodule, an additional volume is required to interconnect these submodules. For the module volume estimates in Section 3.5, it was assumed that the submodule's interconnections are 1.3 times the volume of the electronic submodules.

Table 3.6-I

Hybrid Circuit Sizing Information

	Area (Sq. In.)
1% Resistor	.03
.01% Resistor	.10
Diode	.03
Transistor	.03
OP amplifiers	.04
Logic Circuit 16 leads	.06
LSI 36 leads	.12
Capacitors (NPO)	
10-180pf	.03
180-100pf	.03
100pf-.015mf	.20
Capacitors (k8000)	
.01-.056 mf	.03
.056-.27 mf	.08
.27-1.5 mf	.30
1.5-3.3 mf	.70
Terminals	.01

3.7 Thermal Design Factors - Introduction

The design of a temperature control system for the standardized, strapdown inertial component modules is primarily dictated by the module performance requirements, the impact on the standardization and submodularization concepts costs, and reliability. An efficient thermal design results from an optimum combination of control of the thermal impedance of the mass to be temperature regulated and the design of the associated temperature controller. Various methods of regulating the thermal impedance between a heat source and a heat sink include the use of mounts to decrease thermal contact, the employment of additional fasteners or filler materials to increase thermal contact, the application of different surface finishes to control radiation, the orientation of certain surfaces in order to heat or cool by convection, the use of radiation louvers, the use of thermal fuzz, the control of coolant temperature and flow rate, use of heat pipes, etc. The prospects for combining the use of these thermal impedance techniques with the standardized and modularized concept designs without excessively proliferating the affected submodules appear unlikely. The temperature controller design will have to bear the principal burden.

The design of the temperature controller is dependent on the type of temperature sensor and thermal power source used. Thermostats, thermistors and resistance wire are the most frequently used temperature transducers. Typical thermal power sources are: conventional heaters, thermoelectric elements, and positive temperature coefficient regulators. Other factors influencing the temperature controller design are inertial component characteristics such as, the power/heat dissipation rate, temperature sensitivity, thermal response, sensor and heater location and thermal resistance.

The following types of temperature control systems were considered in this study.

1. On-Off (Limit Switching)
2. Positive Temperature Coefficient (Passive Regulator)
3. Proportional (dc)
4. Pulse Width Modulated
5. Computer Programmed
6. Thermoelectric
7. Zonal
8. Heat Pipes

The first type, using a creep type bimetallic actuator, is simple, inexpensive and accurate enough to provide the $\pm 5^{\circ}$ temperature control which is probably more than adequate for low performance modules. Contact life limits the reliability. A mercury-in-glass design provides better performance, still at low cost, and an extended life characteristic. This unit would be used in conjunction with a simple switch submodule to limit the contact switching currents.

A passive self-heating and temperature sensing device is another simple, low cost temperature controller for low performance modules. In this system the voltage is applied directly to the PTC element which self-heats to a predetermined temperature at which point the resistance changes abruptly thereby regulating the current and the heat input. At present these devices are available only at a limited number of discrete temperatures. For the standardized module concept this type of controller would be mounted on the inertial instrument submodule.

Two types of controllers are available in the generic class of proportional controllers, one analogue and the other digital. The digital type is identified as a pulse width modulated controller. For moderate, and high performance modules, a proportional controller with higher accuracy circuit components is required to achieve a high performance submodule. Several of these controllers would be required for those high performance applications where zone temperature control is used for the gyro.

The pulse width modulated temperature control circuit can be adapted to be remotely controlled by a programmed computer. By controlling the switching frequency and the ratio of on-time to off-time of the chopper transistor with a pulse width modulated (PWM) source, the rate of temperature change and the temperature control can be programmed. In practice, this approach could include provision for a lower inertial component temperature when the system is in standby to save power. It could also respond to software initiated instructions to achieve flexibility for a standardized design.

Two additional approaches to temperature control were also considered in this study. These are thermoelectric and heat pipe.

Thermoelectric devices consist of pellets of dissimilar semiconductor materials sandwiched between metal plates. They act as a bipolar heat pump, capable of both heating and cooling depending on the direction of current flow. The bipolar characteristic allows substantial savings in temperature control power by setting the system operating point at zero nominal control power.

The thermoelectric devices can be controlled either by a DC proportional controller or by a pulse width modulated controller. Compared to thermal control systems using conventional heaters, power requirements for thermoelectric control for some applications are reduced by 80 to 90%.

The dynamic response of a system using thermoelectrics can be far superior to a system using only heaters. Thermoelectrics at low heat loads can also control a much greater heat flow than the power required to operate them. This advantage, however, is offset by the low voltage required to operate these devices, causing losses in the electric power conversion process.

Costs for thermoelectric control based on current technology are significant and this approach would probably be used only as a special installation to satisfy a unique system requirement.

The heat pipe shown in Fig. 3.7-1 is a high performance heat transfer device which can transport heat at high rates with very small temperature gradients. It consists of a container enclosing a volatile fluid that removes thermal energy from one part of the container by evaporation and transfers this energy to another part of the container by condensation. The capillary action of a wick returns condensate to the evaporation area, providing continuous transfer of thermal energy with essentially no temperature gradients. Two types of heat pipes are available, both operating on the same principle. One type simply transports heat; the other type also maintains a constant temperature. The constant temperature pipe includes a reservoir at the condensor section. This reservoir holds a noncondensible gas which provides a temperature-stabilizing gas-vapor interface.

Advantages of heat pipes in addition to their efficient heat transfer capability are that they have no moving parts, are simple, and are completely self-contained.

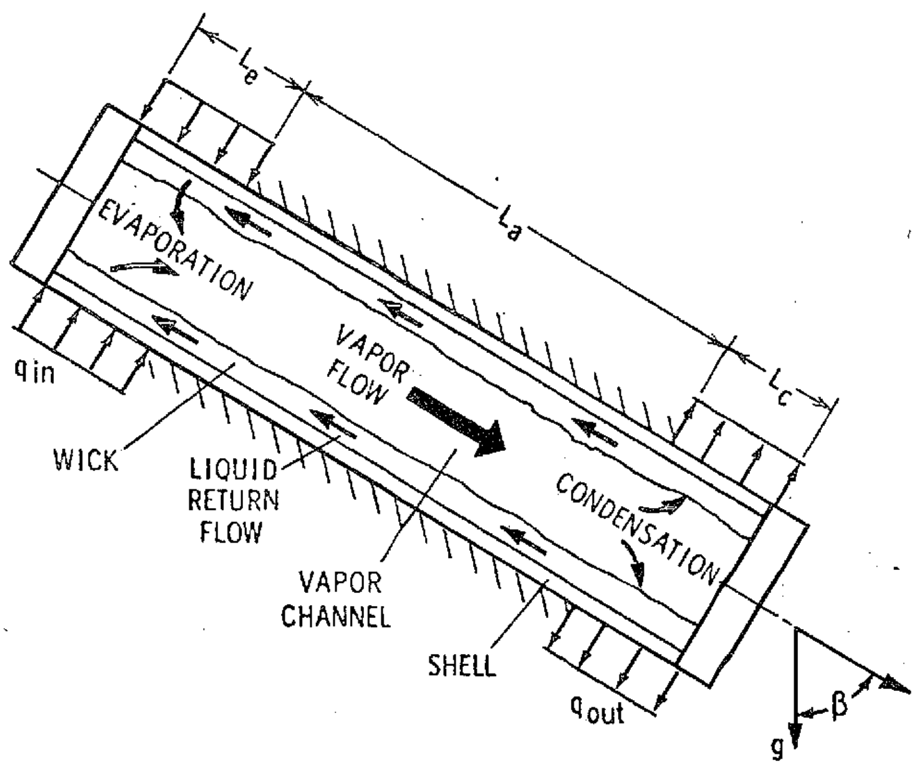


Fig. 3.7-1 Basic Heat Pipe Configuration

Application of heat pipes in inertial systems has been as an integrated element of the inertial instrument. In this context it does not affect the standardized modularization concept. Further consideration of this approach external to the instrument for use in moderate and low performance modules may be warranted.

4.0 Conclusions and Recommendations

This preliminary strapdown modularity study has presented the means and advantages of developing common strapdown inertial component modules. The significant gain in reduced cost of ownership with the modularity approach resulting from ease of maintenance, increased reliability and producibility over present inertial system design practices was discussed. It was shown that three classes of modules (high, moderate and low performance) would be required to meet the various system needs. It has determined a group of candidate instruments representing the three performance classes and discussed the incompatibilities which must be taken into account in a standardization program. Electronic design, hybrid packaging and thermal control considerations as applicable to the different module classes were presented.

To demonstrate the significant advantages of the modularity approach, this study should be extended to a hardware demonstration. A typical hardware demonstration might include the following phases:

1) determine a common module interface. The common inertial component interface would be determined by studying the requirements for current and anticipated spacecraft and military applications. Considerations such as anticipated environments, available voltages and required performance would be used to evolve a standardized mechanical and electrical module interface.

2) test breadboard electronics with different inertial instruments to demonstrate that a set of electronics can be constructed to mate with the candidate instruments and yield a common interface with the required level of module performance. This task should first approach the low performance module application. The lower component cost and performance required for that module will offer an economical demonstration program. The program could then be extended to include a limited number of moderate performance inertial components.

3) design and build hybrid circuitry to demonstrate that size, power, cost, reliability and performance goals can be achieved with an actual design. This task should be demonstrated on a single submodule. For example, a pulse torque power supply can be designed and built as hybrid circuits. Such a configuration will afford a demonstration of packaging techniques, sizes, power component availability, reliability and performance. The resulting hybrid module would be evaluated with the various inertial components as described previously in phase 2.

In addition to the single-degree-of-freedom instruments used in this study, a comprehensive modularity study should consider two-degree-of-freedom instruments and multisensors.

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