

## Space Flight Operations Contract

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# Inertial Measurement Unit Workbook

**IMU 21002**

February 28, 2006

Final Version

This document has been reviewed and updated.  
No subsequent updates to this document are anticipated or required due to the  
approaching shuttle program closure.

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**Inertial Measurement Unit Workbook  
IMU 21002**

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**Inertial Measurement Unit Workbook  
IMU 21002**

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<u>Page No.</u>	<u>Change No.</u>
Preface	Rev B
i – iii	Rev B
1-1 – 1-5	Rev B
2-1 – 2-21	Rev B
3-1 – 3-12	Rev B
4-1 – 4-10	Rev B
5-1 – 5-4	Rev B
A-1 – A-3	Rev B
B-1 – B-5	Rev B
C-1	Rev B
D-1	Rev B

## PREFACE

The Inertial Measurement Unit Workbook, IMU 21002, was prepared by United Space Alliance (USA), Flight Operations. The content of this document was originally created by Lisa Martignetti of the DPS/Navigation Group, Flight Training Branch, Space Flight Training Division, Mission Operations Directorate (MOD), Lyndon B. Johnson Space Center (JSC), National Aeronautics and Space Administration (NASA). Technical documentation support was provided by Integrated Documentation Services (IDS), Hernandez Engineering, Inc. Any questions concerning this training manual or any recommendations should be directed to the training manual book manager, Carla Sugar, department DT35, 281-244-8487.

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A Training Materials Evaluation is included at the end of this document. Inputs on this sheet will be used to evaluate the lesson material. You do not need to sign the sheet.

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## CONTENTS

Section	Page
<b>1.0 INTRODUCTION .....</b>	<b>1-1</b>
1.1 PERFORMANCE OBJECTIVES .....	1-1
1.2 QUESTIONS .....	1-5
<b>2.0 SYSTEM DESCRIPTION .....</b>	<b>2-1</b>
2.1 PERFORMANCE OBJECTIVES .....	2-1
2.2 GIMBALS .....	2-1
2.3 GYROS .....	2-3
2.4 RESOLVERS .....	2-3
2.5 ACCELEROMETERS .....	2-4
2.6 STABILIZATION LOOPS .....	2-4
2.7 PLATFORM REORIENTATION .....	2-4
2.8 SKEW .....	2-5
2.9 BUILT-IN TEST EQUIPMENT .....	2-6
2.10 THERMAL CONTROLS .....	2-8
2.11 ELECTRICAL POWER .....	2-11
2.12 GPC INTERFACE .....	2-14
2.13 DISPLAYS .....	2-14
2.13.1 OVERRIDE Display (SPEC 51) .....	2-15
2.13.2 IMU ALIGN Display (SPEC 21) .....	2-16
2.13.3 GNC SYS SUMM 1 Display (DISP 18) .....	2-18
2.13.4 ENVIRONMENT Display (DISP 66) .....	2-19
2.13.5 SM SYS SUMM 1 Display (DISP 78) .....	2-19
2.13.6 GND IMU CNTL/MON Display (SPEC 104) .....	2-20
2.14 QUESTIONS .....	2-21
<b>3.0 SYSTEM OPERATIONS .....</b>	<b>3-1</b>
3.1 PERFORMANCE OBJECTIVES .....	3-1
3.2 MODES OF OPERATION .....	3-1
3.3 PREFLIGHT .....	3-2
3.4 PRELAUNCH .....	3-2
3.5 ASCENT .....	3-3
3.6 ORBIT .....	3-3
3.7 REFERENCE STABLE MEMBER MATRIX .....	3-4
3.8 IMU ALIGNMENT OPTIONS .....	3-4
3.8.1 Star Align .....	3-4
3.8.2 IMU/IMU Align .....	3-9
3.8.3 Matrix Align .....	3-10
3.9 ENTRY .....	3-11
3.10 QUESTIONS .....	3-12

<b>Section</b>		<b>Page</b>
<b>4.0</b>	<b>SYSTEM MALFUNCTIONS .....</b>	<b>4-1</b>
4.1	PERFORMANCE OBJECTIVES .....	4-1
4.2	REDUNDANCY MANAGEMENT SCHEME .....	4-1
4.3	ATTITUDE REDUNDANCY MANAGEMENT .....	4-2
4.4	VELOCITY RM.....	4-5
4.5	THERMAL CONTROL SYSTEM.....	4-7
4.6	DATA PATH FAILURES .....	4-7
4.7	QUESTIONS.....	4-10
<b>5.0</b>	<b>DIFFERENCES IN THE BFS .....</b>	<b>5-1</b>
5.1	PERFORMANCE OBJECTIVES .....	5-1
5.2	QUESTIONS.....	5-4
<b>APPENDIX</b>		
<b>A</b>	<b>ACRONYMS AND ABBREVIATIONS .....</b>	<b>A-1</b>
<b>B</b>	<b>ANSWERS .....</b>	<b>B-1</b>
<b>C</b>	<b>MEAN OF 1950 COORDINATE SYSTEM .....</b>	<b>C-1</b>
<b>D</b>	<b>REFERENCES .....</b>	<b>D-1</b>



## FIGURES

Figure	Page
1-1 The IMU location .....	1-2
1-2 IMU platform assembly and coordinate system .....	1-3
2-1 IMU gimbal-mounted platform .....	2-2
2-2 Two-degrees-of-freedom gyro .....	2-3
2-3 IMU skew .....	2-5
2-4 IMU air circulation .....	2-9
2-5 Panels L1 and L4 .....	2-10
2-6 IMU electrical power interface .....	2-12
2-7 Panels O14 and O15 .....	2-13
2-8 Panel O16 .....	2-14
2-9 OVERRIDE display .....	2-15
2-10 IMU ALIGN display .....	2-16
2-11 GNC SYS SUMM 1 display (DISP18) .....	2-18
2-12 ENVIRONMENT display (DISP 66) .....	2-19
2-13 SM SYS SUMM 1 display (DISP 78) .....	2-20
2-14 GND IMU CNTL/MON display (SPEC 104) .....	2-20
3-1 Orbit OPS checklist, IMU ALIGN-S TRK procedure .....	3-6
3-2 Orbit OPS checklist, IMU STAR OF OPPORTUNITY ALIGN procedure .....	3-8
3-3 Orbit OPS checklist, IMU Alignment-IMU/IMU .....	3-9
4-1 IMU three-level attitude selection filter .....	4-2
4-2 IMU two-level attitude selection filter .....	4-3
4-3 Typical attitude FD thresholds, time from any on-orbit alignment .....	4-4
4-4 IMU three-level velocity selection filter .....	4-6
4-5 Typical velocity fault detection threshold .....	4-7
4-6 GPC/FF MDM/IMU data path .....	4-8
5-1 BFS OVERRIDE display (SPEC 51) .....	5-3
5-2 BFS GNC SYS SUMM 1 display (DISP 18) .....	5-3

## 1.0 INTRODUCTION

### 1.1 PERFORMANCE OBJECTIVES

As a result of studying this section, you should be able to do the following:

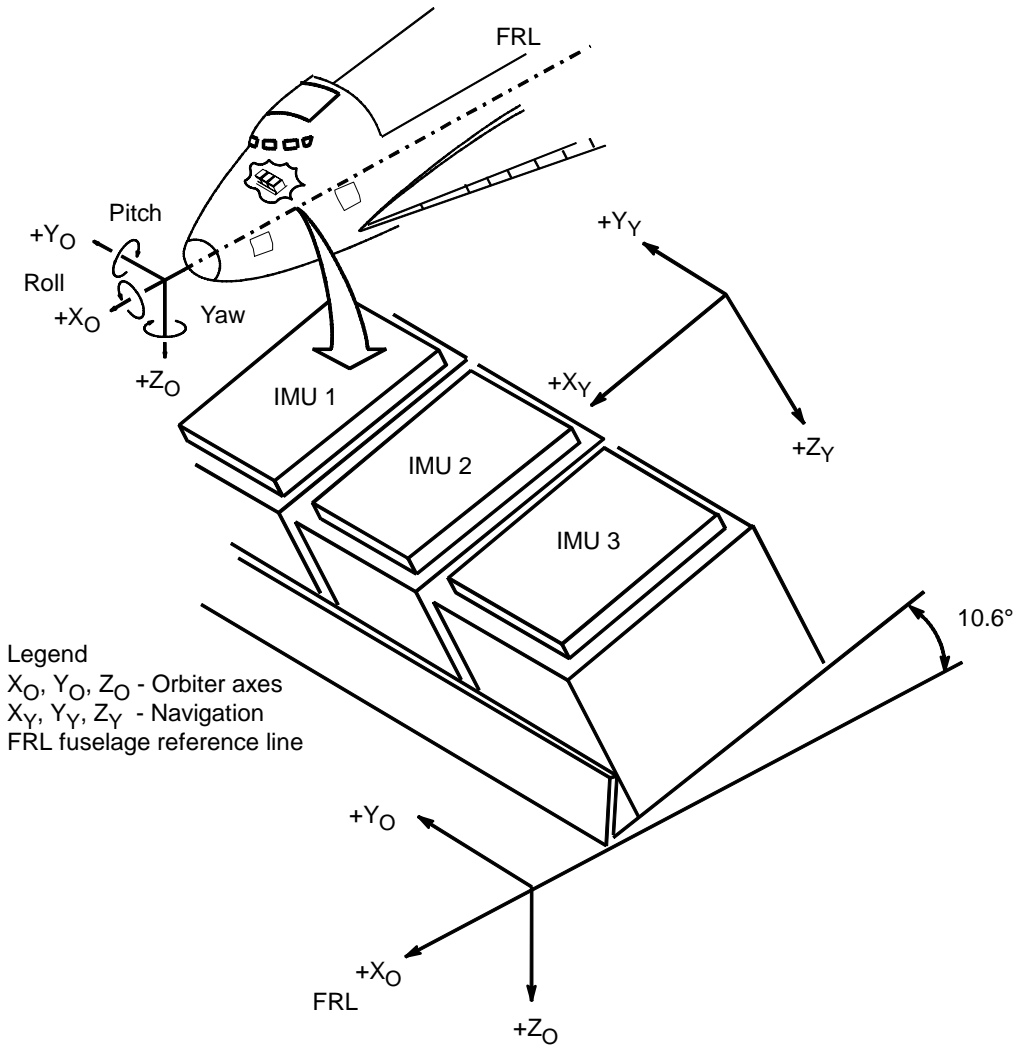
- a. Explain what the Inertial Measurement Unit (IMU) provides
- b. Describe how many IMUs are installed onboard the orbiter

The IMU provides inertial attitude and velocity data to the Guidance, Navigation, and Control (GNC) software functions. Navigation (NAV) software uses the processed IMU velocity data to propagate the orbiter state vector. Guidance uses the attitude data, along with the state vector from the NAV software, to develop steering commands for flight control. Flight control uses the IMU attitude data to convert the steering commands into control surface, engine gimbal, and Reaction Control System (RCS) thruster fire commands.

For redundancy, three IMUs are installed onboard the orbiter, although flight could be accomplished with only one. They are mounted on the NAV base, which is located inside the pressurized flight deck forward of the main instrument panels. The NAV base mounting platform is pitched down  $10.6^\circ$  from the orbiter +X body axis (see Figure 1-1). The purpose of the NAV base is to provide a platform to which the IMUs can be repeatedly mounted with great accuracy. This accuracy enables transformations to be defined that relate IMU reference frame measurements to any other reference frame.

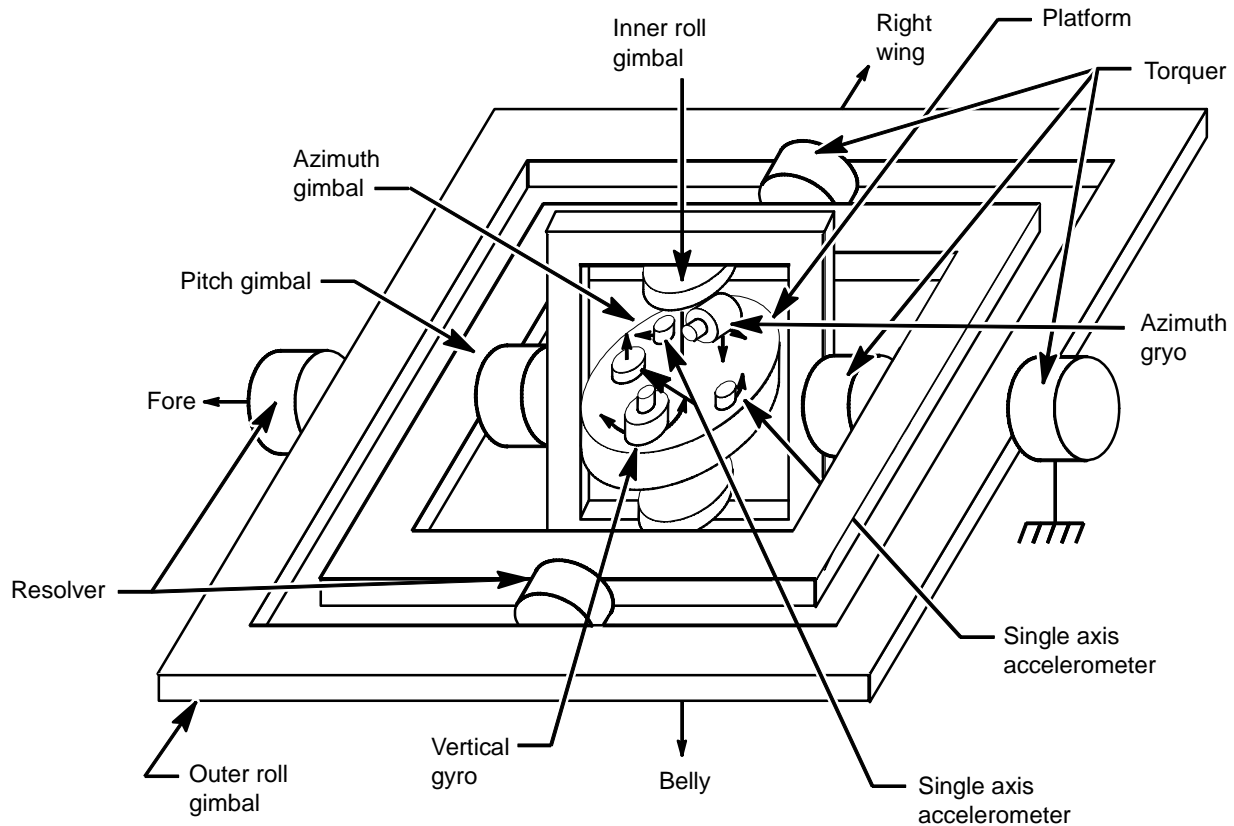
The IMU consists of a platform that is isolated from vehicle rotations by four gimbals (see Figure 1-2). Since the platform does not rotate with the vehicle, its orientation remains fixed in space; that is, an inertial orientation. Mounted upon the platform are the sensors and some of the interface hardware. The inertial sensors consist of two gyros, each having two degrees of freedom and three single-axis accelerometers.

The gyros are used to maintain an inertial orientation of the platform by sensing rotations of the platform due to vehicle rotations. The gyros output a signal proportional to the motion, which is then used by gimbal electronics to drive the appropriate gimbals to null the gyro output. The design of the system is such that this happens almost instantaneously and the platform remains essentially undisturbed, thereby maintaining its inertial orientation while the gimbals respond to the vehicle motion.



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**Figure 1-1. The IMU location**



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**Figure 1-2. IMU platform assembly and coordinate system**

The accelerometers measure linear vehicle accelerations in the IMU inertial reference frame. The input axes of the accelerometers form an orthogonal right-handed coordinate system. The accelerometers output a signal when they are subjected to an acceleration along their input axes. This signal, which is proportional to the acceleration, is then used by the velocity electronics to compute the IMU velocity components.

The resolvers are used to measure vehicle attitude. There are four resolvers in an IMU. A resolver is located at one of the two pivot points between adjacent gimbals. The resolvers electrically measure the angle between the two gimbals. This electrical signal is transformed into a mechanical angle by the IMU electronics. The attitude processors in the Primary Avionics Software System (PASS) GNC General Purpose Computers (GPCs) and the Backup Flight System (BFS) GPC use these measured angles to determine the orbiter Mean of 1950 (M50) attitude. (Reference Appendix C for M50 description.)

The velocity data measured by the IMUs are the main source in propagating the orbiter state vector during ascent and entry. On orbit, a sophisticated drag model is substituted for IMU velocity information, except during large vehicle accelerations. During these large accelerations, IMU velocity data are again used in NAV calculations.

The attitude data provided by the IMUs are always used for attitude control during all phases of flight.

Each IMU interfaces with the five onboard GPCs through a different Flight Forward Multiplexer/Demultiplexer (FF MDM) of the Data Bus Network (DBN). Under the control of the GPCs, each IMU has the capability of orienting its platform to any attitude, determining platform alignment relative to a reference, and providing velocity and attitude data for flight operations.

The IMU and its software are designed to minimize crew interaction. In the optimum case, the crew should need to interface with the IMUs only during on-orbit alignments.

## **1.2 QUESTIONS**

1. What information does the IMU provide?
2. How many IMUs are installed onboard the orbiter?

## **2.0 SYSTEM DESCRIPTION**

In this section of the workbook a more detailed description of the IMU hardware is presented. Also, the IMU thermal control system, electrical power supply, and Data Processing System (DPS) interfaces, displays, and controls are discussed.

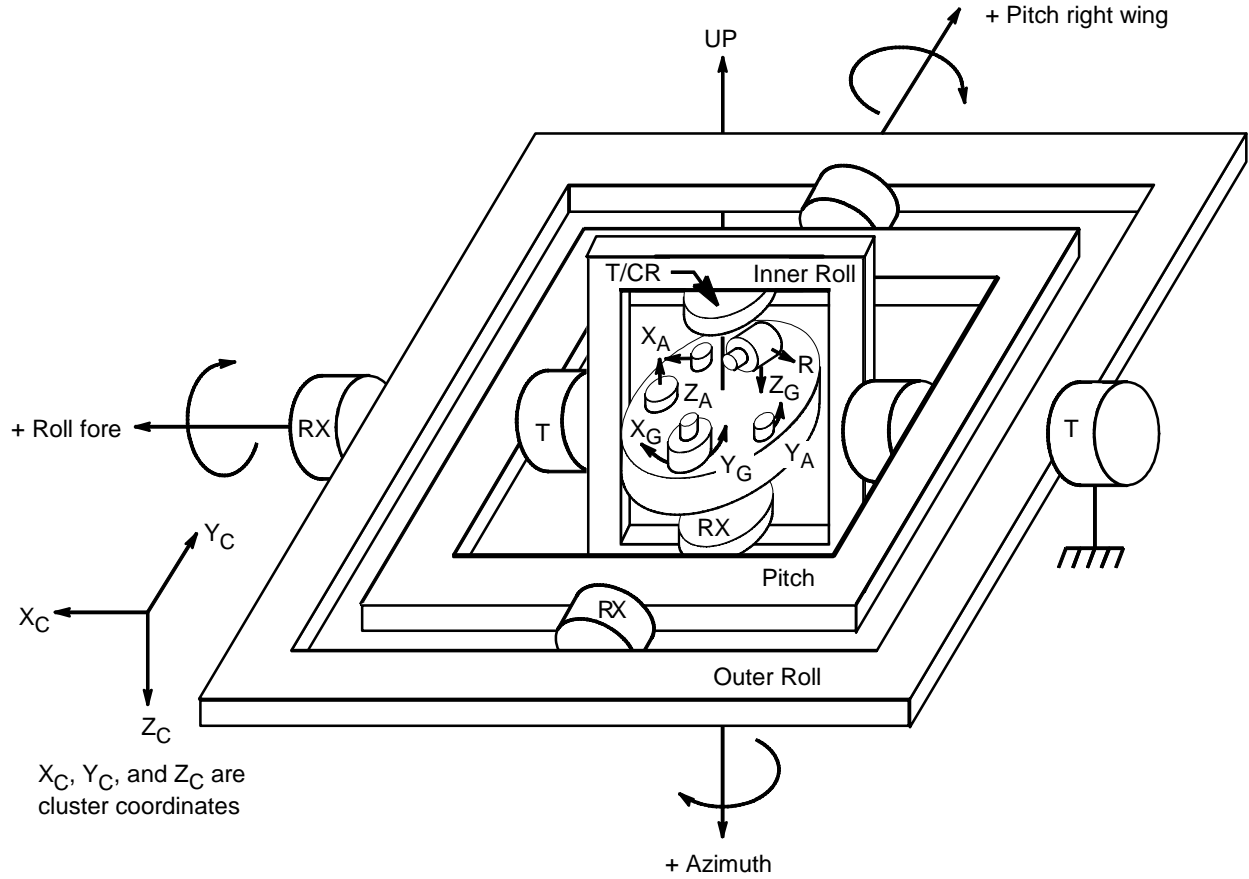
### **2.1 PERFORMANCE OBJECTIVES**

As a result of studying this section, you should be able to do the following:

- a. Describe the major sections of the IMU ALIGN SPEC
- b. Describe the IMU resolver
- c. Explain what an accelerometer is
- d. Explain how the IMU fans are used
- e. Describe how the IMUs are powered

### **2.2 GIMBALS**

The IMU contains four gimbals that isolate the platform from vehicle rotations (see Figure 2-1). The gimbal order from outermost to innermost is outer roll, pitch, inner roll, and azimuth. The platform is attached to the azimuth gimbal. The inner roll gimbal is a redundant gimbal that is used to provide an all-attitude IMU while preventing the possibility of gimbal lock (a condition that can occur with a three-gimbal system causing the inertial platform to lose its reference). The outer roll gimbal is driven from error signals generated from disturbances to the inner roll gimbal. Thus, the inner roll gimbal will remain at its null position and orthogonal to the pitch gimbal.



Notes:

- X<sub>G</sub> = X gyro input axis
  - Y<sub>G</sub> = Y gyro input axis
  - Z<sub>G</sub> = Z gyro input axis
  - R<sub>G</sub> = red. gyro input axis
  - Z<sub>A</sub> = Z accel sens. axis
  - X<sub>A</sub> = X accel sens. axis
  - Y<sub>A</sub> = Y accel sens. axis
  - (T) = gimbal torquer
  - (RX) = gimbal angle resolver
  - CR = coordinate resolver
- } Vertical gyro
- } Azimuth gyro

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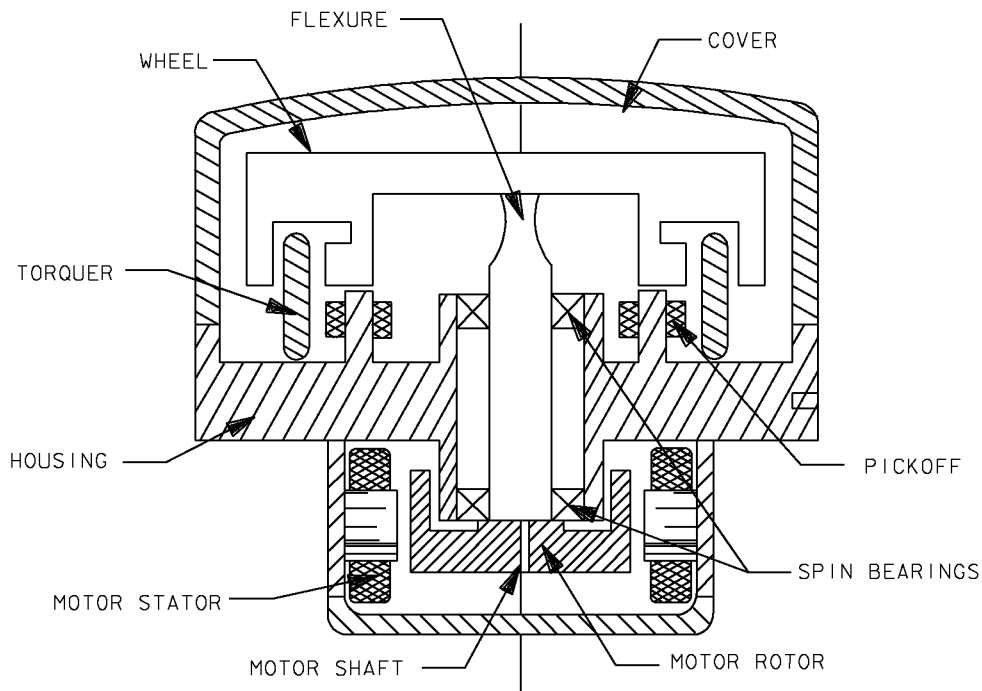
**Figure 2-1. IMU gimbal-mounted platform**



## 2.3 GYROS

The IMU contains two gyros, each having two degrees of freedom, which are used for platform stabilization (see Figure 2-1). One gyro is oriented such that its input axes are aligned with the X and Y platform axes. This gyro, called the vertical gyro, provides the IMU roll and pitch stabilization. The second gyro is oriented such that one input axis lies along the platform Z-axis and the other lies in the X-Y plane. This gyro, called the azimuth gyro, provides yaw stabilization with the Z input axis while the second input axis is used as a platform rate detector for Built-In Test Equipment (BITE).

Each gyro contains a two-axis pickoff that senses deflections of the rotating wheel (see Figure 2-2). The gyro also contains two torquers, each having two axes that provide compensation torquing for gyro drift and a means to reposition the platform. The use of these will become clearer after the discussion of the IMU stabilization loops.



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**Figure 2-2. Two-degrees-of-freedom gyro**

## 2.4 RESOLVERS

The IMU resolvers are electromechanical devices that use the principle of magnetic induction to electrically measure the angle between two adjacent gimbals. There are two resolvers on each gimbal, the one-speed (1X) and the eight-speed (8X). The 1X electrical output represents a coarse measurement of the true gimbal mechanical angle while, for greater resolution, the 8X electrical output represents a measurement eight

times the true angle. These outputs are converted to an angle measurement in the IMU electronics and are sent to the GPCs. The outputs are combined into a single measurement of the gimbal angle and used for vehicle attitude determination.

## **2.5 ACCELEROMETERS**

The IMUs have three accelerometers to measure accelerations along each axis. The accelerometer is basically a force rebalance type instrument. When the accelerometer experiences an acceleration along its input axes, it causes a pendulum mass displacement. This displacement is measured by a pickoff device that generates an electrical signal. This signal, which is proportional to the sensed acceleration, is amplified and returned to a torquer within the accelerometer which attempts to reposition the proof mass to its null (no output) position.

Each accelerometer has its own Digital Accelerometer Loop (DAL). The DAL is a terminal pulse rebalance loop that produces accurate current pulses to restore the pendulum to null and provides an incremental velocity pulse train to the internal computer of the IMU.

## **2.6 STABILIZATION LOOPS**

The stabilization loops are used to maintain the inertial orientation of the platform. There is one stabilization loop for each axis of rotation.

The spin axis of a gyro is its axis of rotation. A property of gyroscopes is the inertial stability of the spin axis. This property is used in the stabilization loops.

The stabilization loops consist of the gyro pickoff, the gimbals, and the gimbal torquers. When the vehicle goes through a rotation, the platform tends to rotate because of friction at the gimbal pivot points. Since the gyro casing is rigidly mounted to the platform, it will also rotate. The gyro resists this rotation because of its tendency to remain inertial, but the resistance is overcome by friction. This rotation is detected by the pickoffs as a deflection of the rotating gyro wheel. A signal proportional to this deflection is sent to the gimbal electronics, which routes the signals to the appropriate torquers. The torquers, in turn, rotate their gimbals to null the pickoff output. When the output is nulled, the loop is closed.

The vertical gyro provides platform roll and pitch stabilization whereas the azimuth gyro provides platform yaw stabilization.

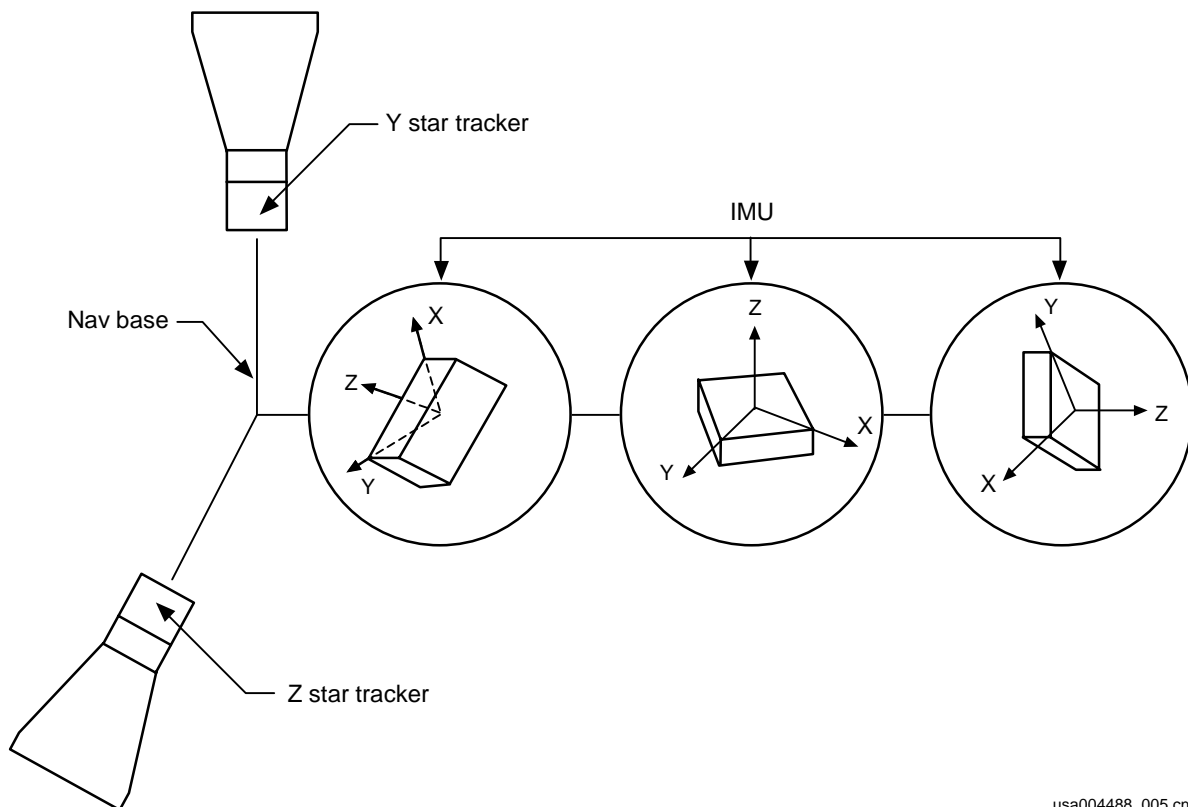
## **2.7 PLATFORM REORIENTATION**

The platform attitude can be reoriented by two methods, slewing or pulse torquing. Slewing rotates the platform at a high rate of 1.2 deg/sec. Pulse torquing rotates the platform very slowly at a rate of 0.007 deg/sec.

Platform reorientation uses another property of gyroscopes. If a force is applied to a spinning gyroscope, the induced motion is  $90^\circ$  from the input force. This is called precession. In the IMU, a two-axis torquer is located along the input axes of both gyros. Commands are sent to the torquers from the GPC to apply a force along the input axes. The result is a deflection of the gyro spin axis that is detected and nulled by the stabilization loops. Since the gyro spin axis is forced to point in a new direction, the platform will have to rotate to null the gyro outputs.

## 2.8 SKEW

Skew is the orientation of the platform of each IMU such that none of the principal axes of the IMUs are parallel (see Figure 2-3). The IMUs are skewed to enable optimum fault detection and isolation and to avoid more than one IMU reaching its gimbal flip condition at the same time. Skew allows single-axis failures on one IMU to be resolved by multiple axes on another IMU, since the possibility of a multiple-axis failure is more remote. The  $\sqrt{6}$  skew has been defined as optimal and was named for the recurring factor in the transformation matrix.



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Figure 2-3. IMU skew

## 2.9 BUILT-IN TEST EQUIPMENT

Each IMU has an extensive self-monitoring capability called BITE. BITE is divided into two categories: hardware- and software-aided. The information provided by BITE is used by IMU Redundancy Management (RM) software to determine the health of an IMU.

Upon detection of a BITE failure, the PASS IMU RM software will annunciate a class 3 alarm Systems Management (SM) alert and generate an IMU BITE/T X fault message. Status fields on the GND IMU CNTL/MON display SPEC 100 in GNC OPS 9; OVERRIDE display SPEC 051 in GNC OPS 1, 3, and 6; and the IMU ALIGN display SPEC 021 in GNC OPS 2, and 3 will display BITE for the pertinent IMU.

Hardware BITE indications, which are found on the mode status word, are as follows:

- a. SYNC
- b. SYNC
- c. SYNC
- d. HAINS GOOD
- e. MUX FAIL
- f. A/D FAIL
- g. PLATFORM FAIL
- h. DIGITAL SUBSYSTEM FAIL
- i. DC/DC FAIL
- j. DISCRETE POWER SUPPLY FAIL
- k. RX FAIL
- l. CIRCUIT CARD OVERTEMP
- m. TRANSMISSION WORD 1 FAIL
- n. TRANSMISSION WORD 2 FAIL
- o. D1 + D8 SEQUENCER DISCRETE
- p. D2 SEQUENCER DISCRETE
- q. D3 SEQUENCER DISCRETE

- r. D4 SEQUENCER DISCRETE
- s. D5 SEQUENCER DISCRETE
- t. PARITY

Limit checks in any of these areas that detect failures will cause BITE to be issued within the IMU. This action also sets certain bits in the IMU output data words that the GPC IMU software reads, and, as a result, the GPC annunciates a BITE message against the pertinent IMU.

The information transmitted to the GPC by the IMU is used not only for attitude and acceleration data, but also to perform certain tests indicating the health of the IMU. The software uses these tests in conjunction with the above hardware BITE to provide assurance that greater than 95 percent of the hardware failures are covered by BITE. IMUs also have an extensive internal BITE/history storage that is accessible only via special ground test software post-flight.

Software-aided BITE consists of seven separate signals, which are listed as follows:

- a. Accelerometer scale factor fail
- b. Echo one fail
- c. Echo two fail
- d. Velocity limit fail
- e. Resolver limit fail
- f. Redundant rate fail
- g. Inner roll null fail

Two temperature discretes are relayed to the GPC software in the IMU output data words. These discretes give the temperature status of the IMU and provide software with the capability to monitor the IMU operating temperature. The limits that set the discretes are listed as follows:

- a. PLAT TEMP SAFE – If the platform temperature is  $<156.5^{\circ}$  F, then it is SAFE.
- b. PLAT TEMP RDY – If the platform temperature is  $>146.5^{\circ}$  F, then it is READY.

The listed hardware and software BITE detections plus the temperature limit indications make up the total IMU BITE indication from the GPC. The IMU BITE word consisting of these parameters is a 16-bit word within the software. The IMU BITE/T X fault message described on page 2-6 is annunciates when any bit within this word is set true.

It is possible for an IMU to annunciate an IMU BITE while having no error condition. This is referred to as a "False BITE."

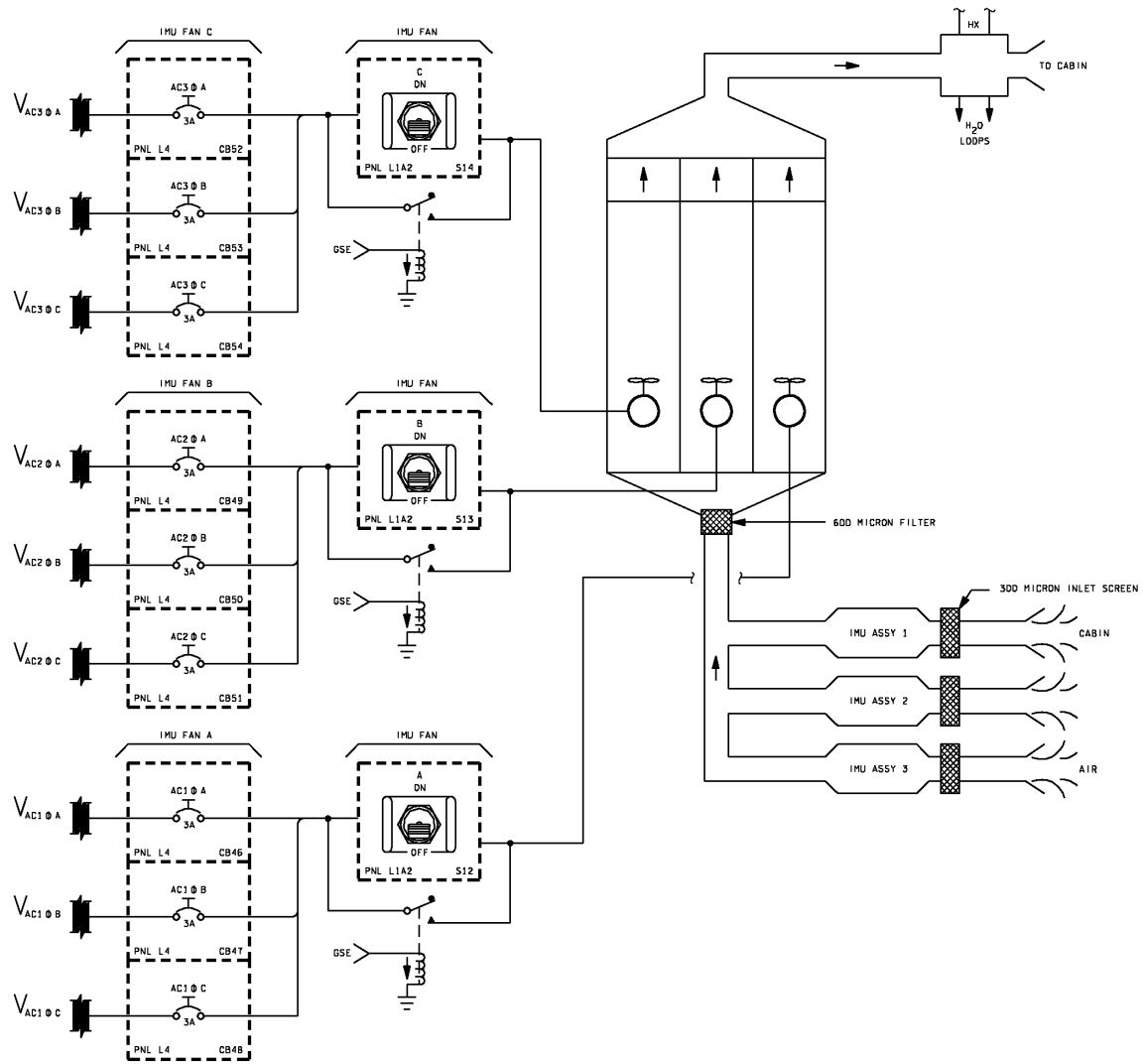
The Mission Control Center (MCC) has the capability to detect false BITEs by monitoring IMU performance through GNC telemetry. Each IMU BITE has characteristic performance problems. If no degradation occurs, the IMU BITE may be false, and MCC may wish to mask the BITE in the GPC software to avoid re-annunciation of the message and to preclude the software from using this indication in determining IMU failures.

## **2.10 THERMAL CONTROLS**

Because of the temperature sensitivity of the platform inertial components, a very precise thermal control system is necessary for the IMUs to meet performance requirements. The IMU thermal control system consists of two major components, an internal heater system and a forced-air cooling system.

The internal heater system is completely automatic. It is powered on when power is initially applied to the IMU and will continue to operate until the IMU is powered off. It is used to maintain critical IMU component temperatures within tight tolerances.

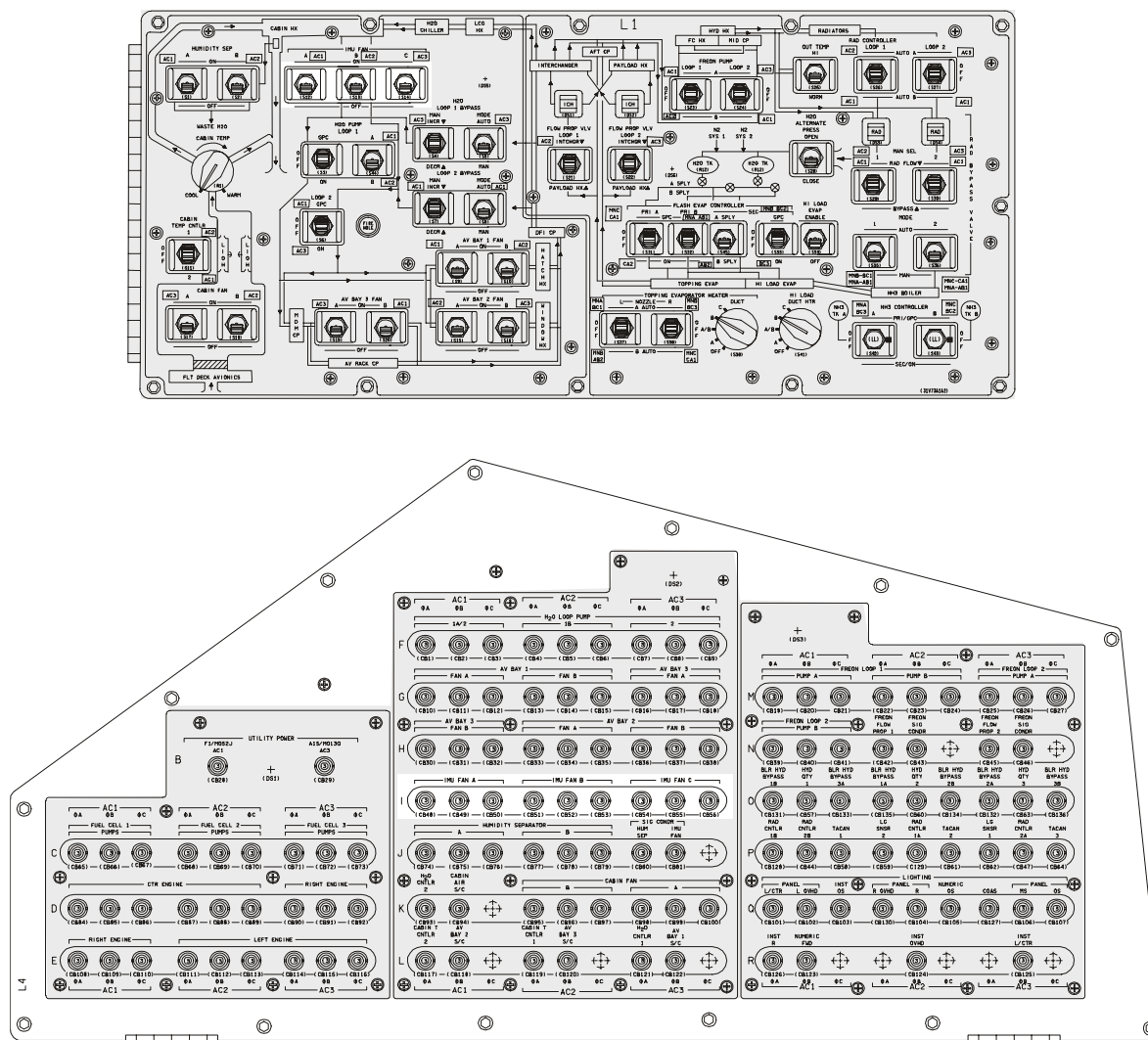
The forced-air cooling system is required to ensure that the internal heaters can do their job. It consists of three fans which serve all three IMUs (see Figure 2-4). The fans pull cabin air through the casing of each IMU. The air is then cooled in a heat exchanger and returned to the cabin. Only one fan is necessary to provide adequate air flow. Each IMU fan is powered by a different ac power supply. The IMU fan power switches are located on Panel L1 and their corresponding circuit breakers are on Panel L4 (see Figure 2-5).



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Figure 2-4. IMU air circulation



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Figure 2-5. Panels L1 and L4

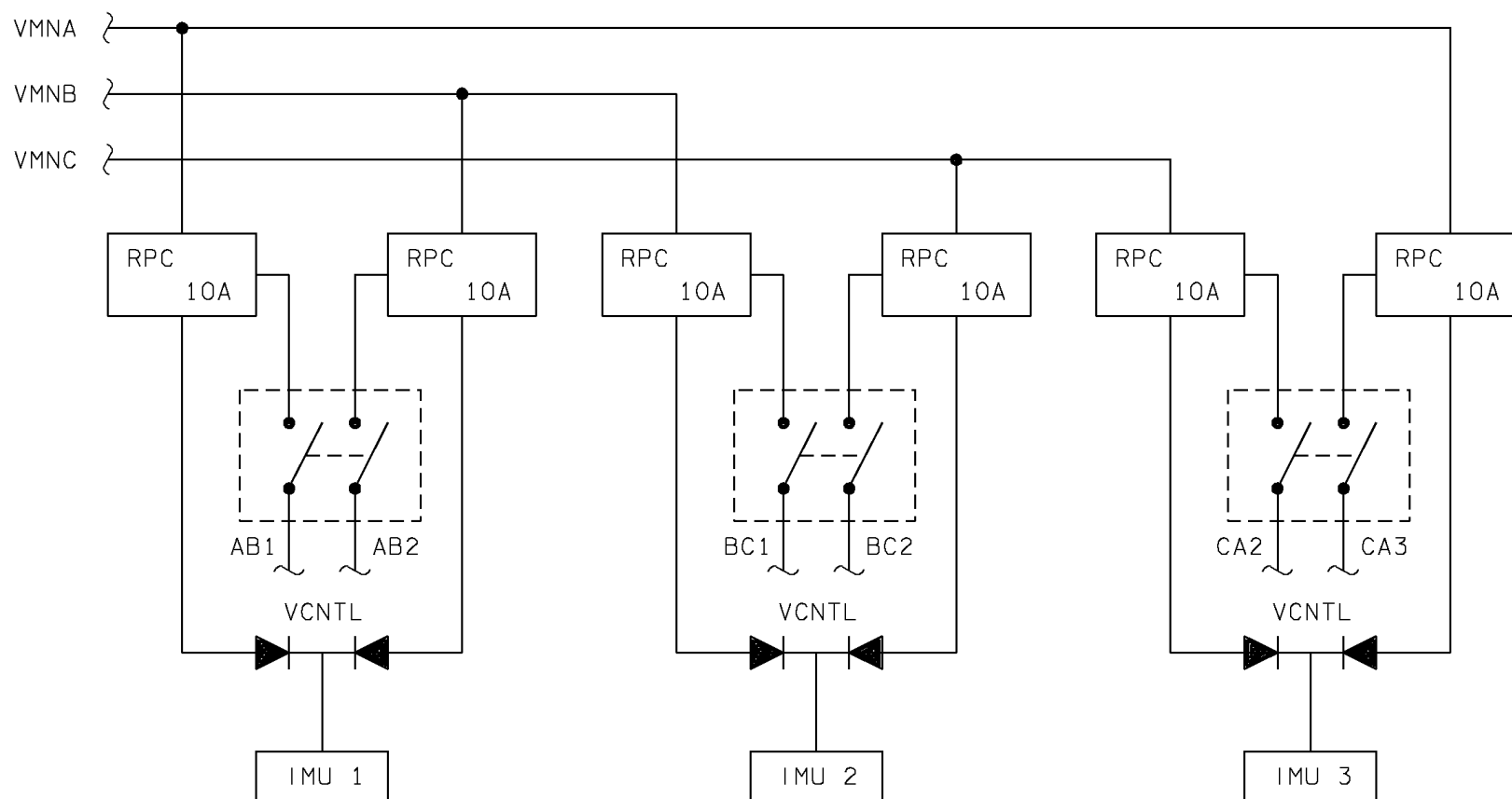


IMU operating temperature indications are available only on the IMU ALIGN display (SPEC 21). Two temperature discretelys are sent from each IMU to be processed and displayed as a single temperature indication. One of the three different temperature indications (LO, OK, and HI) will be present. When an IMU temperature exceeds limits, a class 3 alarm (SM ALERT) will be annunciated as well as an IMU BITE/T X fault message.

IMU fan status can be found on the PASS ENVIRONMENT display (DISP 66) in SM OPS 2, the PASS SM SYS SUMM 1 display (DISP 78), and the BFS SM SYS SUMM 1 display (DISP 78). Each display shows which fan is presently operating (an asterisk present next to or below the particular IMU fan) and a status indication (to the right of the asterisk). Status indications are present only for operating IMU fans. If the status indication field is blank, then there is no problem with the operation of that particular fan. If an "M" is displayed, this indicates that no data are available on the fan indicated. A "↓" denotes that the fan has been operating but its speed has dropped below a predetermined limit.

## **2.11 ELECTRICAL POWER**

Each IMU is supplied with redundant 28 V dc power. This power is fed to the IMU through separate Remote Power Controllers (RPCs) when control bus power is applied to the RPC by the IMU power switch (see Figure 2-6). The IMU power switches are located on the overhead Panels O14, O15, and O16 in row A (see Figures 2-7 and 2-8). Note that the loss of one main bus or any one control bus will not cause the loss of an IMU.



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Figure 2-6. IMU electrical power interface

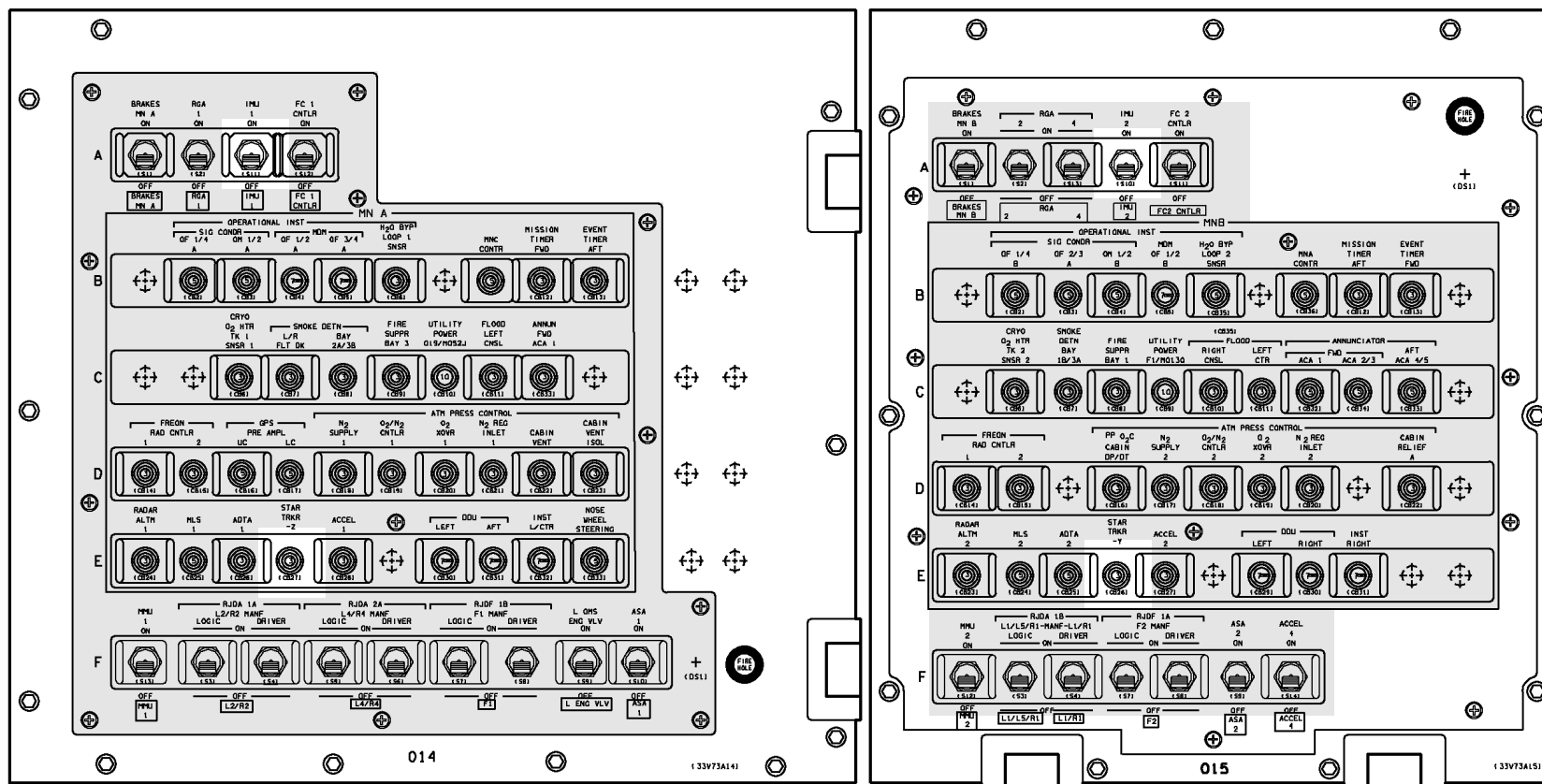


Figure 2-7. Panels O14 and O15

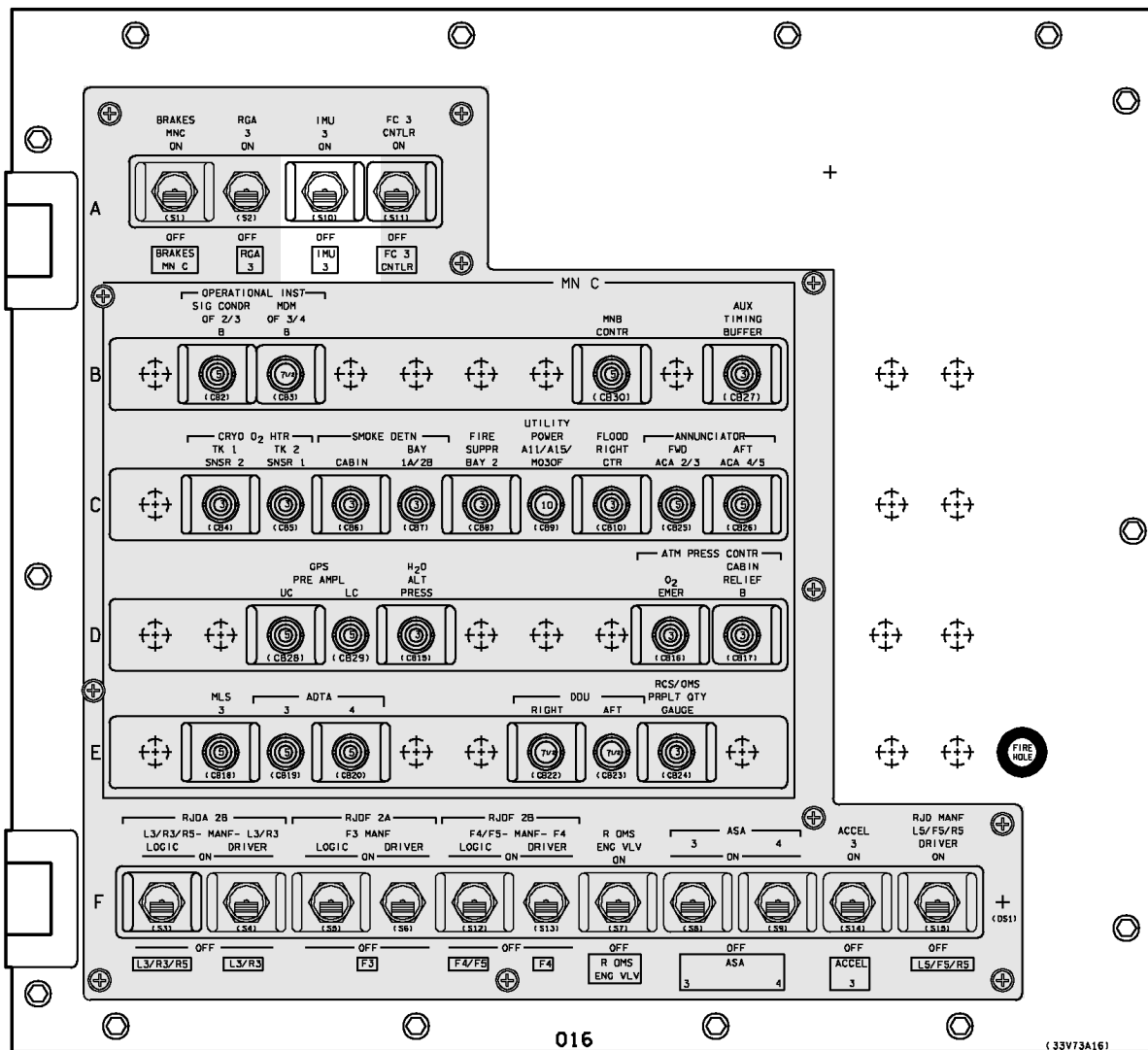


Figure 2-8. Panel O16

## 2.12 GPC INTERFACE

The IMUs interface with the GPCs through the FF MDMs. IMUs 1, 2, and 3 are connected to FF MDMs 1, 2, and 3 respectively. The interface consists of several discrete wires and a serial data bus.

## 2.13 DISPLAYS

In this section a brief review of IMU switch locations is presented along with descriptions of the PASS displays where IMU information can be found.

### 2.13.1 OVERRIDE Display (SPEC 51)

The OVERRIDE display is available in GNC OPS 1, 3, and 6. This display provides the crew with information on IMU operations during ascent and entry (see Figure 2-9). It also gives them the ability to manually deselect an IMU from RM and the data selection filter (both of which are described in Section 4). All IMU information is located in the center of the display.

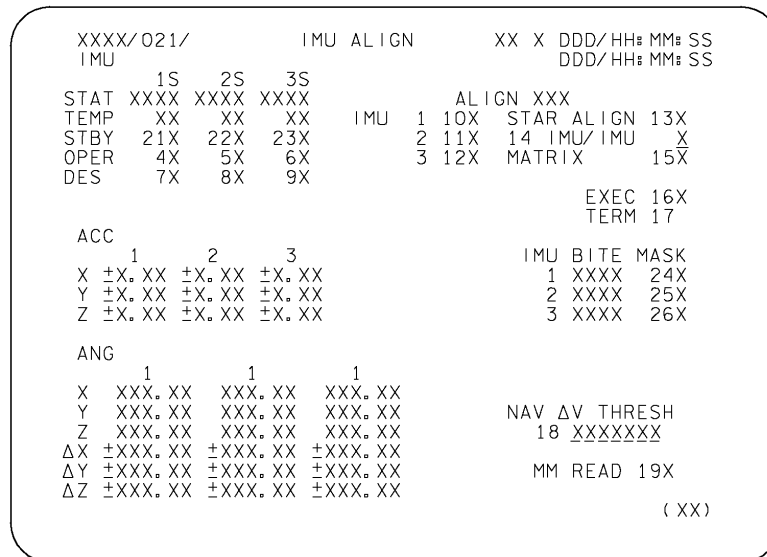
- To the right of the IMU number is the IMU RM status column. The column is blank for normal IMU operations, displays a “↓” for a deselection by RM or the crew, a “?” for an RM dilemma, or an “M” for missing IMU data.
- To the right of the RM status column is the Status (STAT) column. This column is either blank for normal IMU operations or displays BITE for a BITE-detected problem.
- The field just below Attitude (ATT) indicates the IMU presently being selected as a source for attitude data. Rate Gyro Assembly (RGA) will be displayed below the IMU attitude source number if the IMU attitude data is declared invalid for use by the attitude processor.
- Item numbers 25, 26, and 27 allow manual deselection of an IMU from RM and the selection filter. A subsequent re-execution of the item number reselects the IMU and the asterisk will be removed.

XXXX/051/		OVERRIDE		XX X DDD/HH:MM:SS	
				DDD/HH:MM:SS	
ABORT MODE		ENTRY FCS			
TAL 1X		ELEVON	FILTER	ATMOSPHERE	
ATO 2X		AUTO 17X	NOM 20X	NOM 22X	
ABORT 3X		FIXED 18X	ALT 21X	N POLE 23X	
MAX THROT 4X		SSME REPOS 19 XXX		S POLE 24X	
PRPLT DUMP		IMU STAT	ATT DES	PRL	
XXX ICNCT 5 XXXX		1S XXXX X 25X		SYS AUT DES	
OMS DUMP		2S XXXX XXX 26X		1S 28X 31X	
ARM 6X		3S XXXX 27X		2S 29X 32X	
START 7X		ADTA	H	$\alpha$	M DES
STOP 8X		L 1S	XXXXXX	$\pm$ XX.X	X.XX 34X
9 QUAN/SIDE XXX		3S	XXXXXX	$\pm$ XX.X	X.XX 35X
OMS DUMP TTG XXX		R 2S	XXXXXX	$\pm$ XX.X	X.XX 36X
AFT RCS 13 XXX		4S	XXXXXX	$\pm$ XX.X	X.XX 37X
14 TIME XXX		ET SEP		ROLL MODE XXXXXXXX	
FWD RCS 15 XXX		AUTO 38X		AUTO SEL 42X	
16 TIME XXX		SEP 39X			
		ET UMB DR		VENT DOOR CNTL	
		CLOSE 40X		OPEN 43X	
		RCS RM MANF		CLOSE 44X	
		CL OVRD 41			
				(XX)	

Figure 2-9. OVERRIDE display (SPEC 51)

### 2.13.2 IMU ALIGN Display (SPEC 21)

This display, which is available in GNC OPS 2 and 3, provides IMU alignment capability as well as status and controls (see Figure 2-10).



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td\_303b\_012

**Figure 2-10. IMU ALIGN display (SPEC 21)**

The upper left portion of the display contains the status and controls for each IMU.

- Beside the IMU number will be displayed an “M” for missing data (comm fault), a “↓” for a deselection by RM or crew input, or a “?” for an RM dilemma. Blank indicates nominal operation.
- STAT will indicate “BITE” for the particular IMU with a BITE condition or “OFF” when power is removed. A blank indicates a nominal condition.
- TEMP will indicate the current condition of the IMU by displaying one of the following: LO, OK, or HI.
- Items 21, 22, and 23 command the Standby (STBY) mode of the IMU. An asterisk beside the number indicates the current mode.
- Items 4, 5, and 6 command the Operate (OPER) mode of the IMU. An asterisk beside the number indicates the current mode. The STBY and OPER mode asterisks are mutually exclusive.

- f. Items 7, 8, and 9 allow the crew to manually select/deselect the IMU as a candidate for the selection filter. An asterisk indicates deselection. This is a toggle item number. Subsequent executions will alternately remove or replace the asterisk. If RM deselects an IMU upon detection of a failure, an asterisk will be placed in the given column.

The lower left portion of SPEC 21 provides attitude and accelerometer data. These data are useful for comparing the data output between IMUs.

- a. Each IMU's data has been transformed to the M50 coordinate system.
- b. The acceleration (ACC) data is a measure of the acceleration output of the IMU in feet per second squared. These data provide a means for the crew to compare IMU accelerometer (ACCEL) data output for troubleshooting purposes, despite skew.
- c. Angle (ANG) provides attitude data for each IMU in degrees. X, Y, and Z correspond to roll, pitch, and yaw, respectively. As with ACC data, the attitude data allow comparison of IMUs for troubleshooting purposes, despite skew.
- d. Below the attitude data, IMU torquing (or misalignment) angles are displayed ( $\Delta X$ ,  $\Delta Y$ , and  $\Delta Z$ ). These data indicate the angle through which each axis of each IMU will have to be rotated (or torqued) to be realigned. These angles will decrease to zero at the display update rate as an alignment progresses. The units are degrees. These angles are computed cyclically (once per minute) prior to alignment initiation.

The upper right portion of the display contains various alignment controls and options.

- a. The three-space field beside ALIGN indicates that there are stars in the star table (S TABLE) on SPEC 22 that meet the criteria for selection for an IMU alignment. This condition is represented by ENA (Enable) in the field. A blank field indicates that there are no stars in the table or that the stars in the table do not meet criteria for auto selection.
- b. Items 10, 11, and 12 allow selection of the IMUs that are to be aligned. This action is done by executing the item number to toggle the asterisk. An asterisk indicates that the IMU is selected for alignment.
- c. Item 13 (STAR ALIGN) is the alignment option selected when the IMUs are to be aligned using star data. This option is the default option when the display is first called (asterisk will be beside it).
- d. Item 14 is the alignment option selected when one or more IMUs is to be aligned using another IMU as a reference (IMU/IMU alignment). This option is selected by entering the number of the reference IMU.
- e. Item 15 (MATRIX) is an IMU alignment option that aligns the IMU by computing a new matrix (instead of reorienting the IMU physically).

- f. Item 16 EXECUTE (EXEC) initiates an alignment. An asterisk appears and remains beside the item number while the alignment is progressing.
- g. Item 17 TERMINATE (TERM) allows manual termination of an alignment, although any alignment will terminate automatically given time to complete. There will never be an asterisk beside this item number.
- h. Item 18 (NAV  $\Delta V$  THRESH) provides a means by which the NAV IMU velocity threshold may be changed (only in OPS 2).
- i. Item 19 (Mass Memory (MM) READ) allows transfer of IMU calibration parameters from MM to GPC memory.
- j. Items 24, 25, and 26 allow the crew to mask any BITEs present on IMUs 1, 2, and 3. An "\*" is driven next to the item number selected. Execution of these items masks only those BITEs already present; in order to mask any new BITEs, masking must be terminated and then reactivated. The data displayed under BITE reflect the current BITE status, not the mask status.

### 2.13.3 GNC SYS SUMM 1 Display (DISP 18)

The GNC SYS SUMM 1 display (DISP 18) is available in GNC OPS 1, 2, 3, 6, and 8. This display provides an overview of critical GNC hardware operations (see Figure 2-11). The IMU data are located in the NAV subsystem area in the lower right corner of the display. The same status parameters available on the OVERRIDE display are shown here.

1031/051/018		GNC SYS SUMM 1		4/000/00:04:04	
MANFFAILVLV		SURF POS MOM		DPS 1 2 3 4 5	
F1	OP	L	OB	GPC	↓
2	CLM	R	IB	MDM	FF ↓
3	OP			FA	↓
4	OP				
5					
L1	OP	AIL		FCS CH 1 2 3 4	
2	OP	RUD		M	
3	CLM	SPD BRK			
4	OP	BDY FLP			
5					
R1	OP	CNTLR 1 2 3		NAV 1 2 3 4	
2	OP	RHC	L	IMU	M
3	CLM		R	ACC	M
4	OP		A	RGA	M
5			L	TAC	
			A	MLS	
			L	ADTA	
			R		
			A		
			L		
			R		
			A		
			L		
			R		

1475. CRT# 11

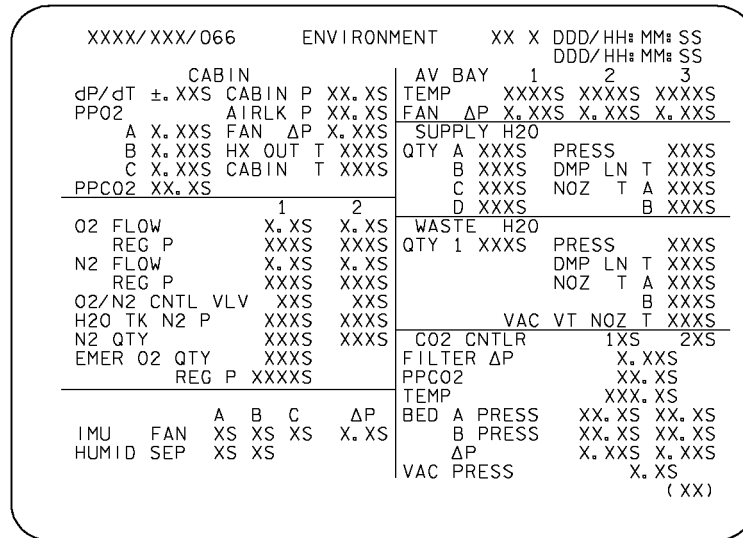
td\_303b\_013

Figure 2-11. GNC SYS SUMM 1 display (DISP 18)



### 2.13.4 ENVIRONMENT Display (DISP 66)

The ENVIRONMENT display (DISP 66) is available in SM OPS 2 (see Figure 2-12). IMU FAN and  $\Delta P$  data are available in the lower left corner of this display. This information is discussed in the thermal control system description.



4947. CRT 3  
td\_303b\_014

Figure 2-12. ENVIRONMENT display (DISP 66)

### 2.13.5 SM SYS SUMM 1 Display (DISP 78)

The SM SYS SUMM 1 display (DISP 78) is available in SM OPS 2 (see Figure 2-13). IMU FAN data are available near the lower left corner of this display. This information is discussed in the thermal control system description.

2011/ /078			SM SYS SUMM 1			4 000/14:44:12		
						000/00:00:00		
SMOKE	1/A	2/B	DC VOLTS	1/A	2/B	3/C		
CABIN	0.0		FC	30.6	30.1	31.0		
L/R FD	0.0	0.0	MAIN	30.6	30.1	31.0		
AV BAY	1 0.3	0.3	ESS	29.6	29.6	29.3		
	2 0.3	0.4					A	B
	3 0.3	0.3	CNTL	1 29.4	29.4	29.6		
CABIN				2 29.4	29.4	29.4		
PRESS	14.0			3 29.4	29.4	29.4		
dP/dT-EQ	+1.00	+1.000	AC					
O2 CONC			VOLT	φA	118	118	117	
PPO2	3.00	3.00		φB	117	117	118	
FAN ΔP	5.00			φC	117	117	118	
HX OUT T	46		AMPS	φA	4.3	6.3	2.1	
O2 FLOW	0.0	0.0		φB	5.5	6.6	2.2	
N2 FLOW	0.0	0.0		φC	3.1	5.0	3.2	
IMU FAN	A	B	FUEL CELL					
ΔV FC1	FC2	FC3	AMPS	180	232	146		
SS1	22	21	REAC VLV	OP	OP	OP		
SS2	22	22	STACK T	+202	+206	+200		
SS3	23	21	EXIT T	150	152	149		
TOTAL AMPS	557		COOL P	61	60	61		
	KW	17	PUMP					

Figure 2-13. SM SYS SUMM 1 display (DISP 78)

### 2.13.6 GND IMU CNTL/MON Display (SPEC 104)

The GND IMU CNTL/MON display (SPEC 104) is available in GNC OPS 9. This display provides monitoring and control of the preflight IMU calibrations and alignment (see Figure 2-14). Procedurally, the crew members never interface with this display. Therefore, it will not be discussed in detail.

XXXX/104/			GND IMU CNTL/MON			XX X DDD/HH: MM: SS		
						DDD/HH: MM: SS		
IMU	1	2	3					
X	1 XXX.XX	4 XXX.XX	7 XXX.XX	SEL IMU	1	16X		
Y	2 XXX.XX	5 XXX.XX	8 XXX.XX		2	17X		
Z	3 XXX.XX	6 XXX.XX	9 XXX.XX		3	18X		
	0 XXX.XX	XXX.XX	XXX.XX	ATT DET	19X			
M	XXX.XX	XXX.XX	XXX.XX	HNGR CAL	A	20X		
I	XXX.XX	XXX.XX	XXX.XX		B	21X		
IR	XXX.XX	XXX.XX	XXX.XX		C	22X		
V	X ±XX.XX	±XX.XX	±XX.XX	PREFLT CAL	23X			
Y	±XX.XX	±XX.XX	±XX.XX	GYROCOMP	24X			
Z	±XX.XX	±XX.XX	±XX.XX		XXXX	XXXX		
VRSS	XX.XX	XX.XX	XX.XX	INERTIAL	25X			
				PLAT POS	26X			
B HWD	XXXX	XXXX	XXXX	TERM/IDLE	27X			
I S/W	XX	XX	XX					
TSTAT	XX	XX	XX	28 MM WRITE	X			
				READ	29X			
PWR ON	X	X	X	MM STATUS	XXXX			
I/O	S	S	S					
STBY	10X	11X	12X	30 SITE SEL	X			
OPER	13X	14X	15X	ACTUAL	XXX			
					(XX)			

TD3030214. CRT: 1  
td\_303b\_016

Figure 2-14. GND IMU CNTL/MON display (SPEC 104)

## **2.14 QUESTIONS**

1. What SPEC is used to align the IMUs?
2. What is the IMU resolver?
3. What is an accelerometer?
4. How many IMU fans are used to cool the IMUs?
5. The IMUs are powered by three power sources. True or False.

### **3.0 SYSTEM OPERATIONS**

#### **3.1 PERFORMANCE OBJECTIVES**

As a result of studying this section, you should be able to do the following:

- a. Name the two IMU modes of operation
- b. Explain Reference Stable Member Matrix (REFSMMAT)
- c. Name the three types of IMU alignments
- d. Explain when the three types of alignments are available

#### **3.2 MODES OF OPERATION**

An IMU has two modes of operation, the warmup/standby mode and the operate mode. At powerup, an IMU enters the warmup/standby mode. In this mode, power is applied only to the heater circuits.

Upon achieving its operating temperature, the IMU is in standby. An asterisk will appear next to the standby item number for the IMU on the GND IMU CNTL/MON display (SPEC 104) in GNC OPS 9 or the IMU ALIGN display (SPEC 21) in GNC OPS 2 or 3. Upon reaching the standby mode, the IMU can be moded to operate. Moding to operate by crew command can occur only in GNC OPS 2, 3, or 9 when the displays mentioned above are available.

The IMUs are in operate mode by the time the crew enters the vehicle pre-launch and remain in that state for the duration of the flight, unless taken to standby to help minimize power consumption. While in the operate mode, the IMU maintains its inertial orientation and is used for calibrations, pre-flight alignment, flight, and on-orbit alignments.

To mode the IMU to operate, the controlling GPC sends the operate discrete to the IMU through the FF MDM. The IMU, upon receiving this command, initiates its startup sequence.

The startup sequence first cages the IMU. Caging refers to the process of reorienting the IMU gimbals, and then mechanically locking them into place so that the gyros may begin to spin. By caging the IMU, its platform orientation will be known when it becomes inertial. The IMU-caged orientation is defined as the point at which all resolver outputs are zero. Physically this causes the IMU platform to lie parallel to the NAV base plane with its coordinate axes lying parallel to the NAV base coordinate axes.

Once the IMU gimbals are caged, the gyros begin to spin and power is applied to the remaining IMU components. When the gyros have reached the correct spin rate, the stabilization loops are powered and the IMU becomes inertial. At this time, the IMU returns an "in operate" mode discrete to the GPC, indicating that it has completed the

startup sequence. An asterisk will appear next to the OPER ITEM number for the IMU on the GND IMU CNTL/MON display or the IMU ALIGN display. The startup sequence takes approximately 85 seconds.

The IMU can be safely powered off from either the warmup/standby mode or the operate mode. The IMU has a built-in dynamic braking circuit to ensure that caging of the platform gimbals will not occur unless both gyro motors are at zero speed. The time needed to slow the gyro motors with the braking circuit is incorporated in the 85-second startup sequence.

### **3.3 PREFLIGHT**

The IMUs are taken through three levels of calibration to correct for hardware inaccuracies: factory calibration, hangar calibration, and preflight calibration. Sixty-one IMU parameters are developed during this extensive calibration period. At the completion of the factory calibration, this set of calibration parameters is written to a region of the IMU internal hardware memory, called Electrically Erasable Programmable Read Only Memory (EEPROM), for internal compensation. Following the storage of calibration parameters to EEPROM, any subsequent testing will result in delta compensation, which is the difference between the whole error and the internally compensated value. These delta compensation terms would then have to be compensated by the GPC and stored in the GPC Solid State Mass Memory (SSMM). These data can be placed in the GNC major function base (GPC software) by executing the MM READ item number on the GND IMU CNTL/MON display or the IMU ALIGN display.

### **3.4 PRELAUNCH**

About 10 hours before lift-off, the IMUs are taken to the operate mode. They must be aligned pre-flight and attitude determination has to be accomplished prior to the alignment. Attitude determination is done by using resolver and velocity information to determine the orientation of the NAV base with respect to the North-West-Up (NWU) coordinate frame. The attitude determination submode takes about 4 minutes. The IMUs are aligned first to the local vertical. Then the azimuth is aligned. This alignment takes 38 minutes. Once it is complete, the IMUs go into a continuous align mode. The continuous alignment runs in 8-minute cycles, which is done by measuring the drift for seven minutes 50.4 seconds and then torquing out the measured errors for 9.6 seconds. Attitude determination, alignment, and continuous alignment make up a three-step sequence that is nominally performed three times prior to launch.

Seven and one-half hours before launch, the preflight calibration (cal) of the IMUs is accomplished. The IMUs have been calibrated earlier in the hangar and at the factory, but this cal is used to update the parameters computed in the previous cals. The final cal data is written to the SSMMs.

Once the cal is complete, the IMUs go through the attitude determination, the alignment, and the continuous alignment sequence two more times. Once the last continuous align

starts, the IMUs stay in this mode until T-4 minutes when the platforms are released and the IMUs enter the inertial mode. At this point the Attitude Direction Indicator (ADI) will flip around since it is now using the IMU data. Once the IMUs are in the free inertial mode, they are flight ready and all IMU functions stay the same throughout the flight.

Note: This is a very simplified explanation. For a detailed explanation refer to the GNC Systems Briefs, Sections 6.3.2.2 and 6.3.2.3.

### **3.5 ASCENT**

During ascent the IMUs provide accelerometer and resolver data to the GNC software for use in propagating the state vector and determining attitude. There is little IMU data available for crew viewing in the OPS1 software, but two displays provide status indications and selection filter controls. The PASS GNC SYS SUMM 1 display indicates any RM action or commfaults for each IMU. PASS GNC OVERRIDE (SPEC 51) allows crew selection/deselection of each IMU and displays the following: RM action (fail or dilemma), commfault, BITE, IMU currently selected for attitude data, and, in the case where no IMU is selected for attitude (three IMUs failed), display of "RGA" to indicate that RGA output data are being used to determine attitude.

### **3.6 ORBIT**

During the orbital phase of flight, the IMUs continue to provide GNC software with attitude and accelerometer data, but use of the accelerometer data for propagating the NAV state vector depends on two criteria.

First, the use of IMU accelerometer data can be manually controlled by a software "switch" available on two displays. This "switch" is labeled AVG G ON and may be enabled or disabled, thereby allowing NAV software to use or not to use, respectively, IMU accelerometer data. AVG G ON is located on the REL NAV display (Major Mode (MM) 201, SPEC 33) and on the FCS/DED DIS C/O display (MM 801, OPS display) and is nominally always enabled. In MM 202, AVG G ON is always enabled, thereby ensuring that a targeted maneuver cannot be done without NAV knowing about it.

Secondly, IMU accelerometer data must exceed a threshold before it will be used to propagate the NAV state. This threshold is called the NAV  $\Delta V$  THRESH and is an I-loaded value displayed on the IMU ALIGN display (SPEC 21). The displayed value uses units of micro-g's over a NAV cycle (one NAV cycle is a software execution time of 3.84 seconds). The current I-loaded value is 3840, which is 1000 micro-g's, since a NAV cycle is 3.84 seconds.

On-orbit alignments are necessary to correct platform misalignment caused by uncompensated gyro drift. Recall that the GPC will compensate the predicted drift of the IMU by continuously pulse-torquing the IMU. However, there will still be a small amount of drift. We will correct the misalignment caused by this drift by performing an IMU alignment. These are usually performed approximately once every two days to ensure minimal misalignment of the IMUs. Three options are available to align the

IMUs. Before these options are discussed, an understanding of Reference Stable Member Matrix (REFSMMAT) is needed.

### 3.7 REFERENCE STABLE MEMBER MATRIX

A REFSMMAT is simply a 3 by 3 transformation matrix that enables measurements from one coordinate system to be expressed in another. For the orbiter, this transformation allows attitude measurements in the platform coordinate system to be expressed in the M50 coordinate system. In equation form it looks like this:

$$\begin{bmatrix} X \\ Y \\ Z \end{bmatrix}_{M50} = \text{REFSMMAT} * \begin{bmatrix} X \\ Y \\ Z \end{bmatrix}_{\text{PLATFORM}}$$

Three REFSMMATs are defined for each IMU. Two are always present in GPC memory, while the third is computed to support IMU alignments.

The **current** REFSMMAT defines the orientation of the IMU platform at the end of the previous alignment (tells where the GPC thinks the IMU is). It resides in the GPC Common Datapool (COMPOOL) and is used by GNC software for determining attitude, velocity, instrument Line-of-Sight (LOS), and other pointing computations. The IMU software always assumes that the IMU platform is aligned to this orientation despite uncompensated drift. The initial **current** REFSMMAT is computed at the end of the velocity/tilt initialization just prior to the platform release to inertial operation during the pre-launch phase.

The **desired** REFSMMAT defines the preferred IMU platform orientation at the end of the next star alignment or IMU/IMU alignment (where the IMU is desired to be). It is resident in the IMU alignment software and may be changed by uplink.

The **present** REFSMMAT relates the present orientation of the IMU to a reference, which is determined by the align option selected (where the IMU platform actually is). If STAR ALIGN or a MATRIX align option is selected, the **present** REFSMMAT is computed relative to the stars acquired for the alignment. If IMU/IMU alignment is selected, this REFSMMAT is computed relative to the selected reference IMU.

### 3.8 IMU ALIGNMENT OPTIONS

#### 3.8.1 Star Align

The IMUs are normally aligned using this mode. Data are normally collected on two stars by the star trackers. The data can be obtained by maneuvering the orbiter to an attitude such that a known star appears in each star tracker. It is usually obtained by allowing the star trackers to randomly select “stars of opportunity” to be used for IMU alignments. If the star trackers are unavailable, data can be collected by manually

sighting on stars through the Head Up Display (HUD) or Crew Optical Alignment Sight (COAS).

These data are used to compute the measured LOS vectors to the two sighted stars with respect to the **current** REFSMMAT of each IMU. These vectors and the ideal LOS vectors stored in software are then used to compute the **present** REFSMMAT for each IMU to be aligned. The **present** REFSMMAT and the **desired** REFSMMAT are then used to compute the torquing angles displayed on the IMU ALIGN display. These angles update every 60 seconds if the alignment has not been initiated. When the alignment is initiated, the gyros are pulse-torqued causing the platform to move at a slow rate (.007deg/sec) to remove the misalignment. Once this is completed, the **current** REFSMMAT is set equal to the **desired** REFSMMAT.

The crew procedures for executing an alignment using star data are located in the Orbit OPS Checklist of the Flight Data File (FDF), GNC Section. Both the IMU ALIGN - S TRK and the IMU STAR OF OPPORTUNITY ALIGN use star data to compute the torquing angles. The Star of Opportunity procedure will be used if MCC sees two good stars currently stored in the Star Table. The IMU ALIGN- S TRK procedure will be used if there is no good star data currently in the table, or if MCC desires a particular pair of stars to provide star data. An example of each of these procedures is given in Figure 3-1 and Figure 3-2.



**IMU ALIGN – S TRK, GNC 201,202,301**

1. COLLECT STAR DATA

√In attitude

GNC 22 S TRK/COAS CNTL

S TABLE CLR – ITEM 20 EXEC

√STAR TRK – ITEM 3,4 (\*)

√S TRK -Y,-Z: STATUS – (no BITE)  
SHUTTER – OP

- \* If SHUTTER – CL: \*
- \* √Attitude,MET correct \*
- \* Visually verify no bright object in FOV \*
- \* After data collected and before changing \*
- \* attitude, return shutter to AUTO \*
- \* To open shutter: \*
- \* MAN OP – ITEM 15(16) EXEC (\*) \*
- \* To return shutter to AUTO: \*
- \* MAN OP – ITEM 15(16) EXEC (no \*) \*

2. VERIFY STAR DATA

√S TABLE: TRK ID 1,2 correct #s

ANG ERR  $1 \leq 0.08$

SEL, ITEM 17,18 – (\*)

Wait ~1 min for new IMU ΔANGs

- \* If no data after 3 min or bad data: \*
- \* Repeat step 1 \*
- \* √Attitude,start,MET correct \*
- \* √S TRK -Y,-Z: TRK ID: correct #s \*
- \* ΔANG: < 1.0 \*
- \* If still no data or bad data: \*
- \* Perform S TRK SELF-TEST, then: \*
- \* If both STATUS – ST FAIL: \*
- \* | Inform MCC before proceeding \*
- \* If both STATUS – ST PASS: \*
- \* | Repeat step 1 at new att, stars \*
- \* If one STATUS – ST PASS: \*
- \* Perform single tracker steps \*

Cont next page

**Figure 3-1. Orbit OPS checklist, IMU  
ALIGN-S TRK procedure**

- \* Single tracker procedure \*
  - \*  $\sqrt{\text{TERM/IDLE, ITEM 9(10) - (*)}}$  \*
  - \* Good S TRK, STAR TRK – ITEM \*
  - \* 3(4) EXEC (\*) \*
  - \* S TABLE CLR – ITEM 20 EXEC \*
  - \*  $\sqrt{\text{S TABLE: TRK ID 1 correct \#}}$  \*
  - \* Good S TRK, TERM/IDLE – ITEM \*
  - \* 9(10) EXEC (\*) \*
  - \* Mnv to second attitude, star \*
  - \* Good S TRK, STAR TRK – ITEM \*
  - \* 3(4) EXEC (\*) \*
  - \* Repeat step 2 with good S TRK only \*
3. CHECK IMU  $\Delta$ ANGs
- GNC 21 IMU ALIGN
- CRT IMU 1,2,3: STAT – blank
- $\sqrt{\text{STAR ALIGN, ITEM 13 - (*)}}$
- $\sqrt{\text{ANG 1,2,3: } \Delta X, \Delta Y, \Delta Z \leq 0.50}$
- If no comm, record  $\Delta$ ANGs
- \* If ANG  $\Delta X, \Delta Y, \Delta Z > 0.50$  for two or \*
  - \* more IMUs, repeat steps 1,2,3 \*
- CAUTION**

If ANG  $\Delta X, \Delta Y, \Delta Z$  still  $> 0.50$  for two or more IMUs, DO NOT TORQUE PLATFORMS EXCEPT UNDER MCC INSTRUCTIONS
4. ALIGN IMUs
- ALIGN IMU 1(2,3) – ITEM 10(11,12) EXEC (\*)
- EXEC – ITEM 16 EXEC (\*)
- $\sqrt{\text{EXEC, ITEM 16 - (no *)}}$
- If not deorbit align >>
5. D/O ALIGN VERIFICATION
- When D/O align complete, mnvr to VERIF ATT (FLIGHT PLAN, Detailed Timeline), perform steps 1,2 using verif stars
- $\sqrt{\text{IMU 1,2,3 ANG } \Delta X, \Delta Y, \Delta Z < 0.1}$
- \* If ANG  $\Delta X, \Delta Y, \Delta Z \geq 0.1$ ,  $\sqrt{\text{MCC}}$  \*
  - \* If no comm, repeat steps 1-5 \*

**Figure 3-1. Orbit OPS checklist, IMU ALIGN-S TRK procedure (concluded)**

## IMU STAR OF OPPORTUNITY ALIGN

1. VERIFY STAR DATA  
√S TABLE: TRK ID 1,2,3 for correct #s  
ANG ERR 1,2,3:  $\leq 0.08$  for correct #s  
SEL, ITEM 17,18,19 – (\*) for correct #s
  
2. CHECK IMU  $\Delta$ ANGs  

GNC 21 IMU ALIGN
------------------

  
IMU 1,2,3: STAT – blank  
√STAR ALIGN, ITEM 13 – (\*)  
√ANG 1,2,3:  $\Delta X, \Delta Y, \Delta Z \leq 0.50$   

<u>CAUTION</u> If ANG $\Delta X, \Delta Y, \Delta Z > 0.50$ for any IMU, DO NOT TORQUE PLATFORMS EXCEPT UNDER MCC INSTRUCTIONS
---
  
3. ALIGN IMUs  
ALIGN IMU 1(2,3) – ITEM 10(11,12) EXEC (\*)  
EXEC – ITEM 16 EXEC (\*)  
√EXEC, ITEM 16 – (no \*)

**Figure 3-2. Orbit Ops checklist, IMU STAR OF OPPORTUNITY ALIGN procedure**

### 3.8.2 IMU/IMU Align

The IMU/IMU alignment mode uses an IMU as a reference in place of LOS vectors to stars (as in STAR ALIGN). The IMUs to be aligned use the reference IMU to compute a **present** REFSMMAT. The **present** REFSMMAT and the **desired** REFSMMAT of each IMU are used to compute the torquing angles on the IMU ALIGN display. When the alignment is initiated, the platform is slewed and/or pulse-torqued to remove the misalignment.

If the misalignment is greater than  $1^\circ$ , the IMU platform is slewed to within  $1^\circ$  of its desired orientation. Once it reaches this point, it continues to slew for 19.84 seconds in one direction and then 19.84 seconds in the reverse direction. This is done to remove any directional sensitivity. When slewing is complete, the platform is pulse-torqued until the misalignment is nulled, and again, the **current** REFSMMAT is set equal to the **desired** REFSMMAT.

If the misalignment is less than  $1^\circ$ , the platform is pulse torqued to remove the misalignment. When completed, the **current** REFSMMAT is set equal to the **desired** REFSMMAT.

If the reference IMU is to be aligned, it is done after the alignment of the other IMUs. It is accomplished in the same manner, with the lowest numbered non-reference IMU in the operate mode acting as the next reference while alignment of the previous reference occurs. Usually the reference IMU will not require alignment (since declaring it as a reference implies it is correctly aligned). However, if the **desired** REFSMMAT has been updated, all three IMUs will be reoriented by the new REFSMMAT; therefore, all three should be selected for alignment.

Since this alignment mode is the only one that uses the IMU slew capability, it will be used when applicable to remove large misalignments. The procedure for performing this type of alignment is also located in the Orbit OPS Checklist, GNC section. It is entitled IMU ALIGNMENT - IMU/IMU with an example given in Figure 3-3.

**IMU ALIGNMENT – IMU/IMU**

NOTE

Procedure must be accomplished  
in GNC OPS 2 or 3

<u>GNC 21 IMU ALIGN</u>		
IMU/IMU – ITEM 14 + (REF IMU) EXEC		
	1	2
$\Delta X$ ( )	_____ ( )	_____ ( )
$\Delta Y$ ( )	_____ ( )	_____ ( )
$\Delta Z$ ( )	_____ ( )	_____ ( )
ALIGN IMU 1(2,3) – ITEM 10(11,12) EXEC (*)		
EXEC – ITEM 16 EXEC (*),		
Rcd MET	____/____:____	____/____:____
	____/____:____	____/____:____
	____/____:____	____/____:____

NOTE

Align will require 3-6 min

Report IMU align results

VERIFY GOOD IMU/IMU ALIGNMENT

√EXEC, ITEM 16 – (no \*)  
IMU/IMU – ITEM 14 +(SAME REF IMU) EXEC  
√IMU 1,2,3 ANG  $\Delta X, \Delta Y, \Delta Z < 0.13$

\* If ANG  $\Delta X, \Delta Y, \Delta Z \geq 0.13$ , report to MCC \*

If in GNC OPS 2 or MM 301,  
STAR ALIGN – ITEM 13 EXEC (\*)

ALIGN IMU 1(2,3) – ITEM 10(11,12) EXEC (no \*) |

**Figure 3-3. Orbit OPS checklist,  
IMU ALIGNMENT-IMU/IMU**

**3.8.3 Matrix Align**

The MATRIX ALIGN gives the crew the capability to use star data collected by the star trackers, HUD, or COAS to update the **current** REFSMMAT instead of physically realigning the platform. In this case the **present** REFSMMAT is determined in the same manner as during a star alignment. The torquing angles displayed are computed from the **current** and **present** REFSMMAT of each IMU instead of the **desired** and **present**

REFSMMAT. When the alignment is initiated, the **current** REFSMMAT is set equal to the **present** REFSMMAT. Since there is no platform movement, this alignment is instantaneous. However, since the **desired** REFSMMAT is not used, the relative skew is not optimum for RM purposes. The IMUs are still completely usable and an IMU/IMU alignment or star alignment may be used later to reinstate the **desired** REFSMMAT.

This type of alignment is not performed in nominal operations. Therefore, it is located only in the Malfunction Procedures Volume of the FDF, GNC Section.

### **3.9 ENTRY**

During entry, IMU operation differs only in the manner in which accelerometer data are used by NAV. This is discussed in the Navigation Workbook.

As stated previously, SPEC 21 is available throughout OPS 3. However, all IMU alignment options are not. STAR ALIGN and MATRIX ALIGN are available only in Major Mode 301. IMU/IMU ALIGN is available in all OPS 3 major modes.

### **3.10 QUESTIONS**

1. List the two IMU modes of operation.
2. What is a REFSMMAT?
3. Name the three types of IMU alignments. Which one is normally used?
4. All three alignment types are available in all of OPS 3. True or false.

## 4.0 SYSTEM MALFUNCTIONS

The IMUs, like all redundant sensor systems, have a software scheme designed to select the best data for use by the GPCs and to detect system failures. This scheme is called IMU RM.

### 4.1 PERFORMANCE OBJECTIVES

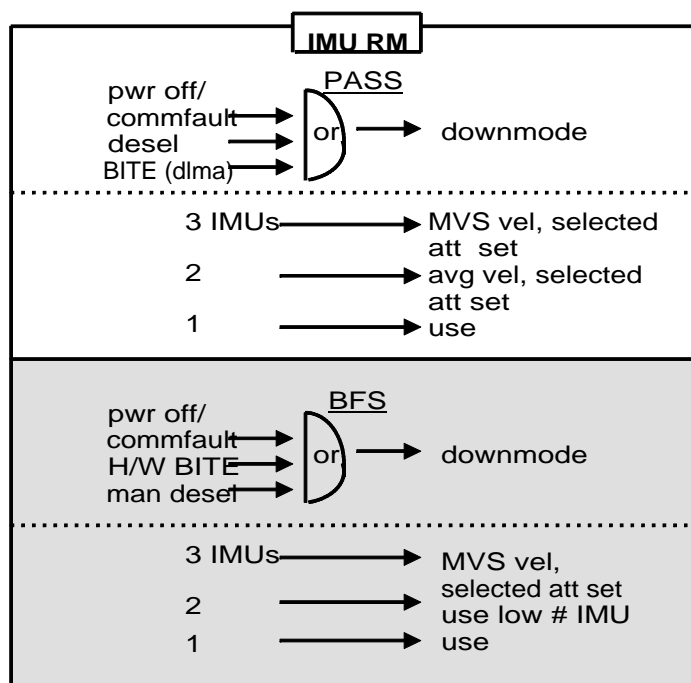
As a result of studying this section, you should be able to do the following:

- a. Describe the IMU RM scheme
- b. Explain the purpose of the attitude Selection Filter (SF) and the velocity SF
- c. Explain the purpose of the Fault Detection, Identification, and Reconfiguration (FDIR)

### 4.2 REDUNDANCY MANAGEMENT SCHEME

The IMU RM scheme consists of an SF and FDIR software. The SF selects the best data from the available IMUs. FDIR searches for faulty data, attempts to identify the IMU producing this data, and if successful, reconfigures the SF to exclude data from the faulty IMU.

The following diagram from the Ascent Pocket Checklist (APCL) shows an overview of IMU RM. The top block indicates the requirements for an IMU to be available for use. The second block shows how they are used based on the number of IMUs available. The remainder of this section is a more detailed explanation of RM.





The IMU RM software is divided into two distinct areas, attitude RM and velocity RM.

The first step in both attitude and velocity RM is to determine which IMUs are candidates for RM processing. Candidacy is determined from the following criteria:

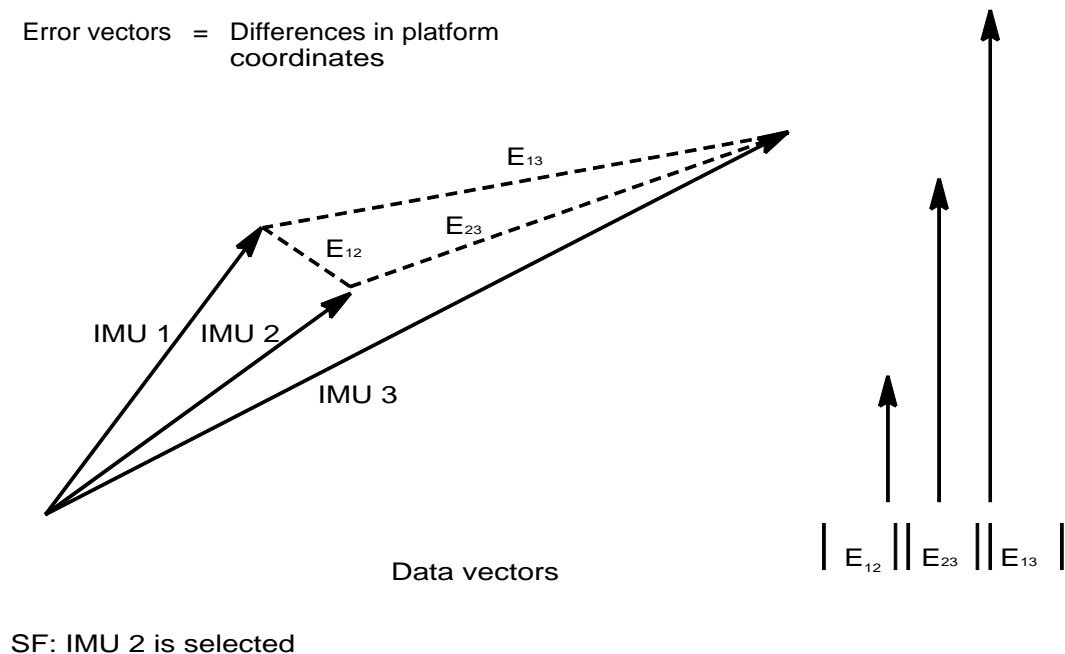
- a. No manual deselection - The IMU has not been deselected by the crew.
- b. No commfault - The GPC has not bypassed IMU data.
- c. No current failure - The IMU has not been previously failed by RM (i.e., automatically deselected).
- d. No slewing - The IMU is not being slewed during an IMU/IMU alignment.

If all of the above criteria apply, the IMU is a candidate for use by RM.

There is no FDIR software processing if only one IMU is available. Any IMU will continue to operate if it is deselected manually or declared failed by RM.

### 4.3 ATTITUDE REDUNDANCY MANAGEMENT

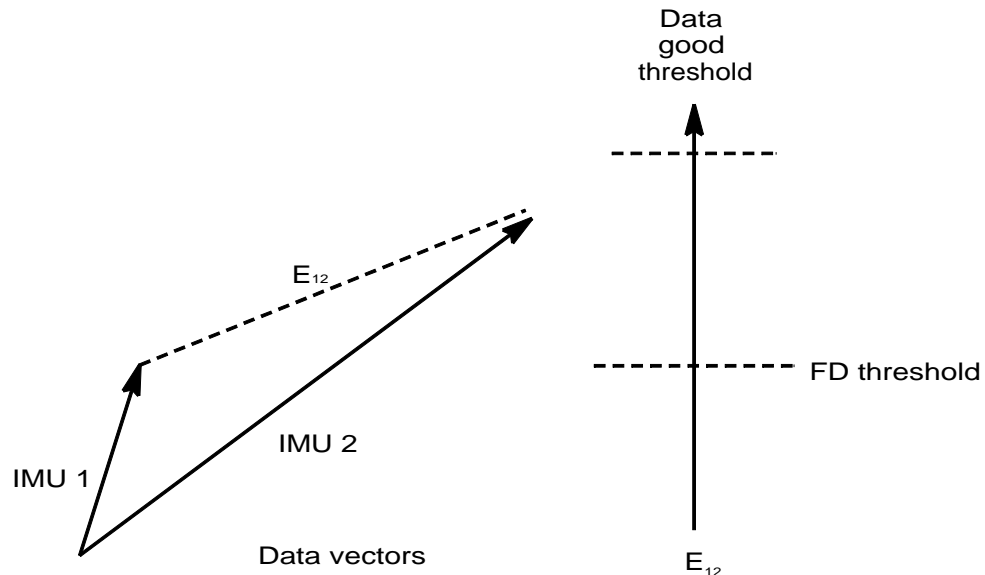
The purpose of the attitude SF is to select one IMU as the attitude source for the GNC software. If there are three candidate IMUs, the SF uses a Midvalue Select (MVS) scheme (see Figure 4-1). The SF calculates the misalignment between each pair of IMUs. It then finds the largest of these values. The IMUs that produced this misalignment are obviously the farthest apart, so the IMU that is not part of this maximum value is the middle value IMU and is used as the attitude source.



td\_303b\_017

**Figure 4-1. IMU three-level attitude selection filter**

If only two IMUs are candidates, the SF calculates the misalignment between the two IMUs (see Figure 4-2). This value is compared to the I-loaded attitude data good threshold. This value is  $1^\circ$  for ascent and orbit operations and  $2.5^\circ$  for entry.



SF: The selected IMU is left unchanged from its previous value if this IMU is a candidate; otherwise, the selected IMU is set equal to the lowest-numbered candidate IMU

td\_303b\_018

#### Figure 4-2. IMU two-level attitude selection filter

If the misalignment is greater than the attitude data good threshold, the attitude data good flag is set bad, causing the attitude processor to exclude IMU data in its attitude computations. Also, if this threshold is violated, FDIR processing increases from 1/16 Hz to 1 Hz to try to isolate which of the two IMUs has the failure. On orbit, this causes the Digital Autopilot (DAP) to downmode to free drift, since no attitude data are available to the GNC software.

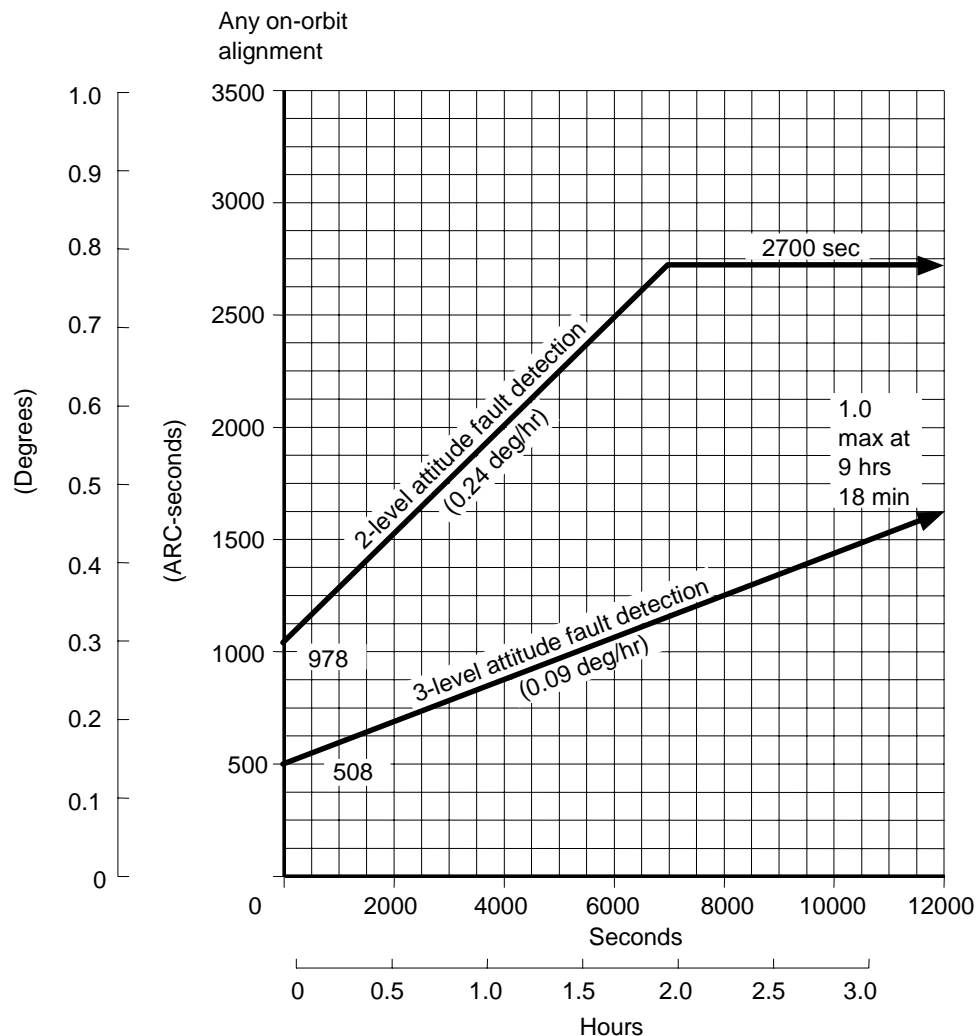
During ascent and entry, the attitude processor will use RGA data to maintain attitude control. When this is the case, "RGA" will be displayed under the IMU attitude source on the GNC OVERRIDE display.

If the misalignment is less than the attitude data good threshold, the IMU used as the last attitude source is selected. If it is not available, the lowest numbered available IMU is chosen.

If only one IMU is a candidate, its data is used, unless during OPS 2 or 8 it has a BITE indication. If this is the case, the attitude data good flag is set bad. In OPS 1 or 3, with a BITE against the one IMU, its data continue to be used.

If no IMUs are candidates, the attitude data good flag is set bad.

Once an attitude source has been selected, the FDIR starts processing. If three IMUs are candidates, the misalignments computed in the SF are compared to the three-level Fault Detection (FD) threshold. This threshold is reinitialized at the end of any IMU alignment and increases with time to a maximum, at which point it remains constant. Figure 4-3 is a typical FD threshold chart for attitude. If the misalignment for a given IMU pair exceeds the threshold, a miscompare flag is set that is sent to the fault identification software.



**Figure 4-3. Typical attitude FD thresholds, time from any on-orbit alignment**

The three-level FDIR software checks the number of miscompare flags. If only two flags are present, the software records the number of the IMUs that are common to the two flags and starts a counter. No failure is announced unless there are three consecutive execution cycles through the FDIR software that identify the same IMU as the cause of the miscompares. If this is the case, IMU RM declares the IMU failed and deselects it from the SF. A class 3 SM alert will be announced along with an RM FAIL

IMU fault message. The FDIR software runs at a 1/16 Hz rate, so an attitude failure will require 48 seconds to be isolated.

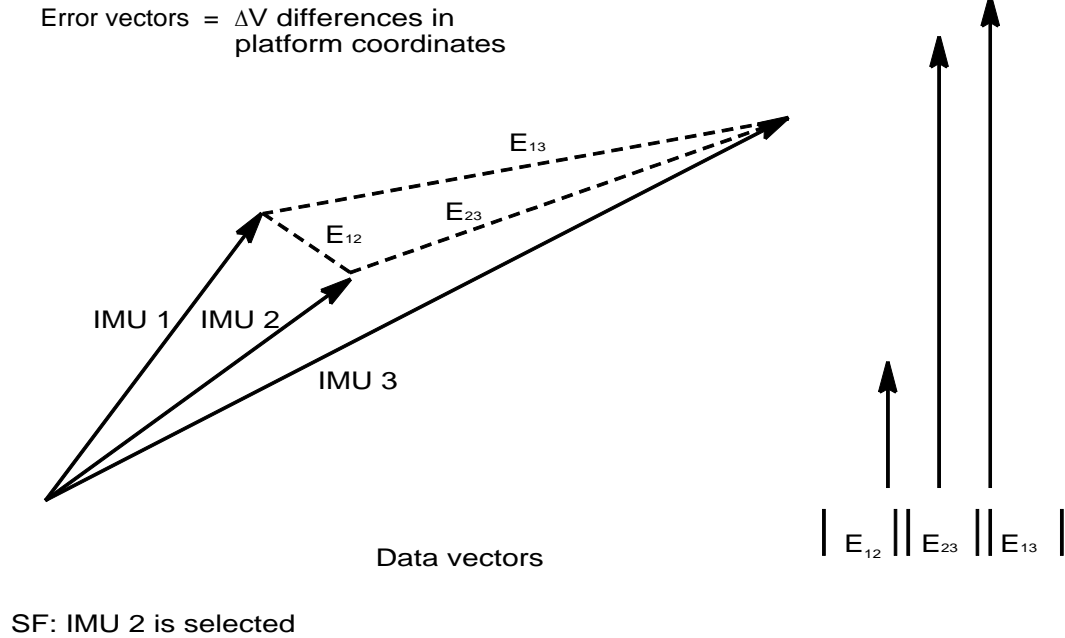
If two IMUs are candidates, a new FD threshold is computed. The misalignment between the two IMUs is recomputed using a different equation, and the two are compared. If the misalignment exceeds the threshold, a miscompare flag is sent to FDIR software.

If a miscompare flag is present, the two-level FDIR software checks for a BITE failure on both IMUs. If a BITE is present on only one IMU, it is recorded in the counter. Again, three consecutive passes with the BITE indication present will cause the IMU to fail. If both IMUs, or neither IMU, have a BITE, the software looks for failures in the gyros. It will attempt to isolate the misalignment to the drift of a single gyro. After three cycles if the problem cannot be identified, FDIR will issue an RM Dilemma (DLMA). The redundant gyro monitor is then used to solve the dilemma. FDIR will solve an attitude DLMA by identifying the IMU with the highest rate on the redundant gyro.

#### **4.4 VELOCITY RM**

The purpose of the velocity SF is to select the best available data from the IMUs for use in propagating the orbiter State Vector (SV). To minimize velocity errors sent to NAV, a rectification cycle is present. Rectification causes the velocity of each IMU to be set equal to the total velocity used by NAV every 8 seconds. This rectification is done by computing a bias which is added to the IMU sensed velocity, allowing IMUs that were temporarily out of the RM scheme to be reselected without causing bad data to be used in propagating the SV.

If three IMUs are candidates, the SF midvalue selects the total velocity vector from the three biased IMU velocity vectors (see Figure 4-4). The MVS scheme is done on a component-by-component basis, which could result in selection of one component from each IMU. If two IMUs are candidates, the SF computes a velocity error vector between the two IMUs, based on the current and the previous cycle measurements. This error vector is compared to the velocity data good threshold.



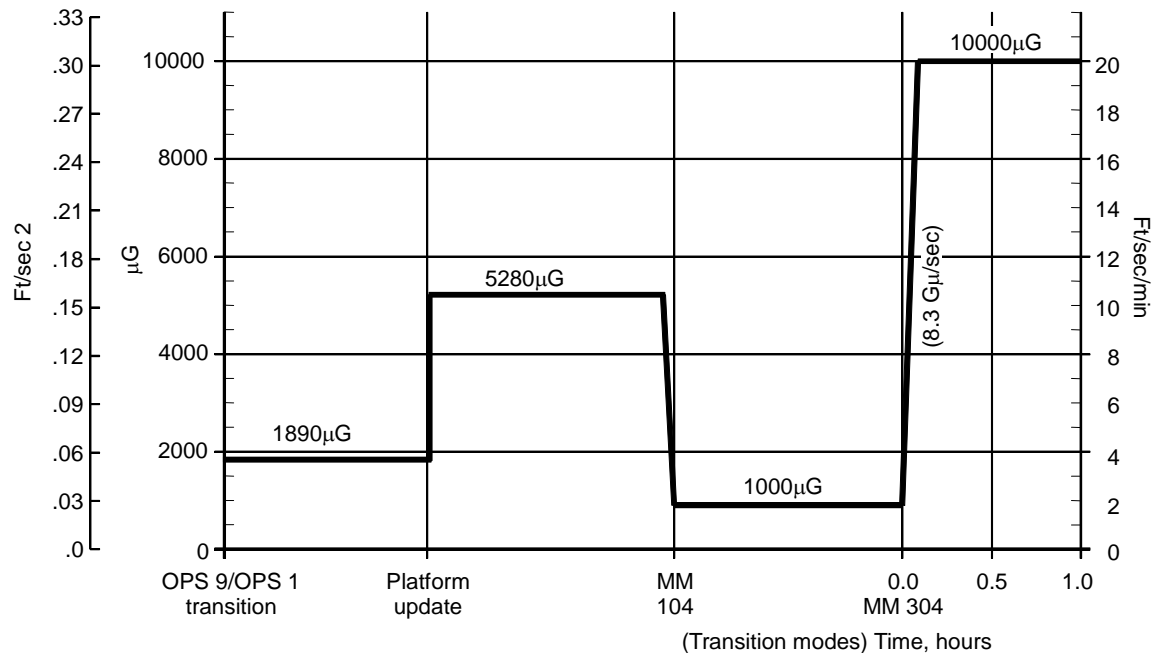
td\_303b\_020

**Figure 4-4. IMU three-level velocity selection filter**

If the error vector is greater than the threshold, the SF looks for a BITE indication on both IMUs. If only one IMU has a BITE indication, the SF downmodes to one good IMU (the IMU without the BITE), and it is used as the velocity source for NAV. If no BITE indication is present, the RM software attempts to isolate the problem to one of the accelerometers. If it can be isolated, a downmoding again occurs. If not, or if both IMUs have BITE indications, or if the error vector is less than the threshold, the velocities of the two IMUs are averaged to compute the total velocity.

If only one IMU is a candidate, its data are used. If no IMUs are candidates, the last sample of data from the previously selected IMU is used.

The velocity FDIR software uses the same logic as the attitude FDIR software, except only two consecutive passes are required to fail an IMU or annunciate a dilemma. Also, no redundant gyro monitor is available to solve velocity DLMAs, and the data will continue to be averaged until the crew deselects one of the two IMUs. (Figure 4-5 is a typical FD threshold chart for velocity.)



usa004488\_021.cnv

**Figure 4-5. Typical velocity fault detection threshold**

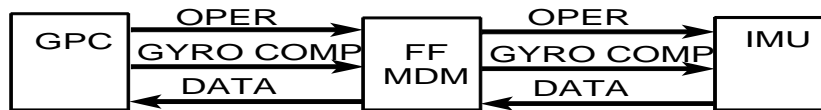
#### 4.5 THERMAL CONTROL SYSTEM

Two types of failures can affect the thermal control system, fan failures and internal heater failures. Fan failures are not as critical since the fan system is a triply redundant system. If a fan fails, either of the other two fans can be powered up to support IMU cooling. A heater system failure is more critical, but it should not cause loss of the IMU.

Since the IMU electronics are highly temperature sensitive, a heater either failed-on or failed-off will cause degraded IMU performance, since the IMU will not be operating at its design temperature. Through GNC telemetry, the MCC should see a heater failure problem well in advance of failure annunciation (depending on telemetry availability) in the form of off-nominal gyro drifts and accelerometer biases. If the problem is a heater failed on, a backup thermostat will open at a higher temperature and the IMU temperature will stabilize at that point. The gyro drifts and accelerometer biases will stabilize, enabling the MCC to compute and uplink (into IMU software) compensation for each, thereby making the IMU usable. Likewise, if the heater fails off, the same results will be attained and the same actions can be taken.

#### 4.6 DATA PATH FAILURES

As stated before, IMUs are linked to GPCs through FF MDMs (see Figure 4-6). For an IMU in the OPER mode, GPC IMU software sends torquing commands, gyro bias compensation, slew commands, and an accelerometer scale factor in the form of two input data words. The IMU returns BITE status, resolver data, and velocity data to the GPC in the form of 14 output data words.



**Figure 4-6. GPC/FF MDM/IMU data path**

Failures in this data path between the IMU and GPC necessitate the execution of procedures in an attempt to regain the data path. Some procedures contain a step in which the affected IMU is deselected from RM.

This is done because of the possibility that velocity data from an IMU that has not been rectified might be selected for navigation. Rectification is explained as follows: The SF provides a selected total velocity to NAV in M50 coordinates. These total velocities are rectified every 8 seconds to limit the errors sent to NAV. Rectification involves calculating the difference between the total velocities from each IMU and the selected total velocity. This difference for each IMU is then added to the total velocities for each IMU every 8 seconds. This results in agreement between the total velocities from each IMU and the selected total velocity every 8 seconds. The bias computed at a given rectification cycle is applied to each IMU total velocity until the new computation on the next rectification cycle.

Therefore, if the IMU is deselected while the data path is being recovered, by the time it is reselected after data path recovery, its velocity data will have been rectified.

At the three-level (i.e., all three IMUs are being used by RM), failure to deselect an IMU presents no problem since RM uses MVS to determine the total velocity vector. It does become a problem when one or two IMUs have failed or have been deselected.

The scheme used here to compute the total velocity vector is either averaging the two remaining IMU velocity vectors or using that of the lone IMU. It can be seen how a bad velocity vector in one of the remaining IMUs or the lone IMU will cause SV problems.

The IMU OPER discrettes are channeled through FF1, 2, and 3 MDMs to IMUs 1, 2, and 3, respectively. They are normally in the ON or "1" state. A loss of this discrete for 8 to 14 seconds causes an IMU to go to standby, which makes it useless (it will cage when moded to operate) until it is realigned.

In the case of a GPC failure, the OPER discrete output from the GPC fails to "0." However, the FF MDM latches its OPER discrete to the IMU at the last value ("1"); therefore, the IMU maintains the OPER mode.

FF MDM data path problems are annunciated by the fault message, I/O ERROR FFx (where x is 1, 2, 3, or 4). A data path failure due to loss of MDM power will result in loss of the OPER discrete, since MDM power is required to maintain output. A data path failure between the MDM and the GPC will not cause loss of the OPER discrete.

In all instances where the IMU does lose the OPER discrete, a BCE STRG x IMU fault message will be annunciated indicating that the IMU is not in OPER. Once back into inertial operation, the caged IMU must be realigned before being included in the selection filter. The IMU has a total time of 84 seconds from loss of OPER mode until back into inertial operation, awaiting realignment.

Although not technically a data path failure, an IMU that loses power will also lose its OPER discrete. In this case, you will get the BCE STRG x IMU message and an IMU BITE/T message simultaneously. On SPEC 21, an 'OFF' indication will be displayed in the STAT field for the IMU.

An operating IMU is constantly pulse torqued by digital command from the GPC to remove known drift (gyro bias compensation). This drift is characteristic of individual IMUs and is measured during ground calibration. Data path failures prevent these torquing pulses from reaching the IMU, causing it to drift at its uncompensated rate. An IMU could operate for a long period without GPC pulse torquing because most of the IMU compensation is housed in the EEPROM hardware memory.



#### **4.7 QUESTIONS**

1. What comprises the IMU RM scheme?
2. What is the purpose of the attitude SF and the velocity SF?
3. What is the purpose of the FDIR?
4. List the two types of failures that can affect the thermal control system.

## **5.0 DIFFERENCES IN THE BFS**

### **5.1 PERFORMANCE OBJECTIVES**

As a result of studying this section, you should be able to do the following:

- a. Describe the BFS RM scheme
- b. Describe how the BFS will downmode an IMU (from SF candidate)

BFS design requirements do not dictate support of all IMU operations. The BFS will not control the IMUs during warm-up, the startup sequence, calibration, or alignments. BFS assumes that, upon being engaged by the crew, the IMUs are in inertial operation, and properly aligned.

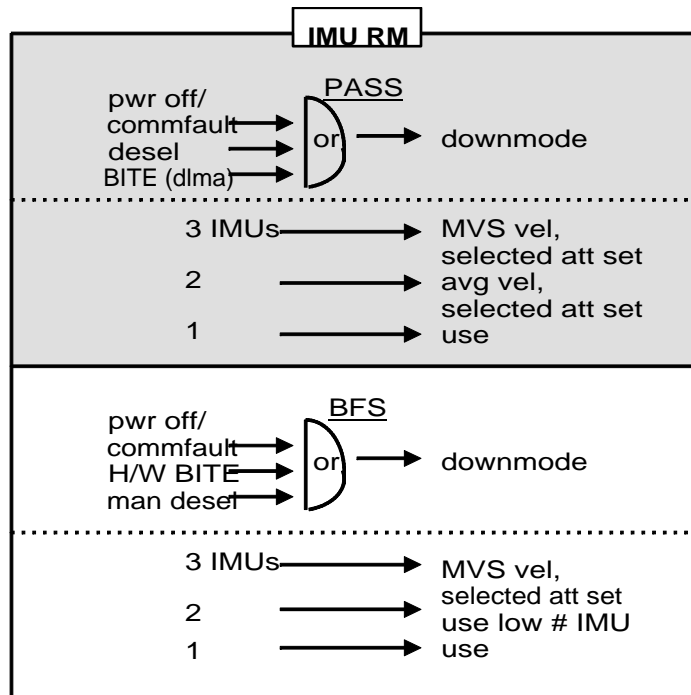
Pre-engage, the BFS IMU Hardware Interface Program (HIP) processes the available accelerometer and resolver data and provides them to other BFS programs. All gyro compensation and torquing are performed by the PASS.

Post-engage, the BFS IMU HIP continues processing the available data, but it also uses pre-flight calibration data, transferred during its Initial Program Load (IPL) process along with PASS-calculated IMU calibration data sent at the one-shot transfer, to periodically torque the gyros to correct drift.

Upon BFS engage, commands are sent to the IMUs to stop any slewing, set the accelerometer scale factors to low, and halt all non-BFS initiated torquing commands. BFS also sends the IMU operate discrete to ensure that the IMUs do not downmode to standby during the engage process.

The BFS does not have a sophisticated IMU RM scheme like PASS. Its RM scheme consists of an SF with no FDIR. If there are three good IMUs (no previous deselections), the SF selects the mid-value on a component-by-component basis for the selected velocity vector and selects an attitude source. This resembles the three-level scheme in PASS. The BFS will downmode an IMU (from SF candidate) by (1) crew manual deselection, (2) IMU power off or commfault, or (3) a hardware BITE. If deselection occurs, the lowest numbered non-failed IMU is selected as the velocity and attitude source. At the one-level (i.e., two IMUs have been deselected), the remaining IMU is the data source. The BFS will never return to the three-level SF after the first downmoding except when the BFS is moded through OPS 000. Crew manual deselections are carried across OPS transitions.

The following diagram from the APCL shows an overview of BFS IMU RM.



The BFS does not recognize PASS IMU RM failures. If PASS downmodes an IMU, it will have to be manually deselected in the BFS. When an IMU is downmoded in the BFS, a class 3 SM alert is annunciated along with an RM FAIL IMU fault message on a DPS Display driven by the BFS.

IMU information in the BFS is available on two displays. BFS OVERRIDE display (SPEC 51) provides the crew with the capability to deselect/reselect IMUs from the SF (see Figure 5-1). SPEC 51 also provides insight as to which IMU the BFS is using for attitude. Execution of the appropriate item number (item 25, 26, or 27) causes deselection of the particular IMU, and this is indicated by an asterisk. A subsequent re-execution of the item number reselects the IMU and the asterisk will be removed. Commfaults are not indicated on this display.

The other display with IMU information is the BFS GNC SYS SUMM display (DISP 18) (see Figure 5-2). This display provides information on any IMU deselection and commfault. A down arrow (↓) indicates the particular IMU that has been deselected for any one of the BFS deselection criteria. If the status area is blank, that particular IMU is usable.

```

XXXX/051/          OVERRIDE          XX X DDD/HH:MM:SS
                                BFS DDD/HH:MM:SS
ABORT MODE          ENTRY FCS
TAL      1X      ELEVON      FILTER      ATMOSPHERE
ATO      2X      AUTO 17X     NOM 20X     NOM      22X
ABORT    3X      FIXED 18X    ALT 21X     N POLE 23X
MAX THROT 4X      SSME REPOS 19 XXX     S POLE 24X

      PROFLT DUMP      IMU DES ATT      AA      RGA      SURF
      1 25X X LRU DES      DES      DES
XXX ICNCT 5 XXXX      2 26X      1 31X      35X      39X
OMS DUMP      3 27X      2 32X      36X      40X
      ARM      6X      3 33X      37X      41X
      START 7X      4 34X      38X      42X
      STOP 8X
      9 QUAN/SIDE XXX
OMS DUMP TTG XXX

AFT RCS 13 XXX      ET SEP          VENT DOOR CNTL
      14 TIME XXX      AUTO 28X      OPEN      43X
      SEP 29X      CLOSE      44X

FWD RCS 15 XXX      ET UMB DR
      16 TIME XXX      CLOSE 30X

```

(XX)

**Figure 5-1. BFS OVERRIDE display (SPEC 51)**

```

XXXX/XXX/018      GNC SYS SUMM 1      XX X DDD/HH:MM:SS
                                BFS DDD/HH:MM:SS

SURF      POS      MOM      DPS      1 2 3 4
L OB      XXX.X      XXS      MDM FF S S S S
      IB      XXX.X      XXS      FA S S S S
R IB      XXX.X      XXS      PL S S
      OB      XXX.X      XXS

AIL      XXX.X
RUD      XXX.X      FCS CH 1 2 3 4
SPD BRK XXX.X      S S S S
BDY FLP XXX.X

MPS      L      C      R      NAV 1 2 3 4
HE TK P XXXXS XXXXS XXXXS IMU S S S
REG P A XXXXS XXXXS XXXXS TAC S S S
      B XXXXS XXXXS XXXXS ADTA S S S S
dP/dT XXXS XXXS XXXS
ULL P LH2 XX.XS XX.XS XX.XS
      LO2 XX.XS XX.XS XX.XS
MPS PNEU HE P MANF P
TK XXXXS LH2 XXXS
REG XXXXS LO2 XXXS
ACUM XXXXS

```

(XX)

TD3030502. CRT: 2  
td\_303b\_023

**Figure 5-2. BFS GNC SYS SUMM 1 display (DISP 18)**

## 5.2 QUESTIONS

1. What comprises the BFS RM scheme?
2. How will the BFS downmode an IMU (from SF candidate)?

**APPENDIX A      ACRONYMS AND ABBREVIATIONS**

A/D	Analog/Digital
ACC	Acceleration
ACCEL	Accelerometer
ADI	Attitude Direction Indicator
ANG	Angle
AOA	Abort-Once-Around
APCL	Ascent Pocket Checklist
ATT	Attitude
AUTO	Automatic
AVG	Average
BCE	Bus Control Element
BFS	Backup Flight System
BITE	Built-in Test Equipment
C&W	Caution And Warning
C/O	Checkout
cal	calibration
cb	circuit breaker
CL	Close
CNTL	Control
COAS	Crew Optical Alignment Sight
COMP	Compensation
COMPOOL	Common Datapool
CPLT	Complete
CRT	Cathode-ray Tube
D&C	Display And Control
DAL	Digital Accelerometer Loop
DAP	Digital Auto Pilot
DBN	Data Bus Network
dc	direct current
DED	Dedicated
deg	degrees
DES	Deselect
DEU	Display Electronics Unit
DISP, DIS	Display
DLMA	Dilemma
DPS	Data Processing System
E	Error Vector
EEPROM	Electrically Erasable Programmable Read Only Memory
ENA	Enable

ERR	Error
EXEC	Execute
FCS	Flight Control System
FD	Fault Detection
FDIR	Fault Detection, Identification, and Reconfiguration
FDF	Flight Data File
FF	Flight Forward
FRL	Fuselage Reference Line
g	acceleration due to gravity
GNC	Guidance, Navigation, and Control
GND	Ground
GPC	General Purpose Computer
GYROCOMP	Gyrocompensation
H/W (HDW)	Hardware
HI	High
HIP	Hardware Interface Program
HUD	Head Up Display
I/O	Input/Output
ID	Identification
IMU	Inertial Measurement Unit
IPL	Initial Program Load
LCC	Launch Control Center
LO	Low
LOS	Line-of-Sight
M50	Mean of 1950
micro-g	microgravity
MCC	Mission Control Center
MDM	Multiplexer/Demultiplexer
MET	Mission Elapsed Time
MM	Mass Memory
	Major Mode
MMU	Modular Memory Unit
MNVR	Maneuver
MON	Monitor
MUX	Multiplexer
MVS	Midvalue Select
NAV	Navigation
NWU	North-West-Up

OP	Open
OPER	Operate
OPS	Operational Sequence Operations
P	Pitch
PASS	Primary Avionics Software System
PLAT	Platform
PREFLT	Preflight
PWR	Power
R/W	Read/Write
RX	Resolver
RCS	Reaction Control System
RDY	Ready
REFSMMAT	Reference Stable Member Matrix
RGA	Rate Gyro Assembly
RGM	Redundant Gyro Monitor
RM	Redundancy Management
RPC	Remote Power Controller
S Table	Star Table
S/W	Software
SEL	Select
SF	Selection Filter Scale Factor
SM	Systems Management
SOP	Subsystem Operation Program
SPEC	Specialist Function
SSMM	Solid State Mass Memory
SSR	Single-system Recovery
STAT	Status
STBY	Standby
STRG	String
SUMM	Summary
SV	State Vector
SYS	System
TCS	Thermal Control System
TEMP	Temperature
TERM	Terminate
THRESH	Threshold
TRANS	Transmission
TRK	Tracker
VEL	Velocity
VERN	Vernier



## **APPENDIX B ANSWERS**

### **ANSWERS TO SECTION 1**

1. The IMU provides inertial attitude and velocity data to the GNC software functions.
2. There are three IMUs installed onboard the orbiter.

**ANSWERS TO SECTION 2**

1. IMU ALIGN (Spec 21) is used to perform an IMU align.
2. The IMU resolvers are electromechanical devices that use the principle of magnetic induction to electrically measure the angle between two adjacent gimbals.
3. An accelerometer is basically a force rebalance type instrument. When the accelerometer experiences an acceleration along its input axes, it causes a pendulum mass displacement.
4. One fan is used to cool the IMUs. There are three IMU fans, but only one is used at a time.
5. False. The IMUs are powered by only two sources.

**ANSWERS TO SECTION 3**

1. The two IMU modes of operation are the warmup/standby mode and the operate mode.
2. A REFSMMAT is simply a 3 by 3 transformation matrix that enables measurements from one coordinate system to be expressed in another.
3. The three types of IMU alignments are the star alignment, the IMU/IMU alignment, and the matrix alignment. Star alignments are normally used on orbit.
4. False. STAR ALIGN and MATRIX ALIGN are available only in MM 301. IMU/IMU align is available in all OPS 3 major modes.

**ANSWERS TO SECTION 4**

1. The IMU RM scheme consists of an SF and FDIR software.
2. The purpose of the attitude SF is to select one IMU as the attitude source for the GNC software. The purpose of the velocity SF is to select component by component the best available data to propagate the orbiter SV.
3. FDIR searches for faulty data, attempts to identify the IMU producing these data, and if successful, reconfigures the SF to exclude data from the faulty IMU.
4. Two types of failures that can affect the thermal control system are fan failures and internal heater failures.

**ANSWERS TO SECTION 5**

1. The BFS RM scheme consists of an SF with no FDIR.
2. The BFS will downmode an IMU by crew manual deselection, IMU poweroff or comm fault, or a hardware BITE.

**APPENDIX C MEAN OF 1950 COORDINATE SYSTEM**

Name: Aries Mean of 1950 Cartesian coordinate system

Origin: The center of the Earth

Orientation: The epoch is the beginning of Besselian year 1950 or Julian ephemeris date 2433282.423357.

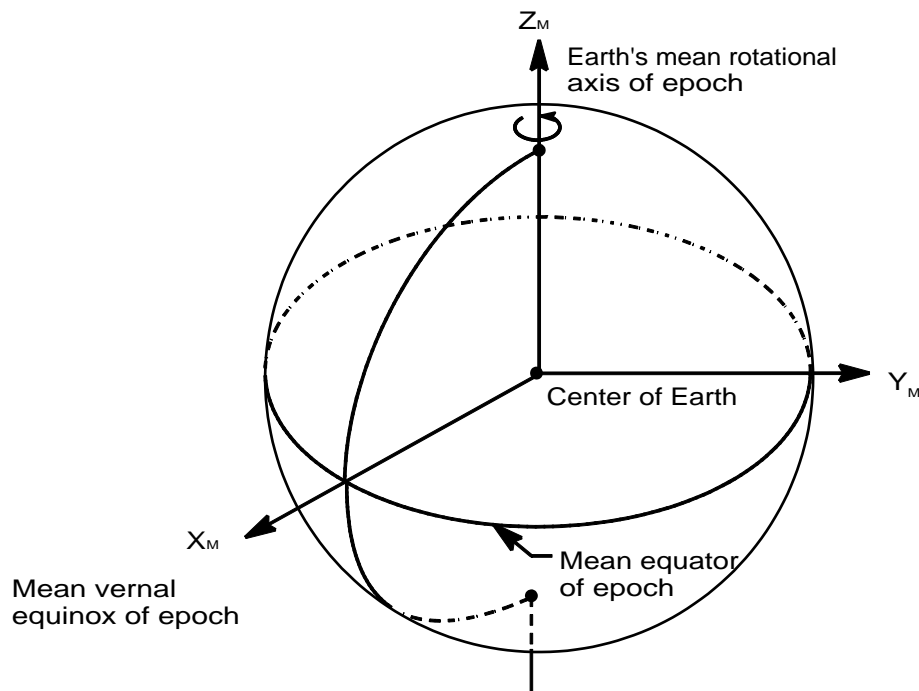
The  $X_M$ - $Y_M$  plane is the mean Earth's equator of epoch.

The  $X_M$  axis is directed towards the mean vernal equinox of epoch.

The  $Z_M$  axis is directed along the Earth's mean rotational axis of epoch and is positive north.

The  $Y_M$  axis completes a right-handed system.

Characteristics: Inertial, right-handed Cartesian system



td\_303b\_024

**Figure C-1. Aries Mean of 1950  
Cartesian coordinate system**

## **APPENDIX D REFERENCES**

1. Attitude and Pointing Flight Procedures Handbook.
2. GNC Systems Briefs, Section 6, IMU.
3. Inertial Measurement Unit Alignment Flight Procedures Handbook.
4. Level C FSSR, GNC, Part E, Inertial Measurement Unit Subsystem Operating Program.
5. S TRK/COAS 21002 Workbook.

# Training Materials Evaluation

Please answer the following questions regarding the lesson that you have just completed. Your feedback allows us to produce more effective training materials. When completed, mail to: **DPS/Navigation Group, DT 35.**

<b>TITLE/LESSON CODE:</b>	<b>Inertial Measurement Unit Workbook/IMU 21002</b>
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<b>SIZE OF AUDIENCE/CLASS:</b>	
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<p><b>1. How well did this lesson meet its purpose?</b> For each statement below, mark one box on the scale:</p> <p>a. <i>The lesson objectives are clearly stated.</i> b. <i>The lesson objectives are clearly defined.</i> c. <i>The lesson effectively teaches skills and information.</i> d. <i>The lesson meets its purpose and objectives.</i></p>	<p style="text-align: center;">Strongly Disagree <span style="float: right;">Strongly Agree</span></p> <table style="width: 100%; text-align: center;"> <tr> <td><input type="checkbox"/></td><td><input type="checkbox"/></td><td><input type="checkbox"/></td><td><input type="checkbox"/></td><td><input type="checkbox"/></td><td><input type="checkbox"/></td> </tr> <tr> <td><input type="checkbox"/></td><td><input type="checkbox"/></td><td><input type="checkbox"/></td><td><input type="checkbox"/></td><td><input type="checkbox"/></td><td><input type="checkbox"/></td> </tr> <tr> <td><input type="checkbox"/></td><td><input type="checkbox"/></td><td><input type="checkbox"/></td><td><input type="checkbox"/></td><td><input type="checkbox"/></td><td><input type="checkbox"/></td> </tr> <tr> <td><input type="checkbox"/></td><td><input type="checkbox"/></td><td><input type="checkbox"/></td><td><input type="checkbox"/></td><td><input type="checkbox"/></td><td><input type="checkbox"/></td> </tr> </table>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>												
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<p><b>2. How satisfying is the content of this lesson?</b> For each statement below, mark one box on the scale:</p> <p>a. <i>The information is structured in a logical flow.</i> b. <i>The content is clear.</i> c. <i>The content is complete.</i> d. <i>The level of detail is correct for this information.</i> e. <i>The amount of information is effective.</i> f. <i>The graphics contribute to my understanding.</i></p>	<p style="text-align: center;">Strongly Disagree <span style="float: right;">Strongly Agree</span></p> <table style="width: 100%; text-align: center;"> <tr> <td><input type="checkbox"/></td><td><input type="checkbox"/></td><td><input type="checkbox"/></td><td><input type="checkbox"/></td><td><input type="checkbox"/></td><td><input type="checkbox"/></td> </tr> <tr> <td><input type="checkbox"/></td><td><input type="checkbox"/></td><td><input type="checkbox"/></td><td><input type="checkbox"/></td><td><input type="checkbox"/></td><td><input type="checkbox"/></td> </tr> <tr> <td><input type="checkbox"/></td><td><input type="checkbox"/></td><td><input type="checkbox"/></td><td><input type="checkbox"/></td><td><input type="checkbox"/></td><td><input type="checkbox"/></td> </tr> <tr> <td><input type="checkbox"/></td><td><input type="checkbox"/></td><td><input type="checkbox"/></td><td><input type="checkbox"/></td><td><input type="checkbox"/></td><td><input type="checkbox"/></td> </tr> <tr> <td><input type="checkbox"/></td><td><input type="checkbox"/></td><td><input type="checkbox"/></td><td><input type="checkbox"/></td><td><input type="checkbox"/></td><td><input type="checkbox"/></td> </tr> <tr> <td><input type="checkbox"/></td><td><input type="checkbox"/></td><td><input type="checkbox"/></td><td><input type="checkbox"/></td><td><input type="checkbox"/></td><td><input type="checkbox"/></td> </tr> </table>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
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<p><b>3. How appealing was the presentation of this lesson?</b> For each statement below, mark one box on the scale:</p> <p>a. <i>The overall presentation is appealing.</i> b. <i>The visuals chosen are appropriate for the lesson.</i> c. <i>The visuals make the information more interesting.</i> d. <i>The graphics are legibly reproduced.</i> e. <i>The audio/visual or print quality is good.</i></p>	<p style="text-align: center;">Strongly Disagree <span style="float: right;">Strongly Agree</span></p> <table style="width: 100%; text-align: center;"> <tr> <td><input type="checkbox"/></td><td><input type="checkbox"/></td><td><input type="checkbox"/></td><td><input type="checkbox"/></td><td><input type="checkbox"/></td><td><input type="checkbox"/></td> </tr> <tr> <td><input type="checkbox"/></td><td><input type="checkbox"/></td><td><input type="checkbox"/></td><td><input type="checkbox"/></td><td><input type="checkbox"/></td><td><input type="checkbox"/></td> </tr> <tr> <td><input type="checkbox"/></td><td><input type="checkbox"/></td><td><input type="checkbox"/></td><td><input type="checkbox"/></td><td><input type="checkbox"/></td><td><input type="checkbox"/></td> </tr> <tr> <td><input type="checkbox"/></td><td><input type="checkbox"/></td><td><input type="checkbox"/></td><td><input type="checkbox"/></td><td><input type="checkbox"/></td><td><input type="checkbox"/></td> </tr> <tr> <td><input type="checkbox"/></td><td><input type="checkbox"/></td><td><input type="checkbox"/></td><td><input type="checkbox"/></td><td><input type="checkbox"/></td><td><input type="checkbox"/></td> </tr> </table>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>						
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<p><b>4. How valuable is this information?</b> For each statement below, mark one box on the scale:</p> <p>a. <i>The lesson teaches skills and information I need.</i> b. <i>The lesson meets my expectations.</i> c. <i>This information is useful for later reference.</i> d. <i>I would recommend this lesson to others.</i></p>	<p style="text-align: center;">Strongly Disagree <span style="float: right;">Strongly Agree</span></p> <table style="width: 100%; text-align: center;"> <tr> <td><input type="checkbox"/></td><td><input type="checkbox"/></td><td><input type="checkbox"/></td><td><input type="checkbox"/></td><td><input type="checkbox"/></td><td><input type="checkbox"/></td> </tr> <tr> <td><input type="checkbox"/></td><td><input type="checkbox"/></td><td><input type="checkbox"/></td><td><input type="checkbox"/></td><td><input type="checkbox"/></td><td><input type="checkbox"/></td> </tr> <tr> <td><input type="checkbox"/></td><td><input type="checkbox"/></td><td><input type="checkbox"/></td><td><input type="checkbox"/></td><td><input type="checkbox"/></td><td><input type="checkbox"/></td> </tr> <tr> <td><input type="checkbox"/></td><td><input type="checkbox"/></td><td><input type="checkbox"/></td><td><input type="checkbox"/></td><td><input type="checkbox"/></td><td><input type="checkbox"/></td> </tr> </table>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>												
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**PLEASE WRITE YOUR COMMENTS/QUESTIONS ON THE BACK OF THIS FORM.  
EXPLAIN ANY NEGATIVE ANSWERS IN SPECIFIC TERMS  
THANK YOU IN ADVANCE FOR YOUR ASSISTANCE!**