Shuttle Orbiter Stellar-Inertial Reference System

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The Space Shuttle stellar-inertial reference system provides orbiter velocity and attitude data during flight operations. The system is composed of inertial measurement units, star trackers, a navigation base, and a manual optical sight. The Orbiter's computers direct the operation of the system elements; perform the required alignment, velocity, and attitude computations; and interface with the crew. This paper discusses design requirements, hardware operation, and techniques for star sighting and inertial measurement unit alignment and calibration. Alignment accuracy, star tracker capability, and gyro and accelerometer accuracy are discussed with emphasis on flight test results. A brief description of system enhancement and growth possibilities is also presented.

Nomenclature

BITE	= built-in test equipment
BOS	= bright object sensor
COAS	= crew optical alignment sight
CRT	= cathode ray tube
FOV	= field of view
FO/FS	= fail operational/fail safe
GN&C	= guidance, navigation, and control
GPC	= general-purpose computer
IMU	= inertial measurement unit
LS	= light shade
MDM	= multiplexer-demultiplexer
M50	= Aries mean of 1950
NB	= navigation base
REFSMAT	= reference system matrix
RGA	= rate gyro assembly
RM	= redundancy management
SAD	= star angle difference
ST	= star tracker
STS	= Space Transportation System
TS	= target suppression
X	= Orbiter body axis (forward)
Y	= Orbiter body axis (right wing)
Z	= Orbiter body axis (downward)

Introduction

A MAJOR space flight milestone was achieved with the highly successful maiden flight of the Space Shuttle Columbia. The performance of the Space Shuttle elements and systems was nearly perfect during the historic 54 h flight in April 1981. The subsequent flights have clearly demonstrated Shuttle's reusability, payload capability, operational flexibility, and performance. The Orbiter's stellar-inertial reference system contributed to this success, demonstrating excellent performance, system flexibility, data handling, and redundancy management. This paper presents an overview of the stellar-inertial reference system and discusses design concepts, functional operation, and performance capabilities. Other papers discuss the IMU[1] and the RM[2] software in more depth.

The stellar-inertial system is the source of velocity and attitude data for inertial navigation, flight control, and other functions. Before liftoff, the initial orientation of the system is established by a preflight alignment mode (gyrocompassing). During flight, the data are measured in the stellar-inertial coordinate frame and transformed to the standard M50 coordinate frame. The GN&C functions use the data to guide and control the vehicle during ascent and entry flight phases, and to support on-orbit functions such as attitude maneuvers, translational maneuvers, rendezvous, and payload pointing. The stellar-inertial system consists of three IMUs, two STs, a COAS, and a NB upon which IMUs and STs are mounted (Fig. 1).

System Requirements

The Orbiter inertial attitude reference provided by the IMUs must be accurate to within 0.26 deg (3σ) at the 400,000 ft altitude entry interface to meet landing footprint performance requirements. The stellar reference for IMU alignment must be provided by either the STs or the COAS. Approximately 2 h of gyro drift must be accommodated between final IMU alignment and entry interface.

Functional Requirements

The function of the IMU subsystem is to provide compensated increments of change in velocity along predefined inertial axes, as well as attitude reference for vehicle orientation. The primary function of the ST subsystem is to provide direction vectors with reference to stars so that IMU gyro drifts can be corrected during orbital flight. A secondary function of the ST subsystem is to track rendezvous targets. The COAS functions as a manual star-sighting device. The NB supports the IMUs and STs in a stable angular relationship and provides acceptable thermal and vibrational characteristics.

Design Approach

The stellar-inertial system design and component selection were guided by the following fundamental decisions established early in the Space Shuttle Program: 1) the subsystem must be FO/FS, 2) computations are performed by the

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GPCs, not by local processors, 3) components are selected from mature designs whenever possible, 4) routine component replacement must not require the use of precision alignment equipment, 5) ST line of sight is pointed by maneuvering the Orbiter, and 6) BITE is augmented by software-implemented RM.

An IMU design already in production and in field use was selected and modified for the Shuttle. The FO/FS requirement was met by using three IMUs, each controlled by one of the five GPCs. Each GPC is capable of assuming control of two or all three of the IMUs in the event of GPC malfunction.

ST triple redundancy was envisioned in early designs, but considerations of system weight and complexity led to the choice of two STs plus the COAS. An important factor in this decision was the need to eliminate a large door in the Orbiter's outer hull by substituting two smaller, less entry-critical doors. The COAS was available from the Apollo program and adaptable to the Shuttle with minor changes.

Hardware Description

Inertial Measurement Unit

The Orbiter IMU consists of an all-attitude, four-gimbal, gyro-stabilized platform, and associated equipment. Major components include a gimbal structure, two dual-axis gyros, one dual-axis accelerometer, one single-axis accelerometer, dual-speed resolvers, power supplies, and electronic circuits for platform control and interface with the GPCs. The gyros and accelerometers, which are mounted on the platform, are thermally stabilized by heaters attached to the gimbals. The resolvers provide roll, pitch, and yaw attitude data for Orbiter angular rates up to 35 deg/s and angular accelerations up to 35 deg/s^2. The accelerometers provide velocity data along orthogonal axes for acceleration inputs up to 6 *g* per axis.

The IMU platform is stabilized about three axes by outputs from three of the gyro channels. The fourth gyro channel output is used to monitor platform drift. The GPCs control platform orientation by slewing the gyros at a high rate of 1.2 deg/s or by precision digital torquing at rates up to 80 deg/h. The accelerometers are operated in high-gain mode during preflight calibration and alignment and in low-gain mode during flight.

The IMU gimbal structure, stable platform, and electronic circuits are packaged in a pressurized housing and cooled by forced cabin air. Power is supplied from redundant buses. The IMUs are warmed up for approximately 24 h to insure nominal gyro and accelerometer stability.

Each IMU contains circuitry that monitors the health of various internal circuits and reports the status to the GPCs. In addition, the GPCs check the accuracy of torquing and slewing commands sent to the IMUs and test the resolver and velocity data for reasonableness. If any discrepant conditions are detected, a failure indication is sent to the selection filter and RM functions.

IMU compensation values for gyro and accelerometer misalignments, biases and scale factors, resolver offsets, gimbal misalignments, and attitude sensitivities are determined by GPC-controlled calibration programs that are run during vehicle turnaround and preflight operations. The compensation values are stored in the GPCs and used to process the resolver and velocity data and the torquing commands.

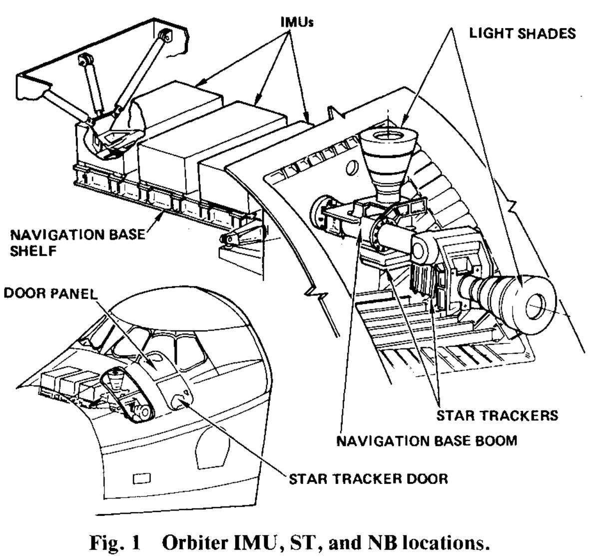

Fig. 1 Orbiter IMU, ST, and NB locations.

Star Tracker

The Orbiter ST is a strapped-down, 10 deg square-field-of-view, electro-optical image-dissecting device for obtaining precise line-of-sight angular measurements of selected stars and illuminated orbiting objects. The ST system shown in Fig. 2 consists of a tracker, a protective quartz window mounted in front of the tracker lens, and a LS that allows objects farther than 30 deg from the sun (−26 magnitude) and 20 deg from the sunlit horizon (−12 magnitude) to be tracked. The LS consists of an outer shell containing several baffles coated with black anodized surface material. The LS includes a bright object sensor that automatically closes the shutter when the background light is sufficient to degrade or damage the image-dissector tube. The ST also contains a target suppression circuit that closes the shutter when the tube current becomes excessive.

The ST FOV can be searched in 12 s. To search for a specific object, the GPC can direct the ST to search a 1 deg square anywhere within the total FOV in 1.2 s. To achieve tracking accuracy, star location is digitally calibrated on the bases of position in the field and temperature. The ST's sensitivity permits it to track objects from +3 to −7 magnitude. The crew can adjust the ST threshold through GPC control.

The ST performs a self-test upon GPC command by generating a simulated star that is reflected from the inner surface of the quartz window through a 4 deg angle, through the lens, and into the ST at a known location. The test verifies the mounting alignment, accuracy, sensitivity, and shutter operation. The STs are mounted in an unpressurized compartment in the Orbiter's forward section, and each ST sights through a separate door opening in the outer hull. The doors are closed during ascent and entry to protect the STs and LSs from debris, contaminants, and heating. Dual redundant motors are used to actuate each door.

The ST has a spectral response much wider than that of the human eye. By spectrally matching the known characteristics of each star as seen by an S-20 detector, approximately 200 stars were identified as bodies the ST can track. Fifty stars were initially chosen from these 200 stars for spatial distribution and ease of crew identification to compile a flight catalog, which includes most of the 37 stars used for the Apollo program. Visual identification of stars is necessary for COAS sightings.

Navigation Base

The NB shown in Fig. 3 is the structure that supports the IMUs and STs in a fixed angular orientation with respect to each other. The NB is supported by the three pins that slide freely in ball joints supported by the crew module structure. This arrangement prevents structural distortions associated with delta pressures and temperatures from bending the NB. The NB shelf is located inside the pressurized crew compartment. The boom is located in the unpressurized ST compartment and is rigidly bolted to a cylindrical stub on the NB shelf that extends through the crew module wall. A pressure seal fits around the stub and is designed to sustain a pressure differential across the wall without applying bending moments to the NB.

To accommodate structural clearance requirements, the forward ends of the IMUs tilt 10.6 deg downward, the inboard ST line of sight diverges from the Orbiter $-Z$ axis by 3 deg, and the outboard ST line of sight lies in the orbiter X-Y plane, pointing 10.567 deg forward of the $-Y$ axis. Precision mounting pads on each IMU mate with matching pads on the NB to achieve angular control about roll, pitch, and yaw axes. Each ST is equipped with a similar set of pads to control the direction of the line of sight. The STs, LSs, and protective window assemblies attach to adapter plates that are permanently assembled to the ST boom.

Crew Optical Alignment Sight

The COAS (Fig. 4) is a manually operated sighting device consisting of a collimating tube with an objective lens, reticle, beam splitter, and light source. The COAS can be installed at the forward window (Fig. 5) or the overhead window to permit sighting from both the forward and aft crew stations. The COAS FOV is a circle 10 deg in diameter. Stars are normally sighted in darkness but can also be seen under some daylight conditions.

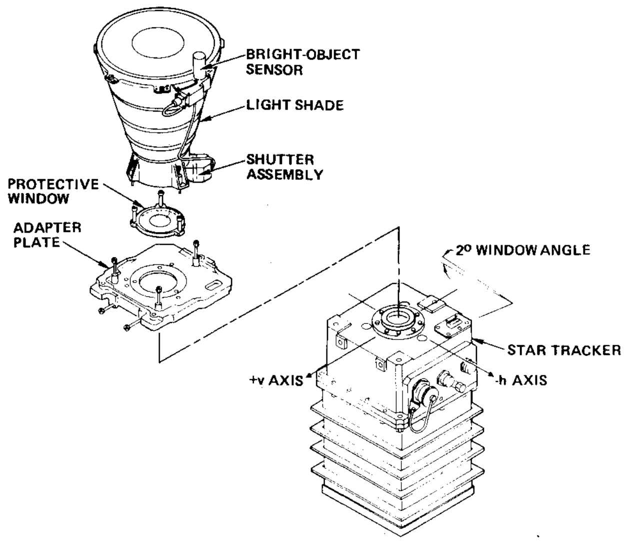

Fig. 2 Star tracker system.

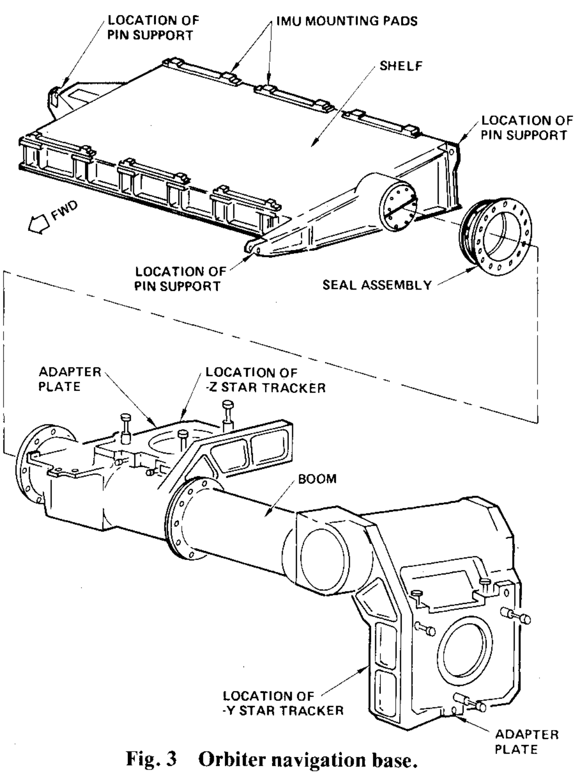

Fig. 3 Orbiter navigation base.

Installation and Alignment

IMU alignment by stellar reference depends upon angular calibration of STs, IMUs, and the NB. Each ST and IMU is calibrated at the factory. The NB is calibrated by a bench check following initial assembly and by an alignment process during installation in the Orbiter.[3] During NB bench check, calibrated alignment tools are mounted at the two ST stations and at one of the IMU stations. The other two IMU stations are loaded with tools (mass simulators) of the same weight and center of gravity as the IMUs. The alignment tools are equipped with mirrors that permit optical measurement of roll and yaw displacements for each ST and IMU station with respect to IMU station 1. Relative pitch displacements are measured with an electronic level. The IMU alignment tool is moved from station to station and exchanged with the IMU mass simulators. Both IMU and ST tools are repeatedly removed, replaced, and remeasured to insure proper tool seating on the mounting pads.

The fixture that supports the NB during bench check also provides for inverting the entire assembly, permitting measurement of gravity bending effects that are particularly significant at the ST stations. Distortions caused by gravity are applied as corrections to the station displacements measured in the upright position so that the computed angular relationships of the STs to IMUs will be correct for the on-orbit condition.

During NB installation in the Orbiter, support brackets are adjusted to position and orient the shelf portion until the following conditions are established: 1) the stub shaft is correctly aligned with the pressure seal, 2) the IMU mounting pads are inclined at 10.6 deg, and 3) the NB and vehicle Y axis are aligned. Optical sightings on the tool in IMU station 1 guide adjustment of the NB in roll with respect to gravity and in yaw with respect to the left payload-bay-door hinge line. An electronic level provides the pitch reference. The Orbiter, supported on hard tooling at this point, is assumed to be level.

Next, the ST boom is attached and a fit check is performed to insure proper clearance of the LSs with respect to the door-equipped outer hull panels. The angular relationships between ST stations and IMU station 1 are remeasured because of the uncertainty incurred by boom detachment and reassembly between bench check and installation. Tool calibration data and the gravity corrections from bench check are combined with station-to-station displacement data to compute alignment transformation matrixes. These matrixes are utilized in orbit during an IMU alignment. The orientation of the NB with respect to Orbiter body axes is also expressed as a

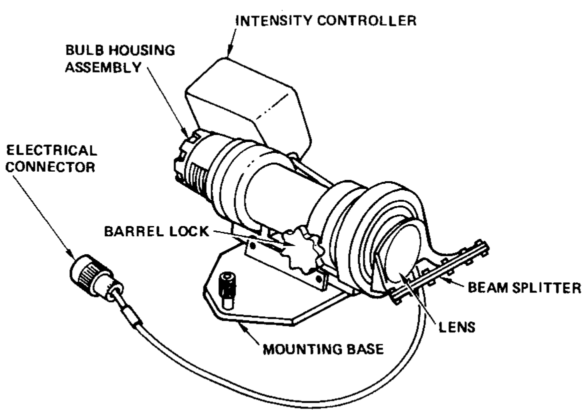

Fig. 4 Crew optical alignment sight.

transformation matrix, which is loaded into the GPCs for use in body attitude computations during flight.

The alignment techniques and procedures are designed to support a budget uncertainty of 14 arc-s (1σ) per axis in determining the orientation of each set of IMU and ST mounting pads with respect to IMU station 1. This uncertainty is combined statistically with IMU and ST internal errors and mounting uncertainties to estimate the on-orbit alignment performance of the stellar-inertial system. Alignment of the NB to Orbiter axes is measured on the ground to the same uncertainty, but vehicle distortions of up to 0.5 deg are anticipated because of aerodynamic forces in atmospheric flight and thermal/pressure gradients in orbital flight.

The COAS is aligned to NB axes while the Orbiter is supported on hard tooling or jacked to level the NB. Calibrated alignment fixtures, secured externally to the window frames, carry collimated light sources that project reticle images into the COAS when it is mounted at either station within the cabin. The fixture on the overhead window is adjusted in roll and pitch by bubble levels. Reticle rotation around the line of sight is preset. For the forward station, the yaw orientation of the collimated light source is set by reference to an optical sighting on the NB. The COAS mounts are adjusted until the COAS reticles are aligned to and concentric with the projected reticles.

The accuracy requirement for the COAS in the procedure just described is 0.5 deg because of the known large deflections that result from crew module pressure distortion in space. Final calibration of the COAS is performed in orbit to 0.1 deg (3σ).

Stellar-Inertial Operations

Preflight Initialization

The IMUs are calibrated approximately two weeks before launch. During launch countdown, the IMUs are powered up approximately 30 h before launch; selected parameters are again calibrated 7 h before launch. IMU alignment begins 80 min before launch and is complete 30 min before launch. At this time, the IMUs are placed in the inertial mode to support ascent, on-orbit, and entry operations. The STs are powered up and self-tested several hours before launch; they are then powered down until on-orbit operations commence.

IMU Flight Operations

The data provided by the IMUs consist of an absolute inertial attitude reference and a measure of change in inertial velocity (i.e., delta velocity). The GN&C and crew display functions receive these data at various rates, which typically vary from 12.5 to 0.25 Hz, depending on each particular requirement. IMU data processing (Fig. 6) requires considerable central processing unit time; therefore, the processing rates are set as low as possible to stay within the GPC capability. The IMU RM software continually performs IMU selection because of the variable number of available IMUs resulting from failures, turnoffs, or crew-initiated deselection.

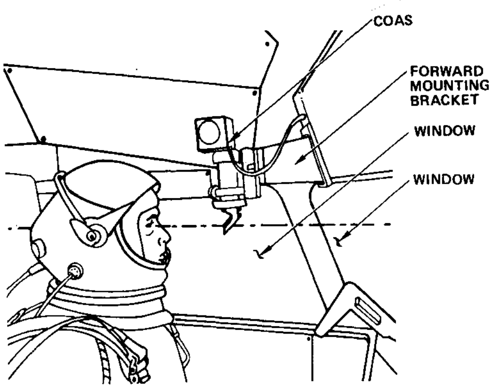

Fig. 5 COAS forward location.

Attitude Processing

The selected IMU is the primary attitude reference source for all flight phases. During ascent and entry, data from body-mounted RGAs are also used for supplemental attitude information to reduce GPC usage. Orbiter body attitude is computed during ascent at 1.04 Hz by using data from the selected IMU and by integrating RGA body rates at 12.5 Hz between IMU readings. Orbiter attitude is computed during entry at 1.04 Hz by using data from the selected IMU and by integrating RGA body rates at 6.25 Hz. During the on-orbit phase, the reduction of electrical power consumption is of greater importance than GPC usage. Consequently, the RGAs are powered down and the IMU processing rate is increased to the maximum attitude user rate of 6.25 Hz.

Velocity Processing

The data source for Orbiter IMU-sensed delta velocity processing is not usually a single IMU as in the case of attitude. Each available IMU sends its sensed delta velocity to the IMU RM. The delta velocities are transformed to M50 coordinates and the selections are made for each component of the vector, resulting in a mixture of sensed delta velocities from all available IMUs.

ST Flight Operations

The STs provide star or rendezvous target tracking data at 25 Hz in the form of horizontal and vertical angular deflections from the ST boresight axis. These data are sampled by the software at 6.25 Hz and processed at rates of 1.04-6.25 Hz. The typical selection filter techniques and RM processing do not apply to the STs. To insure validity and accuracy of tracking data, the ST software performs reasonableness tests on the data. ST utilization and mode control are managed by the crew.

Selected Star Tracking

When the crew members prepare to align the IMUs with data from the STs, they generally use stars that are selected before the mission on the basis of availability at the scheduled alignment time. The crew maneuvers the Orbiter to an attitude that places one of the stars near the center of the $-Z$ ST and the second star within a few degrees of the center of the $-Y$ ST.The catalog numbers of the stars selected for each ST are entered into the GPC.

As each ST is successively brought into the star track mode, the GPC transforms the catalog star vector (M50 coordinates) through the current reference IMU orientation into the ST's FOV to obtain an approximation of the star's location. Using this location as a starting point, the GPC commands the ST to the small-field acquisition mode. If the star is not acquired in 4 s, the GPC changes the command to allow the ST to search the total FOV for up to 40 s. Upon successful tracking of the selected star, the GPC returns to the terminate/idle mode for that ST and waits for further input from the crew.

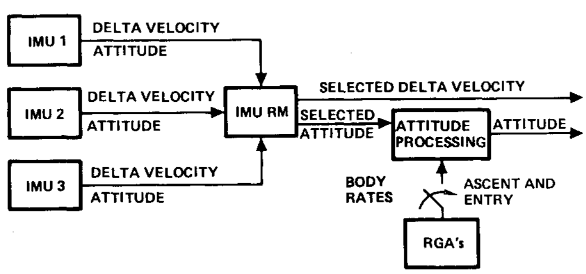

Fig. 6 Attitude and velocity processing.

Vehicle Pointing

In the absence of preplanned attitudes for near-simultaneous tracking of two stars, or when only one ST is powered up, the crew can point a particular ST to a selected catalog star by using the Orbiter pointing function. In this manner, data can be taken from two selected stars in succession with one ST. After the automatic maneuver is completed, the crew enters the catalog star number and commands the ST software to the star track mode. Operation then proceeds in the same manner as the dual ST method discussed previously, after which the ST is returned automatically to the terminate/idle mode.

Stars of Opportunity

The star-of-opportunity mode does not require dedicated maneuvers to point the STs toward selected stars. In this mode, the GPC searches the star catalog, looking for stars located within 8 deg of the ST line of sight. When a star is found, its vector is transformed into ST coordinates. If the coordinates are located within the ST FOV, the GPC directs the ST to make the small-field search about that location. Subsequent operation of the software in cases of no acquisition or of false acquisition is idential to that of the crew-selected star method, except for one significant difference: in the star-of-opportunity mode, when tracking is completed or when a star is not found within the maximum time, the GPC repeats the catalog search, using the new pointing direction of the ST. In this way, nearly every catalog star that passes through the ST FOV can be tracked.

Sighting Data Management

After the sighting data are obtained, several reasonableness tests are made by the GPC before it accepts the data into the sighting table for use in IMU alignments. For each star that is tracked, 21 data samples are taken, each separated in time by 160 ms. Each new ST angle is compared to the previous value to detect abnormal conditions, such as electrical noise bursts or ST distraction from sun-illuminated particles near the real star's position in the ST FOV.

During the 3.2 s in which the 21 samples are taken, the ST and IMU angles may change significantly. A characteristic of real star data, however, is inertial stability: if the first and last data samples are converted into inertial vectors, they should be very close. Any deviation beyond anticipated noise effects indicates a false target and the data are discarded.

After 21 samples have been accepted as reasonably consistent, the GPC determines the average vector and performs further checks to insure that the star was correctly identified. A comparison is made between the measured star vector and the catalog star vector. The tolerance for rejection is 0.7 deg if the small-field search is used to acquire the star and 1.4 deg if full-field search is used. This angle check is significant because it determines the maximum time that the IMUs can be allowed to drift and still permit the STs to be used for IMU alignment. The COAS can be used to recover from larger misalignments.

After passing the reasonableness checks, the measured star vector may be entered into the star-sighting table, which contains up to three sets of vectors for each of the three IMUs. The GPC compares each new vector to the last table entry to determine if the new vector should be accepted or rejected. Additional logic is used to discard the least desirable vector if the table is full. Preference is first given to more recent data and then to the star pair closest to 90 deg separation.

The sighting table can be cleared upon keyboard request by the crew. In addition, when an IMU is aligned, the sighting table is cleared to prevent reuse of obsolete data. For alignments made from selected stars, the crew may reacquire the sighting data after completing the alignment to verify that the resulting IMU misalignment angles are small.

ST Self-Test

Self-test software is used in orbit to verify the operation of the ST before its use. Normally, self-test is performed once when the unit it turned on and before each scheduled IMU alignment. The first phase involves a small-field search for the self-test-simulated star, followed by a second phase in which the search is made on the wrong side of the field. When phase 1 results in successful tracking and phase 2 results in failure to acquire the star, the ST is performing properly. The software verifies that alarm messages are issued when a failure occurs. To conclude the test, phase 3 removes the self-test command and verifies that all failure indications are removed.

COAS Flight Operations

The COAS, stowed for launch and entry, is installed in either the aft overhead or forward position during on-orbit operations to support COAS calibration and manual star or target sighting. The COAS line-of-sight vector is calibrated in orbit to compensate for shifts in mounting alignment (up to 0.5 deg) caused by pressure-induced cabin structural deformation. Calibration involves sighting a catalog star and updating the COAS vector in the GPC. This calibration technique uses an aligned IMU as an inertial reference; therefore, the COAS must be calibrated shortly after orbit is reached (a preflight aligned IMU is used) or immediately after an IMU alignment to ST sightings.

The crew sights an object with the COAS by looking through the beam splitter and maneuvering the Orbiter until the object passes through the center of the reticle pattern. At that instant, the crew initiates a "mark" with a pushbutton that signals the GPC to store the selected gimbal angles. The GPC later uses this information to determine star line of sight in NB coordinates and to align the IMUs or calibrate the COAS.

The COAS is stowed after calibration and is currently used during flight only as a backup device when the STs are inoperable or when all IMUs are misaligned. COAS sightings are generally made during orbital darkness. The Orbiter window shades can be used to reduce ambient light during daylight sightings.

IMU Alignment

During flight, the IMUs require periodic alignment updates to maintain the required inertial reference accuracy for on-orbit and entry operations in the presence of gyro random drift. When an IMU is returned to operation from an off or standby condition (gyros inoperative), a complete realignment is necessary. Additionally, a programmed change in relative orientation among IMUs may be desired, requiring a precomputed rotation of one or more platforms. The crew may select one of three options in response to the current alignment situation.[4]

Star Alignment Option

The most frequently used option is the alignment of all three IMUs to star sightings provided by the STs. Star alignments are typically performed twice each day, once following crew wakeup and once before the crew sleep period. The alignments are scheduled to minimize impact upon daily flight activities. If the STs cannot be used, because of failures or ST door problems, the star sightings are taken manually with the COAS.

The line-of-sight data from two stars are used to determine present IMU orientation with respect to the M50 inertial reference frame. The misalignment angle between the present IMU orientation and the desired IMU orientation are computed and displayed to the crew. Upon crew command, each designated IMU is aligned by the physical movement of the gimbals to null the misalignment angles. The gimbals are moved by precise gyro torquing through the required angles at approximately 25 deg/h. Alignment typically takes less than 2 min after the stars are sighted. IMU alignments are scheduled to keep the misalignments under 0.5 deg. The IMUs continue to provide valid attitude and velocity data during star alignments.

Matrix Alignment Option

When misalignment angles are large and the crew wishes to complete the alignment quickly, matrix alignment can be used. This option is generally used for situations in which the alignments of all IMUs are unknown, such as a power failure when only one IMU is operating. For such a situation, quick re-establishment of IMU alignment is desirable. This option also uses data from two star sightings to determine actual IMU orientation and misalignment angles. When the crew commands alignment execution, however, the IMU-to-M50 reference transformation matrix is mathematically changed to represent the current alignment. The IMUs are not physically moved. Star sightings are taken manually with the COAS, since the ST data can be utilized only when IMU alignment is accurate to within 1.4 deg. When matrix alignment is performed, no attempt is made to establish a particular IMU orientation relative to the M50 reference system or to another IMU.

IMU-to-IMU Alignment Option

This option allows IMU alignment to M50 coordinates by using another IMU as a reference. This method assumes that the reference IMU is aligned accurately and does not require the use of star data. If the IMUs to be aligned must be moved through large angles, they are moved rapidly at 1.2 deg/s by applying slewing commands to the gyros. When the IMUs have been driven close to the desired orientation, they are torqued precisely to null misalignment residuals.

Upon completion of the IMU-to-IMU alignment, the IMU orientation corresponds to the desired IMU-to-M50 reference attitude and has the desired relationship with the reference IMU. The flexibility of this option permits the selection of one, two, or three IMUs for alignment. Any of the three IMUs can serve as the reference IMU, provided its alignment is reasonably accurate. From any starting IMU orientation, the maximum time required to align all three IMUs is 10 min. The attitude and velocity data from a nonreference IMU are not valid while that IMU is being aligned in this mode.

The IMU-to-IMU alignment option is typically used during flight to change the IMU orientations from the ascent configuration to the desired on-orbit and entry configuration. This option is also used after a matrix alignment as part of the IMU alignment recovery procedure.

Alignment Reference Matrixes

IMU platform orientations are defined by three matrixes (one for each IMU) designated as the desired REFSMATs. The matrixes are initialized in the GPCs during preflight IMU alignment. All on-orbit alignments except matrix alignment orient the IMUs to correspond to the desired REFSMATs. The Orbiter data processing system has provisions for modifying the REFSMATs during flight by means of a data uplink from Mission Control. During the first IMU alignment after a REFSMAT uplink, the IMU orientations are changed to correspond to the newly uplinked REFSMATs. This flexibility permits the use of different IMU orientations for various mission phases and operating conditions.

Gyro and Accelerometer Bias Compensation

It is desirable to modify gyro and accelerometer bias compensation values during flight to correct the preflight calibration values for small shifts in bias characteristics in the on-orbit environment. New compensation values are uplinked to the GPCs periodically throughout flight to maintain gyro drifts of less than 0.02 deg/h and accelerometer biases of less than 50 μg. Mission Control utilizes telemetry and voice data to determine the current gyro drift rates and accelerometer biases. Drift rate is determined from IMU star alignment data (misalignment angles and elapsed time from previous alignment). Accelerometer bias in the nonthrusting environment is determined by monitoring compensated accelerometer data for several minutes. The revised compensation values are computed by Mission Control and uplinked to the Orbiter GPCs as required (e.g., once per day).

Displays and Controls

IMU, ST, and COAS system operation is monitored and controlled by the crew through an IMU display and an ST/COAS display available on either the forward or aft crew station CRTs. The upper left corner of the display shown in Fig. 7 indicates the status and operating mode of each IMU. Acceleration data are displayed at the left center position. Body attitude angles and IMU misalignment data are displayed in the lower left corner. IMU alignment selection and control entries are located in the upper right corner. The ST/COAS display shown in Fig. 8 presents the ST mode controls in the upper left corner. The tracking status, BITE status, and controls for star selection, threshold adjustment, and shutter position are in the lower left corner. Star-sighting data are displayed in the upper right corner. COAS displays and controls are grouped in the lower right corner.

The two displays can be presented individually or simultaneously on two CRTs. Modes are controlled and data are inserted by entering the predefined CRT item numbers and data on the keyboards. The system responds by displaying asterisks adjacent to item numbers for modes and selections that are active. System data and status messages are displayed in the locations designated by Xs. The processing rate for item inputs and displays varies by parameter. A typical rate is 1.04 Hz.

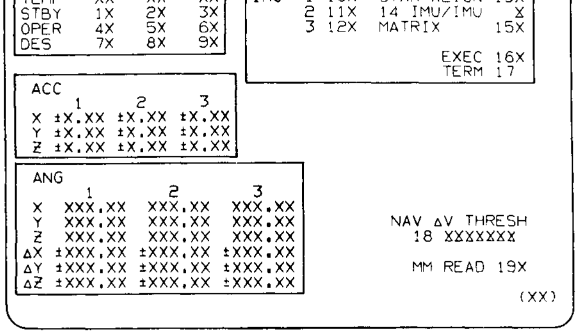

Fig. 7 IMU CRT display.

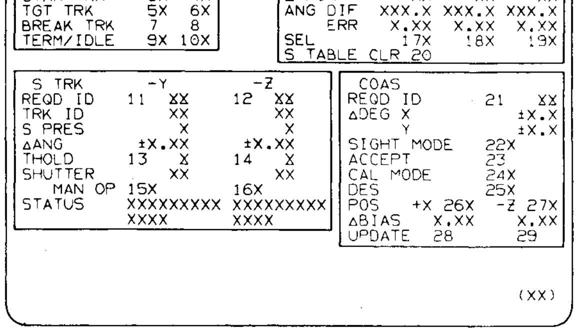

Fig. 8 ST and COAS CRT display.

Table 1 IMU alignment accuracy (on orbit)

Method of determination	Standard deviation per axis, arc-s
Error analysis predictions	68
Flight results from verification angles	64
Flight results from SADs	53

Table 2 Uncompensated gyro drifts, deg/h

Drift computation	Estimate	STS-1	STS-2	STS-3
Initial IMU alignment to ST	0.020	0.018	0.018	0.018
Subsequent alignments	0.020	0.009	0.007	0.011

Flight Performance

IMU Alignment Budget and Accuracy

Before the first Orbiter flight, the accuracy of the Orbiter IMU alignment to the STs was predicted by error analysis to be 68 arc-s per IMU axis (1σ).[5] The flight test results shown in Table 1 indicate that this level of accuracy is actually attained. IMU-to-ST alignment accuracy for the Shuttle flights has been determined by two methods during postflight analysis. The first method evaluates verification alignment results. These data are available whenever an alignment using two star sightings is immediately followed by a second alignment using different star sightings to verify the previous IMU alignment. The data indicate IMU alignment accuracy to be 64 arc-s per axis (1σ).

The second method evaluates SAD measurement data. The SAD parameter is defined as the absolute difference between the ST-measured angular separation of a star pair and the actual angular separation of that pair. Since the measured star pair angles are available for each of the three IMUs and the actual angular separation is known, an estimate of the IMU misalignments can be obtained. The SAD data indicate IMU alignment accuracy to be 53 arc-s per axis (1σ).

ST Performance

The test flights have demonstrated that the STs can sight stars both in daylight and darkness. The light shades permitted star tracking to within 16 deg of the sunlit horizon and 32 deg of the sun. Stars as dim as +3.4 magnitude were tracked, which insures that all catalog stars can be used for IMU alignment. ST stability was monitored periodically through the use of self-test data. These data were taken on the launch pad before each flight, during on-orbit operations, and after each flight when the Orbiter was returned to the servicing facility. The BITE star position data varied by a maximum of 45 arc-s per ST axis for the $-Y$ ST and by a maximum of 27 arc-s for the $-Z$ ST.

No in-flight measurement data other than the self-test data give a sufficiently accurate indication of the actual ST measurement error. Postflight analysis results, however, indicate that the total system error for Orbiter in-flight IMU alignment is nearly equal to error analysis predictions. Therefore, it appears that ST accuracy is as predicted.

COAS Calibration and Sighting Performance

The forward $(+X)$ COAS station was calibrated several times on the first three flights. The initial calibration indicated a shift of 0.23 deg from the ground calibration, well within the expected on-orbit structural deviation. Subsequent calibrations on the second and third flights were within 0.1 and 0.2 deg of the initial calibration. IMU alignment star sightings at the $+X$ COAS location produced alignment errors of approximately 0.05 deg per axis, well within the 0.26 deg entry requirement.

Table 3 Total gyro compensation change, deg/h

Gyro axis	STS-1 54.3 h	STS-2 54.2 h	STS-3 192.1 h
IMU-1 X	+0.018	−0.007	−0.026
IMU-1 Y	−0.012	−0.007	−0.021
IMU-1 Z	+0.018	+0.015	+0.014
IMU-2 X	+0.029	+0.055	+0.076
IMU-2 Y	−0.011	−0.001	−0.019
IMU-2 Z	−0.003	0.000	−0.001
IMU-3 X	+0.016	+0.009	−0.010
IMU-3 Y	−0.008	−0.017	−0.031
IMU-3 Z	+0.037	+0.043	+0.028
Mean absolute change	0.017	0.017	0.025

Table 4 Accelerometer compensation change, μg

IMU axis	STS-1 54.3 h	STS-2 54.2 h	STS-3 192.1 h
IMU-1 X	+28	+13	+28
IMU-1 Y	+1	+5	−29
IMU-1 Z	+12	−5	−4
IMU-2 X	−20	−32	+31
IMU-2 Y	−61	+25	−27
IMU-2 Z	+11	+15	+45
IMU-3 X	+55	−11	(−321)[a]
IMU-3 Y	+27	−3	(+359)[a]
IMU-3 Z	+23	+18	+61
Mean absolute change	26.4	14.1	32.1

[a] Suspected failure; IMU replaced after flight. These values are not included in the mean absolute change.

The aft $(-Z)$ COAS station was calibrated during STS-3. The indicated shift of 0.5 deg was almost exactly as predicted. Aft station COAS sightings produced IMU alignment errors of approximately 0.06 deg. COAS thermal stability tests indicated line-of-sight shifts of less than 0.05 deg during an orbit day/night cycle. It was also determined that the COAS reticle can be illuminated by external light in the event that the reticle lamp does not work.

Gyro Performance

The initial determination of gyro drift is made a few hours after launch at the first IMU-to-star alignment. The measured misalignment angles include the effects of preflight alignment errors, g-sensitive drifts during final countdown and ascent, attitude sensitivity, non-g-sensitive drift during on-orbit flight, and star alignment error sources. A more accurate evaluation of gyro drift is made during subsequent alignments to stars (typically every 10-14 h) because the preflight alignment and g-sensitive error sources are eliminated and the long time between alignments tends to minimize the effect of alignment errors. As indicated in Table 2, the uncompensated gyro drifts are significantly less than the estimated 1σ performance values.

One or more gyro compensation parameters are frequently modified during flight to reduce the uncompensated drift rates. The change in drift compensation values from lift-off to touchdown for each IMU gyro axis is shown in Table 3. The gyro drifts generally remain within the predicted 0.020 deg/h (1σ) stability range.

Accelerometer Performance

Uncompensated accelerometer bias is frequently monitored throughout flight. The compensation values are changed as required to maintain an uncompensated bias of less than the 50 μg (1σ) performance value. Typical bias residuals after modification are less than 15 μg. The changes in accelerometer bias compensation values from lift-off to touchdown for the first three flights are shown in Table 4.

Operational Anomalies

Two anomalies associated with ST operation were observed during the test flights. The first was caused by a sensitivity difference between the BOS and the TS function. During certain lighting conditions, light too faint to trigger the BOS entered the FOV and enabled the TS function to close and latch the shutter, requiring a crew keyboard entry to reopen it. This nuisance, resulting from an oversimplified model of the sunlit horizon, will be alleviated initially with a software change and later with a hardware change to eliminate the BOS/TS sensitivity difference.

The other anomaly was the detection of occasional erroneous commands sent from the MDM to the ST, triggering alarms that in one case awakened the crew. The errors were apparently caused by noise on the interface between the MDM and ST. Because the ST is designed to ignore erroneous commands, its performance was not affected. A software change has been implemented to eliminate the nuisance alarms. The noise problem is being investigated.

Status of Operating Modes

Rendezvous Target Tracking

Rendezvous target tracking is scheduled for implementation on early operational flights. The current software design for automatically tracking rendezvous targets with the ST consists of: 1) verifying that the rendezvous target is within the ST FOV; 2) attempting to acquire the rendezvous target within the small FOV; 3) if this effort fails, attempting to acquire the rendezvous target within the full FOV; and 4) computing an average of 21 consecutive target-sighting measurements after acquisition and tracking are successful. The COAS can also be used as an alternative method of sighting rendezvous targets manually. IMU data are made available to the rendezvous navigation software each time a COAS sighting is taken. COAS sighting data are not averaged. Confirmation checks on the data, made within the rendezvous navigation software, consist of three consecutive comparisons of the measured and estimated line of sight.

Fully Automatic IMU Alignment

Fully automatic IMU alignment is being considered for possible implementation on later operational flights. This capability would provide software to accomplish the following crew tasks: 1) determine availability of sufficient star-sighting data that pass all necessary criteria, 2) determine reasonableness of alignment computations by evaluating IMU gyro drift and verifying that a minimum time interval has elapsed since the previous IMU alignment (e.g., 2 h), and 3) reposition the IMUs when these tasks have been completed.

Autonomous On-Orbit IMU Calibration

Autonomous semiautomatic on-orbit calibration of gyro and accelerometer biases has potential for implementation on future flights. The principal advantage of this capability is to eliminate dependence upon the Mission Control Center in computing current biases and uplinking new values to the Orbiter. Current biases could be computed by the Orbiter GPCs, which would use the same data and algorithms as the ground-based computers. Bias compensation parameters could be monitored by the crew and modified by keyboard command. This capability was initially included in the Orbiter GPC software but was later deleted to alleviate a memory overload. Subsequent increases in memory size permit additional growth possibilities for improvements such as autonomous IMU calibration.

Conclusions

The outstandingly successful Space Shuttle orbital flight test program confirms both the design approach and the implementation of the stellar-inertial reference system. The system supports the specified functional and performance requirements and demonstrates landing dispersions well within footprint limits at widely separated touchdown sites. Coordination between the Mission Control Center and the Orbiter has been thoroughly exercised for IMU alignment and calibration. Replacement of IMUs and STs confirms the conceptual alignment chain based on NB calibration. IMU alignment verification from the COAS establishes confidence that the backup alignment concept is indeed a viable option. Thus, the Space Shuttle stellar-inertial system operates and performs well within established design goals and specifications.

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Because of the recent move of AIAA Headquarters to 1633 Broadway, New York, N.Y. 10019, journal issues have unavoidably fallen behind schedule. The Production Department at the new address was still under construction at the time of the move, and typesetting had to be suspended temporarily. It will be several months before schedules return to normal. In the meanwhile, the Publications Staff requests your patience if your issues arrive three to four weeks late.