FAILURE MODES EFFECTS ANALYSIS (FMEA) -- CRITICAL HARDWARE
NUMBER: 05-1-GN21-HA-INS-X

SUBSYSTEM NAME: GUIDANCE, NAVIGATION, & CONTROL
REVISION: 3 01/10/94

		PART NAME / VENDOR NAME	PART NUMBER / VENDOR NUMBER
LRU	:	HAINS IMU	MC409-0126-1004
		KEARFOTT GUIDANCE & NAV (KG&N)	K160A065-21

PART DATA

EXTENDED DESCRIPTION OF PART UNDER ANALYSIS:

High Accuracy Inertial Navigation System (HAINS)
Inertial Measurement Unit (IMU)
HAINS: Slot No: 1, 2, 3.

REFERENCE DESIGNATORS: 30V71A13
30V71A14
30V71A15

QUANTITY OF LIKE ITEMS: 3
Three redundant functional paths

FUNCTION:

Provides outputs representative of the vehicle attitude changes and accumulated velocity changes with respect to the reference inertial axes for the update of the state vector in the General Purpose Computer (GPC).

FAILURE MODES EFFECTS ANALYSIS (FMEA) -- CRITICAL FAILURE MODE
NUMBER: 05-1-GN21-HA-INS-02

REVISION: 3 01/10/94

SUBSYSTEM NAME: GUIDANCE, NAVIGATION, & CONTROL
LRU: HAINS IMU
ITEM NAME: HAINS IMU

CRITICALITY OF THIS FAILURE MODE: 1R2

FAILURE MODE:

Erroneous output or zero output.

MISSION PHASE:

LO LIFT-OFF
OO ON-ORBIT
DO DE-ORBIT
LS LANDING SAFING

VEHICLE/PAYLOAD/KIT EFFECTIVITY:
102 COLUMBIA
103 DISCOVERY
104 ATLANTIS
105 ENDEAVOUR

CAUSE:

Vibration, shock, excessive vehicle acceleration, excessive vehicle rates, Navigation Base motion, loss or volumetric reduction below minimum specified flow of IMU cooling air, loss of ambient cabin temperature control (high or low), input power transients, piece part failure, memory failure, microprocessor failure, microprocessor firmware error, Primary Avionics Software System (PASS) erroneous software commands.

CRITICALITY 1/1 DURING INTACT ABORT ONLY? NO

REDUNDANCY SCREEN
A) PASS
B) PASS
C) FAIL

PASS/FAIL RATIONALE:

A)

The HAINS IMU will undergo a Hanger Calibration "A" (HCA) after initial installation and a series of tests prior to launch which include Attitude Determinations, Preflight Calibration "A" (PCA), Gyrocompass, Velocity Tilt, and Tuned Inertial tests.

If a problem were to occur during testing, any Built-In Test Equipment (BITE) annunciation(s) or other failure indication(s) would be detected by personnel monitoring at Kennedy Space Center (KSC), Johnson Space Center (JSC), and Rockwell International Space Systems Division.

The Ground Launch Sequencer (GLS) automatically monitors each IMU during the launch sequence until T - 31 seconds. During this time GLS will halt the countdown to launch if any IMU exhibits a fail indication. After the T - 31 second mark, IMU failures are handled in accordance with the Flight Rules. GLS will not halt a countdown to launch in the last 31 seconds.

B)

Redundancy Management (RM) and Built-In Test Equipment (BITE) are the primary sources of real-time failure detection of the IMU during flight.

The major elements of RM are a Selection Filter (SF) element and a Fault Detection, Identification, and Reconfiguration (FDIR) element. The SF provides a single datum output source to user programs derived from redundant input data. Redundant data are input to the SF from the IMU Subsystem Operating Program (SOP).

The SF operates in several modes which are determined by the number of usable entities in the data set. If there are three usable IMUs, a mid value select mode is used. If two IMUs are usable, they are averaged for velocity. For attitude, use the previously selected IMU if available; otherwise, use lowest slot numbered IMU. If only one entity is usable, the SF operates in a pass mode.

The inputs to the FDIR are the same as those to the SF plus select/deselect commands from the comm/fault files and IMU BITE status. FDIR shall examine the data in the redundant set for out-of-tolerance conditions. An IMU failure shall be declared whenever a specified number of consecutive out-of-tolerance conditions are detected. After a fault has been detected, various tests shall attempt to identify the faulty IMU. BITE shall be used to identify the faulty IMU when only two IMUs are in the redundant set. Detected faults and identified failed IMUs shall be sent to the crew via the fault status outputs.

IMU RM detects and identifies failed IMUs based on their attitude and velocity output data, together with selected signals from the IMU BITE. In addition, IMU RM contains the attitude and velocity selection filters. IMU RM functional requirements are specified separately for attitude error processing and velocity error processing. Each attitude and velocity error processing function is divided into the subfunctions of selection filtering, fault detection, and fault identification. To facilitate the two-level attitude and velocity fault identification functions, IMU alignment is required to be skewed by the square root of six. Two-level fault identification functions would be impossible with co-aligned IMUs except when BITE was able to identify the failure.

RM is software internal to the General Purpose Computer (GPC) and cyclically monitors key data parameters from each IMU. The data parameters from each IMU are compared analytically to determine data validity. When data exceeds comparison tolerances, a potential data validity failure exists. Repeated validity failures will cause the RM software, under certain conditions, to deselect the failed IMU. Then the RM software will annunciate to the crew that an IMU failure has occurred.

BITE is internal to each IMU and is used to monitor the hardware and software status of key IMU functions. BITE uses a complement of hardware and software tests to provide an effective method of assuring the functional integrity of the IMU. When a monitored function exceeds preset thresholds, the failure indication(s) can be found as a part of the BITE/Status Word (Data Word 1). The BITE failure is also annunciated to the crew.

RM and BITE cannot detect 100% of the possible IMU failures. However, the combination of RM monitored IMU data parameters including BITE monitored IMU hardware and software failures provides the essential screening required to maximize IMU failure detection.

FAILURE MODES EFFECTS ANALYSIS (FMEA) – CRITICAL FAILURE MODE
NUMBER: 06-1-GN21-HA-INS-02

C)

An externally induced failure may cause the loss of one-to-three IMUs.

The IMU contains an Operational Flight Program (OFP) which resides in a 24K word (16 bits per word) fusible link Programmable Read Only Memory (PROM) on the Memory circuit card. The OFP is the means by which acceleration data and attitude data are accumulated, processed, and compensated. This program has been verified by repeated testing at the vendor, Kearfott Guidance & Navigation (KG & N), and at the Inertial Systems Laboratory (ISL). The testing includes but is not limited to Acceptance Test Procedure (ATP), Verification And Calibration Sequence (VACS), Attitude Determination, Hanger Calibration "A" (HCA), Preflight Calibration "A" (PCA), Gyrocompass, Velocity Tilt, and Tuned Inertial tests. Even though every IMU is subjected to and required to pass rigorous testing, the firmware associated with the OFP has not been 100% validated. The inability of the OFP to perform to its specifications could result in an erroneous output or zero output failure of one-to-three IMUs.

Cooling air is required by the IMU to ensure proper temperature regulation of the inertial components in the stable element. IMU performance degradation may begin to occur when the cooling air reaches 90 degrees F or higher.

Cooling air is drawn through the inlet port located on the upper right hand side of the aft end of the IMU. The air passes through an Electromagnetic Interference (EMI) honeycomb filter into the card stack. Each card is equipped with an aluminum fin heat exchanger or a heat transfer plane. Air flows over and through the card stack and is exhausted through the outlet port located on the lower right hand side of the aft end of the IMU. Cooling air to the inertial platform is controlled by a bimetallic spring valve regulator. When the cooling air temperature is below 80 degrees F, the valve is closed to prevent overcooling. When the cooling air temperature is 120 degrees F, the valve is fully open. At temperatures in between, the modulator valve position is approximately proportional to temperature. The exhaust air from the platform is drawn through a flexible air boot and leaves the IMU via the outlet port.

Cooling air can be affected by a blocked IMU fan assembly screen (CIL 06-1B-0574-01) or a dislodged duct to the IMU fan inlet (CIL 06-1B- 0629-01). The failure mode criticality for these failures are 1/1. A failure of the IMU fan assembly check valve (CIL 06-1B-0427-01) or the remaining IMU cooling air ducting (CIL 06-1B-0630-01) could reduce the cooling air flow. These failures have a criticality of 1R2. There are an additional six failures affecting air flow. All six have a criticality of 2/2. Those failures are:

1. IMU heat exchanger restricted air flow (CIL 06-1B-0557-06)
2. IMU heat exchanger external air leakage (CIL 06-1B-0557-05)
3. Avionics bay ducting external air leakage (CIL 06-1B-0611-01)
4. Avionics bay ducting restricted air flow (CIL 06-1B-0611-02)
5. Cabin return ducting restricted air flow (CIL 06-1B-0616-01)
6. Cabin return ducting external air leakage (CIL 06-1B-0616-02)

Any change to the IMU cooling air has the potential of increasing the IMU temperature. Elevated temperature could cause an erroneous output or zero output failure of one-to-three IMUs through an induced piece part, memory, or microprocessor failure. The loss of ambient cabin temperature control could also contribute to an erroneous output or zero output failure. The effect of a cabin temperature control problem would raise or lower the cabin temperature to unacceptable levels where IMU performance degradation may start.

The occurrence of free water during zero gravity environment could potentially cause erroneous output or zero output failure of one-to-three IMUs. The electronic circuit card NAFI pin fields and motherboard sockets inside the IMU are not conformally coated. Any free water entering the IMU via the cooling air path could cause damage to the IMU. There are 24 CILs documenting the possibility of free water as a result of another failure. One of those 24 failures is external water leakage from the IMU heat exchanger (CIL 06-1B-0557-01) a 1R2 criticality.

The Navigation Base is considered to be a part of the secondary Orbiter structure. Since each IMU is collocated on a secondary Orbiter structure, the IMU fails screen C.

- FAILURE EFFECTS -

(A) SUBSYSTEM:

There is no effect on the subsystem for erroneous output or zero output failures of one or two IMUs. Deselected IMU outputs are ignored by the General Purpose Computer (GPC) and the outputs from the remaining IMUs are processed. An IMU will continue to operate until manually downmoded to STANDBY or OFF.

If the third and final IMU has an erroneous output or zero output failure in OPS 2 (On Orbit) or OPS 8 (Flight Control System (FCS) checkout), the data from that IMU will be utilized until a Built-In Test Equipment (BITE) failure occurs.

If a third erroneous output or zero output failure occurs in OPS 1 (Ascent), OPS 3 (Entry), or OPS 6 (Return To Landing Site (RTLS)), the loss of crew and vehicle would be the worst case result. Erroneous data would be used to update the Navigation state vector, vehicle attitude, and vehicle velocity information. This may put the safety of crew and vehicle in jeopardy.

The failure effect of erroneous data on the subsystem is indeterminable. The effect is dependent on the OPS mode, what data are erroneous, the magnitude of the error, and the amount of time available to correct the error.

(B) INTERFACING SUBSYSTEM(S):

There is no effect on interfacing subsystems for an erroneous output or zero output failure of one or two IMUs.

If the third and final IMU exhibits erroneous data in OPS 2 or OPS 8, the data from that IMU will be utilized until a BITE failure occurs.

If a third erroneous output or zero output failure occurs in OPS 1, OPS 3, or OPS 6, the loss of crew and vehicle would be the worst case result. Erroneous data would be used to update the Navigation state vector, vehicle attitude, and vehicle velocity information. The corruption of this data may place the safety of crew and vehicle in jeopardy.

The failure effect of erroneous data on interfacing subsystems is indeterminable. The effect is dependent on the OPS mode, what data are erroneous, the magnitude of the error, and the amount of time available to correct the error.

(C) MISSION:

The first IMU to fail will be detected and deselected by Redundancy Management (RM). Should the loss of an IMU by deselection occur during a mission, there would be in a Minimum Duration Flight (MDF) in accordance with Flight Rule 8-60.

In a two IMU configuration, should either remaining IMU fail, the mission would be put in a next Primary Landing Site (PLS) posture, again in accordance with Flight Rule 8-60.

If the third and final IMU exhibits erroneous data in OPS 2 or OPS 8, the data from that IMU will be utilized until a BITE failure occurs.

If a third erroneous output or zero output failure occurs in OPS 1, OPS 3, or OPS 6, the loss of crew and vehicle would be the worst case result. Erroneous data would be used to update the Navigation state vector, vehicle attitude, and vehicle velocity information. The corruption of this data may place the safety of crew and vehicle in jeopardy.

The failure effect of erroneous data on the mission is indeterminable. The effect is dependent on the OPS mode, what data are erroneous, the magnitude of the error, and the amount of time available to correct the error.

(D) CREW, VEHICLE, AND ELEMENT(S):

There is no effect on the crew, vehicle, or elements for an erroneous output or zero output failure of one or two IMUs.

If the third and final IMU exhibits erroneous data in OPS 2 or OPS 8, the data from that IMU will be utilized until a BITE failure occurs.

If a third erroneous output or zero output failure occurs in OPS 1, OPS 3, or OPS 6, the loss of crew and vehicle would be the worst case result. Erroneous data would be used to update the Navigation state vector, vehicle attitude, and vehicle velocity information. The corruption of this data may place the safety of crew and vehicle in jeopardy.

The failure effect of erroneous data on the crew, vehicle, or elements is indeterminable. The effect is dependent on the OPS mode, what data are erroneous, the magnitude of the error, and the amount of time available to correct the error.

(E) FUNCTIONAL CRITICALITY EFFECTS:

The criticality of the IMU is 1R3, in most cases, because the loss of crew and vehicle will not occur until after the third IMU failure. However, a condition exists where the criticality becomes 1R2. This condition happens when one IMU has previously been deselected and there exists a deselection dilemma between the remaining two IMUs. Crew procedures address the actions to be taken in the case of a dilemma between the remaining two IMUs. Under that condition, the crew deselects either the lower number IMU or deselects the IMU determined by ground support to be the most likely failed IMU. By deselecting the lower number IMU in the Primary Avionics Software System (PASS), the Backup Flight System (BFS) will be utilizing a different IMU than the PASS. The BFS software always uses the lowest number IMU available for vehicle information while the PASS uses a software algorithm to determine vehicle information. The safety of the crew and vehicle hinges upon the mission phase in which a deselection dilemma occurs and how much time is available to determine the most likely failed IMU.

-DISPOSITION RATIONALE-

(A) DESIGN:

The High Accuracy Inertial Navigation System (HAINS) is an all- attitude, four gimbal, space stable Inertial Measurement Unit (IMU). The inertially stabilized platform and associated electronics supply outputs proportional to vehicle attitude (roll, pitch, and azimuth angles) and velocity (X, Y, and Z axes) to the General Purpose Computer (GPC). Each gimbal is gyro stabilized using signals derived from the vertical gyro (X-Y axes) and the azimuth gyro (Z-Redundant axes). Each gyro is a two degree of freedom gyro and is mounted on the innermost (azimuth) gimbal. Acceleration data are provided by three mutually orthogonal single axis accelerometers mounted on the azimuth gimbal. The X and Y accelerometers are physically located on the upper half of the azimuth gimbal next to the vertical gyro. The Z accelerometer is located on the lower half of the azimuth gimbal on the back plate of the coordinate resolver.

The HAINS contains an Operational Flight Program (OFP) which resides in a 24K word (16 bits per word) Programmable Read Only Memory (PROM) on the Memory circuit card. The OFP has been designed to provide the following:
- transparency to the GPC between the HAINS and KT-70 IMU
- internal compensation for I-load parameters
- data extrapolation and interpolation for senescence
- augmented I-load parameter compensation
- expanded BITE capability.

The OFP is the means by which acceleration data and attitude data are accumulated, processed, and compensated.

The detailed functional requirements and formulations for the IMU Subsystem Operating Program (SOP) are documented in the Functional Subsystem Software Requirements (FSSR). The IMU SOP defines the GPC software associated with multiple IMU moding, self test, failure identification, hanger calibration, preflight calibration, preflight alignment, and inertial operation.

The IMU design has passed Qualification, Acceptance, Shuttle Avionics Integration Laboratory (SAIL), and Verification and Calibration Sequence (VACS) tests.

Electronic, Electrical, Electromechanical (EEE) parts and/or JAN-TX parts are used wherever possible. The IMU design also utilizes hybrid modules to reduce the number of parts and part types. Applicable derating guidelines are used to assure adequate safety factors in parts applications.

Redundancy Management (RM) and BITE are the primary sources of failure detection in the IMU. The BITE status is contained in Output Data Word 1 - HAINS Mode/BITE Status. Word 1 is a 20 bit word that is defined as follows:

Bit 1	Sync pulse	
2	Sync pulse	
3	Sync pulse	
4	HAINS Good BITE -	This bit will be set ("1") when bits 5 - 12 are clear ("0").
5	MUX Fail BITE -	This bit will be set when the end around transmission test fails or the MUX BITE detects a fail condition.
6	A/D Fail -	This bit will be set when the A/D BITE detects a fail condition.
7	Platform Fail -	This bit will be set when the Platform BITE detects a fail condition or the Gyro Wheel Supply (GWS) BITE detects a fail condition.
8	Digital Subsystem Fail -	This bit will be set when the BITE

	detects a CPU, I/O, or Memory failure.
9 DC/DC Fail -	This bit will be set when the DC/DC BITE detects a fail condition.
10 Discrete Power Supply Fail -	This bit will be set when the BITE detects a +5 Vdc isolated power supply failure.
11 Resolver Fail -	This bit will be set when the resolver voltage or current limits are exceeded.
12 Circuit Card Overtemperature -	This bit will be set when a circuit card overtemperature condition exists.
13 Transmission Word 1 Fail -	This bit will be set when the parity, gap, or Manchester coding in word 1 fails.
14 Transmission Word 2 Fail -	This bit will be set when the parity, gap, or Manchester coding in word 2 fails.

15 D1/D8 Sequencer Discrete
16 D2 Sequencer Discrete
17 D3 Sequencer Discrete
18 D4 Sequencer Discrete
19 D5 Sequencer Discrete
20 Parity

Output Data Word 15 and 16 contain detailed BITE information that is accessible only during laboratory test. Words 15 and 16 are not currently read by the GPC.

(B) TEST:

The platform and circuit card assemblies are subjected to 100 percent burn-in and screening for workmanship defects. The Acceptance Test Procedure (ATP) that is performed on each IMU at the vendor includes a Thermal and a Vibration test. In addition, each IMU is subjected to a Verification and Calibration Sequence (VACS) test at the Inertial Systems Laboratory (ISL). Further, each IMU not immediately installed on a vehicle is subjected to Periodic Calibration Sequence (PCS) at 120 day intervals for Flight ready spares and 180 day intervals for a Periodic Operation Sequence (POS) at the ISL. Vehicle preflight tests include an Attitude Determination, Hangar Calibration "A" (HCA), Preflight Calibration "A" (PCA), Gyrocompass, Velocity Tilt, and Tuned Inertial tests. IMU performance is monitored during each vehicle Terminal Countdown Demonstration Test (TCDT) and during prelaunch to verify proper operation. Integrated and subsystem verification is performed periodically during turnaround. Note - the additional VACS tests performed at the ISL are required to augment the existing ATP at the IMU vendor, Kearfott Guidance & Navigation (KG & N).

Extensive software requirements and verification tests are performed prior to launch. Acceptance Test Procedure (ATP) is witnessed by Inspection. A part of the ATP is the testing of environmental (vibration and thermal) conditions. Vibration testing is run in three different axes

FAILURE MODES EFFECTS ANALYSIS (FMEA) – CRITICAL FAILURE MODE
NUMBER: 05-1-GN21-HA-INS-02

(X, Y, and Z). Once the selected axis is aligned with the vibration axis of the test table, tilts are estimated until the tilts are stable. The vibration is started and another tilt estimate is taken. At the conclusion of the vibration, three more tilt estimates are performed. The last tilt estimate before vibration is averaged with the first tilt estimate after vibration. The average tilt is compared to the tilt estimate during the vibration and a pass/fail is recorded. The differences between the pre- and post- vibration data on the level accelerometer axes and the vertical resolver axis are limit checked and pass/fail indications are recorded.

The random vibration specifications are as follows:

Flight Acceleration Spectral Density		Qualification Acceptance Vibration Acceleration Spectral Density	
20 - 80 Hz	+6 dB/octave	20 - 80 Hz	+3 dB/octave
80 - 350 Hz	0.01 g2/Hz	80 - 350 Hz	0.067 g2/Hz
350 - 2000 Hz	-6 dB/octave	350 - 2000 Hz	-3 dB/octave
Duration: 34 minutes in each axis		Duration: 10 minutes in each axis	

These reductions in Certification Requirements are based on flight data from STS-1 through STS-6.

The shock requirement for the IMU basic design is a 20 g terminal sawtooth shock pulse of 11 ms duration in each of three orthogonal axes in both directions. The crash safety shock is twice the basic design with one addition requirement. The equipment and its mounting attachments shall not break loose, create a hazard to personnel, or prevent egress from a crashed vehicle. Operating performance is not required after a crash safety shock.

Loss of input power does not cause damage to the IMU. The IMU will shut itself down if the input voltage falls below the low voltage (+24 Vdc).

(C) INSPECTION:

RECEIVING INSPECTION -
Incoming material is verified by Receiving Inspection.

CONTAMINATION CONTROL -
Final assembly and rework is performed in a clean room. The stable platform assembly is performed in a class 100,000 clean room per FED-STD-209. The completed assembly is visually inspected and vacuumed to detect and remove any internal conductive contamination before the top and bottom closeout covers are installed.

NONDESTRUCTIVE EVALUATION -
Radiographic inspection is performed and is verified by inspection.

ASSEMBLY/INSTALLATION -
All assembly benches are equipped with grounding straps and bench covers. Visual Aids provided for printed wiring board component assembly and all processes are visually verified before conformal coating.

CRITICAL PROCESSES -
Quality Engineering derived procedures are used for bonding, soldering, coating, and potting. These processes are imposed through process specifications. Operators are certified for critical processes. Processes are controlled by Quality Control. All solder operators are certified.

FAILURE MODES EFFECTS ANALYSIS (FMEA) – CRITICAL FAILURE MODE
NUMBER: 05-1-GN21-HA-INS-02

TESTING -
The Acceptance Test Procedure (ATP) is verified by inspection.

HANDLING/PACKAGING -
Packing/Packaging requires special containers which are used for transportation and shipping. Vibration and shock are tested in accordance with MIL-STD-794 as defined in FED-STD-101. Accepted and returned hardware is kept in a bonded storage area.

(D) FAILURE HISTORY:

No Space Shuttle flight failure history for the HAINS IMU exists. All other applicable failure history is limited to manufacturing and bench testing at the vendor Kearfott Guidance and Navigation (KG & N), Shuttle Avionics Integration Laboratory (SAIL), and at the Inertial Systems Laboratory (ISL).

(E) OPERATIONAL USE:

There are no actions/procedures which can be taken by the crew in order to preclude the effect of a failure. Crew training includes the nominal management of the IMUs as well as the implementation of crew procedures for recovery of a failed/deselected LRU. The ground, during monitoring of the IMU subsystem, is required to ensure that an IMU is maintained within a 3 sigma performance envelope. The operational constraints on the mission are as follows:

1. A landing at the Edwards complex or a lakebed runway will be required for the loss of one (1) or two (2) IMUs respectively. This requirement provides the energy downmoding options necessary due to subsequent failure or performance degradation of the remaining IMU(s) which affect the onboard navigation state vector.

2. Entry should not be performed if the predicted RSS misalignment of an IMU at Entry Interface (EI) is greater than 0.5 degrees. Exceeding this limit could (in the worst case) result in violation of the 342 psf flight control design limit for dynamic pressure. Due to the lack of visibility by the crew on the IMU performance, the ground is required to ensure that an IMU misalignment does not violate the 0.5 degree RSS limit. Three sigma drift from deorbit alignment would result in 0.09 degree misalignment at EI. Note: Deorbit will be waved off if necessary and Star Tracker/IMU alignment will be accomplished prior to deorbit burn

- APPROVALS -

EDITORIALLY APPROVED	: RI	
EDITORIALLY APPROVED	: JSC	1/19/94
TECHNICAL APPROVAL	: VIA CR	~~: DRB0003~~ S50270L