Flight Procedures Handbook

Inertial Measurement Unit Alignment

Flight Operations Directorate Operations Division

Basic, Revision C September 1981



Lyndon B. Johnson Space Center Houston, Texas

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IMU ALIGNMENT FLIGHT PROCEDURES HANDBOOK

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FLIGHT PROCEDURES HANDBOOK PUBLICATIONS

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The following is a list of the Integrated Flight Procedures Handbooks of which this document is a part. These handbooks document integrated and/or flight procedural sequences covering major STS crew activity plan phases.

Title	JSC No.
ASCENT/ABORTS	10559
ENTRY	11542
RENDEZVOUS/ORBITAL NAVIGATION	10589
OMS/RCS	10588
ATTITUDE AND POINTING	10511
STS WORKDAY	10541
SPACELAB ACTIVATION	10545
SPACELAB DEACTIVATION	12803
CREW DATA MANAGEMENT	12985
PROXIMITY OPERATIONS	1 2802
IMU ALIGNMENT	12842
DEPLOYED PAYLOAD	16191
POSTINSERTION DEORBIT PREPARATION	16219
ASCENT/ORBIT/ENTRY POCKET CHECKLISTS	16873

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SECTION 1 INTRODUCTION

1.1 PURPOSE

This handbook is an orbit phase flight training supplement and ready reference for use by Space Transportation System (STS) flight crews and Mission Control Center (MCC) personnel. It provides background information and rationale used in preparation of flight procedures to meet test and operational objectives.

1.2 SCOPE

The overall objective of this handbook is to be general enough to cover all Orbital Flight Tests (OFT's) and early operational flights; however, the dynamic nature of the Shuttle development program has precluded complete satisfaction of this objective. The detailed flight procedures given in this edition of the handbook are those included in STS-2 Orbit Operations Checklist, Final Edition. This Flight Procedures Handbook will continue to be subject to an iterative revision process as the STS program matures.

Redundancy to other Shuttle documentation has been avoided except as needed to highlight the procedures. The procedures and techniques presented are the results of blending past crew experience, equipment specifications, systems analysis (both theoretical and empirical), and functional simulations. Most of the contents have been discussed in On-Orbit Flight Technique Meetings (OFTM) held at NASA Johnson Space Center (JSC).

1.3 REFERENCES

General references for preparation and use of this handbook are as follows.

SFOM Vol 10, Displays and Controls SFOM Vol 6, GN&C Hardware SFOM Vol 7, Applications Software SFOM Vol 12, Crew Systems FSSR Book 13, GN&C, Part E, IMU - IMU software requirements FSSR Book 14, GN&C, Part E. Nav Aids - S TRK/COAS software requirements OSOP (systems procedures) FDF Preparation Standards (checklist formats) STS Work Day Handbook, (flight information) STS-2 FRD (test objectives) STS-2 FRD (test objectives) STS-2 Flight Data File, (flight schedule and checklists) OFTM Minutes (flight techniques) Singer Company Document Y254A176 - IMU Technical Description Ball Brothers Research Corporation Spec No. 43610 - Star Tracker Specifications

1.4 ABBREVIATIONS AND ACRONYMS

ACC ADI ALIGN ANG ATT AUTO	Acceleration Attitude Direction Indicator Alignment Angle Attitude Auto	
3 I TE 30S 3 /U	Built-in Test Equipment Bright Object Sensor Backup	
C CAL CAP CAPRI C&W Cb CDR CK C/L CL CLR CLR CMD COAS COMPOCL CRT	Cluster (coordinate system) Calibrate(tion) Crew Activity Plan Capacitive Reset Integrator Caution and Warning Circuit Breaker Commander Check Checklist Close Clear Command Crew Optical Alignment Sight Common Pool of reference data (GPC software) Cathode Ray Tube	
DAP DC DD/HH:MM:SS DEG DES DFI DIF DISC DPS	Digital Autopilot Desired Cluster (coordinate system) Day/Hour:Minute:Second Degrees Deselect Development Flight Instrumentation Difference Discrete Data Processing System	
ENA ERR EXEC	Enable Error Execute	
F DF F O V	Elight Data File Field of Vision, Field of View	4
GCD GNC GMBL GND GPC GYRO	Gyro-Compass, Desired cluster orientation (coordinate system) Guidance, Navigation, and Control Gimbal Ground General Purpose Computer Gyroscope	

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H HI	Horizontal High	
ID IMU I-LOAD IMU/IMU INRTL	Identification Inertial Measurement Unit Initial Data Load IMU to IMU Inertial	
3C	Johnson Space Center	
L LAT LED LH L IM LOS LRU	Left Large Angle Torquing Light Emitting Diode Left Hand Limits Line of Sight, Loss of Signal (time) Line Replaceable Unit	
MAG MALF MAN MCC MET MIN MM	Magnitude Malfunction (Systems Malfunction Procedures book) Manual Mission Control Center Mission Elapsed Time Minute(s) Mass Memory	
MNVR MSG M50	Major Mode Maneuver Message Mean of 1950 (coordinate system)	
NAV NB NWU	Navigation Navigation Base (also coordinate system) North/West/Up (coordinate system)	
0 OFT OFTM OP OPER OP S	Overhead Orbital Flight Test On-orbit Flight Technique Me≘ting Open Operate(tion) Operational Sequence	
P PAD	Pitch Preliminary Advisory Data, parameters and data (form, format)	
PARA pb PC PDP PLT PNL POS PRES	Paragraph Pushbutton Present Cluster (coordinate system) Post-Insertion Deorbit Preparation Pilot Panel Position Present	
PNL POS PRES PROC	Panel Position Present Procedure	

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PWR	Power
R	Right
	Roll
RCS	Reaction Control System
REF	Reference Reference Stable Member Matrix
REFSIMMAL	Required
מנעט	Right Hand
RHC	Rotational Hand Controller
RM	Redundancy Management
RSS	Root of the Sum of the Squares (of given varues)
S	Star
SEL .	Selected
SOP	Software Operating Procedure
SDEC	Specialist Function
SPEL	Single System Recovery (procedure)
S TABLE	Star Sighting Table
S TRK/ST	Star Track(er)
STAT	Status
STBY	Standby Space Transportation System
SIS	Star Magnitude
-	Turneformation (matrix)
1	Talkback
LD TEMD	Temperature
TERM	Terminate
TGO	Burn Time Remaining
TGT	larget Targets
1615	Translational Hand Controller
THOLD	Threshold
TIG	Time of Ignition
ТК	Tank
TM	Tolerances
	Track(er)
TVC	Thrust Vector Control
UI	User Interface
v	Vertical
WT	Weight
x	X-Axis (direction)
Y	Y-Axis (direction) Yaw
Z	Z-Axis (direction)

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1.5 SYMBOLS

*	Selected; Active
(no *)	Deselected; Not Active
∆ANG	Delta Angle
ΔMIN	Elapsed Time in Minutes
ΔX	Misalignment in X (direction)
ΔY	Misalignment in Y (direction)
ΔZ	Misalignment in Z (direction)
ΔVX	Change in Velocity in X (direction)
∆VY	Change in Velocity in Y (direction)
A 1/7	Change in Valesity in 7 (direction)

- Change in Velocity in Z (direction) Δ٧Ζ
- T_A_B Transformation matrix to go from coordinate system A to coordinate system B where A and B can be any two coordinate systems.

1.6 DEFINITIONS

Reference Stable Member Matrix (REFSMMAT): This term is assigned to each 3 x 3 transformation matrix which mathematically defines the position of the Inertial Measurement Unit (IMU) platform (cluster) axes relative to the Aries Mean of 1950 (M50) Cartesian coordinate system. There is a separate set of three REFSMMAT's (Desired, Current, and Present) for each IMU. Two REFSMMAT's of each set, Desired and Current, are maintained in GPC memory throughout the mission. The Present REFSMMAT is computed when needed to support IMU alignments and is available only during alignment activities.

Current REFSMMAT (T C M50): This is the transformation currently residing in the General Purpose Computer (GPC) Common Data Pool (COMPOOL) at any given time. It is used by the Orbiter Guidance, Navigation, and Control (GNC) systems software for determining attitude, velocity, instrument Line-of-Sight (LOS) and other pointing computations. The Current REFSMMAT is updated at the end of an IMU alignment. This transformation does not change between alignments even though the IMU platform may have drifted or a new Desired REFŠMMAT is uplinked. The GPC always assumes that the IMU platform is aligned to this Current REFSMMAT position.

NOTE: The Current REFSMMAT used from launch through the first on-orbit alignment is computed by the GPC during Vel/Tilt Calibration. It is placed into COMPOOL prior to IMU inertial operation being initiated at T-20 minutes.

Desired REFSMMAT (T_DC_M50) (transpose, T_M50_DC, used in FSSR): This transformation is stored in the IMU alignment module of the GPC to define the desired position of the IMU platform at the end of the next IMU alignment (Star-Align or IMU/IMU alignment options). A new Desired REFSMMAT may be uplinked as required to support specific flight objectives or operational requirement.

Present REFSMMAT (T PC M50): This transformation is computed when any of the three IMU alignment options is selected. The matrix defines the actual measured platform position at the time of computation. It is based on either star sighting data or the Current REFSMMAT of a specified reference IMU. If the IMU being aligned is also the reference, the Present REFSMMAT is set equal to the IMU's Current REFSMMAT. 5

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SECTION 2 BACKGROUND

2.1 IMU ALIGNMENT

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A stable attitude reference is provided on the Orbiter by one of three Inertial Measurement Units (IMU's), each containing accelerometers and gyros on a gimbaled platform as shown in figure 2-1. The IMU platforms must be constantly repositioned to the desired inertial orientation to compensate for drift caused by inherent variations in equipment or operating conditions.

To compensate for anticipated gyro drift between on-orbit alignments, a gyro drift bias for each IMU is maintained in the General Purpose Computers (GPC's), and supplemental torquing pulses are continuously sent to the gyros. The supplemental pulse rate is proportional to the amount of bias required. The bias is periodically recomputed and updated by Mission Control Center (MCC) personnel to incorporate new drift data as the flight progresses. Likewise, an accelerometer bias is computed and updated to compensate for inherent accelerometer output errors.

On-orbit alignment of the platforms is a precise navigational procedure. Each platform is normally aligned after first determining its present orientation by taking directional measurements on a pair of stars. These measurements are expressed as unit Line-Of-Sight (LOS) vectors in a fixed Aries Mean of 1950 (M50) coordinate system. Through a series of mathematical transformations, using the star LOS data, the GPC provides the exact orientation of the platform.

Two types of star-sighting instruments are provided on the Orbiter to determine the M50 orientation of the IMU platforms. Two Star Trackers (S TRK's), aided by the GPC, electronically scan given segments of space, locate navigation stars, and track the stars while obtaining LOS data. A Crew Optical Alignment Sight (COAS) can be mounted at either of two locations within the crew compartment to obtain LOS data on stars when required. Regardless of the star-sighting instrument used, the GPC interrogates the data for positive star identification, compares the data with stored information, and determines the present orientation of the platforms.

The IMU's, S TRK's, and COAS will be described in sufficient detail in this handbook to allow an understanding of the procedures and techniques presented in later sections. More information on these items may be found in Volumes 6, 7, and 12 of the Shuttle Flight Operations Manuals (SFOM's).

2.2 [MU

2.2.1 Functional Overview

Each Shuttle IMU consists of an all-attitude four-gimbal inertially stabilized platform and associated equipment. The IMU includes the gimbal



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structure, gyros, accelerometers, power supplies, platform electronics, interface electronics, Built-In-Test Equipment (BITE), thermal control circuitry, and provisions for housing and mounting the various components. Resolvers within the IMU provide outputs (gimbal angles) proportional to attitude, and accelerometer channels provide outputs proportional to changes in velocity. The gyros sense disturbances to the stable element (platform) and develop signals that drive the platform stabilization loops. Under the control of the Shuttle GPC, the IMU has the capability of orienting the platform to any attitude, determining platform alignment to a reference, and providing velocity and attitude data for flight operations.

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The IMU resolvers provide roll, pitch, and yaw gimbal attitude outputs through the range 0° to 360° for vehicle angular rates up to 35 deg/sec and angular accelerations up to 35 deg/sec². The IMU accelerometers provide linear acceleration outputs along orthogonal axes for acceleration inputs up to 6g per axis.

The IMU gimbal sequence is outer roll, pitch, inner roll, and azimuth. The outer roll gimbal rotates about a case-supported pivot. The platform (cluster - consisting of the gyros, stable member, and accelerometers) is attached to the azimuth gimbal. The outer roll gimbal is redundant to the inner roll gimbal and is driven from error signals generated from disturbances to the inner roll gimbal. Gimbal flipping action, resulting in high rates on the outer roll gimbal, occurs when the pitch gimbal is displaced approximately 90° with respect to the outer roll gimbal and a disturbance is applied to the inner roll gimbal. The three IMU cases are aligned colinearly on the navigation base, so that the IMU case pitch axes are nearly colinear with the vehicle pitch axis, the forward end of each case being mounted $10.6^{\circ} \pm 0.5^{\circ}$ pitchdown.

The gimbals are gyro-stabilized, using signals derived from two, 2-axis gyros mounted on a platform connected to the innermost gimbal. The gyros sense cluster motion, their pickoff signals are amplified by the gimbal loop electronics, and the appropriate gimbals are torqued via direct-drive dc torquers to null the motion sensed by the gyros. Gimbal position can be controlled by torquing the gyros through high-rate torquers (slew) or through precise fine torquers (digital pulse) on the gyros under computer control.

Acceleration data is provided by a 2-axis accelerometer (X and Y axes) and a single-axis accelerometer (Z axis) which, together, form a triad of mutually orthogonal accelerometer axes. These accelerometers are forcerebalance-type accelerometers. The accelerometer proof mass is kept at a null position by a servoloop. The displacement of the proof mass is measured by the pickoff. The error signal is amplified, and a current proportional to acceleration is fed back to the accelerometer torquer to capture the proof mass at null. This current is sensed across a precision resistor located in the voltage-to-frequency converter (CAPRI). The CAPRI converts the voltage to pulses (each pulse = 0.034 fi/sec) whose frequency is proportional to acceleration. These pulses are accumulated in X, Y, Z up-down counters and transmitted as total velocity components to the computer. The accelerometers are mounted on the IMU platform with the gyros.

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Power is applied to each IMU individually through manually-controlled switches/circuit breakers. A positive indication that the IMU is actually powered (IMU power present) is not available. When power is initially applied to the IMU, only the heater and blower circuits are energized. 7

The IMU nominally takes 30 min to achieve warmup and thermal equilibrium for attitude determination, although warmup can take as long as 2 hr under worst-case conditions (low cabin temperature, cold start). The accelerometers can support nominal and contingency flight activities after 30-45 min of warmup. Although a 15-hr warmup would provide optimum accelerometer performance with decreased scale factor error, this error is less than 6 percent of the overall downrange error on entry; thus the improvement is considered insignificant.

Once warmup has been achieved and the IMU's have reached a standby condition, they can be individually commanded to upmode to the operate modes. The IMU Subsystem Operating Program (SOP), in response to a manual 'operate' command (keyboard entry), causes the IMU to cycle through a runup sequence in which it becomes fully powered and operable. The runup sequence normally takes between 38 and 53 sec. It should be noted that the IMU has an internal delay timer designed to prevent equipment damage should the IMU be commanded to the operate mode within 3 min of a previous downmode to standby, or if power is interrupted. If necessary, the IMU's can be commanded to the operate mode before the normal warmup period has been completed. However, degraded performance may be exjected under these circumstances.

IMU performance characteristics may be degraded if the IMU is operated outside the normal temperature and pressure ranges. Equipment damage is likely to occur if the IMU is continuously operated with an overtemperature condition. However, thermostats within the IMU are designed to remove power from heater circuts before severe overheating occurs.

In the operate mode, the IMU will support all of the major functions of calibration, alignment, self-test, inertial operation, and on-orbit operations. The INU's can be individually downmoded from operate to standby (time interval of 1 to 4 sec required to downmode). The IMU SOP will respond by initiating the 3 min rundown timer and by removing all internal power except for the heater and blower circuits. The IMU's can be downmoded to the off state individually by manually turning off power to the IMU. All intervals including the heaters, are deactivated in the off state. The IMU's can be safely powered down from either the warmup/standby mode or the operate mode.

Each MU contains BITE circuitry that monitors the health and status of vario s internal circuits and performance characteristics. The BITE becomes active during the runup sequence and is monitored by the IMU SOP during operate mode to detect IMU failure. The BITE status word is transmitted to the GPC in addition to temperature, pressure, and operate discretes.

2.2.2 Software Overview

The Orbiter IMU SOP controls and monitors the operation of the three IMU's and processes IMU data for use by other GPC program elements. The IMU control specialist function (SPEC) display interfaces with the IMU hardware previously defined to perform the moding functions associated with the transitions between off, warmup/standby, and operate. The IMU SOP responds to inputs from the keyboard and provides responses to the Cathode Ray Tube (CRT) displays, as required. The IMU SOP performs logic operations on input/output data validity indicators and IMU BITE data, and it conducts software-aided BITE tests to determine the status and quality of IMU data. The IMU SOP then reports this status to display control, redundancy management, and other affected software elements.

The crew interface with the IMU SOP is through the keyboard/CRT and associated GPC switches. The CRT display (IMU ALIGN, SPEC 21) is used to control the IMU mode of operation, monitor the IMU status, and align the platform (fig. 2-2). A full discussion of each item on the display is given in SFOM Volume 14.

X X X X / 0 2 1 / XX X ODD/HH:MM:SS INU ALIGN INU DDD/HH:MM:SS15 25 35 STAT **** **** **** ALIGN XXX TENP XX XX XX INU 1 1 0 X STAR ALIGN 13X STBY 1 X 2 X 3 X 2 11X. 14 INU/INU X OPER 4 X 5 X 6 X 3 1 2 X HATRIX 15X 8 X DES 7 X 9 X EXEC 16X TERN 17 ACC 2 3 1 X . X X ± X . X X ± X . X X ± X . X X ± X . X X ± X . X X ***** ***** ***** ANG 1 2 3 X X X . X X X X X . X X X X X . X X X X X . X X X X X . X X X X X . X X NAV AV THRESH 2 X X X . X X X X X . X X X X X . X X 18 <u>XXXXXX</u> AX ±XXX.XX ±XXX.XX ±XXX.XX Δ¥ ±XXX.XX ±XXX.XX ±XXX.XX ΔZ ±XXX.XX ±XXX.XX ±XXX.XX NN READ 19X (XX)£

Figure 2-2.- IMU Alignment display (SPEC).

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A list of IMU SOP modules, including the submodes listed above is given in table 2-I. The GPC Operational Sequence (OPS) during which each module is available is indicated. A complete description of the IMU SOP and its modules is given in the Functional Subsystem Software Requirements (FSSR), Level C, SD 76-SH-0013. In the operate mode, the IMU SOP performs various submode options as follows. 3

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- A. <u>Terminate/Idle</u>: This option represents the quiescent or default state of IMU SOP processing. The torque and slew outputs are set to zero. Resolver, accelerometer, and BITE data are processed for display whenever the IMU control/monitor display is active. This option is not used in on-orbit operations.
- B. <u>Attitude determination</u>: The Attitude Determination submode computes the transformation from navigation base to a North/West/Up (NWU) reference coordinate system. The transformation is a prerequisite for running all subsequent options involving alignment and calibration. This option is executed for each operating IMU every time that the vehicle/navigation base is moved, or whenever the transformation data may have been destroyed in GPC memory. The attitude determination function utilizes resolver and velocity data to determine the orientation of the navigation base with respect to the NWU coordinate frame. A gyrocompassing technique is used to determine the position of north, west, and up relative to cluster position. This, in conjunction with the gimbal angles, is used to define the required navigation base to NWU transformation. The duration of this submode is approximately 4 min. This option is not used in on-orbit operations.
- C. <u>Hangar calibrations A, B and C</u>: The Hangar Calibration A submode consists of a calibration of (1) accelerometer biases, scale factors, symmetry, and misalignments and (2) gyro scale factors, restraints, mass unbalances, and misalignments. Hangar Calibration B submode determines the azimuth, inner roll, and pitch-resolver offset errors, outer roll gimbal, nonorthogonality error, and certain gyro and accelerometer errors. Hangar Calibration C submode consists of a calibration of the IMU-to-IMU relative attitude errors at the selected skewed cluster position for use in gyrocompassing.
- D. <u>Preflight alignment</u>: The Preflight Alignment submode establishes each IMU's cluster orientation relative to the M50 coordinate system at the beginning of flight operations. It also provides other IMU-related ground-to-flight switchover functions, as well as the software interface with the crew initiated GO-INERTIAL command. Preflight alignment consists of a two-position gyrocompassing procedure, a tilt update correction, and the final preflight transformation and velocity initializations that establish the navigation reference. This submode requires approximately 45 min.
- E. <u>Inertial operation</u>: The Inertial submode consists of operating the IMU in an inertial state to provide velocity and attitude data for flight computations. The IMU is torqued only to correct for errors due to gyro drifts.

TABLE 2-1.- IMU SOP FUNCTIONAL MODULES AND OPS SEQUENCES

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,		OPS sequences						
		GN&C						
Module Description	SOP Module name	A s c n t	0 r b i t	E n t y 3	R T L S	C Oh re bc ik to u t	P e c u n t	
IMU BITE processing Accelerometer processing Resolver processing Gyro torque processing BITE summary	IMU BITE ACP-ACUM RES_PROC GYO_TORO BITE_SUM	X X X X X X	X X X X X X	X X X X X	X X X X X X	X X X X X	X X X X X X	
Accelerometer pulse compensa- tion Gyro compensation Accelerometer pulse transfor- mation Reference to cluster transfor-	ACP_COMP GYO_COMP ACP_TRSF	X X X	x x x	X X X	x x x	x x x	x x x	
mation update Torque rate transformation Large angle torquing Least squares fit processing Nav base to cluster transfor-	T UPDATE TOR TRSF LAT_FUNC LSF_FILR		x				X X X X	
mation Cluster to-cluster relative rate Sinusoidal excess rate	TNB_CL CL CLRATE SINE EXRTE		X				X X X	
Display support	DI SP_SUP		x				x	
*Term/Idle *IMU attitude determination *Hangar calibration A *Hangar calibration B *Hangar calibration C *Preflight calibration *Gyrocompass alignment Velocity and tilt	TERM/IDLE IMU ATT HANG CALA HANG CALB HANG CALC PFLT CALA GC ATIGN VET_TILT	x					X X X X X X X X	
*Inertial *IMU on-orbit alignment *Platform positioning	INERTIAL IMU ORB AL PLAT_POS	x	X X	X X (301)	X	x	x x	

*Modules are also submodes.

- F. <u>On-orbit alignment</u>: The purpose of the on-orbit alignment submode is to provide an accurate definition of the IMU platform orientation with respect to inertial space. This may be done by physical realignment to known references. The time required for this submode is variable, depending on which of the several available options the crew chooses to employ. A physical realignment of the platform through large angles may take in excess of 2 hr.
- G. <u>Platform positioning</u>: The platform positioning submode consists of positioning the platforms to manually-selected orientations to support checkout. This submode is not used in on-orbit operations.

2.2.3 Preflight Calibration and Alignment

The achievement of required IMU performance accuracy is based primarily on ground calibration. The calibrated values of 60+ parameters are entered into the GPC prior to each Orbiter flight. Ground calibration is performed at the factory, in the hangar, and on the launch pad. These calibrations are both operator and computer-software controlled. Factory testing is the most extensive, consisting of approximately 125 hr of testing.

Hangar calibration is accomplished several days prior to launch and requires about 6.5 hr. During this hangar activity, all three IMU's are calibrated in the operate mode as their platforms are torqued to as many as 22 predefined orientations (13 for STS-1).

During the hangar calibration, one of two sets of transformation matrices, describing desired platform orientations relative to the navigation base (T_NB_GCD) , is loaded into the GPC. Two distinct sets are available as a contingency provision to allow for alternate launch parameters. Both sets of desired platform orientations provide for the platform to be skewed relative to each other. The platform skewing is primarily for redundancy management purposes and also prevents more than one IMU experiencing 'gyro flip' at the same time. The actual skews are discussed in par. graph 3.3.

The launch pad preflight calibration is started no earlier than 15 hr prior to launch. The calibrated parameters are valid for 17 hr, thus providing at least 2 hr of on-orbit use before degradation. The IMU's will remain in the operate mode from the beginning of this calibration through launch. The calibration requires 2.5 hr, during which time each IMU cluster is torqued to seven cardinal positions. Accelerometer and drift data are collected at each position to enable the calibration of accelerometer biases, accelerometer scale factors, and gyro restraint biases.

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A preflight platform alignment, consisting of 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 (described by T_NB_GCD) for launch, to maintain this orientation until launch initialization (T-12 sec), and to provide platform orientation data ($T_C M50$ at T-20 min) to the GPC. This Reference Stable Member Matrix (REFSMMAT) is used to support launch, orbit insertion, and early on-orbit activities, as well as early flight termination if required. A full discussion of REFSMMAT'S can be found in the definitions, section 1.6.

The gyrocompass phase of the preflight alignment positions the IMU platforms relative to the navigation base reference systems. The desired orientation (T_NB_GCD) loaded into the GPC during hangar 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 system 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 waiting the transition to OPS 1. When the transition command is received (T-20 min), the IMU platforms are released to GO INERTIAL. At this time, the GPC uses the Velocity/Tilt data, the position of the platforms relative to the navigation base (T_GCD_M50), the navigation base-to-NWU transformation (T_NWU_M50), and a time dependent NWU-to-M50 transformation (T_NWU M50) to compute a Current REFSMMAT (T_C_M50) for each IMU. The Current REFSMMAT's are also stored in GPC memory as the Desired REFSMMAT's for on-orbit IMU alignments; i.e., T_DC_M50 set equal to T_C_M50.

If a technical hold is imposed (launch delay encountered) between gyrocompass alignment and T-20 min, the inertial orientation of the IMU platforms (Current REFSMMAT's) computed from Velocity/Tilt will differ from the current REFSMMAT's expected for a nominal on-time launch. Since many ground systems supporting the Orbiter's GNC functions use the Current REFSMMAT's, it is imperative that these ground systems incorporate the REFSMMAT's computed by the Orbiter software at T-20 min. These REFSMMAT's will be made available to the ground through Telemetry (TM) downlink.

After transition to OPS 1, Velocity/Tilt compensation is applied to the gyro torquing signals to compensate for the estimated drift, keeping the platforms aligned to the M50 coordinate system. This compensation is terminated at T-12 sec, when the STS enters flight mode.

If a technical hold is imposed after transition to OPS 1 (T-20 min), the computed Current REFSMMAT remains unchanged; however, Velocity/Tilt drift compensation may be degraded with a resultant difference between the actual platform positions and the positions described by the Current REFSMMAT's. If the error exceeds <u>TBD</u> arc sec, the count must regress to some time prior to T-20 min so that new Current REFSMMAT's can be computed. If the error exceeds <u>TBD</u> degrees, the count must regress to some time prior to gyrocompass alignment in order to realign the IMU platforms.

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2.2.4 On-Orbit Alignment and Calibration

Maintaining the required IMU accuracy for the duration of on-orbit and reentry operations is primarily a matter of periodically determining the actual M50 orientation of the platforms. Steps can then be taken to adjust the orientation, change the mathematical definition of the orientation, or both. On-orbit alignments are performed by the flight crew.

IMU alignments are required for one or more of the following reasons.

- A. The platform may move a significant amount from the orientation currently in use by the GPC (Current REFSMMAT) due to uncompensated gyro drift induced through mechanical/environmental restraints.
- B. Power interruption, loss of GPC control, or other system anomaly may cause loss of platform orientation.
- C. An IMU may be reactivated from OFF or STANDBY.
- D. A more favorable platform orientation may be desired for subsequent flight activities (new Desired REFSMMAT).

A bias torquing voltage is constantly applied to each gyro's bias torquing coils to compensate for estimated gyro restraint drift. The gyro precession caused by this bias would ideally balance the precession caused by the gyro restraints, resulting in an output to the platform gimbal torquing motors that keeps the platform inertially stable. However, if the actual restraints differ from the estimate, the platform will drift away from the inertial orientation stored in GPC memory (Current REFSMMAT). An alignment is performed to determine the magnitude and direction of platform drift and to initiate corrective action.

The misalignment between the measured platform orientation and the Current REFSMMAT defined orientation is recorded by the crew. The misalignment values, and execution time for each alignment is voiced down to the ground at the next ground station pass. After a series of alignments, the misalignment values are used to compute a new estimate of the gyro restraint drift. The gyro bias voltage is recalibrated as required to maintain the desired platform accuracy between alignments. The new gyro bias value is uplinked to the IMU software in the GPC.

The effect of IMU alignment intervals on the gyro bias accuracy, along with contributing factors, is shown in figure 2-3. A high frequency of alignments (short intervals) adversely affecting the accuracy of the calibration is apparent from the chart. Although it is not shown on the chart, a large number of misalignment readings using star sightings (without performing alignments) would favorably affect the accuracy. Optimization of star sighting/alignment scheduling for bias calibration is impractical because of restraints imposed by other activities. However, the performance curve will be taken into consideration when contemplating a gyro bias update.

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IMU alignments are scheduled to preclude a total platform misalignment greater than an amount that would adversely affect subsequent flight activities. For nominal on-orbit activities, the maximum allowable platform misalignment is 0.34° in any axis. This value was chosen to keep the total misalignment less than 0.5° and thus enhance S TRK ability to obtain star data. Entry and payload operations require greater accuracy (0.25°). For planning purposes, the maximum allowable interval between alignments is based on an estimated drift rate of 0.015 deg/hr for the first few hours of flight and 0.02 deg/hr for the remainder of the flight. The 0.02 deg/hr value is based on 1-sigma IMU operation that can be maintained through gyro bias calibration and update. If for some reason a gyro bias calibration is not performed within 17 hr of the last alignment (ground or onorbit), a drift rate of 0.035 deg/hr must be anticipated.



Figure 2-3.- Gyro drift bias calibration factors.

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Bias is also applied to the accelerometers' outputs to compensate for variations in the equipment and environment; i.e., electrical characteristics: friction, temperature gradients, g-loading, etc. This bias is checked by the ground crew at scheduled times during orbital flight and a calibration value uplinked, if required. The accelerometer bias check is performed by collecting accelerometer output data, while the flight crew maintains a quiescent (non-accelerating) attitude over a ground TM receiving station. The ground crew monitors the velocity counter for 320 sec. A single velocity pulse (equivalent to 0.034 ft/sec) evident over this time period would equate to an acceleration of 1.06×10^{-4} ft/sec² or $3.32 \, \mu$ g. The accelerometer bias will normally be updated if accelerometer output is in excess of 50 μ g. This value allows for deceleration from atmospheric drag, a $10-\mu$ g instrument acuity, and other small perturbations.

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2.3 STAR TRACKER

2.3.1 Functional Overview

The STS Orbiter S TRK's are strapped-down, wide Field-Of-View (FOV), imagedissecting, electro-optical devices. Their primary function is to obtain precise LOS angular measurements of selected stars and illuminated orbiting objects (targets). They also provide magnitude (brightness) data. Data from the S TRK's are sent to the GPC's in digital formats. Some data are downlisted to the ground for use in monitoring the health of the S TRK's and IMU's.

The S TRK's are physically located in an unpressurized cavity, forward and to the left of the crew station. They are mounted on the navigation-base boom, which extends through a bulkhead from the avionics bay containing the IMU's. The -Y axis S TRK certerline is approximately 10.5° from the Orbiter -Y axis in the X-Y plane. The -Z axis S TRK centerline is approximately 3° from the Orbiter -Z axis in a plane rotated 41° from the Orbiter +X axis toward the Orbiter -Y axis. The location and components of the S TRK's are shown in figure 2-4.

The S TRK system consists of a tracker for detecting and processing star/ target position and magnitude, a light shade to allow for star/target tracking at close angles to bright sources, and a quartz window in front of the tracker lens to protect it from radiation and contamination. The window also reflects the image of a simulated star, Light Emitting Diode (LED), into the tracker FOV for self-testing the S TRK. The light shade contains a Bright Object Sensor (BOS) integrated with a normally closed shutter to protect the S TRK against high source radiance levels, which would damage it or degrade its performance. The BOS contains an LED to self-test its function. The tracker is also provided with a video signal overcurrent sensing circuit that will issue a signal to close the shutter in the event the dynamic range of the S TRK s in danger of being exceeded.



Figure 2-4.- View looking into S TRK cavity.

The tracker uses a magnetically focused, magnetically deflected image dissector tube as shown in figure 2-5. The total FOV is a 10° square that can be completely scanned in 10 sec. The GPC software can dictate a 1° square offset scan to search for a specific star. A cruciform track scan, centered on the light source, is initiated when the star is detected. The tracker will search out and acquire items of a +3 to a -7 magnitude. This includes the 150 brightest navigation stars.

When power is applied to the S TRK system and no mode other than term/idle is commanded, the S TRK will automatically start searching the total FOV. The search scan pattern is a left-to-right, right-to-left Horizontal (H) axis sweep. A staircase signal is applied to the Vertical (V) axis to move the horizontal scan progressively from top to bottom (raster pattern). The search scan continues until the first star or target that exceeds the commanded threshold level is encountered. When this occurs, the star/target is acquired and track scan begins.

The track scan pattern (cruciform) centers on the star image and provides two-axis position signals at the system output. If the star moves within the FOV, due to small vehicle attitude changes, the track scan pattern will follow and remain centered on the star image. Tracking on the same star continues until (1) it leaves the total FOV, (2) its magnitude falls below the commanded threshold, or (3) the system receives a BREAK TRACK command from the GPC. When one of these events occurs, the search scan resumes and will search the remaining portion of the total FOV.



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Figure 2-5.- Star Tracker operation.

If the S TRK is commanded to a reduced FOV (offset scan) and a star is acquired, it will track that star throughout the total FOV as described above. If the star is lost for the same reasons as above, the system will return to the reduced FOV position originally commanded and start a search scan of that FOV.

The S TRK system may be commanded to perform a self-test by the GPC. In self-test, the S TRK generates a simulated star which is returned into the FOV by a reflective surface on the protective window and is acquired and tracked. The S TRK shutter is commanded closed during the self-test through activation of the BOS by a separate light source. The angular position and magnitude of the simulated star is compared with stored values within the S TRK to determine if the system is within operational accuracy requirements. At one point in the self-test, erroneous data is used to verify proper operation of the B TE. The crew will be advised (via the SOP) whether the S TRK passes or fails the self-test.

Doors in the Orbiter's outer surface must be opened to allow the S TRK's to track on stars or targets. Each S TRK door is equipped with a primary and secondary motor for redundancy. The door opening circuits are crosswired so that the control logic of both primary motors is enabled from one door control switch (system 1) and both secondary motors from the other switch (system 2). The door motor control logic requires that power be applied to a given S TRK in order to apply power (3Φ ac) to the motor(s) to open the door covering that S TRK. The presence or absence of power to the S TRK has no effect on closing the door. Both door control systems may be activated simultaneously to reduce opening/closing time from 12 sec (one motor) to 6 sec (two motors).

2.3.2 Software Overview

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The S TRK SOP controls and monitors the operation of the two S TRK's and processes S TRK data for use by other program elements. The S TRK SOP interfaces with the S TRK hardware to perform the moding functions, tracking functions, data enhancement and self-tests shown in table 2-II. The S TRK SOP responds to inputs from the keyboard and the navigation function and provides response to the CRT display (fig. 2-6). The S TRK SOP also provides alignment data to the IMU SOP. When the S TRK is in the operate mode, the S TRK SOP will respond to requests to perform various submodes in support of IMU alignments as follows.

- A. <u>Terminate/Idle</u>: This submode terminates processing associated with other submodes and sets S TRK output commands to the nominal idle conditions.
- B. <u>Self-test</u>: This submode tests the ability of the S TRK to acquire and track a simulated star. Star Magnitude (SMAG) and position data are checked against hardware prestored values for reasonableness. Pass or fail status is made available for display on the CRT (SPEC 22). The time required is approximately 10 sec.
- C. <u>S TRK</u>: This submode accepts either computer- or crew-selected star identification numbers and issues the required outputs to the S TRK's

for offset scan mode or full field scan mode search. S TRK/star LOS data are compared to determine if the star is within the S TRK FOV. Sighting data are compensated for optical and celestial aberration errors. Appropriate status displays are made available to the crew. The S TRK submode is normally utilized whenever an IMU is sufficiently aligned to provide a suitable inertial reference. If a crew selected star is input, this submode will return to term/idle at the completion of one search cycle. If stars of opportunity are to be selected, this submode will continue until term/idle is requested.

D. <u>COAS Sighting and Calibration</u>: These submodes perform computations associated with COAS star sightings. Star LOS vectors are computed for each star sighting and are stored for subsequent IMU alignment calculations or to support on-orbit calibration of the COAS.

A target track submode and a target track option of the COAS submode are available in the S TRK SOP. These submodes do not pertain to IMU alignments.

Module Description	Module Name
*ST terminate/idle	ST_TERM_IDLE
*ST self-test	ST_SELF_TEST
*Star Track	STAR_TRACK
*Target track	TARGET_TR4 CK
Star in field-of-view test	FOV TEST
Star confirm test	STAR_CONFIRM
Sighting data filter routine	DATA_F ILR
+COAS sighting	COAS_SIGH
	COAS_CAL IB
CT/COAS star location	ST_COAS
ST control/monitor display support	DISP_SUP

TABLE 2-II.- ST SOP FUNCTIONAL MODULES

*Modules are also submodes

X X X X / 0 Z Z / \$ TRK/COAS CNTL XX X DDD/HH:MMISS DDD/HH:NM:SS TABLE S TRK CHTL - Z \$ 1 2 3 - 1 SELF-TEST 1 1 2 X TRK ID XX XX XX 3 X 4 X NIN XX TRK XX XX STAR TOT TOK 5 X 6 X ۵ DIF X X X . X X X X . X X X X . X BREAK TRK 7 8 FRR X . X X X.XX X . X X TERM/IDLE 9 X 1 O X SEL 17X 18X 19X S TABLE CLR 20 S TRK COAS - 7 REQD ID 12 REOD ID 11 XX XX 21 XX XX XX TRK ID ADEG X ±X.X PRES X X ± X . X ± X . X X ± X . X X AANG NODE 2 2 X THOLD 13 X 14 X ACCEPT 23 SHUTTER XX XX CAL MODE 24 X HAH 161 01 15X DES 25 X STATUS * POS + X 26X -Z 27X * * * * XXXX ABIAS X . X X X . X X UPDATE 28 29 (XX)

Figure 2-6.- Generic S TRK/COAS CNTL display.

2.4 COAS

2.4.1 <u>Functional Overview</u>

The COAS is a manually operated navigation instrument consisting primarily of a light source, a reticle lens, a collimating tube with objective lens focused at infinity, and a combining glass. To use the COAS, the crewman sights on the selected star through the combining glass upon which the reticle pattern is projected (fig. 2-7). A crewman/software interface is provided to 'snapshot' Orbiter and IMU platform orientation data at the crewman's command (mark). These data are used by the GPC to determine star actual-LOS variation from software computed-LOS for use in calibrating the COAS or aligning the IMU's. The COAS must be calibrated on-orbit, using an aligned IMU, to meet subsequent IMU realignment accuracy requirements.

The COAS, which is stowed when not in use is provided with a precision mounting plate to allow installation in either of two positions. One mounting bracket is located adjacent to the starboard overhead window (W7). The COAS mounted in this bracket is said to be in the -Z position. Stars sighted through the overhead window will have a LOS parallel to the -Z



Figure 2-7.- Crewman optical alignment sight.

dynamic body axis. Likewise, when the COAS is mounted in a bracket above the port forward window (W3), it is in the +X position.

An aperture stop is provided to assist the crew in sighting on a star by reducing the field of view. A filter is also provided for use in sighting on targets in daylight. The aperture and filter both clip on the COAS lens mounting bracket and they cannot be used simultaneously.

2.4.2 <u>Software Overview</u>

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The COAS software is a portion of the S TRK software. The COAS submode of the S TRK SOP does not interface directly with the COAS hardware. The crewman uses the keyboard (S TRK/COAS control display, fig. 2-6) to tell the GPC in which position the COAS is mounted, the desired mode of operation (calibration or sight), and the star at which the COAS is pointed. The GPC assigns the Attitude Reference pushbutton (ATT REF pb) the alternate COAS/star mark function when either COAS mode of operation is selected. The ATT REF pb remains a mark initiator until such time that the COAS mode is deselected or a S TRK control mode is selected.

The crewman informs the GPC when the star is in the center of the COAS by pressing the ATT REF pb (marks on the star). The GPC records the Orbiter attitude data (IMU gimbal angles) at the instant the mark is initiated to determine the LOS vector to the star. These data are used to compute the COAS LOS offset from the prime body axis (+X or -Z) for COAS bias calibration or to determine the IMU platform misalignments (two marks required), depending on the mode selected. The GPC feedback to the crewman is through the CRT display. Although the COAS modes and the S TRK modes cannot operate simultaneously, there is an S TRK SOP module that prov des -Z S TRK star position data to the crewman in -Z COAS coordinates (body coordinates for future S/W releases). This feature allows visual verification that the S TRK is tracking the correct star.

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2.5 STARS

2.5. Star Catalog

Ephemeris data for designated navigation (NAV) stars are I-loaded into GPC memory for use in performing on-orbit IMU alignments. These stars are also marked on Flight Data File (FDF) tables and charts to assist the crew in star acquisition when needed. The STS star catalog contains 50 of the approximately 150 stars that fall within the S TRK's specified detection capability.

Criteria for choosing the 50 STS NAV stars to be in the catalog are as follows.

A. <u>Apollo NAV stars</u>: Apollo NAV stars that met the magnitude requirements of the STS S TRK were chosen to form a baseline because the flight crewmen were already familiar with these stars. B. <u>Spatial distribution</u>: Stars were picked to fill the gaps in the celestial sphere left by the Apollo NAV stars. Consideration was given to the predicted orbital flight path of the Orbital Flight Test (OFT) flights when filling the gaps.

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- C. <u>Celestial density</u>: Stars that fell within a 5^o angular separation from another NAV star or cluster of non-NAV stars were avoided when possible.
- D. <u>Brightness</u>: Consideration was given to visual magnitude to allow for use with the COAS. The brightest stars were selected when other criteria were met.

The 50 STS NAV stars are listed in table A-I in the appendix, along with their visual magnitude, S-20 (S TRK sensitivity) magnitude, and celestial position. The stars are numbered in descending order of brightness beginning with number 11. These numbers are the S TRK SOP I-loaded catalog ID numbers. ID numbers 1 through 10 are reserved for the Sun, Moon, Earth, and other celestial or orbiting objects. Star number 49 is an exception in the order of magnitude due to a substitution after the original 50 stars were cataloged. Celestial maps showing the NAV stars are included in the appendix.

2.5.2 Star <u>Selection for Alignments</u>

Any two stars in the S TRK's catalog may be used to align the IMU's. However, alignment accuracy improves as the LOS separation approaches 90° from either direction as shown in figure 2-8. Other factors affecting IMU alignment accuracy will be discussed in section 2.6. Star selection for IMU alignments may be accomplished by either the GPC or the crew when using the S TRK. The crew must select the stars when using the COAS.

In the S TRK's automatic (GPC) star-selection mode, the S TRK SOP uses the star catalog to determine which stars are available within the S TRK FOV and obtains the necessary data on the available stars. The S TRK SOP presents data on up to three stars in the Star Sighting Table (S TABLE) on the CRT display (fig. 2-6) and selects two stars (a pair) whose data best satisfy I-load criteria to use for IMU alignment. The criteria used by the software in determining which stars' data to retain for display in the S TABLE are as follows.

- A. Data on a newly-acquired star are always retained if the data are determined to be valid.
- B. If the S TABLE is already full when a new (fourth) star is acquired, the SOP looks for a star whose data are older than a specified (2loaded) value for elimination.
- C. If none of the star lata is older than the specified value when fourth star is acquired, the pair of stars whose LOS separation angle is closest to 90° is retained.
- D. If two pairs can be formed with the same LOS separation angle variance from 90° , the pair with the most current data is retained.

E. After the pair of stars for retention is determined, data on the oldest of the remaining two stars are deleted to make room for the new star's data.

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The S TRK SOP also uses the LOS separation angle variance from 90° to determine which star pair in the S TABLE to select for IMU alignment. When a star pair's variance is within the I-loaded specified value (55° for OFT), the software notifies the crewman via the CRT (Align Enable, SPEC 21). If more than one pair is within the I-loaded value, the pair closest to 90° is chosen. Whether or not the software designates a star pair, the crew may still select any two stars from the table via keyboard entry.

For OFT IMU/ST/COAS activities, the crewman maneuvers to an attitude which points the sighting instrument's LOS to specific navigation star(s) to be tracked. The crewman is assisted in his choice of stars by the Crew Activity Plan (CAP) which provides star ID's, names, separation angles, and Orbiter attitudes for scheduled alignments. The criteria used to choose the stars contained in the CAP are as follows.

A. <u>Scheduled time of alignment</u>: The time of the alignment determines which part of the celestial sphere is visible when consideration is given to occultation by the Earth, Moon and Sun. The orbital trajectory of an individual flight dictates how long each star is visible. Stars are selected that are available for a minimum of 10 min for S TRK sightings and 20 min for COAS sightings. These times allow for vehicle maneuvers.





- B. <u>Bright object avoidance</u>: Stars in close proximity to planets or clusters of non-NAV stars were not selected. These light sources, as well as the Sun, sunlit Earth, and sunlit Moon could interfere with efficient acquisition of the desired NAV star.
- C. <u>Gimbal flip avoidance</u>: Stars that require a vehicle attitude causing an IMU to operate in the gimbal flip region (pitch gimbal within 3⁰ of either 90⁰ or 270⁰) were not selected. A high gimbal rate associated with the gimbal flip could result in the IMU's present platform position being miscalculated, leading to a gross misalignment when a minor realignment was attempted.
- D. <u>Star separation</u>: Star pairs have been chosen that have approximately 90° separation between their LOS's in order to provide maximum IMU alignment accuracy.
- E. <u>S TRK geometry</u>: The CAP calls for both S TRK's to obtain star data simultaneously in order to avoid having to maneuver to two different attitudes. The FOV centerline of the two S TRK's are separated by an angle of 87.65° as shown in figure 2-9. Since the FOV of each S TRK is a 10° square, theoretically, a star pair separation within 10° of 87.65° would satisfy this criterion. However, to allow for attitude deadbanding and to avoid loss of track, a separation range within 5° of 87.65° is required, with those within 3° being preferred. The star pairs which meet this criterion are shown in table A-II.



Figure 2-9.- S TRK/COAS geometry.

- F. <u>COAS usage</u>: In addition to being used as a backup star data acquisition device, the COAS may be used to verify the star being tracked by the -Z S TRK as discussed in paragraph 2.4.2. To assist in both of these functions, the star pairs chosen for IMU alignments are easily located and identified visually.
- G. <u>One S TRK usage</u>: Stars which meet the preceding criteria will also support one S TRK operation. As is the case with the COAS, an additional maneuver will be required when only one S TRK is available to obtain data on both stars.
- H. <u>Special note</u>: Although the star Sirius is in the STS NAV star catalog, it will not be scheduled for S TRK sightings on STS-1 due to a suspected problem with reflected lights in the S TRK optics. A bright light source may cause a reflected image bright enough to be tracked by the S TRK. The reflected image's data should be rejected by the S TRK SOP; however, Sirius (the only star in the catalog bright enough to reflect a detectable image) will not be used as a precaution on this first flight.

The detailed procedure for computing the vehicle attitudes given in the CAP for obtaining star LOS data is presented in the Attitude and Pointing Procedures Handbook, JSC-10511. Briefly, the procedure involves pointing one instrument's (S TRK or COAS) centerline at a candidate star, then rotating about this centerline until the second star lies as close as possible to the second instrument's centerline.

2.6 ALIGNMENT OPTIONS

2.6.1 <u>Star-Align</u>

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The primary IMU SOP alignment option uses star LOS data to determine the present attitude of the IMU platform. This attitude is defined by the Present REFSMMAT (section 1-6). Misalignment angles (ANG ΔX , ΔY , ΔZ ; SPEC 21) between the present attitude and desired attitude are computed as shown in paragraph 2.6.7 for each operating IMU. The IMU is aligned by physical movement (torquing) of the platform until the misalignment angles are zeroed. The platform is moved slowly (0.417 deg/min) by means of additional torquing pulses applied to the gyros. This slow movement allows the IMU to continue providing valid inertial reference data. After the platform is repositioned, the Current REFSMMAT is set equal to the Desired REFSMMAT, if they are different. A difference in these two REFSMMAT's could result if a matrix alignment (paragraph 2.6.5) had preceded the Star-Align or if a new Desired REFSMMAT had been uplinked prior to the alignment.

NOTE: Some of the following subsections discuss platform alignment accuracy in terms of alignment errors. The total expected error is computed by finding the Root of the Sum of the Squares (RSS) of the contributing errors.
SOURCE ERRORS	
Installation measurement errors (IMU bench installation)	
Star Tracker IMU	14 arc sec 14 arc sec
Line Replacement Unit (LRU) reinstallation errors	
Star Tracker IMU	20 arc sec 20 arc sec
Navigation base thermal bending (Star Tracker to IMU)	<15 arc sec
IMU stable member errors	
Pitch to outer roll gimbal Case to outer roll gimbal Resolver errors	30 arc sec 28 arc sec 44 arc sec
Star Tracker error (line-of-sight with respect to case)	42 arc sec
TOTAL ALIGNMENT ERROR (RSS 1-sigma/ax	is)
All source errors 1-sigma 3-sigma error for Star Tracker only	82 arc sec 145 arc sec

TABLE 2-III.- ST/IMU ALIGNMENT ERROR BUDGET

2.6.2 Star-Align Accuracy

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IMU alignment accuracy is affected primarily through errors introduced by the star sighting instrument, physical relationship between the sighting instruments and the IMU platform, and platform positioning. Computer programs have been developed to simulate, scale, and model IMU performance using ground test and specification data. The predicted accuracy values presented in this handbook are the results of these computer programs and technical analyses as presented to the on-orbit flight techniques panel.

The error budget for an alignment using S TRK LOS data is shown in table 2-III. This table does not consider the several possible variations in method of obtaining star data; i.e., manual star selection, automatic star selection, two S TRK's, one S TRK, etc. The 1-sigma alignment error value

TABLE 2-IV.- ST/IMU ALIGNMENT VS. STAR PAIR SEPARATION

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The on-orbit 1-sigma Star Tracker/IMU realignment uncertainties with various star pair separation angles are as follows:

Star pair separation	1-Sigma realignment uncertainties
(degrees)	(arc sec/axis)
10	392
30	143
50	100
70	86
90	82
110	86
130	100
150	143

of 82 arc sec per axis is based on a star pair separation angle of 90° with star data having been obtained with 1-sigma S TRK's and 1-sigma IMU operation. The 145 arc sec value is based also on 90° star separation and 1-sigma IMU operation, but with 3-sigma S TRK's. Greater confidence can be placed in the latter case because the S TRK's operate independently while the 3 IMU's are redundant. The effect of various star separation angles on the alignment was shown in figure 2-10 from data presented in table 2-IV.

The error budget for an IMU alignment using the -Z COAS to sight on stars 90° apart is presented in table 2-V. An error budget for the +X COAS is approximately of the same magnitude and will be included in later editions of this handbook. Since the COAS must be calibrated prior to use, the COAS/IMU alignment budget is based on the following assumptions.

- A. COAS remains in -Z position after calibration
- B. Ground-aligned IMU-based calibration performed at 02:23:00 MET, 1sigma IMU alignment error equal to 160 arc sec per axis
- C. S TRK-aligned IMU-based calibration performed back-to-back with the S TRK/IMU alignment, 1-sigma IMU alignment error equal to 82 arc sec per axis (table 2-III).
- D. Error budget for all included errors are random.

TABLE 2-V.- COAS/IMU ALIGNMENT ERROR BUDGET

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SOURCE ERRORS				
Installation measurement error (IMU bench installation)	14 arc sec/axis			
LRU reinstallation errors (line and on-orbit)			
IMU COAS COAS	20 arc sec/axis 20 arc sec/axis			
Navigation base thermal bending (IMU to NAV base)	<15 arc sec/axis			
Structural deformation (overhead window)				
Cabin pressure variation; -Z(+X) Temperature variation Glass bending	50 (18) arc sec/axis 4 (TBD) arc sec/axis			
Vehicle dynamics	75 arc sec/axis			
Crew vision	21 arc sec/axis			
IMU stable member errors (stable member with respect to case)				
Pitch to outer roll gimbal Case to outer roll gimbal misalignment Resolver errors	30 arc sec/axis 28 arc sec/axis 44 arc sec/axis			
COAS instrument error (Parallax)	52 arc sec/axis			
COAS on-orbit calibration error (reference	dependent)*			
Ground aligned IMU as reference Op-orbit Star Tracker aligned IMU	174 arc sec/axis			
(1-sigma Star Tracker)	137 and sec/axis			
(3-sigma Star Tracker)	181 arc sec/a×is			
TOTAL ALIGNMENT ERROR (RSS 1-sigma/Axis/Star measurement using the following for calitration basis)				
Ground aligned IMU: -Z(+X)	215 (210) arc sec/axis			
Star Tracker aligned IMU; -Z(+X) (1-sigma Star Tracker)	187 (181) arc sec/axis			
Star Tracker aligned IMU; -Z(+X) (3-sigma Star Tracker)	221 (216) arc sec/axis			

 $\star Includes$ some of the same errors as above

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The budget considers COAS calibrations based on both preflight (ground) and on-orbit aligned IMU's. This is necessary since the first calibration will be performed prior to the first on-orbit IMU alignment. The effect of star LOS separation angles on COAS/IMU alignments is shown in table 2-VI.

TABLE 2-VI.- COAS/IMU ALIGNMENT ERROR VS. STAR PAIR SEPARATION

various star pair separation angles are as follows.Star pair separation (degrees)1-Sigma realignment uncertai (arc sec/axis)			
	-Z(+X) COAS calibrated to ground aligned IMU	-Z(+X) COAS calibrated to ST aligned IMU (SPS = 90 deg)	
30 50 70 90 110 130 150	372 (369) 261 (257) 224 (219) 215 (210) 224 (219) 261 (257) 372 (369)	324 (321) 227 (222) 195 (189) 187 (181) 195 (189) 227 (222) 324 (321)	

The on-orbit 1-sigma (NAS/IMU realignment uncertainties with

2.6.3 IMU/IMU Alignment

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This alignment option differs from the Star-Align option in two areas. First, one IMU is considered to be already sufficiently well aligned to be used as a reference in lieu of star data. Secondly, if an IMU other than the reference is to be aligned, the platform is moved rapidly by applying slewing signals to the gyros. The platform gimbals drive (at 1.2 deg/sec) until the platform is within 1° of the desired position. The platform is then slewed past the desired position for a given number of seconds (20 for OFT) and slewed back for an equal number of seconds to eliminate slew-direction sensitivity. The IMU is removed from the Redun-dancy Management (RM) selection filter while the platform is being slewed. The reference IMU platform is not slewed. Final positioning is done by torquing the gyros as is done in the Star-Align option except that a maximum torque time is set (120 sec) rather than a required time being calculated. If the misalignment is nulled prior to the set time, the alignment is terminated.

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There are three suboptions of the IMU/IMU alignment option. These suboptions are presented here to assist in understanding the similarities and differences.

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- o Option A: IMU i > One or both may be selected IMU j > for alignment IMU k - Selected for reference only
- o Option B: IMU i > One or both may be selected IMU j > for alignment IMU k - Selected for alignment and reference
- o Option C: IMU i > Neither selected for alignment IMU j > Selected for alignment and reference

Option A

o Assume both IMU's i and j are selected to be aligned to reference IMU k.

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o Compute Present REFSMMAT's for operating IMU's using Current REFSMMAT for IMU k and resolver data for pertinent IMU's.

$$T_{PC(i)}M50 = [T_{C(k)}M50] [T_{NB}FC(k)]^{T}PC(i)_{NB}^{T}$$

= [T_{C(k)}M50] [T_{PC(i)}PC(k)]
$$T_{PC(j)}M50 = [T_{C(k)}M50] [T_{NB}FC(k)]^{*}[T_{PC(j)}NB]^{*}$$

= [T_{C(k)}M50] [T_{PC(i)}PC(k)]
$$T_{PC(k)}M50 = [T_{C(k)}M50] [T_{NB}PC(k)]^{*}[T_{PC(k)}NB]^{*}$$

= T_{C(k)}M50

*Resolver data

- o Determine misalignment (torquing) angles for IMU i and IMU j using the respective Present REFSMMAT's and Desired REFSMMAT'S.
- o Remove IMU i and IMU j from RM selection filter.
- o Slew and torque out the misalignment incrementally using the Large Angle Torquing (LAT) function.
- o Update displayed misalignment angles, as required.
- o Set Current REFSMMAT for IMU i and IMU j equal to their respective Desired REFSMMAT's.
- o Reinstate IMU i and IMU j to RM selectior filter.

Option B

o Assume all IMU's (i, j, and k) are to be aligned with IMU k selected by the crewman to be the reference.

- o Perform alignment for IMU i and IMU j same as option A.
- Compute Present REFSMMAT for IMU k using the new Current REFSMMAT of IMU i (computer selected to be new reference) and resolver data from IMU i and IMU k.

 $T_PC(k)_M50 = [T_C(i)_M50] [T_NB_PC(i)]^*[T_PC(k)_NB]^*$ = [T_C(i)_M50] [T_PC(k)_PC(i)] *Resolver data

- Determine misalignment angles for IMU k using the Present REFSMMAT and Desired REFSMMAT.
- Remove IMU k from RM selection filter.
- o Slew and torque out the misalignments using LAT function.
- o Set MU k's current REFSMMAT equal to its Desired REFSMMAT.
- o Reinstate IMU k to RM selection filter after slewing is completed.

Option C

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- Assume only IMU k is operating and is to be aligned to a new Desired REFSMMAT (i.e., new Desired REFSMMAT uplinked since last alignment).
- o Determine Present REFSMMAT by setting it equal to the Current REFSMMAT.

 $T_PC(k)_{M50} = T_C(k)_{M50}$

- o Determine misalignment angles using the Present and Desired REFSMMAT's.
- o Incrementally torque out the misalignment angles (does NOT slew).
- o Update display, as required.

o Set Current REFSMMAT equal to Desired REFSMMAT.

The IMU/IMU alignment options A and B are useful when platform attitudes are several degrees from the desired attitudes. Option C is a means to change the platform position when only one IMU is operating and should only be used for very minor (i.e., less than 1°) adjustments. Option A will be used on STS-1 after the new Desired REFSMMATs are uplinked and if IMU's are reactivated while on-orbit. Options B and C are not available in the software for STS-1. Option B will be used for Desired REFSMMAT updating on later flights. Operational use of option C has not been identified.

Error Source	lơ Error <u>per axis</u>	lg Error <u>3 axis</u>
Ref IMU C1 to M50	0	0
Ref IMU C1 to case	60	103.92
Ref IMU install err	. 20	34.64
NB pad to pad error	14	24.25
NB bending pad to pad	13	22.52
Align IMU install err	20	34.64
Align IMU cl to case	60	103.92
RSS 1-sigma/axis 3-sigma axis	91.5 274.5	158.4 475.2

TABLE 2-VII.- IMU/IMU ALIGNMENT ERROR BUDGET

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2.6.4 IMU/IMU Alignment Accuracy

The predicted errors for an alignment of one IMU when a second IMU is used as the reference is shown in table 2-VII. The 1-sigma error of 91.5 arc sec per axis does not allow for any error in the reference IMU orientation to M50. The predicted alignment error of the reference IMU would have to be included in the given RSS value.

2.6.5 Matrix Alignment

This option differs from the Star-Align option in that the computed misalignment angle shows the difference between the star data determined present attitude and the attitude defined by the Current REFSMMAT from the preceding alignment. In lieu of moving the platform, the new Current REFSMMAT is set equal to the Present REFSMMAT. The Desired REFSMMAT is not addressed in this type of alignment. However, unless a new Desired REFSMMAT has been uplinked since the previous alignment, the misalignment values will be the same as those obtained in the Star-Align option. The matrix alignment option is useful when the platform is misaligned by several degrees and there is no compelling reason to maintain a particular platform attitude (skew) relative to the other IMU platform or to the M50 coordinate system.

2.6.6 Matrix Alignment Accuracy

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The accuracy of this type of alignment is nearly the same as that given in table 2-IV for the Star-Align option.

2.6.7 Misalignment Angle Computation

Misalignment angles are presented on the CRT (fig. 2-7) to assist the crewman in deciding whether to proceed with the alignment or change alignment options. The misalignment values (ANG ΔX , ΔY , ΔZ) given for each IMU on SPEC 22 indicate the difference between the Orbiter's inertial attitude based on two different inertial references. The first reference is the IMU platform position as described by the Present REFSMMAT. The second reference is the IMU platform position described by either the Desired or Current REFSMMAT, depending on which IMU alignment option is selected.

It may be noted that the Orbiter inertial attitude based on the Current REFSMMAT is presented on the display. The attitude (ANG X, Y, Z) given is an Euler angle rotation of the body axis from the M50 axis, i.e., ANG X, Y, Z are the angles about the respective axis through which the Orbiter would have to be rotated sequentially (roll, pitch, then yaw) to coincide with the M50 axis. If all operating IMU's were properly aligned, these angles would be the same for a given axis regardless of the skew between IMU platforms.

The misalignment angles are computed by the IMU SOP using appropriate REFSMMAT's as follows.

ANG ΔX , ΔY , ΔZ are a function of a directional cosine matrix (T).

ANG ΔX , ΔY , $\Delta Z = f T$

With the Star-Align or IMU/IMU option selected, T is derived from the Present REFSMMAT and Desired REFSMMAT.

$$T = [T_PC(k)_M50] [T_M50_DC(k)]$$

For the matrix align option selected, T is derived from the Present REFSMMAT and Current REFSMMAT (transposed).

T = [T PC(k) M50] [T M50 C(k)]

The use of T in deriving the ANG ΔX , ΔY and ΔZ values is the same regardless of the option selected. The matrix is first changed to a quaternion.

$$T = M CB I \rightarrow Q CB I$$

where Q CB I is the equivalent quaternion of matrix M_CB_I

Each element of the quaternion is then used to determine the misalignment angles.

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ΔX	=	- ((A)	(Q	CB	I ((2))/BB
ΔΥ	=	-	(A)	(Q	CB	[]	(3)))/BB
۸Z	8	- ((A)	(Q	CB	<u>[</u>]	(4)))/BB

where A is the Eigen angle of rotation

A = 2 ARCSIN(BB) X 57.29578 deg/rad

 $BB = [(Q_CB_I(2))^2 + (Q_CB_I(3))^2 + (Q_CB_I(4))^2]^{1/2}$

When a platform is being torqued to a new position, the misalignment angles will be updated once every 2 sec (sample rate). However, when a platform is being slewed to a new position, the misalignment angles are recomputed once every 0.3 to 20 sec, depending on the absolute value of the misalignment. The update rate will thus vary from once every 2 sec (sample rate) to once every 20 sec. At the end of platform slewing, there will be a 40-sec gap between misalignment angle update as the gimbals are slewed past the desired position for 20 sec and then reversed for an additional 20 sec to null out directional sensitivity.

NOTE: During digital torquing the updated misalignment angle values are simply computed values based on torquing rates and time. They ARE NOT measured values based on resolver data and thus DO NOT reflect the actual movement of the platform.

SECTION 3 ASSUMPTIONS, GUIDELINES AND CONSTRAINTS

3.1 ALIGNMENT MAINTENANCE

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During the Operational Flight Test (OFT) program, special consideration will be given to Inertial Measurement Unit (IMU) platform alignment maintenance. This section will present pertinent operational decisions which influenced the procedures and their prospective use on OFT missions.

3.2 STAR TRACKER I-LOADS

Many parameter values are I-loaded into General Purpose Computer (GPC) memory prior to each flight. Of special concern when developing and using the IMU alignment procedures are those parameter values associated with the Star Track (S TRK) Software Operating Procedure (SOP) for collecting and evaluating star Line-of-Sight (LOS) data. Since all the alignments on OFT missions (will be made using data on specific stars obtained while the vehicle is holding at a specific attitude, with the crew being the final data filter, some of the I-loaded acceptance criteria are more lenient than will be the case for later flights. This leniency is primarily to allow for some tolerance on the system's performance as predicted by mathematical analysis. Without the tolerance, the software may prevent a sighting or discard sighting data without allowing the crew the prerogative of further evaluation.

Key S TRK Limits (LIM) and Tolerances (TOL) I-loaded for early OFT are as follows.

- A. ST Output Back Difference (TOL 6), 0.0244°: A S TRK sighting is comprised of 21 marks on the stars that are averaged. After each of the 21 marks other than the first mark, the software does a reasonability check to see if the last mark is within TOL 6 of the next to last mark. Based on hardware performance specs and analyses, TOL 6 could be 0.122°. To be ultra-conservative, the analytical estimate was doubled.
- B. Angular Body Rate Limit (TOL 8), 0.75 deg/sec: If the measured Orbiter rate of angular rotation in any axis exceeds the I-loaded value during a sighting, the sighting will be discarded. The S TRK will track with rates up to 0.2 deg/sec with guaranteed accuracy and at rates up to 0.5 deg/sec with slightly degraded accuracy. Approximate error will be 0.004° (15 arc sec) for each additional 0.3 deg/sec rotation. All early OFT sightings used for alignments will be done at attitude hold with 0.2 deg/sec or smaller rates. The value is placed at 0.75° to allow sightings at higher attitude maneuver rates between alignments.
- C. Star Pair Separation Angle Difference (TOL 10), 0.20 (.003490659 rad): If, during S TRK SOP interrogation of the sighting data, the difference between the measured star pair separation angle and actual separation angle is greater than TOL 10, the sighting is discarded. If only one other star is in the star table, that star's sighting data is also discarded.

Based on 3-sigma S TRK operation the value could be limited to 0.08^{9} . The limit was opened up for STS-1 to 0.2 in order to provide a margin for error on the analysis and to obtain data on as many sightings as possible. The actual acceptance of data for IMU alignments will be by the crewman using 0.09^{0} as the criterion. This is shown as ANG ERR on the SPEC 22 display.

- D. Star LOS Rate Limit (TOL 12), 0.03 deg/sec (2.78x10⁻⁶): This limit is set to preclude accepting data on debris, ice crystals, satellites or celestial bodies other than stars. The S TRK requires 3.2 sec to take 21 sighting marks on an object being tracked. If during this time, there is a shift in the inertial position of the object, the sighting data is discarded. Although the limit is designated as a rate, the I-loaded value is the square of the sine of the angle between the first and twenty-first LOS vectors. Current IMU, NAV base, and S TRK models predict an angle of 0.065° between the vectors due to hardware and computational errors. This equates to a rate of 0.02 deg/sec when divided by the 3.2-sec time lapse between the first and twenty-first sightings. To provide a margin for model errors, a value equating to about 0.03 deg/sec is I-loaded for STS-2.
- E. Old Data Age Limit (TOL 13), 60 min: If data on a new star are obtained after the star table (SPEC 22) is full. the S TRK SOP will eliminate the oldest star whose data are older than this limit before applying other criteria to eliminate one of the stars already in the table. In future flights this limit will probably be set equal to the time recuired to complete one orbit.
- F. Optimum Star Pair Separation Angle (TOL 14), 35° to 145° (0.819): The S TRK SOP will automatically select a pair of stars from the SPEC 22 star table for IMU alignment only if the separation angle between their LOS's is within the tolerance given ($|COS 145^{\circ}| = |COS 35^{\circ}| = 0.819$). This tolerance does not affect the crew's capability to select any pair of stars for an alignment. The separation deadband was set at 90° ± 55° for OFT to provide for sighting on many more star pairs than 1 a more nearly optimum value of 90° ± 5° would allow.
- G. Offset Scan Mode Star Position Limit (T LiM 1), 0.70: In the offset scan mode, the S TRK looks for a star in a 10 square, centered where the SOP thinks the star should be. T LIM 1 is a software limit that will accept the star in this mode only if it is located within a circle, centered where the SOP thinks the star should be, with a radius equal to the limit. The value is set at 0.70 for OFT to cover the entire 10 square; i.e., if the S TRK can find a star, the data will be processed. The need for this limit is being reviewed for possible elimination on later flights.

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H. Full Scan Mode Star Position Limit (T LIM 2), 1.4°: If the required star is not obtained in the offset mode, the S TRK scans the full FOV. If it locks onto anything in the T LIM 2 radius of where an eligible star should be, the S TRK SOP will process sighting data. T LIM 2 must be large enough to allow for 3-sigma equipment operation including maximum IMU drift between alignments. However, the limit must be small enough to prevent sighting on the wrong star. Based on current alignment schedules and equipment specifications, the value could be 1° or less. Since the crew will provide the final filter of star data based on other criteria (ANG ERR = 0.09°), this limit was set at 1.4° to provide a pad on the math.

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3.3 SKEW MATRICES

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One IMU platform is said to be skewed relative to another if none of their principal axes are coaligned. The three IMU platforms are skewed in order to allow fault identification at the 2-level; i.e., if the platform orientations were coincident and one IMU failed, the RM function would have difficulty isolating subsequent attitude faults in the remaining two IMU's.

There are an indefinite number of possible skew relationships between the platforms. Three skew orientations have been considered for STS-1. They are named $\sqrt{2}$, $\sqrt{5}$ and $\sqrt{6}$ because there are several of the respective square root values in the nine-element transformations describing the relative orientations.

During factory calibration of the IMU's to be flown on STS-1, the $\sqrt{5}$ orientation was thought to optimize failure-detection capability. This skew was considered when 13 platform positions were developed for the IMU calibration program. This extensive program was conducted using these positions to allow optimum IMU operation during launch and orbit insertion. However, recent studies have shown that the $\sqrt{6}$ skew would have been a better choice for both launch and entry when considering RM requirements with three IMU's operating. When only two IMU's are operating, the $\sqrt{2}$ skew provides the best single-axis RM performance in the flight-critical (-Z) direction and provides for dual and triaxial failure detection.

Since time and expense versus gained operational capability does not justify a repeat of the factory calibration, a compromise decision has been made by the flight technique panel for early OFT:

- A. Launch, and postinsertion activities will be made with REFSMMATS that provide for $\sqrt{5}$ skewing.
- B. The launch and entry skews will be computed such that one IMU platform's orientation remains constant for both skews. Normally this will be IMU 3.
- C. Prior to the final alignment on the first flight day, new Desired REFSMMATs which provide for a $\sqrt{6}$ skew will be uplinked to the Orbiter if all three IMU's are operational. If only two IMU's are operational a $\sqrt{2}$ skew will be uplinked.
- D. The crew will realign the IMU platforms to the new Desired REFSMMAT as soon as possible after it is received.

3.4 GUIDELINES AND CONSTRAINTS LIST

The following guidelines and constraints were used in developing both the IMU/ST/COAS procedures and the schedule for use of these procedures as presented in the Postinsertion Deorbit Preparation (PDP) book and Crew Activity Plan (CAP).

- A. COAS
 - 1. Initial calibration will be scheduled to be performed as soon as possible after entering Operational Sequence (OPS) 2. This action is to ensure availability of a calibrated COAS as a contingency star sighting instrument for IMU alignments.

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- COAS calibrations subsequent to 4 hours MET will be immediately preceded by an IMU alignment. This ensures an accurate basis for calibration.
- 3. The COAS may be calibrated in both positions. This guideline provides necessary flexibility to ensure availability of the COAS as a contingency sighting instrument and to obtain COAS data for satisfaction of test objectives.
- 4. Once a good COAS calibration has been performed, the COAS need not be recalibrated if removed then remounted at the same station. The mounting brackets are designed, according to specifications, to allow precise remounting.
- 5. The COAS will be recalibrated at the beginning of each flight day. These supplemental calibrations are to obtain additional data for COAS calibration verification.
- 6. The COAS will be recalibrated if the cabin is depressurized when two S TRK's are not available. This provides for fail-safe redundancy for IMU alignment.
- 7. The COAS calibration will be updated (△ BIAS value will always be incorporated) each time the calibration is performed. More confidence can be placed on later calibration as the Orbiter vehicle structure should stabilize, and the crew will gain expertise in taking COAS/star marks in the orbital environment.
- 8. COAS activities will be scheduled to be performed in orbital darkness. Visual acuity for star sighting is enhanced by lack of direct or incident sun light.
- 9. COAS and star tracker(s) will not be scheduled to obtain star LOS data simultaneously. However, -Z COAS and -Z star tracker can be used together for star ID verification. The COAS and star tracker software cannot process star LOS data simultaneously.

B. Star Trackers

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- 1. Stars/attitudes for both S TRK and COAS sightings will be selected preflight as specified in paragraph 2.5.2. Real time changes will be made by the ground Mission Control Center (MCC) crew as required when time permits. The selection criteria are established to provide the greatest accuracy with the minimum expenditure of time and fuel. The flight crew may use the back-up star table (see Section 4.4) if circumstances do not allow for ground crew star/attitude selection.
- At least one S TRK will be continuously powered for the entire onorbit portion of flight. This is to preclude loss of both S TRK's without crew awareness as well as to provide engineer-ing data for the ground.
- 3. The powered S TRK's will be placed in auto mode except during scheduled alignments. The automatic star data-gathering mode will allow ground monitoring of the S TRK's health.
- 4. A self-test of the S TRK's will be performed when they are initially turned on (during postinsertion) and at the beginning of each flight day. The self-test will provide the crew with information regarding S TRK data acquisition capability. This activity will also provide data on the self-test circuitry reliability.
- 5. Failure of a self-test does not preclude use of the S TRK. The ground will assist in the evaluation of self-test failures as the self-test is very stringent.
- C. IMU's
 - 1. The vehicle will be launched with $\sqrt{5}$ skew between platforms. For rationale, reference section 3.3.
 - 2. IMU cluster reorientation for entry will be performed as necessary to optimize RM, except at the final (entry) alignment. Performing the orientation at the end of launch day makes the entry skew $(\sqrt{6} \text{ or } \sqrt{2})$ available in case a nominal deorbit is required. Although it is not optimum, the launch skew orientation (or almost any skew orientation) will support a contingency deorbit and landing.

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- 3. All scheduled IMU alignments will be based on star data obtained while the vehicle is holding at attitude. They will be made using stars and attitudes provided in the CAP. Manual star data selection gives more control over the star LOS data and assures its availability when needed.
- 4. IMU gyro drift bias terms will be updated following scheduled IMU align times whenever the drift exceeds 1-sigma (.02 deg/hr). The largest interval between alignments will be in conjunction with the crew sleep period. This interval could be up to 10 hr. At a 0.02 deg/hr per axis drift rate, the drift (misalignment) would be 0.2^o and thus within the 0.25^o (900 arc sec) allowable for deorbit. This

drift limit will also allow S TRK star sightings in the offset scan mode.

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- 5. IMU gyro drift bias terms will be updated immediately when the drift exceeds 3-sigma (0.06 deg/hr). If left unattended, this drift rate would result in a platform misalignment greater than that needed for deorbit. Star data are necessary to verify the amount of platform drift since the last alignment.
- The IMU's will not be realigned with star data to support a deorbit on orbits 2 or 3. The predicted misalignment at orbit 3 deorbit burn (3:50 MET) is less than 0.25° considering a 3-sigma IMU.
- 7. For launch day deorbits on orbits 4, 5, or 6, the IMU's will be aligned as planned for a normal mission. The IMU's will not be tweaked (aligned for a second time) should the deorbit slip to orbit 5 or 6. To be conservative, the possibility of a 3-sigma IMU must be considered. Thus, orbit 4 at 5:25 MET and subsequent deorbit opportunities could be faced with an IMU misalignment greater than 0.25° if an on-orbit alignment is not accomplished.
- 8. If the critical entry IMU alignment has been accomplished and the S TRK doors are closed, the IMU's will not be realigned to support backup-orbit deorbit. If a NO-GO for deorbit is given prior to the IMU alignment, and if timeline permits, the alignment will slip to the same relative place as nominal with respect to the new backup-deorbit opportunity. The alignment will support deorbit up to 3 hr with a 3-sigma IMU (misalignment error = $3 \times 0.021^{\circ} = 0.063^{\circ}$, drift = 3×3 hr $\times 0.02$ deg/hr = 0.18° , total = 0.243°).
- Final Stress Stress
- 1). The MCC is prime for verifying noncritical alignments. The ground crew will continuously monitor IMU alignments and advise MCC and the flight crew of any anomalies.
- 11. If the initial misalignment angles for any two IMU's are greater than a value contributable to gyro drift, the crew will collect new data using two new stars. An apparent misalignment greater than that attributable to uncompensated 3-sigma gyro drift could actually be bad star LOS data. To discount the possiblility of having taken data on debris or malfunctioning star trackers, new data will be acquired.
- 12. An IMU shall be declared adequately aligned when the verification torquing angles are $\leq 0.1^{\circ}$. If the torquing angles are $> 0.1^{\circ}$, the crew will select two new stars and repeat the measurement. This allowable value is based on 3-sigma star tracker operation and will allow the IMU to support a deorbit until the next scheduled alignment.

- 13. For IMU alignments where the initial torquing angles are 0.034°, verification cannot be accomplished. This value falls in the noise region of discernable IMU accuracy.
- 14. IMU gyro calibration will be based on torquing angles gathered at least 3 hr from the time an IMU was last torqued. This time lapse is necessary to allow the gyros to stabilize.
- 15. IMU gyro and accelerometer calibrations normally will not be performed during MM301. Major mode 301 will normally be entered with confidence that the IMU's will support the deorbit and landing. Tweaking of the biases is not warranted amidst the other activities programmed for this time.
- 16. The IMU accelerometers will be calibrated after an IMU is powered up. The accelerometers are heat sensitive; thus it is necessary to verify that the velocity bias is correct after allowing for thermal stabilization.
- 17. Anytime the ground detects a gross accelerometer error $(150 \mu g)$, an IMU accelerometer calibration will be performed ASAP. A larger accelerometer error may not support a deorbit. It is also possible that the accelerometer is bad. Another calibration after the bias update will check this possibility.
- 18. An IMU accelerometer bias update will be performed after calibration to keep the accelerometer bias less than 1-sigma (50 μ g 0.0016 ft-sec²). The purpose of the accelerometer calibration is to keep the instrument accurate.
- 19. For nominal IMU alignments, all operating IMU's should be torqued if the torquing angles are ≤0.80°. If the torquing angle for any axis is >0.80°, the IMU should not be torqued without first receiving guidance from the ground or verifying the torquing angles using two new stars. The first part of this guideline allows simplification of the nominal alignment procedures by not requiring the crew to make a decision regarding extremely small misalignments. The second part avoids moving the platform when the probability is high that something is wrong with the star data rather than the IMU's.

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D. Critical Alignments

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Two of the scheduled alignments are considered critical and will be verified upon completion to ensure IMU accuracy. The critical alignments are the ones performed in conjunction with the postinsertion activities, and during pre-entry activities on the final day of the flight. Each is considered critical because there is a possibility that entry burns (scheduled or contingency) may follow these alignments. The criterion for acceptance of each of these alignments is a platform misalignment angle (ANG ΔX , ΔY , ΔZ) value of 0.1° or less.

- E. Time Estimates for Scheduling Purposes
 - 1. The S TRK warmup time is 15 min. This is the value given in the S TRK specification for full operational capability.
 - 2. The COAS does not require a warmup time. Power to the COAS is provided for reticle illumination only.

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- The IMU warmup for attitude reference is 30 to 35 min based on nom-3. inal cabin temperature. This is per specifications.
- The IMU warmup time for accelerometer data is 4.5 hr for nominal 4. on-orbit operations and 8.0 hr for deorbit. The accelerometer accuracy increases as the temperature stabilizes as discussed in paragraph 2.2.1.
- 5. Initial COAS calibration time is 20 min. This very conservative value is used because this will be the crewman's first opportunity to perform this task in the orbital environment. It allows for a maximum (180⁰) maneuver.
- 6. IMU alignment times are the following.
 - o Five minutes if no maneuver is required
 - o Twenty minutes if one maneuver is required
 - o Five minutes added to the above for each additional maneuver
 - o Five minutes added to the above if the COAS is used

These numbers are best estimates allowing for display preparation, manual data transcription, and alignment execution.

SECTION 4 PROCEDURES DESCRIPTION, GENERIC

4.1 OVERVIEW

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Flexibility in Inertial Measurement Unit (IMU) alignment procedures is provided by several software and hardware combinations. The primary requirement for an alignment is determination of the current attitude of the IMU platforms relative to the stars. This attitude may be computed through the use of two star trackers (S TRK's), one S TRK, a Crewman Optical Alignment Sight (COAS) or a reference IMU. Star data for attitude determination can be obtained by the trackers in either the automatic or manual mode. The Orbiter may or may not have to be reoriented to obtain sufficient star data.

The second alignment requirement is to either physically drive the selected IMU platform to its desired attitude or to introduce mathematical corrections into the General Purpose Computer (GPC) to account for the misalignment. One, two, or all three IMU's may be realigned. Crew station interfaces used by the crewman in executing the IMU/ST/COAS procedures are shown in figure 4-1.

The generic IMU alignment procedures are divided into the following functional groups for discussion.

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o EQUIPMENT ACTIVATION PROCEDURES

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- o IMU's
- o COAS

O NOMINAL ALIGNMENT/CALIBRATION PROCEDURES

- o Normal IMU alignment using S TRK(s)
- o IMU/IMU alignment
- o COAS calibration
- o IMU Accelerometer Calibration
- o IMU Gyro Calibration
- o S TRK self-test

o CONTINGENCY PROCEDURES

- o Matrix alignment
- c COAS/IMU alignment
- c One S TRK star data acquisition



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The nominal and contingency IMU alignment procedures assume that the equipment has been activated. On early Orbital Flight Test (OFT) flights, star data for alignments will normally be gathered on specific navigation stars using both star trackers. The attitude required to obtain data on the specified stars will be included in one or more of the following Flight Data File documents.

- o Crew Activity Plan (CAP)
- o Post-Insertation Deorbit Preparation (PDP) book
- o Star Pairs cue card

A flow diagram showing the early OFT normal IMU alignment procedure as well as the backup options is shown in Figure 4-2. The normal procedure begins in the CAP then moves to the Orbit Operations Checklist (Orbit OPS C/L) as depicted by the straight lines. The major steps are numbered as they appear in the IMU Alignment-S TRK procedure. Backup procedures are shaded and the points where they interface with the normal procedure are designated with broken lines. The final step in all IMU alignment procedures is to place the switches and CRT display to the nominal on-orbit configuration. After this clean-up, the crewman resumes CAP directed activities.

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Some IMU alignments are considered critical because they support activities requiring very accurate attitude data. For these alignments, the align verification procedure is exercised prior to the cleanup activities discussed above.

The procedural flow for COAS calibration which must proceed any COAS/IMU alignment is shown in Figure 4-3. This calibration will probably be performed only once per flight after OFT and should be performed as soon after launch as possible.

The IMU/IMU alignment procedure discussed in Section 4.3.4 will be used for updating the inertial orientation of the IMU platforms to the desired skew for reentry. This change in Desired REFSMMAT'S will be accomplished only once per flight and may be done any time prior to the final predeorbit IMU alignment.

4.2 EQUIPMENT ACTIVATION PROCEDURES

Equipment required to support IMU alignments is activated early in the flight for immediate use or functional check as appropriate. The procedures for activating the IMU's, S TRK's, and COAS are given in Flight Data File (FDF) documents other than the Orbit OPS Checklist. A brief description of the procedures is given to familiarize the reader with the equipment interfaces.





4.2.1 IMU's

At least one IMU is operating at all times to provide attitude data for guidance and control. The number of IMU's in each mode (OPERATE, STANDBY, DESELECT, OFF) varies with the particular flight requirements and IMU status. Early OFT calls for all three IMU's to be operating continuously. IMU activation from OFF is made by toggle switches on overhead panels 014, 015, or 016 for IMU 1, 2, or 3, respectively. If the IMU operating status is changed after a GPC OPS transition or reconfiguration, an Input/Output



Figure 4-3.- COAS calibration flow charts.

(I/O) reset command must be entered on the keyboard. This command clears a GPC communication fault. Specialist display SPEC 21, IMU ALIGN, is called up to verify status and proper operation of powered-up IMU's. Execution of items on SPEC 21 places designated IMU's in the OPERATE, STANDBY or DESELECT mode.

4.2.2 S TRK's

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The S TRK's are activated by closing circuit breakers on overhead panels Ol4 and Ol5 (-Z and -Y respectively) and placing the power toggle switches on overhead panel O6 to the ON position. If the S TRK operating status is changed after a GPC OPS transition or reconfiguration, an I/O reset command must be entered on the keyboard. This command clears a GPC communication fault. The S TRK doors are opened by using toggle switches on overhead panel O6. For a S TRK door to open, the S TRK power must be on and the door control toggle must be in the open position. Closing of the doors does not require the S TRK power switch to be on. S TRK operational status is shown on specialist display SPEC 22, S TRK/COAS control (CNTL), which also provides control of the mode of operation. A 5 TRK self-test mode is executed once each flight day. This mode checks the ability to track and interrogate a simulated star, then presents PASS or FAIL indication to the crew. The S TRK software is initialized in the TERM/IDLE mode when power is applied to the hardware. The crew will not change the mode until the 15 minute warm-up time has elapsed. Early OFT missions call for one S TRK to remain on and in the automatic star data gathering mode throughout most of the orbital flight. This is to provide S TRK/IMU data for ground monitoring via telemetry.

4.2.3 COAS

The COAS is stored during launch and re-entry to prevent damage. Since the aperture is stored separately, the first step when activating the COAS is to instal' this star-sighting aid. The COAS is mounted in either the port forward window (W3) or the starboard overhead window (W7), which are designated the +X and -Z positions, respectively. Mounting the COAS in the +X position requires an adapter plate which is stored separately from the COAS. Before connecting the COAS cable, the COAS power toggle switch on panel 01 (+X) or 019 (-Z) is verified to be in the OFF position. After connecting the power cable, the power toggle switch is placed in the ON position to verify that the light bulb illuminates. Power is then turned off until needed. Window shades and filters may also be installed if required to eliminate or subdue incident external light which may adversely affect COAS observations.

4.3 NOMINAL ALIGNMENT/CALIBRATION

The nominal IMU/ST/COAS procedures, as presented below, will be part of the Orbit OPS Checklist and may be used at any time during orbital flight. The procedures are described in detail to provide insight into their development.

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4.3.1 IMU ALIGNMENT - S TRK

IMU's will normally be aligned using the following procedure during OFT flights. The procedure provides for the alignment of one, two, or all three IMU's using one or both S TRK's in the auto star-select submode to obtain data on specific stars by holding the vehicle at a predetermined inertial attitude.

IMU ALIGNMENT - S TRK, GNC 201, 301

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C3 (A6U) (A6U) (A6U) CRT /S TRK -Y,-Z: REQD ID, ITEM 11,12 - 0 STATUS - (no BITE) SHUTTER - OP * If SHUTTER - CL: * * /Att - correct * * MAN OP - ITEM 15(16) EXEC *

√S TABLE CLR, ITEM 20 - (no unwanted data)

The S TRK's and IMU's will have been activated prior to beginning this procedure. An attitude maneuver will have been executed to position the vehicle so that a catalog star will be within the Field-of-View (FOV) of each S TRK.

The vehicle Digital Autopilot (DAP) will be set for maintaining the required inertial attitude to within <u>+1</u> degree. After calling SPEC 22, S TRK/COAS ONTL, the crew verifies that the required star identification numbers for the two S TRK's are set to zero. This ensures that the auto star-select mode of operation will be entered. If the ID's are not initially zero, the crew must place the S TRK's in the S TRK mode. The S TRK Subsystem Operating Program (SOP) will command the manual starselect mode for one cycle (~1 min) at the end of which the S TRK's will return to TERM/IDLE and the RECO ID's will zero. The crew also verifies that there are no BITE indications for the S TRK's and that the shutters are open. If the shutters are closed, the crew verifies that the attitude is correct. The crewmen should manually open the closed shutters only after verifying the vehicle attitude (visually verify the attitude if the shades are not installed) to ensure the tracker is not looking at the Sun.

The status of the S TRK is monitored while trying to obtain star data. An OUT FOV indication may be seen if the vehicle attitude is wrong or the attitude deadband is too large. HI RATE is an indication that the angular rate of the vehicle may be too high. A FALSE TK indication means that the S TRK tracked on something that was not stationary in space; i.e., probably tracked on debris. A NO STAR indication will be displayed if software has determined that a NAV star should be visible and the S TRK cannot find a star to track. The latter may be due to debris or other matter blocking the S TRK FOV. A BITE status could be due to a failure detected in either the S TRK itself or in the transmissions between the S TRK and the PC's.

The star table is checked for unwanted data entries obtained while the S TRK's we e configured for automatic star data gathering. Star data obtained it the automatic mode, while in any attitude other than designated IMU alignment attitudes, is unacceptable for use on nominal OFT IMU alignments. his is due to the very lenient I-loaded tolerance values (ref.

paragraph 3.2). However, randomly obtained star data may be used in certain contingency situations where Reaction Control System (RCS) consumables need to be conserved. For two S TRK operations, the table should be cleared of all entries. For one S TRK operation, the table should be cleared the first time through this step only. The table will then retain data on the first star when setting up to obtain data on the second star. 3

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STAR TRK: ITEM 3,4 EXEC (*) √S TABLE: TRK ID 1,2 - (correct #'s) ANG ERR 1 - <.09,Rcd _.__ SEL, ITEM 17,18 - (*)

+	If no data after 3 min or bad data:	*
<u> </u>	11 110 Gala al CCI o min of our about	*
×	VALT/Stars/MEI = Correct	*
*	$\sqrt{Rot Rate} = \frac{\sqrt{50 eg}}{\sec}$	
*	\sqrt{S} TRK -Y, -Z: TRK ID - (correct #)	*
*	AANG - <1.0	*
+	If proceding checks are good:	*
	The preceding checks are good then	*
*	Perform S IKK SELF IESI, 0-5, chen	
*	If both STATUS - ST FAIL	
*	I Inform MCC before proceeding	*
	TE LOAD STATIN - ST PASS	*
×	IT DOLA STATUS - ST TASS	*
*	Repeat Step 1 at new att, stars	
*	if one STATUS - ST PASS	*
.	/S TARLE. TRY ID 1(2) - (correct #) *
*	YS MDLL. (KK ID I(L) (00) + 000 (x)	′ *
*	TERM/IDLE, ITEM 9,10 - (^)	
*	Do not clear S TABLE	*
+	Move to new att. star	*
	Filly to new acts star	v *
*	Repeat Step I with good S INK ON	J

The crew puts the S TRK into the S TRK mode and watches the star table for input of the specified star ID's. The ID's should appear within three minutes if the vehicle is in the correct attitude at the proper Mission Elapsed Time (MET). If after three minutes, no data or bad data have appeared in the table, an integral contingency procedure directs the crew to verify attitude, stars, MET and rotation rate. If these are all correct, or reasonable, the crew performs a self-test on both trackers. Based upon the results of the self-test, the crew will then proceed with an alternate dual S TRK IMU alignment, a single S TRK IMU alignment, or troubleshooting per MCC direction. The attitude and star information for any of these contingency cases will either be requested from the MCC or obtained from data provided in the FDF.

An '*' will appear in the Star Present (S PRES) line when the S TRK detects a star or illuminated object. The TRK ID number will tell what star the STRK SOP star catalog has listed for that section of the celestial sphere. Although the I-loaded Δ ANG limit is set at 1.4°, a value greater than 1.0° could be indicative of a bad sighting. Zero is the most sensitive T HOLD value and it is also the default value.

The crewman checks the track ID's to ensure that they are the same as the specified ID's. Unless the procedure was interrupted, the elapsed time (∆MIN) since the sightings will be miniscule and need not be checked.

The acceptance criterion is a maximum allowable angular error (ANG ERR) of 0.09° as computed by the STRK SOP. This value is based on 3-sigma S TRK's and 1-sigma selected IMU performance. Since there will be only two stars in the star table and these stars were chosen to fall within the I-loaded star separation angle requirements ($90^{\circ} + 55^{\circ}$), the S TRK SOP will select these stars for use in the alignment ('*' driven beside items 17 and 18).

2 CHECK IMU DANGS

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CAUTION
If ANG ΔX , ΔY or ΔZ still >.80
for or more IMU's:
DO NOT TORQUE PLATFORMS EXCEPT
INDER MCC INSTRUCTIONS

After calling the IMU align display, the IMU's are checked for status. Since the Star-Align (Item 13) alignment option is the default mode, no crew action other than verification should be necessary. Misalignment angles (ANG ΔX , ΔY , ΔZ) are computed for each IMU in OPERATE. The given acceptable misalignment value (0.8°) is lenient and is based on 3-sigma S TRK operation with 3-sigma IMU drift (.06 deg/hr) over the longest expected time period between alignments. If two IMU's show misalignment angles exceeding the limit, there is a possibility that the star data is bad. (S TRK accuracy is discussed in paragraph 2.6.2.) The crew should obtain new star data and try once again before notifying the ground. The crew will not torque platforms which exceept the maximum misalignment until the ground has time to determine possible cause and consequence.

3 ALIGN IMUS

ALIGN IMU 1(2,3) - ITEM 10(11,12) EXEC EXEC - ITEM 16 EXEC, Rc MET / : /Data transcribed into C/P (or UPDATES BOOK) /EXEC, ITEM 16 - (no *)

The crewman selects the IMU's to be aligned by executing the appropriate item number. Torquing signals to actually move the platform(s) are initiated by executing Item 16 (EXEC). Torqu ng initiation can be verified by monitoring the misalignment angles (ANG ΔX , Δ^{\vee} , ΔZ) of the selected

IMU's. The sample rate for these angles is 0.5Hz and the torquing rate is 0.417 deg/min; therefore, extremely small incremental value changes should be evident until the ANG ΔX , ΔY , ΔZ values are zeroed. However, the changes in ANG ΔX , ΔY , ΔZ values do not reflect actual platform movement but are simply mathematical computations based on torquing rate and elapsed time. In addition to the misalignment angles driving to zero, the absence of the Enable (ENA) indication after the word ALIGN and the absence of the '*' after EXEC 16 are indications that platform torquing has been completed. If the '*' behind EXEC 16 does not blank, the crewman will terminate the alignment manually and contact the ground for assistance.

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Although the crew is instructed to watch the IMU alignment display until realignment is completed, the torquing will continue until completion even if the display is dismissed.

NOTE

VERIFICATION: If required, repeat Steps 1 and 2 at prescribed attitude. If ANG $\Delta X, \Delta Y$, or $\Delta Z > .1$, repeat Step 3 and notify MCC

The CAP will provide guidance at this point. If the alignment is considered critical the crew will be directed to perform an alignment verification. The verification attitude given in the timeline will normally permit sighting on two stars other than those used for the alignment. This will force the IMU platforms to move relative to their housings. The resolver data used in the verification will therefore be considerably different than that used in the initial alignment. This minimizes the chance of having alignment errors due to hardware or software attitude-dependent sensitivities. The crew repeats step 1 and collects new star data. In repeating step 2, IMU misalignment errors are verified to be less than 0.1°. This value is based on 3-sigma S TRK's and 1-sigma selected IMU (with no drift). It will provide the required accuracy (0.26°) for major burns until the next scheduled alignment. If any misalignment angles exceed 0.1°, the crew is directed to repeat step 3 and realign the IMU's.

4 S TRK AUTO STAR-SELECT

CRT ✓S TRK -Y(-Z): REQD ID, ITEM 11(12) - 0 S TRK - ITEM 3(4) EXEC (*) ✓Shutter not MAN OP, ITEM 15,16 - (no *)

If the CAP calls for the S TRK's (either or both) to obtain data for downlink to the ground, the crewman will continue. The crewman recalls the ST/COAS CNTL display and verifies that the required ID's (Items 11 and 12) have reset to zero and that the S TRK's are placed in the OPERATE mode via Items 3 and 4 (STAR TRK).

The S TRK's will gather data on navigation stars in the STS catalog which come into the FOV if I-load criteria are met. The star data gathered will be stored in the star table of the S TRK SOP. The S TRK software will automatically select two sets of star data when available and transmit these data to the IMU alignment software for computation of IMU misalignment angles. Although these misalignment angles will not be used to align the IMU's, the data will be made available through telemetry to the ground for general monitoring of S TRK and IMU health.

4.3.2 COAS Calibration

The COAS LOS variation from the Orbiter axis must be accurately known to perform even coarse alignments. Since the COAS is bracket-mounted and transferable between two positions the COAS Δ BIAS must be calibrated for each position to account for variations in brackets. A flow diagram of the procedure is given in figure 4-3. The COAS calibration computes a bias from the Orbiter axis (+X or -Z, as appropriate) to be applied by the GPC to sighting data when the COAS is used. This calibration is completed as early in the flight as possible to take advantage of the preflight IMU alignments to support early deorbit if required. The COAS is unstowed, mounted at each station one at a time, and calibrated for that station by storing a calibration bias in the GPC.

It is assumed that the IMU's and COAS have been activated. The CAP directs the maneuver to the proper attitude to begin the COAS calibration.

COAS	CALIBRATION, GNC 201, 301
01	1 <u>COAS CALIBRATION PREP</u> COAS - ON
COAS	$\sqrt{Barrel Index - FW(OW)}$ <u>GNC 20 DAP CONFIG</u> $\sqrt{Barrel Index - FW(OW)}$ $\sqrt{Barrel Index}$ $\sqrt{Barrel Index}$ $\sqrt{Barrel Index}$ Barr
CRI	DAP A(B) COMP VERI - THEN (2-) OF E
Select Ta DAP A(B)	X COAS WITH PRCS
F6 (A6U)	<u>GNC 22 S TRK/COAS CNTL</u> COAS: REQD ID - ITEM 21 + EXEC POS +X(-Z) - ITEM 26(27) EXEC (*) CAL MODE - ITEM 24 EXEC (*) FLT CNTLR PWR - ON

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COAS power is provided by a switch on either overhead panel 019 (-Z) or O1(+X). The COAS barrel must be rotated to the correct position by pulling out on the knurled knob and aligning the barrel index with the appropriate hash mark. On SPEC 20, DAP CONFIG, a rotational compensation value of 0.003 is entered for use with the vernier jets. This allows for more precise vernier jet control by virtually eliminating rotations in non-command axes.

The S TRK/COAS CNTL display is configured for COAS calibration by designating the required star (star ID number given in the FDF), the position being used, and the Calibration (CAL) mode. Execution of Item 24 (CAL MODE) assigns the Attitude Reference (ATT REF) pushbuttons to the COAS/star mark function. 1

If the calibration is being performed at the +X (forward) station and the primary RCS is being used, the upward firing forward jets should not be used. The plumes from these jets firing could distract a crewman's sight as he marks on a star. All forward jets are deselected by using the tail-only option for attitude control.

> 2 <u>MARK ON STAR</u> C3 DAP: as required for precise manual mnvr (A6U) Mnvr to center star in COAS: F6 ATT REF pb - push (A6U) NOTE

Repeat mark to ensure $\Delta BIAS$ consistency

(C3) DAP ROT: DISC/DISC/DISC (A6U)

The DAP is configured for manual control and the Orbiter is manually maneuvered to center the star in the COAS. The COAS/star position is marked for the GPC by pressing the ATT REF push button when the COAS is centered on the star. This marking of the COAS/star position may have to be repeated until the crewman is confident that the star was centered in the COAS when the mark was made. Each successive mark overrides the previous mark so there is no limit to the number of times a mark is attempted. It is recommended that enough marks be taken to ensure Δ BIAS consistency. The DAP is configured to discrete rate to maintain the desired inertial attitude.

CRT 3 <u>CALIBRATE COAS AND VERIFY</u> Rcd CAL -Z(+X) ∆BIAS: UPDATE - ITEM 28(29) EXEC, RCD MET _/__:___ √∆BIAS goes to zero

The crew records the change in bias (Δ BIAS) from the previous bias value for future ground use. Item 28(29) directs the GPC to add the Δ BIAS to the stored value for the +X(-Z) COAS Line-of-Sight (LOS). The software changes the Δ BIAS to zero to indicate that the operation is completed.

> Repeat 'MARK ON STAR' √∆BIAS <.12

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* If ΔBIAS >.12, repeat step 3 * * If still >.12, notify MCC * A calibration verification is performed to ensure that the bias is as accurate as can be expected. The acceptable Δ BIAS value for verification is based on a 3-sigma equipment accuracy, nominal visual acuity, and nominal eye-hand response time. If a Δ BIAS less than the specified value cannot be obtained by repeating the calibration procedure twice, the crew should contact the ground for further directions.

4 <u>CLEAN-UP</u> <u>COAS:DES</u> - ITEM 25 EXEC (*) <u>|GNC 20 DAP CONFIG</u>| DAP A(B) COMP, VERN - ITEM 7(21) +.0 0 0 EXEC

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> NOTE If S TRK(s) to be left in auto star-select mode, go to IMU ALIGNMENT - S TRK, 6-3, Step 4

The COAS calibration mode is deselected and the ATT REF pushbutton returned to its primary function by executing ITEM 25 (DES). On SPEC 20, the DAP to load A(B) vernier compensation value is set back to .000. Power is removed from the COAS and from the RHC until it is needed. If the S TRK's were not in TERM/IDLE mode when the CAL mode was selected, the deselection will have automatically placed them in that mode if they are powered. The crew then configures the S TRK for automatic star data gathering until needed to support an IMU alignment.

4.3.3 IMU Accelerometer Calibration

Bias is applied to the accelerometers' output to compensate for variations in the equipment and operating environment (friction, thermal gradients, g-loading, etc.). This bias is checked for accuracy by the ground using downlinked data at scheduled times during orbital flight. The check is made with the vehicle in a quiescent (non-accelerating) attitude while over a Telemetry (TM) receiving station. Normally, this calibration will be done during a crew sleep period and thus not require crew participation. If an awake period calibration is desired, the Mission Control Center (MCC) w 11 call out the time to begin this procedure so that vehicle moticns will be dampened at ground station Acquisition of Signal (AOS).

IMU ACCELEROMETER CALIBRATION, SM 2 //

- 1 ESTABLISH FREE DRIFT /Rot Rate <0.1º/sec L1 FLASH EVAP CNTLR PRI A,B (two) - OFF C3 DAP ROT: PULSE/PULSE/PULSE DAP: A/MAN/VERN Prepare to remain still for ~6 minutes after AOS
 - 2 AT AOS

Inform MCC you are configured for IMU CAL Remain still until MCC reports CAL completed 1

The rotation rate is verified to be less than 0.1 deg/sec to delete the possibility of centripetal acceleration causing unwanted biases. The Flash Evaporator System (FES) will be turned off during the calibration procedure to prevent acceleration (thrust) caused by flash evaporator operation. The DAP is configured to put the vehicle into free drift. The flight crew will attempt to avoid any sudden motions and any manual vents which might cause accelerations from AOS until MCC notifies them that the ground has sufficient data or until LOS. The ground crew will monitor and record output data from the IMU's velocity counters.

Ground station coverage will be scheduled for at least 320 seconds. Although TM data for the entire 320 sec period are desirable, bias calibration data can be obtained in a shorter period of time.

3 VEHICLE RECOVERY AND F	<u>ES RESTART</u>
DAP ROT: DISC/DISC/DIS	<u>C</u>
ISM 88 APU/ENVIRON THE	RM

L1 If EVAP OUT TEMP <47 L1 RAD CNTLR OUT TEMP - HI WHEN EVAP OUT TEMP = 50 + 2 Or FLASH EVAP CNTLR PRI A(B) - ON RAD CNTLR OUT TEMP - NORM If EVAP OUT TEMP >47 L1 FLASH EVAP CNTLR PRI A(B) - ON

The Orbiter is then returned to a nominal flight configuration. The DAP is placed in attitude hold by changing to the discrete rotation rate mode. A crewman calls SPEC 88, APU/ENVIRON THERM, to monitor the FES evaporator output temperature. The FES is reactivated if the evaporator output temperature is greater than the 470 F required for restart. If not, the radiator controller outlet temperature is set to the High (HI) position to bring the temperature up. When the temperature is about 570, the FES is reactivated and the radiator controller outlet temperature is set back to the normal (NORM) position.

4.3.4 IMU ALIGNMENT - IMU/IMU

This procedure assumes that at least one IMU is sufficiently aligned to serve as an inertial reference for computing misalignment angles in the other IMU's. It will be used if the IMU's are to be aligned to the desired REFSMMAT without obtaining star data, or if the misalignment angles exceed 1.0°. It is especially useful if an IMU has been powered down or if new REFSMMATS are uplinked.

IMU ALIGNMENT - IMU/IMU, GNC 201, 301
$\begin{array}{c c c c c c c c c c c c c c c c c c c $
$\Delta Y()_{}()_{}()_{}()_{$
ΔΖ() ALIGN IMU T(2,3) - ITEM TO(11,12) EXEC (*)
<u>CAUTION</u> Do not select ref IMU for realignment

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EXEC - ITEM 16 EXEC (*), Rcd MET _/_ _:_ _

✓DATA transcribed into CAP (or UPDATES BOOK) ✓EXEC, ITEM 16 - (no *)

The IMU believed to have the best alignment is selected by the crewman to be the reference IMU. Misalignment angles are calculated and displayed for all operating IMU's.

Slewing signals to move the platform 1.2 deg/sec will be initiated when Item 16 is executed. The time of execution is recorded for ground use in postflight evaluation. The displayed angles for the IMU's being aligned will decrease to indicate how the IMU platform should be moving toward the new orientation. The incremental changes in the misalignment angles and the displayed values will not be uniform. Although the sample rate for the display is 0.5 Hz, the actual update rate depends on the absolute value of the misalignment. The update rate while the platform is slewed varies from once every 20 sec when the misalignment angle is computed to be greater than 32° down to once every 0.3 sec when the misalignment should have decreased to 2°. There will be a 40 sec interval without an angle update as the LAT function slews past the desired position and back again to eliminate the slew-direction sensitivity. After this 40 sec period, the angles will be updated at the 0.5 Hz sample rate as the platform is moved to the final position. The remaining misalignments are zeroed out at the digital torquing rate of 0.417 deg/min applied for a maximum of

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<u>NOTE</u> Align will require 3 to 6 min

160 sec. Note that the misalignment angle values during torquing are computed values and are not measurements showing actual movement. In addition to ANG ΔX , ΔY , ΔZ driving to zero, the absence of the '*' after EXEC 16 is an indication that the alignment is completed. The maximum misalignment (180°) can be zeroed in 6 min.

For early OFT missions, this procedure will be used to accomplish the desired REFSMMAT update scheduled on flight day 1. The MCC will uplink new REFSMMAT's for IMU's 1 and 2. IMU 3 REFSMMAT will not be changed, thereby keeping the platform at the same inertial position throughout the flight. This continuity of position is necessary to protect against loss of attitude determination capability in certain GPC failure cases. IMU 3 was selected as the 'constant' IMU due to powerdown considerations.

4.3.5 <u>S TRK Self-Test</u>

A self-test of the S TRK's will be performed once each flight day. This self-test provides an end-to-end check of the S TRK system.

STAR TRACKER SELF-TEST, GNC 201, 301	
<u>GNC 22 S TRK/COAS CNTL</u> CRT √S TRK -Y,-Z: STATUS - (no BITE) SHUTTER - OP	
<pre>* If SHUTTER - CL, mnvr to avoid bright object in * Do not manually open shutter</pre>	80S
SELF-TEST -Y,-Z - ITEM 1,2 EXEC (*) /S TRK -Y,-Z: SHUTTER - CL S PRES - (*) STATUS - BITE (momentarily) SHUTTER - OP STATUS - ST PASS	Ì
* If STATUS - ST FAIL, repeat * SELF-TEST	k k

* If still FAIL, use only if directed * * by MCC

NOTE

If S TRK(s) to be left in auto star-select mode, go to IMU ALIGNMENT - S TRK, 6-3, Step 4

The crew verifies that there are no BITE indications and that the shutters are open. If either of these verifications proves false, a self-test on the affected tracker will not be possible. If the shutter is closed, the vehicle must be maneuvered so that the bright object causing the shutter to close is no longer within the tracker FOV. Since part of the self-test is to close and open the shutter, manually opening the shutter negates the possibility of performing a self-test.

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One or both S TRK's may be selected for self-test at the same time. However, the S TRK SOP is programmed to run only one test, so the trackers will actually be tested individually in the sequence in which they were selected on the keyboard. It takes a little over 20 sec to test a S TRK. An indication that the test is in progress is a closed shutter. A BITE status will be seen as a result of the self-test circuitry checking the S TRK's ability to detect purposely bad tracking data. The S TRK SOP tolerance for passing the test is so tight that a good S TRK may be declared failed. The test is repeated to confirm the failure. If the S TRK fails twice, the crewman is to contact the ground for assistance.

4.4 CONTINGENCY PROCEDURES

These procedures are contained in the FDF in case one of the nominal procedures cannot be accomplished because of technical or operational requirements.

4.4.1 Matrix Alignment

The specific steps to accomplish the alignment are in the MALF book. This type of alignment is useful when star LOS data is obtainable but the platform misalignment angles are large, and there is no requirement to maintain particular platform attitudes or skewing. A matrix alignment is also useful if a failure makes it impossible to reposition the IMU platform, as it updates the software mathematics and does not require platform movement.

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This procedure requires that star data be obtained through either S TRK or COAS data takes. The data collection steps are identical to those in the nominal procedures. Since circumstances leading to the use of the procedure may be varied, there is nc caution as to misalignment angle magnitude. Upon execution of ITEM 16, the misalignment angles zero immediately. This form of alignment is purely a mathematical alignment and therefore occurs instantly. No platform repositioning occurs.

4.4.2 IMU Alignment - COAS

The specific steps to accomplish the alignment are in the MALF book. The COAS is used to obtain star LOS data when S TRK's are not operational or when the IMU's are misaligned to the point where the S TRK's cannot be used. The IMU's may or may not be sufficiently aligned to use the DAP automatic maneuver option.

Using the COAS to obtain star data for an IMU alignment is similar to obtaining calibration star data with three exceptions. The COAS SIGHT MODE is used instead of the CAL MODE (SPEC 21), the mark must be followed by an 'ACCEPT' entry, and data must be obtained on two stars.

After obtaining data on the first star, the crewman will pick a second star that forms a pair with an LOS separation angle of $90^{\circ} \pm 60^{\circ}$, preferably close to 90° . When at the second star attitude, the Orbiter is maneuvered to sight on the star. Note that the position of the stars in the S TABLE

is not shifted to the right when the COAS is used. The first acquired star will be in position two and the second will go into position one.

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The star data acceptance criterion is an error (ANG ERR) of not more than 0.2° in ANG DIF computed by the S TRK SOP. This acceptance value takes into account COAS calibration accuracy, IMU accuracy, and visual acuity. An '*' should appear beside items 17 and 18 to indicate the stars are selected for use in the alignment. The actual alignment steps of the procedure are the same as if data were obtained with the S TRK(s). The platforms can be torqued to the desired Orientation through use of the Star-Align option or the matrix align option (if circumstances warrant). If the COAS alignment was required because the IMU had drifted too far to allow S TRK data acquisition, a better IMU alignment using S TRK data should follow this course alignment.

4.4.3 One S TRK Star Data Acquisition

Due to S TRK failure, S TRK door failure, or some software anomaly, it may be necessary to obtain star data with one S TRK. The procedure for accomplishing this is contained within the IMU ALIGNMENT-S TRK procedure, section 4.3.1. It is noted here that the Star Pairs cue card discussed in paragraph 4.4.4 of this handbook may be used to pick a star pair for use with either S TRK.

4.4.4 Backup Star Pairs Cue Card

The Star Pairs cue card (fig. 4-4) is an aid provided to the crew in picking star pairs for use primarily in unscheduled normal IMU alignments. It can also be used when obtaining star data in one S TRK data acquisition as described in 4.4.3.

The card is designed so that the day/night markings on the front are the same scale as the day/night of the CAP detailed timeline pages. By aligning the cards day/night scale with that of the CAP, the availability of the star pairs can be determined as a function of MET (figure 4-5).

A representative star pairs cue card (developed for a March 31, 1981, launch) is shown in Figure 4-4. The star pairs on the cue card were chosen to adequately cover the entire orbital period with a small number of star pairs. The availability as shown on the cue card is a minimum value. For any particular orbit the stars may become available earlier, or remain later, than the times designated by the card. For each pair of stars, the availability is given for each star individually. The overlapping time is the pair availability. This time is highlighted by the hack marks and numerical indications of AOS time remaining. The individual star availability is included as an aid in one S TRK or COAS star sightings. In these cases, the crew can begin gathering data on the earliest available star instead of waiting until the pair is available. An ID for each star pair is printed to the right of the pair availability marks and is used to refer to attitude information on the back of the cue card. For each star pair, six attitudes are given on the cue card. Two attitudes are given for the dual star tracker cases (columns A and B). These attitudes reverse the stars in the respective trackers. When using a specific pair of stars, the crew can maneuver to the closer of the two given attitudes, thereby cutting down on maneuver size and saving propellant. Four additional attitudes are given to cover the single star tracker cases (columns A' and B'). For any particular star tracker failure, the crew has four choices for the initial attitude and star. This gives an increased chance of having a rather small maneuver from the current attitude to the initial data take attitude. As an example, for a -Y S TRK failure the initial attitude can be selected from either of the two DUAL S TRK columns (A or B) or from either of the two 2nd ATT -Z columns (one each in A' and B'). After having maneuvered to the closest attitude from the four choices and acquired the necessary star data, the vehicle is maneuvered to the complementary second attitude (A' if A was the initial attitude, B if B' was the initial attitude, etc.). Because these complementary attitudes have been computed to be minimum maneuvers to boresight the star tracker on one star of the pair and then the other, this intermediate maneuver's size will be approximately the same as the ANG SEP between the two stars in the pair.






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Figure 4-5.- Star Pairs cue card with CAP page.

SECTION 5 PROCEDURES DESCRIPTION, STS-2

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5.1 OVERVIEW

This section describes procedures that are especially prepared for verifying the Inertial Measurement Unit (IMU)/S TRK/Crewman Optical Alignment Sight (COAS) systems on STS-2. The results of the flight will determine what activities are to be repeated on subsequent flights and whether the procedures will be modified on a flight-to-flight basis.

These STS-2 flight-peculiar procedures will be discussed.

- o Postinsertion IMU/S TRK/COAS activities
- o COAS verification
- o S TRK Horizon Limit Test
- o S TRK Threshold Verification

Three procedures are in the Orbit Operations (OPS) Checklist and will be repeated in this handbook. The other procedure is in the Postinsertion Deorbit Preparation (PDP) book.

5.1.1 STS-2 Flight Description

The second manned orbital flight of the Space Shuttle will be launched with a two-man crew from Kennedy Space Center. All flight objectives, including verification of the IMU, S TRK, and COAS systems, are to be accomplished during a 103-hour flight. Orbital altitude will be 134 n. mi. with an orbit inclination of 38.0° .

5.1.2 <u>Hardware/Software Configuration</u>

The Orbiter to be flown on STS-2 (OV-102, Columbia) will have three operational IMU's to support Guidance, Navigation, and Control (GNC) functions. Star sighting instruments used to obtain star Line-of-Sight (LOS) data for IMU alignments will be two S TRK's and a COAS. A second COAS will be flown to verify payload bay door closure but will not be configured for star sightings. The software used for IMU alignments on STS-2 differs slightly from STS-1 and will be further modified for subsequent flights.

5.1.3 Flight Test Purpose and Objectives

One purpose of the flight is to verify the in-flight performance of the IMU's. The flight will also demonstrate normal alignment capabilities and verify the backup alignment capabilities.

The STS-2 IMU/S TRK/COAS activities will satisfy the following Functional Test Objectives (FTO) as presented in the STS Flight Requirements Document (JSC-10782).

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- A. COAS Calibration: Demonstrate COAS calibrations (as soon into orbital flight as possible for -Z position) to verify the on-orbit calibration capability and to provide the data necessary to perform a backup COAS/IMU alignment (FTO 273-01, 03).
- B. COAS/IMU Alignment Verification: Verify the operating capabilities of the -Z COAS as a backup device for loss-of-reference IMU alignments by performing an alignment evaluation (FTO 273-02).
- C. Star Tracker Threshold Level Verification: Operate both S TRK's at each of the four selectable star magnitude threshold detection levels (FTO 273-07).
- D. Star Tracker Horizon Limit: Verify the S TRK subsystem performance by determining its ability to track a star whose elevation angle is less than 20 degrees above a sunlit Earth horizon (FTO 273-11).
- E. Star Tracker Performance: Verify the S TRK subsystem performance by determining its ability to track within limits of the Sun and its ability to perform an alignment while the vehicle is rotating (FTO 273-12).
- F. COAS Calibration Verification: Perform a -Z COAS calibration three times during a single night pass to determine thermal effects and verify initial calibration (FTO 273-06).
- 6. Star Tracker/IMU Alignment Verification: Operate the S TRK's to acquire and track catalog stars and determine the angular difference between the measured position and the GPC computed position based on a ground aligned IMU (FTO 273-05).

5.1.4 Functional Test Objective Schedule

The IMU/S TRK/COAS FTO's for STS-2 will be satisfied concurrently with other activities with the exception of the COAS verifications (FTO 273-02 and FTO 273-06). Procedures to satisfy these two FTO's have been combined and scheduled as a special test during a single night pass. The time when data for each FTO will be obtained is indicated in table 5-1.

Table 5-I.- FUNCTIONAL TEST OBJECTIVE SCHEDULE ON STS-2 (Assumes Sept 30, 1981 launch date)

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I FTO I Number I	Title	Scheduled (DD/HH:MM) MET
FT0 273-01	Aft COAS calibration	3/22:10-3/22:22
FT0 273-02	Aft COAS/IMU Alignment Verification (Procedure integrated with that for FTO 173-06.)	4/09:52-4/10:35
FT0 273-03	FWD COAS Calibration	! ! Post Insertion !
FT0 273-05	Star Tracker Alignment Verafication	! ! Post Insertion !
FT0 273-06	Aft COAS Calibration Verification	! ! 4/09:52-4/10:35 !
FT0 273-07	! ! Star Tracker Threshold Test. !	! 0/21:55-1/22:00
FT0 273-11	! ! Star Tracker Horizon Limit Test !	I TBD
FT0 273-12	<pre>! Star Tracker performance ! (Assumed accomplished by data col- ! lected by ground during Passive ! Thermal Control (PTC) using Star ! Tracker Auto Track Mode. No spe- ! cial activity has been scheduled.) !</pre>	

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5.2 POSTINSERTION ACTIVITIES

The postinsertion IMU/S TRK/COAS activities will determine the IMU's capability to support a nominal flight plan. IMU alignment accuracy and ability to maintain the accuracy are part of the criteria for continuing the flight beyond the first few orbits. Specific IMU alignment constraints for continued flight were discussed in section 3.4 of this handbook.

Data to satisfy two of the FTO's will be obtained in conjunction with the postinsertion activities. These FTO's are as follows.

- o Forward COAS calibration capability
- o S TRK alignment verification

5.2.1 Procedures, General Comments

The procedures for performing the postinsertion activities are contained in the PDP. This Flight Data File (FDF) article also denotes the time during the flight when each activity is to be performed. The PDP provides the flight crew with sufficient guidance to accomplish required tasks without ground contact or reference to another document.

The procedures in the PDP are basically adaptations of those in the Orbit OPS Checklist as presented in section 4 of this handbook. The individual steps will be discussed but not repeated in this section.

5.2.2 COAS Calibration

The COAS will be calibrated as soon as possible after launch to provide a backup alignment capability using a ground aligned IMU as reference before the IMU gyro restraint drift degrades the inertial alignment accuracy. Assuming a nominal launch, the COAS calibration will be the first step of the IMU/S TRK/COAS postinsertion activities, since the allotted time begins during orbital darkness. If the schedule changes to begin the tasks during orbital daylight, the S TRK will be checked first.

The COAS is calibrated in the same manner as discussed in paragraph 4.3.2.

5.2.3 Desired REFSMMAT Update

The REFSMMAT's are updated during the postinsertion activities (02:40 MET) so that the entry skew values for IMU's 1 and 2 will be aboard when the contingency (freeze-dried, FD) GPC is refrozen after the OMS-4 burn (07:10 MET). Since IMU 3 REFSMMAT's are the same for both the ascent and entry skews, this procedure makes all three IMU's available in case the FD GPC is needed.

If the FD GPC is not activated and refrozen after the REFSMMAT's are updated, the FD GPC would still have the ascent REFSMMAT's after IMU 1 and 2 were aligned to the entry REFSMMAT's. Then, if a contingency required use of the FD GPC, IMU 1 and 2 would have to be deselected to prevent them from overriding IMU 3 and providing erroneous attitude data.

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5.2.4 Check S TRK's

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A self-test is performed primarily to provide data to determine acceptability of subsequent star sighting data. If an S TRK (or even both star trackers) fails the self-test, the crew will repeat once and then simply note this fact for future reference. A failure to pass the self-test will not in itself preclude future use of the S TRK's.

The S TRK door openings are timed to determine whether the motors, actuating mechanisms, and feed-back circuitry are working properly. If the S TRK door opening time exceeds that required for one motor operation, the proper switches will be repositioned to eliminate power to the motors.

5.2.5 <u>S TRK Data Acquisition</u>

The PDP will provide star ID's for obtaining sighting data in the auto star-select S TRK mode. The goal is to obtain sighting data on two stars with a measured separation angle within 0.09° of the actual separation angle.

If ANG ERR exceeds 0.090 on the first set of star sightings, additional sightings will be made to exclude the possibility of having tracked an erroneous light source and/or to isolate a bad S TRK. If one of the S TRK's previously failed the self-test, it will be declared failed at this point and no longer used in postinsertion activities. (At a later point in the flight, malfunction procedures will be conducted to determine if this S TRK will be used for IMU alignments for the remainder of the flight.) Without clearing the star table, the crew will maneuver as required to obtain sighting data on two additional stars comprising a new star pair. The star table will still retain data on one star in the old pair. The star pairs will have been selected so that any combination of the four stars can be used for an alignment. The crew will select the pair with the smallest ANG ERR, overriding the S TRK SOP selection if necessary. This value may still exceed 0.090 but will be used to determine IMU misalignment angles before further judgment on the S TRK's.

5.2.6 INU Alignment

Using the star sighting data obtained, the IMU's will be aligned to verify this capability. The IMU Star-Align option will compute misalignment angles (ANG ΔX , ΔY , ΔZ) for all three axes of all three IMU's. The misalignment angles for IMU 3 will be compared with the following established criteria to determine if the S TRK sighting and software processing is working properly. The criteria are based on the IMU's preflight alignment and expected performance, including a maximum 3-sigma platform drift in the elapsed time since that alignment.

MET	ΜΑΧ
(HR:MIN)	ΔΧ,ΔΥ,ΔΖ
2:15 - 3:15	0.12
3:15 - 4:00	0.13
4:00 - 4:45	0.14

If the preceding is "GO", the IMU's will be realigned. If the misalignment angles exceed the values given, there is a possibility that the star data is bac, rather than that the IMU has excessive gyro drift. For this reason, new star sightings will be made. When using two S TRK's, if one of them failed the self-test (but still provided star separation data with ANG ERR less han 0.09°), it will be declared failed at this time and no longer used. Using one or two star trackers, new star sighting data will be obtained and the misalignment angles checked again. If the angles are still too large, the crew will look at the data from the previous sightings and declare the star tracker with the largest Δ ANG, bad. If both S TRK's have failed at this point, the crew is to call MCC for further direction.

5.3 COAS VERIFICATION

This Orbit OPS Checklist procedure is simular to STS-1 and satisfies two FTO's.

o Aft COAS/IMU Alignment Verification o Aft COAS Calibration Verification

The FTO's have been combined to obtain the necessary data in the minimum amount of time with minimum fuel expenditure. A procedural flow diagram is shown in figure 5-2. The Aft COAS/IMU alignment verification requires sighting data on two stars and IMU Subsystem Operating Program (SOP) determination of the IMU misalignment (ANG ΔX , ΔY , ΔZ) based on +X COAS obtained sighting data. The IMU's will not be actually aligned. The Aft COAS calibration verification requires three COAS Δ BIAS readings evenly spaced during an orbital night pass to determine thermal effects (cabin deformation) on the +X COAS LOS stability.

An IMU Alignment - S TRK procedure will have been completed immediately preceeding this special test. A maneuver will have been completed to place a catalog star along the +X COAS line of sight. The Crew Activity Plan (CAP) will designate the time to begin this test to ensure proper day/night vehicle transition.





Figure 5-1.- COAS verification FTO flow chart.

COAS VERIFICATION (FTO 273-02 and 06, GNC 201)

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1 019 (01) COAS CRT	COAS CALIBRATION PREF COAS PWR - ON VBARREL Index -OW ! <u>GNC 20 DAP CONFIG</u> ! DAP A(B) COMP, VERN ITEM 7(21) +.0 0 3 EXEC If +X COAS WITH PRCS
•	Select Tail only control DAP A(B) JET OPT P - ITEM 12(26) +3 EXEC . Y - ITEM 13(27) +3 EXEC .
	ICOAS: REQD ID - ITEM 21 + EXEC POS -Z - ITEM 27 EXEC (*) CAL MODE - ITEM 24 EXEC (*)
A6U (F6) A6U (C3)	FLT CNTLR PWR - ON 2 <u>MARK ON STAR</u> (Sunset) DAP: as required for precise manual mnvr Mnvr to center star in COAS:
(F6)	ATT REF pb - pusn <u>NOTE</u> Attempt to get mark as soon as possible aft≩r entering darkness. Repeat mark to ensure ∆BIAS con- sistency
CRT	3 <u>CALIBRATE COAS</u> Rcd CAL -Z(+X) ABIAS: (Sunset)

RT Rcd CAL -Z(+X) ABIAS: ____ (Sunset) UPDATE - ITEM 29 EXEC, RCD MET _/_ _:___ ABIAS goes to zero

The only differences between this part of the COAS verification test and the nominal COAS calibration procedures (paragraph 4.3.3) are the crucial need of a calibration mark as near to orbital sunset as possible and the omission of a verification sighting. The purpose is to provide a baseline data point showing the -Z COAS location relative to the -Z body axis when the Orbiter structure is warmest due to solar heating. The crew will begin trying to visually acquire the star while still in daylight and complete the calibration before eaving the penumbra. Note that the COAS position bias is updated in t is part of the procedure.

A COAS/IMIL ALIGNMENT VERIFICATION PREP
S TABLE CLR - ITEM 20 EXEC SIGHT MODE - ITEM 22 EXEC (*)
5 <u>1ST ALN VER TAKE</u> A6U Repeat 'MARK ON STAR' (C3) DAP ROT: DISC/DISC/DISC CRT COAS: ACCEPT - ITEM 23 EXEC _V S TABLE: TRK ID 2 - (REQD ID)
<u>CAUTION</u> Do not deselect COAS SIGHT ! mode between sightings
6 <u>AUTO MNVR TO 2ND ATTITUDE</u> Mnvr to 2nd star attitude (given in CAP).
7 <u>2ND ALN VER TAKE</u> <u>!GNC 22 S TRK/COAS CNTL</u> ! CRT COAS:REQD ID - ITEM 21 + EXEC A6U Repeat 'MARK ON STAR' (C3) DAP ROT: DISC/DISC/DISC CRT COAS: ACCEPT - ITEM 23 EXEC _/ S TABLE: TRK ID 1 - (REQD ID)
8 <u>EVALUATE STAR DATA</u> S TABLE: ANG ERR 1 - <.2 SEL, ITEM 17,18 - (*)
9 <u>CHECK IMU MISALIGNMENT ANGLES</u>
$\begin{array}{cccccccccccccccccccccccccccccccccccc$
ΔΥ()()()
ΔΖ()()()

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Using the same star previously used for COAS calibration, the first sighting for COAS/IMU alignment verification is made without a major maneuver to a new attitude. The star table is verified to be clear of data. This assures that star data used for calculating IMU misalignment angles has been gathered using the COAS. The COAS SIGHT MODE is selected so that COAS marks are used to compute IMU misalignments rather than COAS ABIAS. A mark is taken on the star and is accepted as the first sighting for the COAS IMU alignment verification. A maneuver must be made to obtain sighting data on a second star. This star will be used for all remaining star sightings. The maneuver and steps 7, 8, and 9 are essentially the same as in the COAS/IMU alignment procedure discussed in paragraph 4.4.2 of this handbook. However, note that the alignment execution is omitted. The purpose is to obtain the sighting data and IMU platform misalignment angles for comparison with the S TRK/IMU alignment performed just prior to this test. ٢

It is important that the required data be obtained as quickly as possible as the following step (10) in this procedure is time critical. No further large maneuvers are required.

The steps in this part of the procedure provide a Δ BIAS reading indicative of any change in -Z COAS position incurred during the time since the vehicle structure began cooling down. The data points are to be at orbital midnight and at sunrise. The time for the sighting will be indicated on the CAP timeline. The COAS position bias is not updated regardless of the magnitude of a Δ BIAS.

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11 CLEAN UP COAS: DES - ITEM 25 EXEC (*) S TABLE CLR - ITEM 20 EXEC IGNC 20 DAP CONFIG! DAP A(B) COMP, VERN - ITEM 7(21) +.0 0 0 EXEC If +X COAS WITH PRCS DAP A(B) JET OPT P - ITEM 12(26) +1 EXEC . Y - ITEM 13(27) +T EXEC . ••••• COAS PWR - OFF 019 (01) FLT CNTLR PWR - OFF A6U (F6) /Data transcribed into CAP

> NOTE If ST(s) to be left in auto star-select mode, go to IMU ALIGNMENT - ST, 6-3, Step 4

The COAS mode is deselected at the end of the procedure to return the ATT REF push button to its primary function and to allow use of the S TRK's. The star table is cleared to provide an open table for acquiring stars of opportunity while the S TRK's are in the auto star-select mode. The remainder of the cleanup is the same as for the COAS/IMU Alignment procedure.

5.4 STAR TRACKER HORIZON LIMIT TEST

This procedure satisfies FTO 273-11, which is to determine the S TRK's ability to operate with its LOS close to the Earth's horizon. This ability is more crucial for target tracking than for star data acquisition; however, useful data will be obtained that will be applicable to both modes of S TRK operation. The test will be conducted by intermittently attempting to acquire data on a star as it sets behind the horizon.

S	TRK HORIZON LIMIT TEST (FTO 273-11)
	1 HORIZON TEST PREP
C3	VDAP: A/AUTO/VERN
CRT	S TRK -Y(-Z): REQD ID, ITEM 11(12) - 0 STATUS - (no BITE)
	MAN OP - ITEM 15(16) EXEC (*) STAR TRK - ITEM 3(4) EXEC (*)

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2 <u>STAR TRACK</u>

/S TABLE: TRK ID 1 - (correct #)

Wait 15 sec

S TABLE CLR - ITEM 20 (EXEC)

(Repeat Step 2 as often as req1)

At star LOS,
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MAN OP - ITEM 15(16) EXEC (nc*)

The vehicle and one S TRK are configured about the same as for acquiring star data for an IMU alignment; i.e., DAP in inertial hold and S TRK in the auto mode looking at a selected star. However, the S TRK shutter is put to the manually opened position to prevent reflected light from the Earth from closing the shutter during the test. This preparation activity is done at about 6 min prior to "star set" to ensure an initial acquisition. The selected star (tentatively Merak, ID No. 44) will set at a rate of approximately 4 deg/min. A data point will be obtained at each 15-sec (1.0 deg) interval by clearing the star table. If the S TRK can track at that horizon angle, new data will appear in the star table. The last horizon angle preceding the angle at which data can no longer be obtained will be considered the horizon limit. These data will be available on the Operational Flight Instrumentation (OFC) recorder for post-mission analysis.

The S TRK shutter is released from the manual-open mode after the test is completed.

5.5 STAR TRACKER THRESHOLD VERIFICATION

This procedure will satisfy FTO 273-07, which is to verify the S TRK's magnitude threshold function. The threshold function allows the S TRK to discriminate between bright and dim objects. It is intended to be used primarily for the Target Track mode where the sunlit Earth-orbiting rendezvous target will normally be brighter than many stars. By making the S TRK insensitive to dimmer objects, the search phase of the Target Track mode can be shortened.

S TRK THRESHO D VERIFICATION (FTO 273-07)
1 <u>SET TH)LD AND TRACK STARS</u> C3 VDAP: A AUTO/VERN (A6U) PIGNC 22 S TRK/COAS CNTL! CRT VS TRK -Y(-Z): REQD ID, ITEM 11(12) - 0 STATUS - (no BITE) SHUTTER - OP
* If SHUTTER - CL: * * /Att,MET - correct * * MAN OP - ITEM 15(16) EXEC (*) *

S TRK -Y(-Z): THOLD - ITEM 13(14) +3 EXEC S TABLE CLR - ITEM 20 EXEC STAR TRK - ITEM 3(4) EXEC (*)

After 2 min or when: S TRK -Y(-Z): STATUS - NO STAR, proceed to next threshold level When star acquired go to Step 2

S TRK -Y(-Z): THOLD - ITEM 13(14) +2 EXEC - ITEM 13(14) +1 EXEC - ITEM 13(14) +0 EXEC

2 RECORD DATA AND CLEAN UP

IS TRK	Acquire	THOLD	STAR	ID !	MET
				!	
	· · · · · · · · · · · · · · · · · · ·				
	[! 1	•	
			•		

CRT VS TRK -Y,-Z: THOLD, ITEM 13,14 - 0

The method of verification is to acquire and track three stars of known magnitude at various threshold levels. The vehicle and one S TRK are configured about the same as they are to obtain star data for an IMU alignment; i.e., DAP to inertial attitude hold and S TRK in auto mode looking at a star. However, the S TRK's sensitivity threshold (THOLD - ITEM 3 or 14) is initially set at level 3 to exclude all but the brightest star those whose visual magnitude has a numerical value of +1 or less. If the S TRK can not acquire the star within 3 min, the threshold level is reduced to successively dimmer settings (2, then 1, then 0) until the star is acquired.

The crew will record acquisition data for post-flight comparison with the stars' actual magnitude values. The S TRK sensitivity threshold is left at level 0 after each verification test in order to obtain data on stars of opportunity.

NOTE: Numerical values for visual magnitudes are inversely proportional to brightness; i.e., -1.0 is brighter than +1.0, which in turn, is brighter than +2. S TRK sensitivity threshold levels correspond to visual magnitudes as follows.

THOLD	Visual Magnitude								
0	+3.0 or brighter								
1	+2.4 or brighter								
2	+2.0 or brighter								
3	+1.0 to -7 (BOS level)								

5.6 PRE-ENTRY IMU ALIGNMENT

The pre-entry IMU alignment will prepare the IMU's to support deorbit and entry guidance, navigation and control functions. The procedure is contained in the PDP book. The PDP procedure essentially combines the steps in the normal IMU alignment and alignment verification procedures discussed in paragraphs 4.3.1 and 4.3.2. The one major difference between this alignment and others is that the GPC's have been transitioned to Operational Sequence (OPS) 3. Any maneuver required to point the star trackers at stars to support the alignment will have to be made in the manual maneuver mode since automatic maneuver mode is not available in OPS 3. Any required accelerometer and gyro calibration biases will have been uplinked to the IMU SOP prior to the transition to OPS 3.

APPENDIX

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SUPPLEMENTARY TABLES AND FIGURES

TABLE A-I.- SHUTTLE NAV (50) STARS FOR EARLY OFT FLIGHTS

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•	No.	Name	S2O magnitude	Visual magnitude	Right ascension	Declination
	11	Similar	3 1500	-1.4	100.95	-16.68
	11		1 5000	-0.5945	95.83	-52.68
	12		8610	0.0083	78,28	-8.23
	13	Noga	8030	0.0840	278.75	38.75
\frown	14	Vega	7450	0 1654	210.43	-60.22
	15	Achonnan	6910	0 2471	24.15	-57.38
<i>,</i>	10	Achernar	6670	0 2855	186.23	-62.93
	1/	Acrux	5140	0.5684	78.63	45.97
	18	Capella	5130	0.5705	200.90	-11.00
	19	Ametumus	4880	0 6247	213.58	19.33
	20	Brooken	4770	0 6495	114.43	5.30
	21	Altain	3690	0 9282	297.33	8.78
	22	Rotolgeuse	3080	1,1244	88.33	7.40
	23	Bollatriv	2740	1.2514	80.83	6.32
	24		2690	1.2714	151.70	12.12
	20	Formalhaut	.2670	1.2795	344.00	-29.78
	20	Deneb	2540	1.3252	310.10	45.17
	20	Al Nalir	2050	1.5664	331.58	-47.12
	20	Alkaid	1970	1,6096	206.60	49.47
	29	Antaros	1930	1,6319	246.90	-26.37
	21	Castor	1910	1.6432	113.18	31.95
	22	Aldobaran	1910	1.6432	68.55	16.45
	22	Peacock	1880	1.6604	305.83	-56.83
~ /	20	Mianlacidus	1870	1.6662	138.23	-69.60
	35	Nunki	1830	1.6897	283.35	-26.33
	35	Kaue Australis	1580	1.8491	275.55	-34.40
	27	Alphoratz	1480	1,9201	1.70	28,92
	32	Cib (Navi)	1460	1,9349	13.73	60.55
	20	Albena	.1370	2.0040	99.00	16.43
	۵ <u>۵</u>	Mirfak	.1160	2.1846	50.55	49.75
	40	Denehola	.1120	2,2227	176.88	14.73
	42	Alphecca	.1100	2.2423	233.35	26.82
	47	Rasalhaque	.1090	2.2522	263.38	12.58
	45	Merak	.0960	2.3901	165.00	56.55
,	45	Polaris	.0959	2.3912	30.63	89.13
	46	Phoeda	.0902	2.4578	178.05	53.87
	47	Gienah	.0893	2.4687	183.58	-17.37
	48	Zubeneschemali	.0869	2.4982	228.85	-9.27
	49	Kochab	.0634		222.71	74.36
	50	Avior	.0764	2.6380	125.48	-59.40
	51	Atria	.0740	2.6727	251.38	-63.98
	52	Hamal	.0720	2.7025	31.38	23.32
	53	Menkent	.0714	2.7115	211.23	-36.23
	54	Diphda	.0698	2.7361	10.53	-18.15
	55	Alphard	.0682	2.7613	141.53	-8.53
•	56	Al Suhail	.0540	3.0148	136.73	-43.32
	57	Acamar	.0540	3.0148	44.28	-40.42
\frown	58	Denab Algeid	.0495	3.1093	326.35	-16.27
	59	Scheat	.0473	3.1586	345.58	27.92
~	60	Enif	.0458	3.1936	325.68	9.75



Figure A-I.- IMU Ground Calibration/Alignment timeline for nominal flight.

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20 .	Denebola	Alphecca	: Rasalhague	: Merak	i Polaris	Phoeda	d Gienah	<pre>S Zubeneschemali</pre>	ð Kochab	5 Avior	c Atria	S Hamal	2 Menkent	2 Diphda	ያ Alphard	5 Al Suhail	2 Acamar	🛱 Denab Algeid	G Scheat	0 Enif	
) 4	11	42	43	44	45 	46 	4/ 	48 	49	50 	51 	52 		J4 							
) $\begin{cases} \\ \\ \\ \\ \\ \\ \\ \\ \\ \\ \\ \\ \\ \\ \\ \\ \\ \\ $	31 96 900 901 9033 78 85 35 62 16 87 94 25 61 03 289 11 05 360 75 100 <td>135 139 150 40 89 143 97 104 49 20 113 63 132 137 77 120 62 115 55 98 134 103 105 55 98 134 103 105 54 </td> <td>163 139 173 30 84 117 95 121 66 48 144 159 161 108 85 1 59 42 127 147 78 114 43 42 127 147 78 114 43 85 1 85 1 85 1 85 1 85 1 85 1 85 1 85</td> <td>90 123 95 70 122 159 121 51 74 56 104 76 81 46 153 74 167 26 108 43 80 159 128 127 129 933 61 63 61 43 56 84</td> <td>106 142 98 52 151 147 154 43 102 72 85 81 82 83 78 119 45 137 41 117 125 60 29 73 39 76 64 78 34 </td> <td>96 126 102 65 117 165 117 59 68 44 70 99 84 89 47 154 73 162 18 100 50 88 151 127 120 121 127 120 151 127 120 151 127 120 65 70 67 39 48 77 87 70 65 70 67 39 48 77 154</td> <td>78 75 102 105 47 103 46 113 18 47 72 115 97 104 43 129 128 109 70 59 83 118 92 59 91 82 168 130 33 65 84 130 33 65 84 130 130 33 65 84 130 130 130 130 130 130 130 130 130 130</td> <td>122 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129 126 115 124 27 39 63 30 129 126 118 153 158 82 112 57 50 129 126 118 153 158 158 153 158 158 153 158 158 157 158 158 157 158 158 158 158 158 158 158 158 158 158</td> <td>96 75 117 97 24 86 97 127 126 74 100 120 120 121 126 74 100 120 120 121 126 74 100 120 120 121 126 74 161 52 154 153 117 161 52 154 153 117 161 167 167 167 167 167 167 167 167</td> <td>85 73 66 103 100 41 999 149 158 105 77 81 74 142 27 84 43 146 109 110 67 61 850 884 48 79 94 77 166 140 1107 143 121 836 122</td> <td>$\begin{array}{c} 40\\ 58\\ 62\\ 131\\ 72\\ 97\\ 63\\ 78\\ 58\\ 76\\ 30\\ 156\\ 55\\ 23\\ 136\\ 142\\ 124\\ 81\\ 100\\ 49\\ 76\\ 113\\ 61\\ 129\\ 123\\ 115\\ 49\\ 97\\ 42\\ 95\\ 123\\ 699\\ 70\\ 42\\ 896\\ 52\\ 99\\ 1125\\\\\\\\\\\\\\\\ -$</td> <td>$\begin{array}{c} 40\\ 28\\ 62\\ 151\\ 46\\ 65\\ 34\\ 103\\ 64\\ 94\\ 53\\ 142\\ 67\\ 71\\ 103\\ 175\\ 89\\ 111\\ 85\\ 78\\ 86\\ 79\\ 204\\ 94\\ 141\\ 142\\ 69\\ 113\\ 125\\ 103\\ 125\\ 103\\ 134\\ 103\\ 47\\ 58\\ 117\\ 117\\ 58\\ 117\\ 117\\ 117\\ 117\\ 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TABLE A-II.- SHUTTLE NAVIGATION STAR PAIR SEPARATION ANGLES

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Figure A-2.- Shuttle navigation star map.



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Figure A-3.- Solar star chart Northern Hemisphere.

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