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Testing of the High Accuracy Inertial Navigation System in the Shuttle Avionics Integration Lab

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Abstract

This paper presents the description, results, and interpretation of comparison testing between the High Accuracy Inertial Navigation System (HAINS) and KT-70 Inertial Measurement Unit (IMU). The objective of the tests were to demonstrate the HAINS can replace the KT-70 IMU in the space shuttle Orbiter, both singularly and totally. This testing was performed in the Guidance, Navigation, and Control Test Station (GTS) of the Shuttle Avionics Integration Lab (SAIL) at the Johnson Space Center. GTS is a space shuttle simulator which is primarily utilized to evaluate and verify the flight software that operates the shuttle's five General Purpose Computers (GPC).

A variety of differences between the two instruments are explained. Besides being smaller and lighter, the HAINS has the capability to be internally torqued by commands from a GPC.

Four, 5-day test sessions were conducted varying the number and slot position of the HAINS and KT-70 IMUs. The various steps in the calibration and alignment procedure are explained.

Results and their interpretation are presented. The HAINS displayed a high level of performance accuracy previously unseen with the KT-70 IMU. The most significant improvement of performance came in the Tuned Inertial/Extended Launch Hold tests. The HAINS exceeded the 4-hour specification requirement. The results obtained from the SAIL tests were generally well beyond the requirements of the procurement specification.

The performance of the HAINS in the SAIL demonstrated the transparency of operation with respect to the KT-70 IMU. In addition, the concept of an internally compensated INS is compatible with the Orbiter avionics systems and flight software.

Purpose and Introduction

This paper presents the description, results, and interpretation of comparison testing between the High Accuracy Inertial Navigation System (HAINS) and the KT-70 Inertial Measurement Unit (IMU). The objective of the tests were to demonstrate the HAINS can replace the KT-70 IMU in the Space Shuttle Orbiter, both singularly and totally. Both pieces of hardware are products of the Kearfott Guidance and Navigation Corp, Wayne, N.J.

Four test sessions were conducted during May, June, July, and August, 1990, in the Shuttle Avionics Integration Lab (SAIL) Guidance, Navigation, and Control Test Station (GTS) located at the Johnson Space Center, Houston, TX. GTS is a six degree-of-freedom space shuttle simulator which is primarily utilized to test the flight software that operates the shuttle's five, IBM AP101S General Purpose Computers (GPCs). These GPCs have a 256K bit memory and employ parallel processing of data.

The KT-70 IMU is presently in use aboard the three operational space shuttles. It provides accurate velocity and attitude information for use in the shuttle's GN&C systems. The inertial sensors contained in the four gimbal platform are two GYROFLEX gyroscopes and two force rebalance accelerometers. One and 8-speed resolvers are utilized to provide digital gimbal angle readouts. The KT-70 IMU consists of an all-attitude stabilized platform and associated electronics to supply output data. The Orbiter employs a triple redundant IMU configuration with skewed inertial clusters. This geometry provides failure detection and isolation techniques. The IMU Subystem Operating Program (SOP) is software that functions during factory calibration/test, hanger calibration, and preflight calibration and alignment. In-orbit IMU updates are provided by on-board star trackers, which are mounted on a common navigation base. The IMU interface to the Orbiter's GPCs is accomplished via a multiplexed serial data line. The KT-70 IMUs are self-contained requiring only external power and cabin cooling air. Each instrument is 10.28 inches high, 11.5 inches wide and 22 inches long, weighing 58 pounds.

The Space Shuttle HAINS is a modified version of the USAF B-1B instrument. The HAINS contains an internal dedicated microprocessor with memory for processing and storing hardware compensation and scale factor data from the vendor's calibration. Therefore, the need to initial-load (I-load) over sixty parameters into the GPCs Mass Memory Unit (MMU) prior to a flight is reduced. The CPU software is called the Operational Flight Program (OFP). It includes Built-In-Test-Equipment (BITE) logic for the hardware and processed data. Navigational data are developed from self-contained inertial sensors consisting of a vertical accelerometer, two horizontal accelerometers, and two, 2-axis displacement GYROFLEX gyroscopes. The sensing elements are mounted in a four-gimbal, gyro stabilized inertial platform with the accelerometers (which are maintained in a known reference frame by the gyroscopes) as the primary source of information. Attitude and heading information is obtained from resolver devices mounted between the platform gimbals. The HAINS is 9.24 inches high, 8.49 inches wide, and 22 inches long, weighing 43.5 pounds.

An inertial navigation system (INS) has: A) sensors that detect instananeous vehicle linear acceleration along three orthogonal axes, and B) derives vehicle linear velocity and position and vehicle attitude and heading. The combination of these two features makes a self-contained system. With respect to the space shuttle, feature A is presently performed by the KT-70 IMU while feature B is performed by the GPCs.

Differences between the KT-70 IMU and HAINS

There are a variety of differences between these two pieces of hardware.

HAINS is smaller and lighter than the KT-70 IMU. HAINS has the capability to be internally torqued by its own microcomputer while the KT-70 IMU is externally torqued by commands from a GPC. The HAINS has one resolver for each axis while the KT-70 IMU has two resolvers per axis. The HAINS gyro error parameters are monitored by the self-contained CPU and transmitted to the GPCs through the MUX card and multiplexer. On the KT-70 IMU, these parameters are stored in and monitored by a GPC. The HAINS takes a longer amount of time than the KT-70 IMU to spin-up and spin-down due to braking circuit design. A Stat value of 3F, on the Ground IMU Control/Monitor display, indicates the IMUs are completely spun up. See Firgure 1. The HAINS gyroscopes contain a gold plate that reduces gyro drift rate trending. Trending is the long term change in a parameter. The HAINS accelerometers allow for a tighter deadband. Not all of the HAINS capabilities are used in the Space Shuttle version because of the need to maintain transparency with the KT-70 IMU.

Initial-loads (I-loads) are predetermined values for various parameters (e.g., gyro errors). I-loads for the HAINS or KT-70 IMU vary from Orbiter Vehicle to Orbiter Vehicle.

Test Descriptions

Four test sequences, each consisting of five test cases, were conducted for approximately one week over the four month period of May, June, July, and August, 1990. The approach for the first three of the test sequences consisted of integrating one HAINS at a time into the GTS in combination with the KT-70 IMU, until a full complement of three HAINS formed the test configuration for the third sequence. Test sequence 4 consisted of five special cases. See Table 1A and B. The GPCs were loaded with OI-8F flight software with both nominal and off-nominal (5-sigma) I-loads for the HAINS. For the KT-70 IMUs, the I-loads were determined at the ISL.

The IMU Redundancy Management (RM) routines were tested by inserting a delta bias into a HAINS during an IMU dilemma condition and observing the deselection of the appropriate IMU by RM.

May 1990 Testing Session

A) One HAINS (Slot 1) and Two KT-70 IMUs

B) All three instruments were controlled from the cockpit. Because there was no Launch Data Bus, the Launch Processing System (LPS) only monitored downlisted data from the GPCs. The LPS is a duplicate of the actual ground station equipment used at the Kennedy Space Center (KSC) from T-2.5 hours through countdown and liftoff.

June 1990 Testing Session

A) Two HAINS and 1 KT-70 IMU (Slot 3)

B) All three instruments were controlled from the cockpit except one test they were controlled from the LPS. Downlisted data from the GPC was monitored at the LPS.

July 1990 Testing Session

A) Three HAINS

B) All three instruments were controlled from the LPS through the Launch Data Bus (LDB). Downlisted data from the GPCs was monitored at the LPS. Raw redundant gyro data is what comes out of the IMU and contains noise. Compensated redundant gyro data is filtered (second ordered) by the GPC.

May, June and July Test Sessions

A) Test Case 1 : Orbiter Vehicle (OV) in horizontal position to simulate change out of units in the KSCs Orbiter Processing Facility (OPF)

B) Test Case 2 - 5 : OV in vertical position to simulate on-the-pad environment

August 1990 Testing Session

A) Two HAINS and 1 KT-70 IMU (Slot 1)

B) All three instruments were controlled from the LPS.

C) All five tests performed in the vertical position

Hanger Calibration A (HCA)

Each IMU is moved through 25 predefined cluster orientations. Using the measured acceleration and drift as measured by the accelerometers at each position, accelerometer biases, scale factors, symmetry, and misalignments as well as gyro bias scale factors, sensitivities, mass unbalances, drift and misalignments are calibrated. All three IMUs are commanded simultaneously in the operate mode. Item 20 on Spec 104 , the Ground IMU Control/Monitor Spec, is used to request initiation of this procedure that takes approximately six hours. See Figure 1. Item 28 on Operational Sequence (OPS) display 9011 (GPC Memory) indicates the position number (0001 - 0013) of the IMU cluster calibration being performed at that time. See Figure 2. During the hanger calibration, one of two sets of transformation matrices, describing desired platform orientations relative to the navigation base, is loaded into the GPC. Two distinct sets are available as a contingency provision to allow for alternate launch parameters.

Preflight Calibration A (PFCA)

Each IMU is sequenced through 13 platform or cluster positions, two times: the accelerometers are set in high gain for the first pass, and, in low gain in the second pass. All gyro calibration data and the high gain accelerometer calibration data are collected in the first pass. The second pass is to collect data for the low gain accelerometer calibration. A two minute delay is required for the accelerometers to stabilize following each gain change. A subset of the accelerometer and gyro compensation parameters are updated. This procedure will calibrate all selected IMUs in the operate mode and takes approximately two hours. The launch pad preflight calibration is started no earlier than 15 hours prior to launch. The calibrated parameters are valid for 17 hours, thus providing at least two hours of on-orbit use before degradation. The IMUs will remain in the operate mode from the beginning of this calibration through launch.

Compensation Criteria (C-Crit)

The compensation criteria provides a basis for accepting or rejecting the results for an IMU calibration. It is used at the Kennedy Space Center to evaluate unit health. For example, the compensation criteria for the KT-70 IMU is 0.035 degrees per hour of drift while for the HAINS it is 0.006 degrees per hour.

Platform Positioning

The IMU gimbals are reoriented and then fixed (or caged) in place. 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. Thus, the nav base and platform coordinate axes are parallel. This procedure takes approximately two minutes.

Attitude Determination

Resolver (attitude) and velocity data is used to determine the orientation of the navigation base to the North-West-Up (launch pad) coordinate frame for each operating IMU. A gyrocompassing technique is used to determine the position of north, west, and up relative to cluster position. This procedure, in conjunction with the gimbal angles, is used to define the navigation base to NWU transformation. The transformation is a prerequisite for running all subsequent options involving alignment and calibration. This procedure takes approximately four minutes. It is required whenever the Orbiter has been moved on the ground or the transformation data may have been destroyed in the GPC memory.

Preflight Platform Alignment

A preflight platform alignment, consisting of a gyrocompass alignment and velocity/tilt initialization, is performed for each IMU after the preflight calibration is completed. The purpose of this alignment is to position the platforms to the desired orientation for launch, to maintain this orientation until T-20 minutes (OPS 1 transition), and to provide platform orientation data to the GPCs. The gyrocompass phase of the preflight alignment positions the IMU platforms relative to the navigation base reference systems. The desired orientation loaded into the GPC during hanger calibration is used for this alignment. Since the navigation base orientation relative to the launch pad is known, this alignment actually positions the IMU platforms to a desired orientation relative to the NWU coordinate frame whose origin is at the launch pad.
Velocity/tilt initialization estimates the tilts and drifts experienced by the IMU's due to the Earth's rotation and gravity effects while awaiting the OPS 1 transition. Preflight platform alignment takes approximately 48 minutes.

Gyrocompass Alignment (GCA)

The platforms are moved to skewed launch orientations defined with respect to the navigation base. The platform skewing is primarily for redundancy management purposes and also prevents more than one IMU experiencing gimbal flip at the same time. During this phase, the IMUs are placed in two orientations relative to the NWU coordinate system. These two orientations differ only in a 90 degree rotation about the up axis. Data is collected for 90 seconds by the accelerometers to remove any misalinement due to the reorientation. The accelerometers are used here because their accuracy is much better than the resolvers and the acceleration due to Earth rotation is definitely known. Therefore, any unexpected acceleration is due to IMU misalinement. Once this misalignment is nulled, the platform is torqued about the north axis to compensate for the Earth's rotation. Data is then collected for ten minutes to measure platform drifts. This sequence of data collecting is repeated at the second orientation. Also the relative attitude errors for each IMU pair are computed using resolver data. This is then repeated using accelerometer data. These two values are subtracted and transformed into body coordinates. A factory-calibrated relative resolver error term is then subtracted. At the end of the GCA, a relative gyrocompassing goodness test is performed on each IMU pair (1:2, 1:3, and 2:3). Failure to pass the goodness test will be indicated on the Ground IMU Control/Monitor display (FAIL will appear under GYROCOMP). Success of the goodness test is depicted on this display when the Hardware Bit Indicator changes from 8010 to 8000 thus signaling the switch of the Capacitive Reset Integrator (CAPRI) Scale Factor Gain Setting from high to low. See Figure 1. GC Fail = 0000, on GNA TOC display GC Align, also verifies a successful GCA. This procedure takes approximately 38 minutes. At the end of GCA, the software will automatically advance to Velocity/Tilt.

Velocity Tilt

The platforms are torqued at Earth's rotational rate, keeping the skewed launch orientations (set up by GCA) constant with respect to the navigation base. This establishes the drift experienced while waiting for the OPS 1 transition and amounts to less than 200 arcseconds per axis between IMUs. These drifts measured by the accelerometers are used to develop a compensation which is applied to the gyros from the OPS 1 transition to T- 12 seconds. They are also used to compute the current platform to M50 reference stable member matrix (REFSMMAT) at the OPS 1 transition. This procedure takes approximately ten minutes, at which point, CPLT appears under GYROCOMP on the Ground IMU

Control/Monitor display. VT Fail = 0000 indicates a successful completion of Velocity Tilt. At the same time, the software will begin performing a level axis tilt test on each platform three times per second.

Inertial Reference Alignment Monitoring System (IRAMS)

The IRAMS was designed to monitor IMU health, measure misalignments, predict launch hold time, and correct misalignments (if necessary) to avert a scrubed mission. IRAMS determines IMU platform misalignment while holding on the launch pad. The IRAMS computes and displays values of gyro drift compensation needed to correct the misalignment over a specified period of time. IRAMS will monitor to determine if the misalignment was corrected. See Figure 3.

Inertial

This submode is requested by the crew using a keyboard item entry. It provides users with attitude and velocity data for flight computations. It also provides IMU torqueing to compensate for gyro drift. At the OPS 1 transition, the IMUs enter the "tuned inertial" drift compensation mode. It is "tuned" because a compensation factor, computed in the velocity tilt, is applied to the IMU gyro torqueing signals to account for the estimated drift, keeping the platforms aligned to the M50 coordinate system. The total accumulated IMU velocity data is compensated for accelerometer errors in order to support the navigation and redundancy management functions. The gimbal angles are compensated and made available to navigation and user interfaces. At T-12 seconds, this compensation is removed and the IMUs enter "free inertial" mode. The IMUs are now flight ready.

If a technical hold is imposed (launch delay encountered) between gyrocompass alignment and T-20 minutes, the inertial orientation of the IMU platforms computed from velocity tilt will differ from the current REFSMMAT expected for a nominal on-time launch. Since many ground systems supporting the Orbiter's GN&C functions use the current REFSMMAT, it is imperative that these ground systems incorporate the REFSMMAT computed by the Orbiter's Onboard Primary Flight Software at T-20 minutes. These REFSMMAT will be made available to the ground through telemetry (TLM) downlink.

If a technical hold is imposed after transition to OPS-1, the computed current REFSMMAT remains unchanged; however, vel-tilt drift compensation may be degraded with a resultant difference between the actual platform positions and the positions described by the current REFSMMATs. This status can be monitored from the ground and if limits are reached, the count must regress to some time prior to GCA in order to realign the IMU platforms.

Redundant Gyro Monitor (RGM)

For simulated on-orbit operation, a redundant gyro monitor test was performed for a roll, yaw, and pitch axis on the Dynamic Motion Simulator (DMS). This table and associated controls allowed for an all-attitude, unlimited rotation of the HAINS and KT-70 IMU in three orthogonal axes. By programming the slope of the frequency sweep, the angular acceleration and the time span of constant rate were accurately controlled. The DMS was tilted to a 45 degree angle from the reference position (launch orientation) in each axis. Starting from the horizontal position, the table was ramped to a rate of 13 degrees/second. It returned to zero degrees/second by the time the table reached a 45 degree incline. This procedure provided a means to calculate the staleness of the resolver angle data. It also checked the IMU's stability and performance under normal on-orbit maneuvering conditions. The table was ramped through a zero to thirty to zero degree/second cycle during testing in August. An IMU platform is capable of remaining inertial for vehicle rotations of up to 35 degrees/second and angular accelerations of 35 degrees per second squared.

Redundancy Management (RM)

The IMU RM scheme consists of a selection filter (SF) and fault detection, identification, and reconfiguration (FDIR) software. The SF selects the best data from the available IMUs. FDIR searches for faulty data, attempts to identify the IMU producing the data, and if successful, reconfigures the SF to exclude data from the faulty IMU.

The RM software is divided into two distinct areas, attitude RM and velocity RM. The purpose of the attitude SF is to choose one IMU as the attitude source for the GN&C software. The purpose of the velocity SF is to choose the best available data from the IMUs for use in propagating the Orbiter's state vector. Depending on the number of available IMUs, the SF uses different schemes to determine which IMU to use. Mid-select and averaging techniques are used in the data selection process.

On-Orbit IMU-to-IMU Alignment

When at least one IMU is already in alignment, this option is available to reposition any IMU(s) back to the desired cluster orientation with respect to inertial space. The aligned IMU is used as reference. Because the platforms are both slew and torqued, this type of alignment is fast and should be used when large misalignment angles are present. IMU-to-IMU alignments do not use star tracker or Crew Optical Alignment System data.

Results, Analysis, and Interpretation

Spin-up and spin-down time for the HAINS took 90 seconds while the KT-70 IMU took 37 seconds. The 53 second difference is due to the HAINS braking circuit design.

A total of ten Hanger Calibration A's were performed with excellent results. Three tests had the IMUs oriented horizontally to simulate the change out of units in the KSCs OPF. The other seven calibrations had the IMUs vertically oriented to simulate an on-the-pad environment. Three of these tests were initialized with 5-sigma off-nominal I-loads while the other four tests had nominal I-loads. Sample results are presented in Table 2. HCAs successfully calibrated the HAINS off-nominal 5-sigma I-loads.

A total of 16 PFCAs were performed with the IMUs in the vertical orientation with excellent results. The initial conditions for these PFCAs consisted of either nominal I-loads or previous SAIL calibrations via a Mass Memory read. Sample results are presented in Table 3.

A total of 38 preflight alignments were performed successfully. An example of HAINS GC results are presented in Table 4. Accelerometer and gyro performance was good. The requirement for the gyro re-straint drift terms is 0.018 deg/hr over a year (3-sigma).

The Tuned Inertial/Extended Launch Hold tests perhaps best depicted the significant improvement of performance realized in the HAINS design. Holds of up to three hours in tuned inertial were successful. The IRAMS monitored platform drift and consistly predicted launch hold capability in excess of the four hour specification requirement.

Two series of OPS Trans were performed successfully. During simulated powered ascent (OPS 1, Liftoff through Orbit Circularization Maneuver Coast) and using the PASS, less torque commands were issued to the HAINS than KT-70 IMU. This decrease can be attributed to the HAINS gyro error parameters being internally compensated.

During each of three runs, one IMU was deselected and a large delta gyro bias was patched via a keyboard input to one of the remaining selected IMUs, in each case a HAINS. This tested the ability of PASS RM to properly fail a badly drifting HAINS in a RM attitude dilemma scenerio. With a delta bias of 4 deg/hour to the y-gyro (DFY) of IMU-3, RM correctly failed IMU-3. With a delta bias of 4 deg/hr input to the x-gyro (DFX) of IMU-2 resulted in the correct fail of IMU-2. With a delta bias of 4 deg/hr input to the z-gyro (DFZ) of IMU-3 resulted in the unexpected fail of IMU-2 instead of IMU-3 as intended. This result disclosed a shortcoming on the part of RM to detect a failure solely in the z-gyro axis. A RM dilemma occurred in about two minutes. For all three runs, the bias was removed followed by a successful IMU-to-IMU alignment and IMU reselection in MM201. The time required for realignment depends on how far the IMU was out. The maximum torque rate is 100 degrees/hour.

The RGM results show no consistent pattern in the data during the indicated disturbances to the DMS. The test attempted to detect disturbances to the redundant gyro when the DMS was rotated sequencially about each of its axes by a high step input command. Large rate step inputs to the DMS were not obviously discernible in the RGM output of either the HAINS or the KT-70 IMU, but the test did show that the HAINS RGM output was compatible with the KT-70 RGM output. It suggests that this parameter may be unreliable when used as a means of deselecting a drifting IMU during an attitude miscompare in the RM dilemma case.

A run with artifically introduced errors to drive the clusters off tested the IRAMS Uplink capability. This was accomplished with a patch to insert errors prior to the start of the Prelaunch sequence. The errors were as follows: IMU1 DIXE = 0.107 deg/hr, IMU2 DSXE = 0.207 deg/hr and IMU3 DSXE = 0.217 deg/hr. The test had two uplinks, the first being the IRAMS correction drift values and the second being the restoration of the initial I-load drift compensations. The performance was good and the uplink capability was adequately demonstrated. The maximum tilt error was 107 arcseconds in S/N 201 North tilt which was mostly due to the introduced drift errors. See Table 4.

There was a delay from the time the IRAMS correction values were determined and when they were actually applied. This accounted for the corrections of the misalignments not actually attaining zero.

Summary and Conclusions

This paper presented the description and explanation of comparison testing, as performed in the SAIL, between the HAINS and the KT-70 IMU. The instruments were evaluated during various operational sequences and major modes of a space shuttle mission.

The HAINS performance in the SAIL demonstrated transparency of operation with respect to the KT-70 IMU. The concept of an internally compensated inertial navigation system is compatible with the Orbiter avionics system and flight software. The HAINS displayed a high level of performance accuracy previously unseen with the KT-70 IMU. The results obtained from the SAIL tests were generally well beyond the requirements of the procurement specificiation.

The HAINS will provide spares support, eventually phasing out the KT-70 IMUs. Flight rated HAINS will be swapped out with any KT-70 IMU that has failed in the three active Orbiters. The Endeavor, presently under construction in California, is being fitted with three HAINS. A full contingency (5) of IBM AP101S GPCs with OI-8 D/F PASS will fly on STS-42 in December,1991. But no firm date has been established when an Orbiter will fly with 3 HAINS and 5 new GPCs.

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9011/104/                 GND IMU CNRL/MON                4  366/23:59:59
                                                             000/00:00:00

 IMU              1              2              3
  X      1     121.23   4 --------     7 --------     SEL   IMU 1   16
  Y      2     121.23   5              8                        2   17*
  Z      3        .00   6              9                        3   18

      O                    357.92
      M                      1.15
      I                      2.97                           ATT DET      19*
      IR                      .02                        HNGR CAL   A   20
 ΔV   X                    - .50                                    B   21
      Y                    - .73                                    C   22
      Z                    + 1.43                       PREFLIGHT CAL   23
 ΔVRSS                       1.68                          GYROCOMP     24

 B HDW       8000          8000          8000
 I S/W       00            00            00               INERTIAL      25
 TSTAT       3 F           3 F           3 F              PLAT POS      26
                                                          TERM/IDLE     27

 PWR ON       *             *             *
 I/O          M                           M               MM WRITE      28
 STBY      10           11            12*                    READ       29
 OPER      13*          14*           15
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Figure 1.- The GND IMU CNTL/MON display.

Table 1A.- Test Case Description for Test Sequences 1, 2, & 3

Volume	Test Case Description*
1	KSC-OPF (Horiz); Nominal I-loads, HCA, PFCA, 3 GCAs
2	KSC-PAD (Vert); Nominal I-loads, HCA, PFCA, 3 GCAs
3	KSC-PAD (Vert); Nominal I-loads, PFCA, GCA, G9 Inertial, GCA, OPS Trans to MM101, 3 Hr Hold (IRAMS), OPS Trans to MM201, Delta Gyro Bias RM test, IMU-to-IMU Align
4	KSC-PAD (Vert); Off-nominal (5-sigma) HAINS I-loads, HCA, PFCA, GCA
5	KSC-PAD (Vert); Nominal I-loads, PFCA, GCA, OPS Trans to MM101, 2 Hr Hold (IRAMS), OPS Trans to MM201, DMS Step Inputs/RGM Noise test

*Note:
OPF - Orbiter Processing Facility
HCA - Hangar Calibration A
PFCA - Preflight Calibration A
GCA - Gyrocompass Alignment
OPS - Operational Sequence
MM101 - Major Mode 101

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Table 1B.- Test Case Volumes for Sequence 4

Volume	Test Case Description
1	KSC-PAD (Vert); Generic I-loads, HCA, MM Write, PFCA, GCA, OPS Trans to MM101, 2 Hr Hold (IRAMS)
2	KSC-PAD (Vert); MM Read, PFCA, GCA, OPS to MM101, 2 Hr Hold (IRAMS), OPS to G9, GCA, OPS to MM101 3 Hr Hold (IRAMS), OPS to MM201, DES IMU-1, Input Delta DFZ to IMU-2, RM dilemma test
3	KSC-PAD (Vert); MM Read, PFCA, GCA, G9 Inertial, 1 Hr Hold, GCA, OPS to MM101, 3 Hr Hold, Des IMU-1, Input Delta KOX to IMU-2, Accel. RM test
4	KSC-PAD (Vert); MM Read, PFCA, GCA, OPS to MM101, 2 Hr Hold (IRAMS), OPS to G9, GCA, OPS to MM304, GPC-2 to Stby, Restring IMU-2 to GPC-4, IMU-2 to IMU-3 Align*
5	KSC-PAD (Vert); Nominal I-loads, PFCA, GCA, BFS oneshot, OPS to MM101, 2 Hr Hold (IRAMS), Uplink IRAMS Gyro Bias, Ops to G9, Insert Misalign Patch, GCA, OPS MM101, 2 Hr Hold, Uplink IRAMS Gyro Bias
4*	KSC-PAD (Vert); MM Read, GCA, OPS to MM303, GPC-2 to Stby, Restring IMU-2 to GPC-4, IMU-2, to IMU-3 Align.

*Note: An abbreviated repeat of Vol. 4 was run due to procedural errors resulting in an unsuccessful IMU-to-IMU align. The repeated test was successful.

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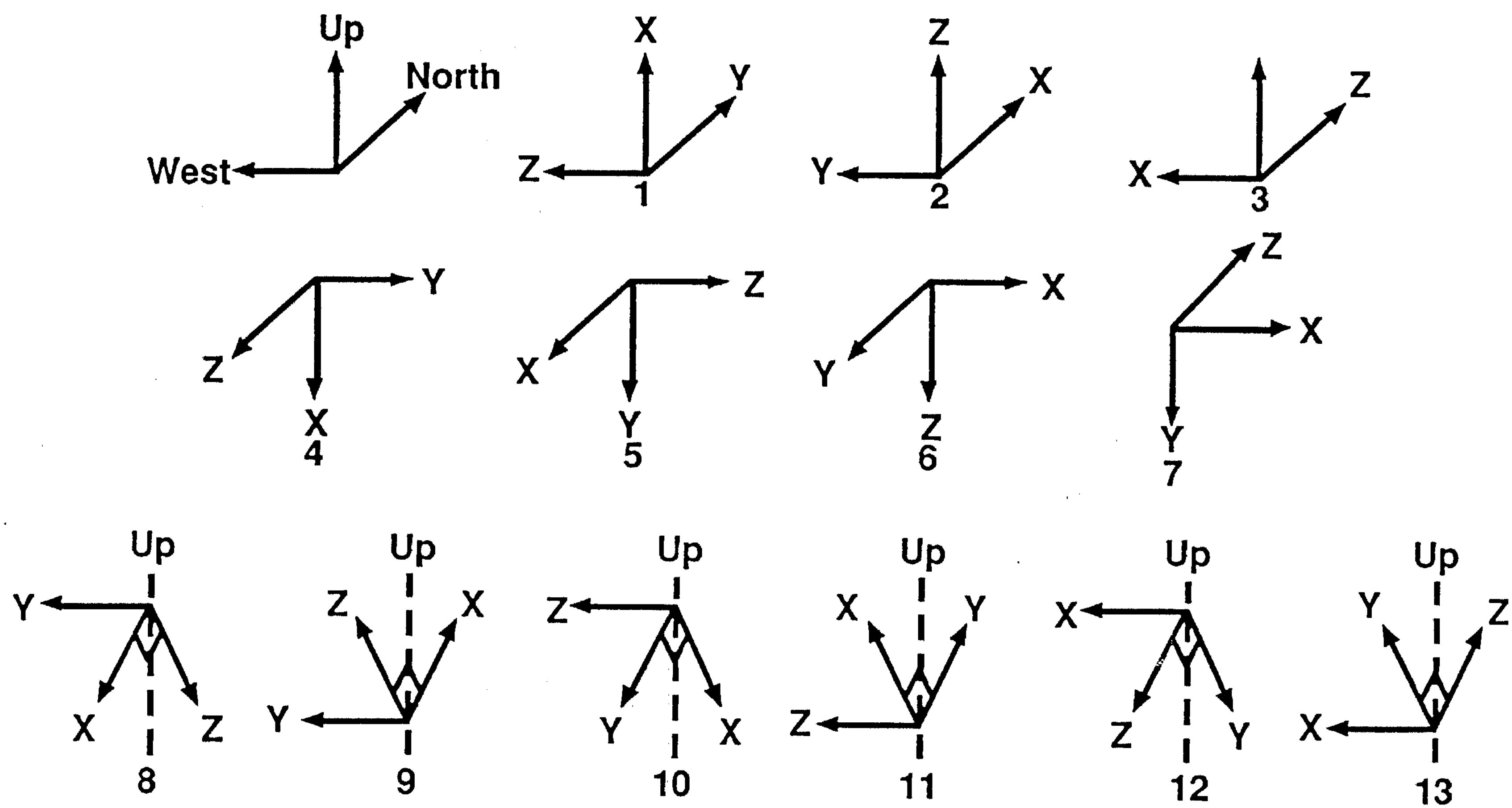
Platform Positions for IMU Calibration



9100101

Figure 2

---------- IRAMS PRELAUNCH ALIGNMENT PERFORMANCE ANALYSIS SUMMARY ----------

MODE: INERTIAL		OPR: NWU ALIGNMENT MONITORING			
PAPAS TIME	229: 0:50:59	ALIGN ELAPSE	1:12: 2	SEQUENCE	10
FLT SYSTEM	230: 0:50: 9	OPS-1 ELAPSE	0:17:45	SEQUENCE TIME	145
ALIGN START	229:23:38: 7	OPS-1 TIME	230:0:32:23	OPS-1 COUNTS	1046

------------------------ ALIGNMENT HOLD PREDICTIONS ------------------------

REMAINING HOLD TIME	1:32:53	IMPACTING IMU	1
LAUNCH BY GMT	230: 2:35:17	IMPACTING REDLINE	A

------ ALIGN ERROR (ARCS) --

IMU	1	2	3
N	-142.	-24.	-57.
W	-19.	61.	2.
U	28.	21.	54.
N	-141.	-137.	3.
W	-46.	-1.	12.
U	47.	27.	19.

--------------- IMU HEALTH MONITOR ---------------

T-ERROR	COUNT		
IMU	1	2	3
V-TILT MARG			
V-DROP OUT COUNTER			
D-V ERROR. COUNTER			
UPLINK LIMIT			

FAILS	OPS-1 TIME		
IMU	1	2	3
V-TILT			
ALIGN TEST			
REDLINE			
HOLD TIME			
ACCEL			
GRYO DRIFT			

--- PAD/VEH/GC BIAS (ARCS) --

U	-19.	-1.	66.

--- ACCEL ERROR (uG) ---

-15.	-13.	-11.

-- D- ACCEL ERROR (uG/H) --

-7.	-3.	-19.

------------- FILTERED ALIGN ERROR (ARCS) -------------

N	-120.	-129.	11.	6.	24.	19.
W	-44.	34.	26.	2.	2.	-6.
U	36.	44.	10.	-36.	-44.	-10.

--------- DRIFT (D/H) ------

N	-0.0126	0.0074	0.0016
W	0.0032	0.0033	-0.0072
U	-0.0294	-0.0242	-0.0140

---- DRIFT CORRECTIONS (D/H) --

X	-0.479	0.006	0.014
Y	-0.843	0.222	0.317
Z	0.987	-0.533	0.110

--- ALIGN ERROR (ARCS) ---

A	6.	24.	19.
B	6.	24.	19.
C	-35.	-43.	-12.

--- UNTUNED DRIFT (D/H) ---

X	-0.0114	-0.0089	-1.0135
Y	-0.0385	0.0183	0.0123
Z	-0.0004	-0.0266	0.0007

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Figure 3

TABLE 2 HAINS S/N 201 HCA TEST RESULTS

MSID	FSSR MNEM	ONE SIGMA SHORT/LONG TERM	INITIAL I-LOAD	HCA(1) 6/11/90	HCA(1) SIGMA	HCA(2) 6/12/90	HCA(2) SIGMA	** HCA(3) 6/14/90	HCA(3) SIGMA	HCA(4) 7/16/90	HCA(4) SIGMA
V99A2520C	KIX	40/100 ppm	0	-2.3511E+01	-0.24	-2.6459E+01	-0.26	-2.6953E+01	-0.27	-4.6825E+01	-0.47
V99A2523C	KIY	40/100 ppm	0	-1.7184E+01	-0.17	-2.4226E+01	-0.24	-2.2067E+01	-0.22	-2.9574E+01	-0.30
V99A2526C	KIZ	40/100 ppm	0	-9.8430E+00	-0.10	-1.9954E+01	-0.20	-2.6029E+01	-0.26	-3.9898E+01	-0.40
V99G2530C	KOX	50 ug	-1000	-1.0278E+03	-0.56	-1.0223E+03	-0.45	-1.0082E+03	-0.16	-1.0368E+03	-0.74
V99G2533C	KOY	50 ug	-1000	-9.3594E+02	1.28	-9.5159E+02	0.97	-9.7386E+02	0.52	-9.3150E+02	1.37
V99G2536C	KOZ	50 ug	-1000	-9.9578E+02	0.08	-9.9724E+02	0.06	-9.9883E+02	0.02	-9.8615E+02	0.28
V99A2681C	KIXH	40/100 ppm	0	-2.4532E+01	-0.25	-2.9918E+01	-0.30	-3.1049E+01	-0.31	-4.6846E+01	-0.47
V99A2684C	KIYH	40/100 ppm	0	-1.6052E+01	-0.16	-2.4938E+01	-0.25	-2.6085E+01	-0.26	-3.0577E+01	-0.31
V99A2687C	KIZH	40/100 ppm	0	-1.4185E+01	-0.14	-2.7168E+01	-0.27	-3.2156E+01	-0.32	-4.5126E+01	-0.45
V99G2670C	KOXH	50 ug	-1000	-1.0287E+03	-0.57	-1.0256E+03	-0.51	-1.0076E+03	-0.15	-1.0365E+03	-0.73
V99G2673C	KOYH	50 ug	-1000	-9.3662E+02	1.27	-9.4865E+02	1.03	-9.7104E+02	0.58	-9.3287E+02	1.34
V99G2676C	KOZH	50 ug	-1000	-9.9283E+02	0.14	-9.9287E+02	0.14	-9.9242E+02	0.15	-9.8350E+02	0.33
V99G2500C	KTX	200 ppm	1	1.00000090	0.01	0.99990630	-0.47	0.99989460	-0.53	0.99997940	-0.10
V99G2503C	KTY	200 ppm	1	0.99998830	-0.06	0.99995200	-0.24	0.99996250	-0.19	0.99998180	-0.09
V99G2506C	KTZ	200 ppm	1	0.99998210	-0.09	0.99997940	-0.10	0.99996850	-0.16	0.99997060	-0.15
V99R2560C	DFX	0.015/0.035 deg/hr	0	4.4080E-04	0.01	-3.8530E-04	-0.01	8.0980E-04	0.02	-2.8561E-03	-0.08
V99R2563C	DFY	0.015/0.035 deg/hr	0	5.2451E-03	0.15	2.0947E-03	0.06	4.5908E-03	0.13	8.4382E-03	0.24
V99R2566C	DFZ	0.015/0.035 deg/hr	0	1.1043E-02	0.32	1.1069E-02	0.32	1.1617E-02	0.33	2.1233E-02	0.61
V99U2576C	DSX	0.025 deg/hr/g	0	3.5980E-04	0.01	4.8790E-03	0.20	5.0761E-03	0.20	-3.4557E-03	-0.14
V99U2679C	DSZ	0.025 deg/hr/g	0	-2.8949E-03	-0.12	-1.9229E-03	-0.08	-2.6463E-03	-0.11	-7.1613E-03	-0.29
V99U2570C	DIX	0.025 deg/hr/g	0	2.4635E-02	0.99	2.1472E-02	0.86	1.8147E-02	0.73	3.7506E-02	1.50
V99U2573C	DIZ	0.025 deg/hr/g	0	1.4686E-02	0.59	2.3771E-02	0.95	1.9203E-02	0.77	9.1388E-03	0.37
V99U2582C	DOZ	0.025 deg/hr/g	0	-7.7986E-03	-0.31	-4.6654E-03	-0.19	-4.4534E-03	-0.18	-1.4644E-02	-0.59
V99A2510C	KSX	40/100 PPM	0	9.7693E+00	0.10	1.1827E+01	0.12	2.8502E+01	0.29	-1.0006E+00	-0.01
V99A2513C	KSY	40/100 PPM	0	4.5340E+00	0.05	1.3862E+00	0.01	1.0372E+00	0.01	1.0506E+01	0.11
V99A2516C	KSZ	40/100 PPM	0	5.7614E+00	0.06	1.1007E+01	0.11	9.8832E+00	0.10	1.7163E+01	0.17
V99H2540C	DELTYX	21 arc sec	0	9.5252E-01	0.05	5.9505E-01	0.03	1.5619E+00	0.07	1.0619E+00	0.05
V99H2543C	DELTZX	21 arc sec	0	1.6624E+00	0.08	-1.3442E+00	-0.06	-1.0245E+00	-0.05	1.6335E+00	0.08
V99H2546C	DELTZY	21 arc sec	0	-1.0182E+01	-0.49	-6.8366E+00	-0.33	-6.4449E+00	-0.31	-9.9831E+00	-0.48
V99H2590C	BXY	60 arc sec	0	-2.0549E+00	-0.03	-1.3372E+00	-0.02	7.1764E-01	0.01	-6.1347E-01	-0.01
V99H2593C	BXZ	60 arc sec	0	1.4037E+01	0.23	-1.3982E+00	-0.02	-3.6988E-01	-0.01	7.2053E+00	0.12
V99H2596C	BYX	60 arc sec	0	-4.9477E+00	-0.08	3.7495E+00	0.06	2.4594E-01	0.00	-1.6939E+00	-0.03
V99H2599C	BYZ	60 arc sec	0	-1.4397E+01	-0.24	-3.0179E+00	-0.05	-4.0460E+00	-0.07	-9.1887E+00	-0.15
V99H2602C	BZX	60 arc sec	0	3.8694E+00	0.06	-1.9737E+00	-0.03	-1.3790E+00	-0.02	1.9765E+00	0.03
V99H2605C	BZY	60 arc sec	0	6.0863E+00	0.10	4.8956E+00	0.08	4.8293E+00	0.08	7.8931E+00	0.13
V99U5870C	DDFR	0.05 deg/hr	0	-1.7047E-01	-3.41	-1.8053E-01	-3.61	-1.7335E-01	-3.47	-1.6454E-01	-3.29
V99U5952C	DFR	0.05 deg/hr	0	-8.3912E-02	-1.68	-7.5130E-02	-1.50	-6.7419E-02	-1.35	-8.5529E-02	-1.71
V99U5955C	DIR	0.05 deg/hr/g	0	2.5347E-02	0.51	2.8983E-02	0.58	3.3545E-02	0.67	4.5601E-03	0.09
V99U5958C	DOR	0.05 deg/hr/g	0	1.2878E-02	0.26	1.4723E-02	0.29	1.7035E-02	0.34	2.3166E-03	0.05
V99U5961C	DSR	0.05 deg/hr/g	0	3.7939E-02	0.76	4.6390E-02	0.93	4.5445E-02	0.91	3.3138E-02	
V99U5964C	KXR	4000 ppm *	0.891673	8.9796E-01	1.57	8.9765E-01	1.49	8.9728E-01	1.40	8.9827E-01	1.65
V99U5967C	KYR	4000 ppm *	0.452609	4.5620E-01	0.90	4.5600E-01	0.85	4.5566E-01	0.76	4.5635E-01	0.94
V99U5970C	KZR	4000 ppm *	0.008004	8.0850E-03	0.02	7.6935E-03	0.08	7.3224E-03	0.17	8.2554E-03	0.06

* ATP CRITERIA

** 5 SIGMA I-LOAD

TABLE 3 HAINS IMU S/N 201 PFCA TEST RESULTS

MSID	FSSR MTEM	ONE SIGMA SHORT/LONG TERM	INITIAL I-LOAD	*** PFCA(1) 6/12/90	PFCA(1) SIGMA	*** PFCA(2) 6/13/90	PFCA(2) SIGMA	PFCA(3) 6/15/90	PFCA(3) SIGMA	PFCA(4) 7/17/90	PFCA(4) SIGMA
V99A2520C	KIX	40/100 ppm	0	-2.8196e+01	-0.04	-4.3190e+01	-0.15	-2.8707e+01	-0.29	-4.8657e+01	0.01
V99A2523C	KIY	40/100 ppm	0	-2.8297e+01	-0.10	-4.0076e+01	-0.12	-2.3084e+01	-0.23	-3.9226e+01	-0.02
V99A2526C	KIZ	40/100 ppm	0	-2.2718e+01	-0.07	-4.0864e+01	-0.18	-2.8407e+01	-0.28	-5.5744e+01	-0.05
V99G2530C	KOX	50 ug	-1000	-1.0236e+03	-0.03	-1.0234e+03	0.00	-1.0537e+03	-1.07	-1.0020e+03	-0.03
V99G2533C	KOY	50 ug	-1000	-9.4857e+02	0.06	-9.4825e+02	0.01	-9.7906e+02	0.42	-9.5932e+02	-0.01
V99G2536C	KOZ	50 ug	-1000	-9.9885e+02	-0.03	-1.0020e+03	-0.06	-1.0126e+03	-0.25	-9.9316e+02	0.04
V99A2681C	KIXH	40/100 ppm	0	-2.7748e+01	0.05	-4.3108e+01	-0.15	-3.0616e+01	-0.31	-4.9548e+01	0.02
V99A2684C	KIYH	40/100 ppm	0	-2.8281e+01	-0.06	-3.8848e+01	-0.12	-2.3015e+01	-0.23	-3.9525e+01	-0.03
V99A2687C	KIZH	40/100 ppm	0	-2.6419e+01	0.02	-4.5050e+01	-0.19	-3.4272e+01	-0.34	-5.6099e+01	0.09
V99G2670C	KOXH	50 ug	-1000	-1.0239e+03	0.03	-1.0275e+03	-0.07	-1.0557e+03	-1.11	-1.0005e+03	0.03
V99G2673C	KOYH	50 ug	-1000	-9.5039e+02	-0.03	-9.4947e+02	0.02	-9.8123e+02	0.38	-9.5866e+02	-0.02
V99G2676C	KOZH	50 ug	-1000	-9.9773e+02	-0.01	-9.9945e+02	-0.03	-1.0111e+03	-0.22	-9.9157e+02	-0.07
V99G2500C	KTX	200 ppm	1								
V99G2503C	KTY	200 ppm	1								
V99G2506C	KTZ	200 ppm	1								
V99R2560C	DFX	0.015/0.035 deg/hr	0	2.2189e-03	0.17	2.7357e-03	0.01	-4.5430e-03	-0.13	-1.5302e-03	-0.11
V99R2563C	DFY	0.015/0.035 deg/hr	0	3.4314e-03	0.09	9.9686e-03	0.19	3.7771e-03	0.11	9.0584e-03	-0.01
V99R2566C	DFZ	0.015/0.035 deg/hr	0	1.0743e-02	-0.02	1.1656e-02	0.03	1.1690e-02	0.33	2.1370e-02	0.00
V99U2576C	DSX	0.025 deg/hr/g	0	6.4297e-03	0.06	4.9968e-03	-0.06	1.9623e-03	0.08	4.0828e-03	-0.05
V99U2679C	DSZ	0.025 deg/hr/g	0	-3.0503e-03	-0.05	-2.1909e-03	0.03	-2.7649e-03	-0.11	-5.8681e-03	0.03
V99U2570C	DIX	0.025 deg/hr/g	0								
V99U2573C	DIZ	0.025 deg/hr/g	0								
V99U2582C	DOZ	0.025 deg/hr/g	0	-4.4903e-03	0.01	-4.1386e-03	0.01	-5.2449e-03	-0.21	-1.2842e-02	-0.03
V99A2510C	KSX	40/100 PPM	0								
V99A2513C	KSY	40/100 PPM	0								
V99A2516C	KSZ	40/100 PPM	0								
V99H2540C	DELTYX	21 arc sec	0								
V99H2543C	DELTZX	21 arc sec	0								
V99H2546C	DELTZY	21 arc sec	0								
V99H2590C	BXY	60 arc sec	0								
V99H2593C	BXZ	60 arc sec	0								
V99H2596C	BYX	60 arc sec	0								
V99H2599C	BYZ	60 arc sec	0								
V99H2602C	BZX	60 arc sec	0								
V99H2605C	BZY	60 arc sec	0								
V99U5870C	DOFR	0.05 deg/hr	0	-1.5779e-01	0.45	-1.6740e-01	-3.35	-1.6574e-01	-3.31	-1.4965e-01	0.51
V99U5952C	DFR	0.05 deg/hr	0	-7.1385e-02	0.07	-6.6307e-02	0.10	-6.9245e-02	-1.38	-7.9636e-02	0.02
V99U5955C	DIR	0.05 deg/hr/g	0	8.6649e-03	-0.41	2.3044e-02	0.29	3.7042e-02	0.74	-3.2634e-03	-0.08
V99U5958C	DOR	0.05 deg/hr/g	0	4.3950e-03	-0.21	1.1703e-02	0.15	1.8807e-02	0.38	-1.6560e-03	-0.43
V99U5961C	DSR	0.05 deg/hr/g	0	4.2438e-02	-0.08	4.3253e-02	0.02	4.0863e-02	0.82	3.3216e-02	-0.46
V99U5964C	KXR	4000 ppm *	0.891673	8.9727e-01	-0.10	8.9795e-01	0.17	8.9734e-01	1.42	8.9724e-01	0.05
V99U5967C	KYR	4000 ppm *	0.452609	4.5511e-01	-0.22	4.5603e-01	0.23	4.5561e-01	0.75	4.5530e-01	0.01
V99U5970C	KZR	4000 ppm *	0.008004	7.3059e-03	-0.10	7.1584e-03	-0.04	7.6741e-03	-0.08	7.7029e-03	0.01

* ATP CRITERIA

Table 4 Prelaunch Sequence Comparisons - Week 4						
	DAY 6 RUN 1 (08/20/90)			DAY 6 RUN 2 (08/20/90)		
HAINS/IMU	18 (KT-70)	201 HAINS	202 HAINS	18	201	202
Gyrocompass						
Tilts:						
North	8.1	17.7	7.6	10.7	29.9	137.3
West	5.4	-0.4	-11.1	31.2	54.6	-49.1
Drifts:						
North	-0.0047	0.0122	-0.0024	-0.0012	0.0302	0.1784
West	0.0030	0.0025	-0.0072	0.0396	0.0737	-0.0779
Reslv/Acc:						
North	-47.6	-9.8	7.3	-63.2	-88.6	-4.2
West	-18.1	132.1	-5.1	-11.4	-7.5	-50.4
PHIT-Up:	-13.3	24.9	39.2	23.1	36.9	-2.4
Vel - Tilt						
Tilts:						
North	-10.8	5.6	-6.4	-8.0	20.9	133.1
West	2.9	-2.4	5.5	-23.7	-57.6	60.8
Drifts:						
North	-0.0034	0.0122	-0.0027	0.0006	0.0314	0.1773
West	-0.0068	0.0018	0.0163	-0.0420	-0.0746	0.0703
Reslv/Acc:						
North	-48.3	-34.5	48.7	-57.1	-104.9	122.2
West	-37.1	95.1	39.9	-15.3	-9.7	-23.1
PHIT-Up:	16.1	2.6	4.7	66.9	1.6	7.0
PAD BIAS:	-20.1	11.7	65.3	-9.0	17.5	67.7
Tuned Inert						
Init. Cond.						
Tilts:						
North	17.9	16.9	18.3	16.7	19.3	16.4
West	-0.7	-0.5	-0.2	-5.6	0.7	-3.7
Drifts:						
North	0.0069	0.0015	0.0003	0.0066	0.0030	-0.0017
West	0.0031	-0.0009	0.0004	0.0143	-0.0016	0.0002
Reslv/Acc:						
North	-29.3	-24.0	63.4	-43.4	-101.3	46.9
West	-29.4	45.6	53.3	-22.0	-93.0	11.5
PHIT-Up:	-2.8	5.2	-4.3	62.9	5.2	-3.3
Final Cond.						
Tilts:						
North	13.3	-15.3	35.6	-18.4	106.8	-90.5
West	27.7	7.9	24.2	-71.2	-15.6	-2.6
Drifts:						
North	-0.0079	-0.0034	-0.0010	-0.0031	0.0772	-0.0634
West	0.0136	0.0067	0.0030	0.0559	0.0106	0.0027
Reslv/Acc:						
North	14.4	-31.2	51.9	2.6	-112.1	33.8
West	-54.6	35.8	56.3	-47.6	-115.9	26.1
PHIT-Up:	-22.0	14.8	-10.2	102.3	-36.9	40.8